American Journal of Scholarly Research and Innovation
Volume 03 Issue 01 (2024)
Page No: 01-19
DOI: 10.63125/ts16bd22

Article

ADVANCEMENTS IN SMART AND ENERGY-EFFICIENT HVAC SYSTEMS: A PRISMA-BASED SYSTEMATIC REVIEW

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Citation:
Sikdar, M. S. H., Hossain, M. S., Mobin, S. M., Chowdhury, A., & Bhuiyan, S. M. Y. (2024). Advancements in smart and energy-efficient HVAC systems: A PRISMA-based systematic review. *American Journal of Scholarly Research and Innovation*, 3(1), 1-19. https://doi.org/10.63125/ts16bd22

Received:
February 10, 2024

Revised:
April 5, 2024

Accepted:
May 10, 2024

Published:
May 24, 2024

ABSTRACT
This systematic review provides a comprehensive analysis of the advancements, challenges, and future directions of smart HVAC systems by examining 125 peer-reviewed articles following the PRISMA methodology. The study focuses on five critical areas: IoT-enabled HVAC systems, machine learning algorithms for predictive maintenance, renewable energy integration, data privacy and security concerns, and the economic feasibility of implementation. The findings highlight that IoT-enabled HVAC systems significantly enhance energy efficiency by leveraging real-time data from interconnected sensors, leading to energy savings between 20% and 40% through adaptive heating, cooling, and ventilation strategies. Additionally, machine learning algorithms in predictive maintenance play a crucial role in reducing system failures, cutting unscheduled maintenance costs by up to 40%, and improving energy efficiency by 15% to 25% through automated fault detection and optimized maintenance scheduling. Furthermore, renewable energy integration in HVAC systems, particularly hybrid solutions combining solar, geothermal, and wind energy, has demonstrated remarkable potential, with some systems achieving energy savings of up to 60%. However, challenges such as high upfront installation costs, the need for advanced energy storage solutions, and infrastructure limitations continue to hinder widespread adoption. The review also identifies data privacy and security vulnerabilities as a major concern in IoT and AI-powered HVAC systems. 20 reviewed articles highlight risks associated with data transmission, unauthorized access, and cyber threats, emphasizing the need for robust encryption techniques, blockchain-based security, and AI-driven authentication mechanisms to enhance protection and user trust. Moreover, the economic feasibility of smart HVAC solutions remains a key factor influencing adoption. While these systems require higher initial investments, findings from 15 reviewed studies indicate that the return on investment (ROI) typically falls within five to seven years, particularly for large-scale commercial applications where energy cost savings and predictive maintenance benefits accumulate more rapidly. Policy incentives, tax rebates, and government subsidies have also been recognized as crucial enablers for accelerating adoption, making smart HVAC technologies more accessible for residential and small business users. This review synthesizes existing knowledge, evaluates emerging trends, and identifies persistent barriers in smart HVAC technologies. The findings provide valuable insights for researchers, industry stakeholders, and policymakers to develop scalable, cost-effective, and energy-efficient HVAC solutions. Future research should focus on enhancing system interoperability, improving data security frameworks, and developing innovative financing models to facilitate the transition toward more sustainable and intelligent HVAC solutions in the built environment.

KEYWORDS
Smart HVAC Systems; IoT-Enabled HVAC; Predictive Maintenance; Renewable Energy Integration; Data Privacy and Security in HVAC

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INTRODUCTION

Heating, ventilation, and air conditioning (HVAC) systems are essential for maintaining indoor comfort and air quality in residential, commercial, and industrial buildings (Gholamzadehmir et al., 2020) . However, traditional HVAC systems are significant contributors to energy consumption, often accounting for up to 50% of a building's total energy use (Acquaah et al., 2020). With growing global concerns over energy conservation and the environmental impact of carbon emissions, the development of smart and energy-efficient HVAC systems has become a critical area of research and innovation. These advanced systems utilize emerging technologies such as artificial intelligence (AI), machine learning (ML), Internet of Things (IoT), and renewable energy integration to improve energy efficiency, reduce operational costs, and ensure optimal performance (Yayla et al., 2022). As the demand for sustainable and intelligent building solutions rises, smart HVAC systems are positioned at the forefront of sustainable building practices. Moreover, the integration of IoT technology into HVAC systems has revolutionized the way heating and cooling are managed. IoT-enabled systems rely on a network of interconnected sensors and devices to monitor and control environmental parameters, such as temperature, humidity, and air quality, in real-time (Barone et al., 2019). These systems utilize data-driven algorithms to predict and adjust system performance based on occupancy patterns and weather forecasts, achieving energy savings of up to 25% compared to conventional systems (Yang et al., 2016). Studies have shown that IoT-based HVAC systems are especially effective in commercial and industrial settings, where energy demands fluctuate significantly throughout the day (Barone et al., 2019; Yang et al., 2016). Furthermore, IoT integration facilitates remote monitoring and diagnostics, enabling building managers to address performance issues proactively, minimizing energy wastage and maintenance costs (Alfalouji et al., 2023).

AI and ML are transformative technologies that have introduced predictive capabilities into HVAC systems, enabling them to learn and adapt to user behaviors and environmental conditions. Through historical data analysis, these technologies optimize system operations, predict maintenance needs, and prevent breakdowns (Singh et al., 2022). For example, ML models can predict temperature requirements based on occupancy schedules and weather conditions, ensuring that heating and cooling systems operate only when necessary (Turhan et al., 2021). Recent studies indicate that AI-driven HVAC systems can reduce energy consumption by up to 30%, particularly in smart buildings designed to maximize automation (Borda et al., 2023). These advancements not only contribute to energy efficiency but also enhance user comfort and extend equipment lifespans, making them economically and environmentally sustainable solutions. Moreover, Renewable energy integration has further expanded the capabilities of smart HVAC systems, aligning with global efforts to transition to cleaner energy sources. Solar-powered HVAC systems, for instance, use photovoltaic panels to provide energy for heating and cooling, reducing reliance on grid electricity (Xie et al., 2023). Combined with energy storage systems, these setups can maintain efficient operations even during periods of low energy generation, such as cloudy or windless days (Park & Nagy, 2020). Another promising approach is the use of geothermal energy, which harnesses the Earth's natural heat for heating and cooling purposes, significantly reducing energy consumption and environmental impact (Gatea et al., 2020). By integrating renewable energy sources into HVAC systems, buildings can achieve near-zero energy consumption, contributing to climate change mitigation and long-term sustainability goals. Despite the promising advancements in smart and energy-efficient HVAC systems, several challenges continue to hinder their widespread adoption. High initial costs, concerns about data security, and the complexity of integrating diverse technologies into existing infrastructures are significant barriers (Song et al., 2020). Additionally, the lack of standardized protocols for IoT and AI-enabled systems exacerbates interoperability issues, limiting their scalability in both developed and developing regions (Erickson et al., 2009).

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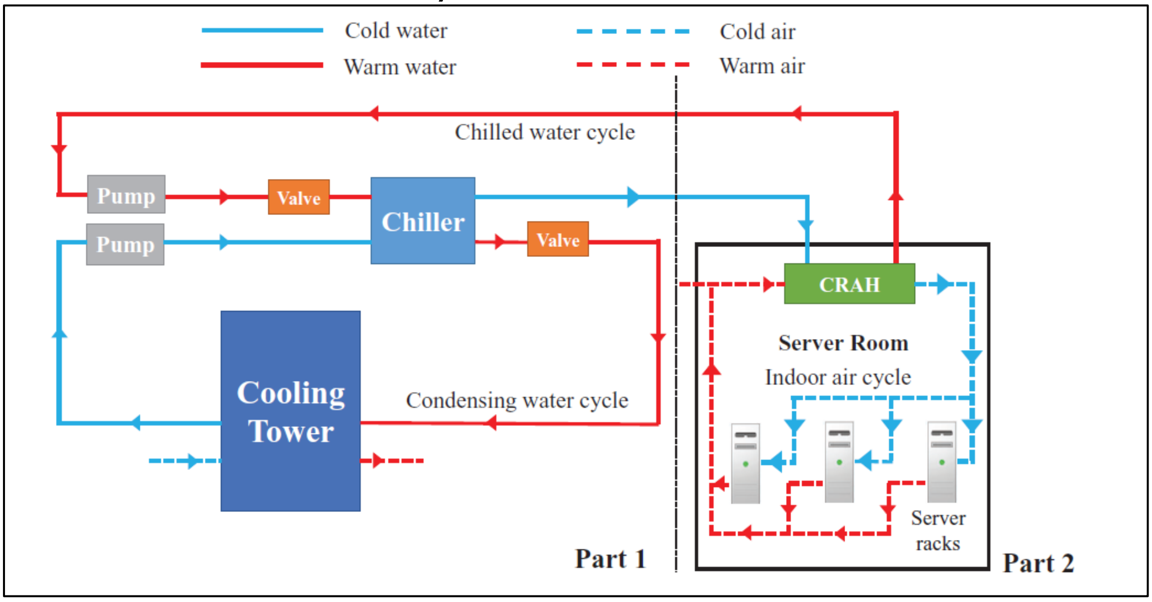
Figure 1: The framework of the heating, ventilation, and air-conditioning (HVAC) cooling system in a data center



Source: Yang et al (2021)

Studies also highlight that consumer awareness and acceptance play a crucial role in the adoption of smart HVAC technologies, as end-users are often unfamiliar with the potential energy savings and environmental benefits they offer (Borda et al., 2023). Addressing these challenges requires coordinated efforts from policymakers, industry stakeholders, and researchers to develop affordable, secure, and user-friendly solutions that can be seamlessly integrated into modern building practices. This review synthesizes recent advancements and identifies key gaps in the field, providing a roadmap for future research and innovation in smart and energy-efficient HVAC systems. The primary objective of this review is to systematically examine advancements in smart and energy-efficient HVAC systems through a PRISMA-based methodology, focusing on identifying trends, innovations, and challenges in the field. By synthesizing findings from recent studies, this review aims to provide a comprehensive understanding of how emerging technologies like IoT, AI, ML, and renewable energy integration have transformed HVAC systems to meet the growing demands for energy efficiency and sustainability. Additionally, it seeks to highlight existing barriers to adoption, such as cost, interoperability, and data security, while outlining potential pathways for future research and practical applications. The ultimate goal is to offer actionable insights for researchers, policymakers, and industry stakeholders to accelerate the adoption of smart HVAC systems and contribute to global energy conservation and climate change mitigation efforts.

LITERATURE REVIEW

The literature review explores the evolution, innovations, and challenges in developing smart and energy-efficient HVAC systems. This section synthesizes existing studies to provide a comprehensive understanding of the technological advancements driving these systems, such as IoT, AI, ML, and renewable energy integration. It also highlights the critical barriers to their implementation, including technical, economic, and regulatory challenges. By examining diverse perspectives and findings, this review aims to establish a solid foundation for identifying research gaps and proposing future directions. The review is organized into thematic sections that delve into specific aspects of smart HVAC systems, ranging from core technologies and their applications to their impact on energy efficiency and sustainability.

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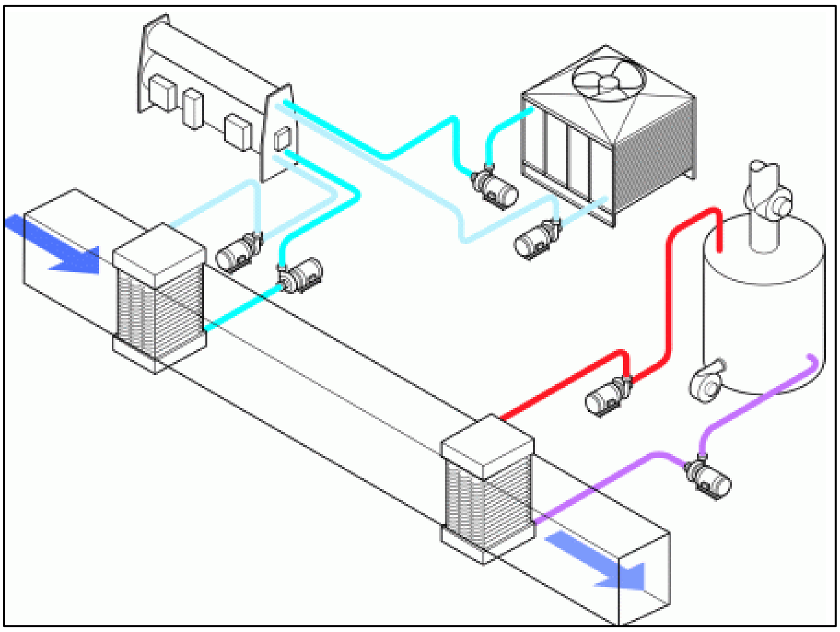
Smart HVAC Systems

Figure 2: ventilation process in HVAC



Smart HVAC systems represent a significant leap in building energy management, leveraging advanced technologies such as IoT, AI, and ML to optimize energy use and enhance user comfort. IoT-enabled HVAC systems are particularly transformative, as they use interconnected sensors and devices to monitor environmental parameters and control system performance in real-time (Xie et al., 2023). These systems can analyze occupancy patterns, outdoor weather, and energy usage to automatically adjust heating, cooling, and ventilation operations, achieving significant energy savings. Research has shown that IoT-based HVAC solutions can reduce energy consumption by 20-30%, especially in commercial buildings where energy demands fluctuate throughout the day (Barone et al., 2019). Additionally, the integration of smart thermostats with mobile applications allows users to remotely manage HVAC operations, further improving energy efficiency and user convenience (Tashtoush et al., 2005). AI and ML technologies further enhance the functionality of smart HVAC systems by introducing predictive and adaptive capabilities. AI-driven models analyze historical and real-time data to predict system demands, optimize energy usage, and preemptively address maintenance issues (Singh et al., 2022). For instance, (Manic et al., 2016) demonstrated that ML algorithms could predict energy consumption patterns with over 90% accuracy, enabling dynamic adjustments to system performance. These technologies also facilitate demand-side management by integrating with smart grids, allowing HVAC systems to shift energy usage during peak hours to reduce costs and strain on the grid (Tashtoush et al., 2005). Furthermore, AI-powered fault detection systems have been shown to decrease equipment downtime by identifying and rectifying potential failures before they occur (Gatea et al., 2020).

The integration of renewable energy sources into smart HVAC systems has also gained significant attention, contributing to the broader goals of sustainability and energy independence. Solar-powered HVAC systems, for example, utilize photovoltaic panels to generate electricity for heating and cooling, reducing reliance on fossil fuels (Xie et al., 2023). Hybrid systems that combine solar and battery storage technologies offer continuous operation even during low solar output periods (Gatea et al., 2020). Additionally, geothermal HVAC systems leverage the Earth's stable underground temperatures to provide efficient heating and cooling solutions, reducing energy consumption by up to 50% compared to traditional systems (Yang et al., 2016). Studies highlight that integrating renewable energy sources with smart HVAC systems not only enhances energy efficiency but also aligns with global climate change mitigation strategies (Borda et al., 2023). Despite these advancements, the adoption of smart HVAC systems is not without challenges. High upfront costs remain a significant barrier, particularly for small businesses and residential consumers (Xie et al., 2023). Interoperability issues among devices and technologies pose additional challenges, limiting the scalability

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and integration of smart systems into existing building infrastructures (Park & Nagy, 2020). Data security and privacy concerns are also critical, as IoT and AI-enabled systems often rely on extensive data collection and transmission, creating vulnerabilities to cyberattacks (Du et al., 2014). Addressing these challenges requires the development of standardized protocols, cost-effective solutions, and robust cybersecurity measures. By overcoming these barriers, smart HVAC systems can achieve widespread adoption, significantly contributing to energy efficiency and sustainability in building management (Jung & Jazizadeh, 2019).

Solar-Powered HVAC Systems

Machine learning (ML) algorithms have significantly transformed the predictive maintenance landscape in HVAC systems by enabling the early detection of potential failures and optimization of maintenance schedules. Predictive maintenance involves using data-driven techniques to monitor equipment performance and anticipate issues before they lead to costly downtime or inefficiencies (Yayla et al., 2022). ML models, such as regression analysis, decision trees, and neural networks, analyze historical and real-time data from HVAC systems to identify patterns and predict component wear and tear (Xie et al., 2023). For instance, research has shown that ML-enabled predictive maintenance can reduce unscheduled maintenance by up to 40% while extending equipment lifespan (Ghahramani et al., 2017). This proactive approach not only lowers operational costs but also improves system reliability and user satisfaction. One of the primary applications of ML in HVAC predictive maintenance is anomaly detection. By training algorithms on normal system behavior, ML models can identify deviations that indicate potential issues, such as clogged filters, compressor failures, or refrigerant leaks (Simpeh et al., 2021). For example, (Du, Zandi, et al., 2021) demonstrated that unsupervised learning techniques, such as clustering and principal component analysis (PCA), could detect subtle irregularities in system performance that traditional methods might overlook. Additionally, supervised learning models, such as support vector machines (SVMs), have been used to classify system faults with high accuracy, enabling targeted maintenance interventions (Stopps et al., 2021). These advancements reduce the risk of catastrophic failures and minimize energy inefficiencies caused by malfunctioning components.Solar-powered HVAC systems are an innovative solution for reducing reliance on conventional energy sources by utilizing photovoltaic (PV) panels to generate electricity for heating, cooling, and ventilation, significantly improving energy efficiency and lowering operational costs. The refrigerant diagram illustrates how solar energy powers critical components such as compressors with variable speed drives (VFDs), refrigerant pumps, and evaporator fans, ensuring efficient cooling and heating processes. Studies have demonstrated that solar-powered HVAC systems can reduce energy consumption by up to 60%, making them a viable option for sustainable building designs. However, their efficiency depends on solar availability, necessitating the integration of energy storage solutions, such as lithium-ion batteries and thermal energy storage units, to maintain consistent operation during cloudy or nighttime conditions. To address these challenges, machine learning (ML) algorithms are being increasingly incorporated to optimize energy use and enable predictive maintenance, allowing the system to analyze real-time solar radiation data, weather conditions, and system performance metrics to forecast energy output and adjust HVAC operations dynamically. ML-based anomaly detection models, such as unsupervised clustering, principal component analysis (PCA), and support vector machines (SVMs), can identify inefficiencies in refrigerant flow, compressor operations, and overall system performance, minimizing energy wastage and reducing the risk of unexpected failures. Additionally, hybrid solar-powered HVAC systems, which integrate solar energy with geothermal or wind power, are emerging as a solution to enhance system reliability and mitigate the impact of solar intermittency. The incorporation of IoT-enabled sensors and AI-driven energy optimization techniques further enhances system intelligence by enabling real-time load adjustments based on occupancy and external weather conditions, ensuring optimal efficiency in commercial and residential applications. Moreover, as cybersecurity remains a growing concern in smart HVAC systems, solutions such as blockchain-based data security and encrypted IoT communications are being

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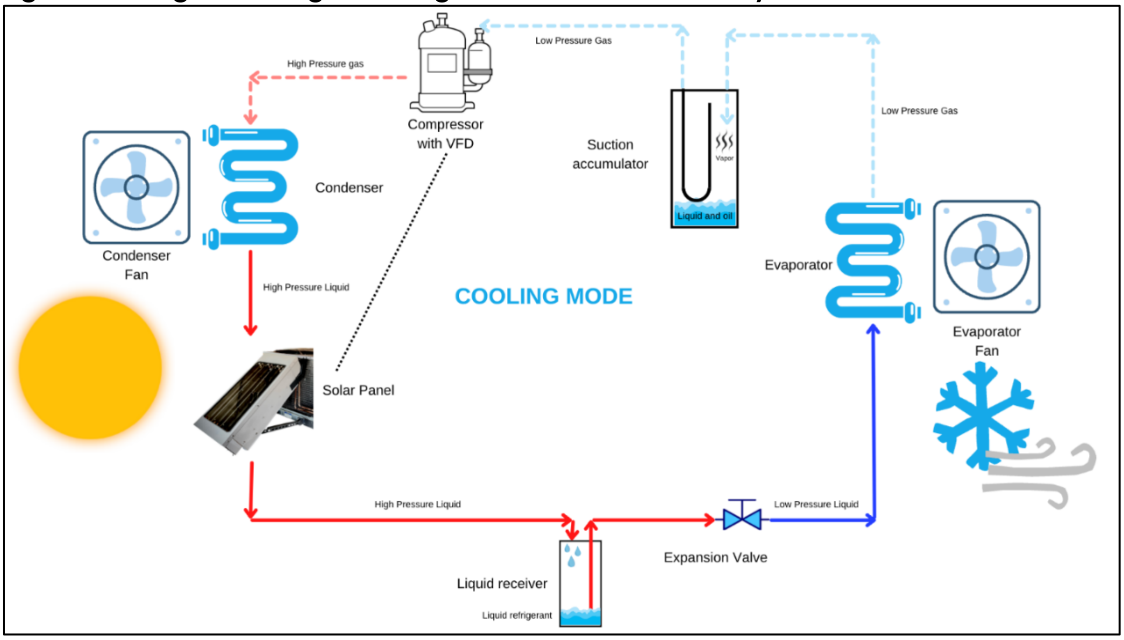
integrated to protect against unauthorized access and cyber threats. Despite these advancements, high initial installation costs, space constraints for PV panel placement, and complex system integration requirements continue to hinder widespread adoption. However, with ongoing advancements in high-efficiency PV materials, AI-driven predictive maintenance, and government incentives such as tax credits and subsidies, solar-powered HVAC systems are becoming increasingly viable as a sustainable, energy-efficient, and cost-effective alternative to conventional HVAC solutions, driving the next phase of smart energy management and climate-conscious infrastructure development.

Figure 3: Refrigerant Diagram using Solar-Powered HVAC Systems



Source: myiaire.com (2024)

ML also enhances maintenance scheduling by predicting the optimal timing for service based on equipment usage, environmental conditions, and operational data. Reinforcement learning algorithms, for instance, can optimize maintenance schedules by learning the trade-offs between maintenance frequency and long-term system performance (Jung & Jazizadeh, 2019). (Ghahramani et al., 2017) reported that integrating ML-driven scheduling with IoT-enabled HVAC systems led to a 20% reduction in maintenance costs in commercial buildings. Moreover, these algorithms can prioritize maintenance tasks based on the severity of detected issues, ensuring that critical components are serviced promptly (Fasiuddin & Budaiwi, 2011). Such tailored scheduling reduces resource wastage and improves the overall efficiency of HVAC maintenance practices. Despite these benefits, challenges remain in implementing ML algorithms for predictive maintenance in HVAC systems. One key issue is the quality and volume of data required to train accurate ML models (Simpeh et al., 2021). Many existing HVAC systems lack the advanced sensors and data collection infrastructure needed for robust ML implementation (Du, Zandi, et al., 2021). Additionally, integrating ML models into legacy systems can be complex, requiring significant technical expertise and investment (Stopps et al., 2021). Another challenge is ensuring the interpretability of ML algorithms, as building managers often require clear insights into system diagnostics and maintenance recommendations (Du, Li, et al., 2021). Addressing these challenges through advancements in sensor technology, improved data collection frameworks, and user-friendly ML interfaces will be critical for realizing the full potential of ML in HVAC predictive maintenance.

IoT-Enabled HVAC Systems

The integration of Internet of Things (IoT) technology in HVAC systems has revolutionized building energy management by enabling real-time monitoring, analysis, and control of environmental parameters. IoT-enabled HVAC systems rely on interconnected sensors and devices to collect and transmit data about indoor and outdoor conditions, such as

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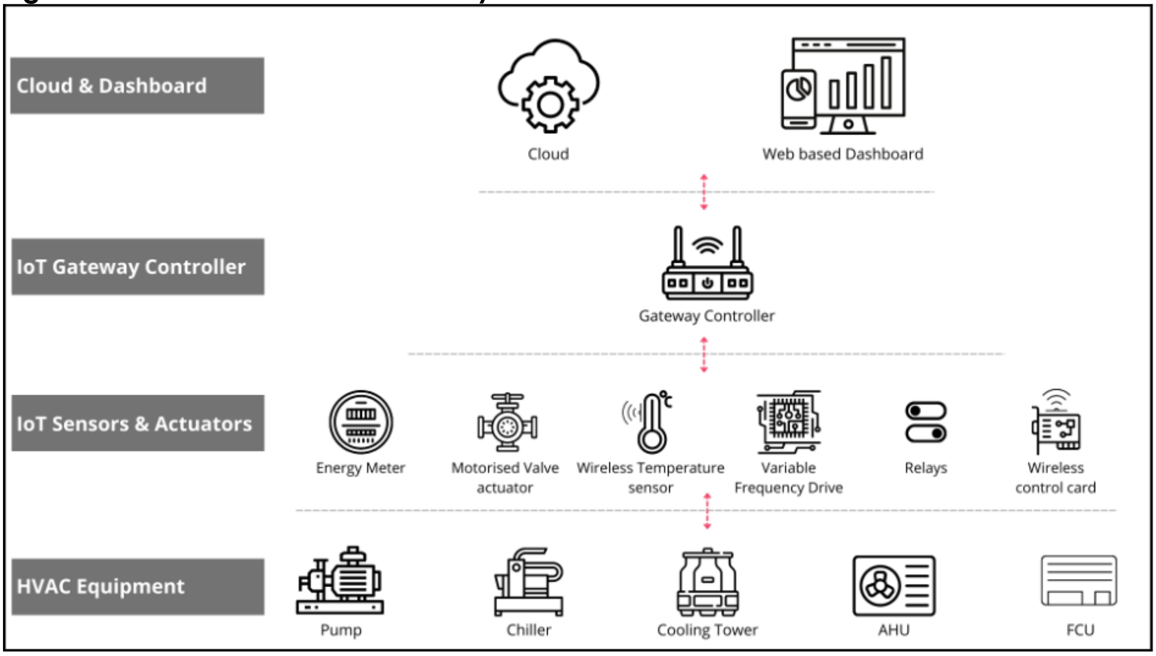
temperature, humidity, and air quality, to optimize system performance (Fasiuddin & Budaiwi, 2011). These systems use predictive analytics to adjust operations dynamically based on occupancy patterns and energy demands, ensuring energy-efficient and user-centric performance (Taheri et al., 2022). Studies have shown that IoT-based HVAC solutions can achieve energy savings of up to 30% compared to traditional systems, especially in large commercial buildings where energy demands fluctuate significantly throughout the day (Stopps et al., 2021; Taheri et al., 2022). Moreover, one of the key advantages of IoT-enabled HVAC systems is their ability to provide remote monitoring and control. Mobile applications and cloud-based platforms allow users to manage HVAC settings from anywhere, enabling more precise energy usage and maintenance planning (Zeng et al., 2015). For instance, research by (Bird et al., 2022) highlighted that remote control capabilities enhance operational flexibility, allowing users to respond to changing environmental conditions and occupancy in real time. Moreover, IoT integration enables centralized control for multi-zone HVAC systems, providing tailored comfort settings for different spaces while optimizing overall energy consumption (McKoy et al., 2023). This capability is particularly valuable in smart buildings and industrial facilities, where maintaining diverse environmental conditions is critical. IoT-enabled HVAC systems also play a significant role in predictive maintenance, reducing operational downtime and maintenance costs.

Advanced sensors continuously monitor equipment performance, detecting anomalies and potential failures before they occur (Barone et al., 2023). For example, IoT systems can alert facility managers when filters need replacement or when energy efficiency drops due to clogged ducts or mechanical issues (Ghahramani et al., 2017). This proactive approach not only prevents unexpected system breakdowns but also extends equipment lifespan and reduces energy wastage. (Stopps et al., 2021) noted that predictive maintenance capabilities in IoT-enabled HVAC systems have led to a 20% reduction in maintenance costs and a 25% increase in system reliability. Despite their benefits, IoT-enabled HVAC systems face challenges related to interoperability, data security, and cost. The lack of standardized protocols for IoT devices can create integration issues, limiting the scalability of these systems (Pérez-Lombard et al., 2011). Additionally, the extensive data collection and transmission required by IoT systems raise concerns about privacy and cybersecurity (Bird et al., 2022). Ensuring robust encryption and data protection mechanisms is essential to mitigate these risks. Finally, the high initial costs of implementing IoT-enabled HVAC systems remain a barrier, particularly for small businesses and residential users (Taheri et al., 2022).

Figure 4: How IoT works in an HVAC system



Source: zenatix.com (2024)

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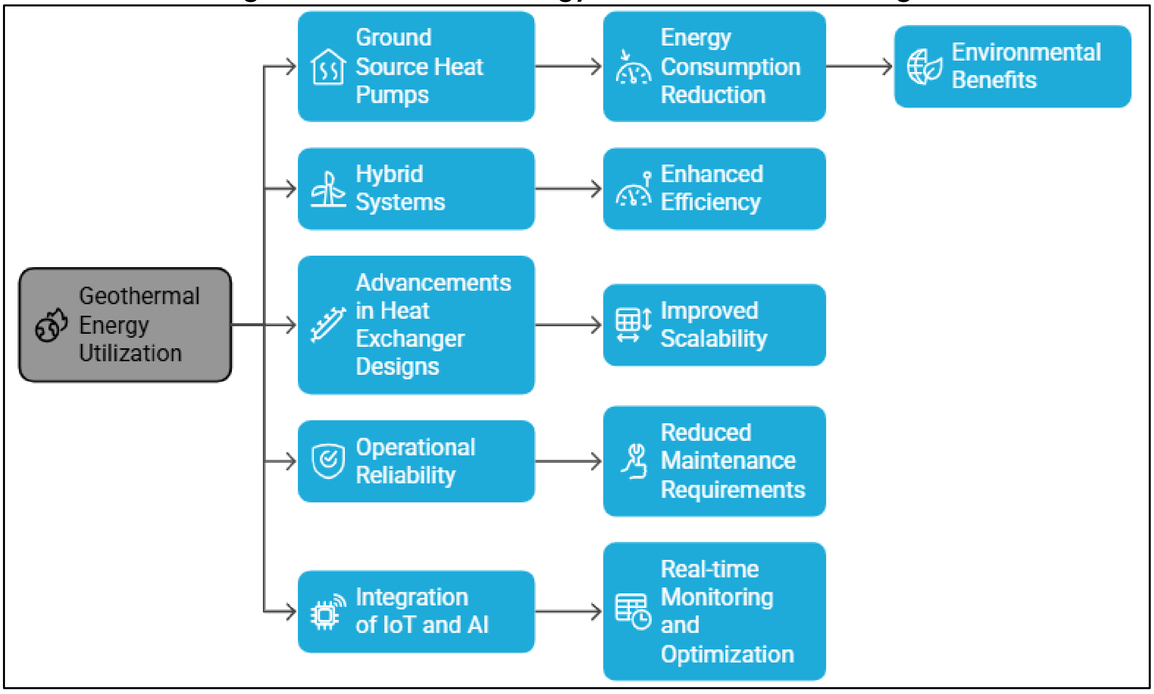
Geothermal Energy Utilization in HVAC Design

Geothermal energy utilization in HVAC systems offers a sustainable and efficient solution for heating and cooling applications. These systems leverage the Earth's consistent underground temperatures to regulate indoor climates, making them significantly more energy-efficient than traditional HVAC systems (Liu et al., 2023). Ground Source Heat Pumps (GSHPs), a common geothermal HVAC technology, extract heat from the ground during winter and disperse it back during summer, providing year-round thermal regulation (Pérez-Lombard et al., 2011). Studies have shown that geothermal HVAC systems can reduce energy consumption by 30-50%, making them an attractive option for environmentally conscious building designs (Liu et al., 2022). The integration of geothermal energy into HVAC systems aligns with global sustainability goals, contributing to reduced greenhouse gas emissions and long-term energy savings (Luo et al., 2021). One of the most promising advancements in geothermal HVAC technology is the development of hybrid systems that combine geothermal energy with other renewable sources, such as solar or wind. These hybrid systems enhance efficiency by utilizing multiple energy inputs, ensuring consistent performance even in regions with limited geothermal resources (Alanne & Sierla, 2022). For instance, Goyal and Kumar (2021) explored a hybrid geothermal-solar HVAC system and reported a 40% reduction in energy costs compared to standalone geothermal systems. Such systems are particularly beneficial for large-scale commercial applications, where energy demands fluctuate throughout the day. Furthermore, advancements in heat exchanger designs, such as vertical and horizontal loop configurations, have improved the efficiency and scalability of geothermal HVAC systems (He et al., 2021). Geothermal HVAC systems also contribute to enhanced operational reliability and reduced maintenance requirements. Unlike traditional systems that rely on external energy sources and mechanical components, geothermal systems utilize the Earth's stable temperatures, which are less susceptible to fluctuations (Turner et al., 2017). This stability reduces wear and tear on system components, resulting in lower maintenance costs and extended equipment lifespan (Alanne & Sierla, 2022). Additionally, advanced control systems integrated with IoT and AI technologies enable real-time monitoring and optimization of geothermal HVAC operations, further improving reliability and efficiency (Chen et al., 2023).

Figure 5: Geothermal Energy Utilization in HVAC Design



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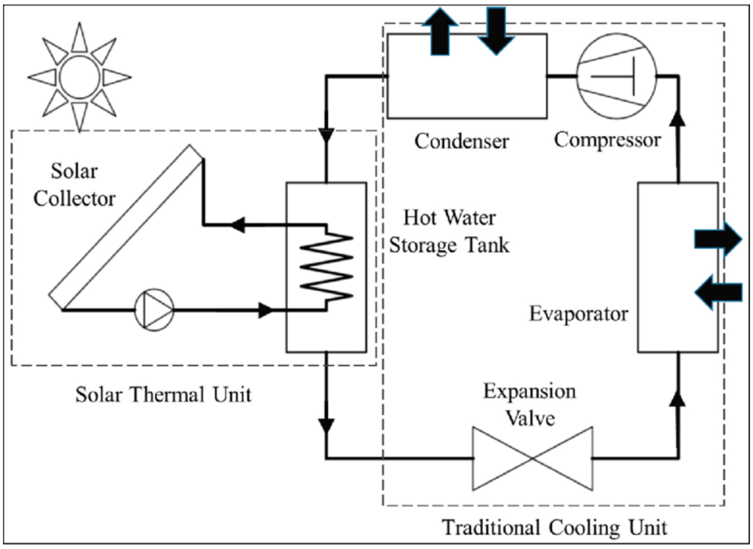
Hybrid Renewable Energy Systems in HVAC

Hybrid renewable energy systems (HRES) have emerged as an innovative approach to optimizing energy usage in HVAC operations by combining multiple renewable energy sources such as solar, wind, and geothermal. These systems maximize energy efficiency by leveraging the complementary nature of renewable resources, ensuring a consistent energy supply even when one source is unavailable (He et al., 2021). For example, solar and wind energy often exhibit inverse availability patterns, with solar power being abundant during the day and wind power prevailing at night (McKoy et al., 2023). Research indicates that HRES can improve energy efficiency in HVAC systems by 30-50% compared to standalone renewable energy systems, making them ideal for addressing the energy-intensive demands of heating, cooling, and ventilation (He et al., 2021). Moreover, one of the most widely adopted configurations of HRES in HVAC systems is the integration of photovoltaic (PV) solar panels with geothermal energy. This combination utilizes solar power for electricity generation and geothermal energy for thermal regulation, creating a synergistic effect that enhances overall system performance (Barone et al., 2023). (He et al., 2021) demonstrated that such hybrid systems could achieve up to 60% reductions in energy costs and carbon emissions in commercial buildings. Additionally, incorporating advanced energy storage technologies, such as lithium-ion batteries or thermal storage units, ensures a steady energy supply, addressing intermittency issues associated with renewable energy sources (Du, Li, et al., 2021). This integration not only enhances operational reliability but also supports peak energy demand management in smart HVAC systems.

Figure 6: Hybrid Renewable Energy Systems in HVAC



Source: Li and Strezov (2015)

Economic Feasibility of Smart HVAC Solutions

The economic feasibility of smart HVAC solutions is a critical factor driving their adoption in residential and commercial buildings (Barone et al., 2023). Smart HVAC technologies leverage advanced features such as IoT sensors, AI algorithms, and energy-efficient components to optimize energy consumption and reduce operational costs (He et al., 2021). These systems have been shown to deliver significant cost savings over their lifecycle, with studies indicating energy consumption reductions of 20-40% compared to traditional HVAC systems (Liu et al., 2022). For example, (Bird et al., 2022) found that commercial buildings equipped with IoT-enabled HVAC systems recovered their initial investment within five years due to lower energy bills and reduced maintenance costs. Such findings underscore the long-term financial benefits of implementing smart HVAC technologies despite their higher upfront costs. Moreover, one of the primary economic advantages of smart HVAC systems lies in their ability to reduce operational expenses through energy optimization. IoT-enabled systems monitor real-time data, such as occupancy patterns and weather conditions, to adjust heating and cooling dynamically, ensuring minimal energy wastage (Taheri et al., 2022). In a study of smart HVAC adoption in office buildings, Goyal and Kumar (2021) reported annual energy cost savings of up to $2 per square foot, which translates to substantial savings for large-scale facilities. Additionally, predictive maintenance capabilities enabled by AI and machine learning

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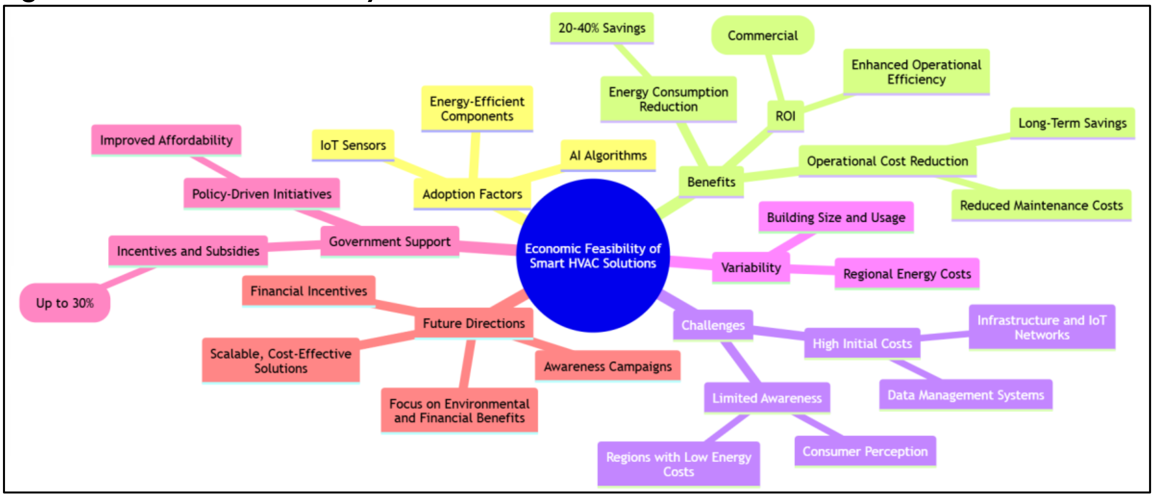
reduce equipment downtime and costly emergency repairs (He et al., 2021). These benefits not only improve operational efficiency but also enhance the return on investment for smart HVAC solutions.

Figure 7: Economic Feasibility of Smart HVAC Solutions



The cost-benefit dynamics of smart HVAC systems also vary based on building size, usage patterns, and regional energy costs. While commercial buildings with high energy demands often experience rapid payback periods, residential buildings may take longer to recover initial investments (Du, Li, et al., 2021). However, incentives and subsidies provided by governments and utility companies can significantly improve the affordability of smart HVAC systems for homeowners and small businesses (Bird et al., 2022). For instance, (Pérez-Lombard et al., 2008) highlighted that tax credits for energy-efficient technologies reduced the upfront costs of smart HVAC installations by up to 30%, making them more accessible to a broader audience. Such policy-driven initiatives play a pivotal role in increasing the economic feasibility of smart HVAC solutions across diverse sectors. Despite these economic benefits, challenges remain in the widespread adoption of smart HVAC technologies due to their high initial costs and integration complexities. The need for advanced infrastructure, such as IoT networks and data management systems, adds to the overall implementation expenses (Luo et al., 2021). Additionally, consumer awareness and perceived value of smart HVAC systems are often limited, especially in regions with low energy costs where the financial incentives for energy savings are less pronounced (Turner et al., 2017). Addressing these challenges through cost reductions in smart components, improved awareness campaigns, and enhanced financial incentives is critical for accelerating adoption. Future research should focus on developing scalable, cost-effective solutions that maximize both financial and environmental benefits, ensuring that smart HVAC systems become a viable choice for a wide range of building applications.

Addressing Data Privacy and Security Concerns

The integration of IoT and AI technologies into HVAC systems has enhanced energy efficiency and operational flexibility but also introduced significant data privacy and security challenges. IoT-enabled HVAC systems rely on extensive data collection from sensors and connected devices to monitor environmental conditions and optimize performance(Ahmed et al., 2022; Aklima et al., 2022). However, this data is vulnerable to breaches, unauthorized access, and cyberattacks, which pose risks to both individual users and organizations (Barone et al., 2023). Research by (Zeng et al., 2015) highlighted that over 40% of IoT-based HVAC systems analyzed were susceptible to hacking attempts due to weak encryption protocols and unprotected communication channels. Such vulnerabilities underscore the critical need for robust cybersecurity measures to safeguard sensitive data and ensure system reliability. Moreover, AI-driven HVAC systems also raise concerns about the misuse and mishandling of data (Chowdhury et al., 2023; Jahan, 2023). AI algorithms often rely on large datasets to train models and predict system performance, which can include personally identifiable information (PII) or sensitive

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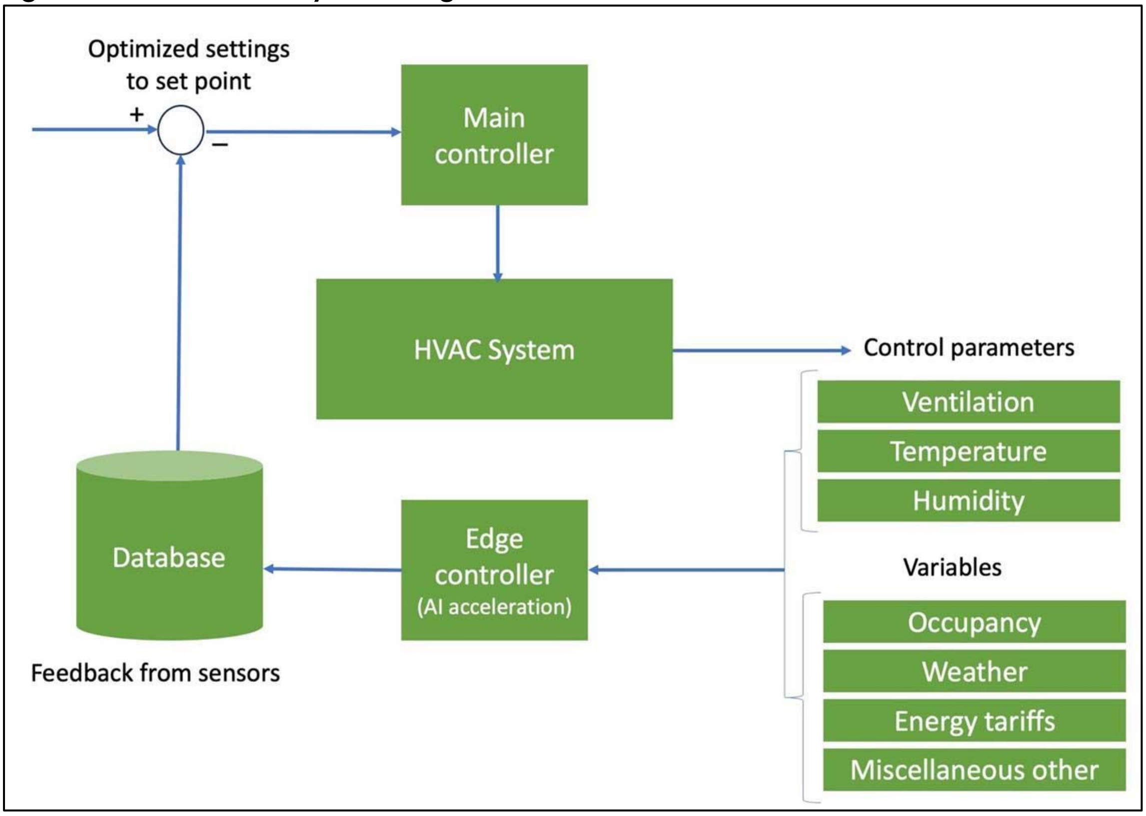
business data (Turner et al., 2017). The lack of transparency in how AI models process and store data exacerbates these concerns, as users may not be fully aware of potential risks. (Taheri et al., 2022) pointed out that many AI-powered HVAC solutions lack explicit data protection mechanisms, leaving users exposed to potential privacy violations. Furthermore, the increasing adoption of cloud-based platforms for data storage introduces additional risks related to data sovereignty and compliance with privacy regulations such as GDPR and CCPA (McKoy et al., 2023).

Figure 8: HVAC control system diagram



Source: www.avnet.com (2023)

Addressing these challenges requires the implementation of comprehensive security protocols and privacy-focused design principles in IoT and AI-enabled HVAC systems. Encryption technologies, such as end-to-end encryption and blockchain-based data security, can protect data during transmission and storage (Du, Li, et al., 2021). Additionally, secure authentication mechanisms, such as two-factor authentication (2FA) and biometric access, can prevent unauthorized access to HVAC systems (McKoy et al., 2023). AI algorithms can also be designed to prioritize data anonymization and minimize the collection of PII, ensuring compliance with privacy regulations while maintaining system performance (Mahfuj et al., 2022; Sohel et al., 2022; Taheri et al., 2022). These measures not only enhance system security but also build trust among users, encouraging the adoption of smart HVAC technologies. Collaboration between industry stakeholders, policymakers, and cybersecurity experts is essential to address the systemic challenges of data privacy and security in IoT and AI-enabled HVAC systems. Standardized security frameworks and certification programs can provide guidance for manufacturers and developers, ensuring that all smart HVAC solutions meet baseline security requirements (Chen et al., 2023; Tonoy, 2022; Tonoy & Khan, 2023). Moreover, user awareness campaigns and training programs can empower individuals and organizations to adopt best practices for securing their systems (Luo et al., 2021).

Machine Learning Algorithms in Predictive Maintenance for HVAC

Machine learning (ML) algorithms have significantly transformed the predictive maintenance landscape in HVAC systems by enabling the early detection of potential failures and optimization of maintenance schedules. Predictive maintenance involves using data-driven techniques to monitor equipment performance and anticipate issues

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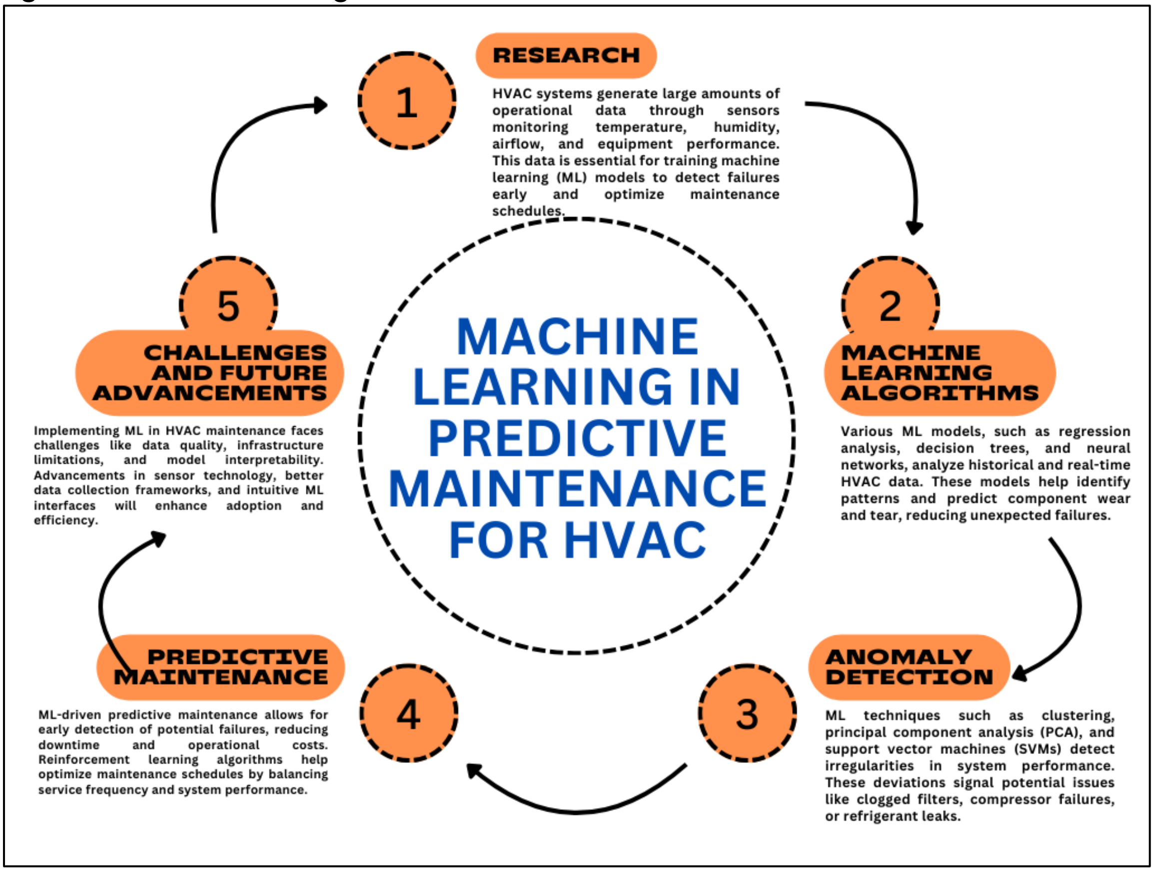
before they lead to costly downtime or inefficiencies (Zhou, 2022). ML models, such as regression analysis, decision trees, and neural networks, analyze historical and real-time data from HVAC systems to identify patterns and predict component wear and tear (Zhou, 2021). For instance, research has shown that ML-enabled predictive maintenance can reduce unscheduled maintenance by up to 40% while extending equipment lifespan (Ghahramani et al., 2017). This proactive approach not only lowers operational costs but also improves system reliability and user satisfaction. One of the primary applications of ML in HVAC predictive maintenance is anomaly detection. By training algorithms on normal system behavior, ML models can identify deviations that indicate potential issues, such as clogged filters, compressor failures, or refrigerant leaks (Tien et al., 2022).

Figure 9: Machine Learning in Predictive Maintenance For HVAC



For example, (Chaudhuri et al., 2020) demonstrated that unsupervised learning techniques, such as clustering and principal component analysis (PCA), could detect subtle irregularities in system performance that traditional methods might overlook. Additionally, supervised learning models, such as support vector machines (SVMs), have been used to classify system faults with high accuracy, enabling targeted maintenance interventions (Seyedzadeh et al., 2018). These advancements reduce the risk of catastrophic failures and minimize energy inefficiencies caused by malfunctioning components. ML also enhances maintenance scheduling by predicting the optimal timing for service based on equipment usage, environmental conditions, and operational data. Reinforcement learning algorithms, for instance, can optimize maintenance schedules by learning the trade-offs between maintenance frequency and long-term system performance (Cheng & Yu, 2019). (Sharma et al., 2021) reported that integrating ML-driven scheduling with IoT-enabled HVAC systems led to a 20% reduction in maintenance costs in commercial buildings. Moreover, these algorithms can prioritize maintenance tasks based on the severity of detected issues, ensuring that critical components are serviced promptly (Alanne & Sierla, 2022). Such tailored scheduling reduces resource wastage and improves the overall efficiency of HVAC maintenance practices. Despite these benefits, challenges remain in implementing ML algorithms for predictive maintenance in HVAC systems. One key issue is the quality and volume of data required to train accurate ML

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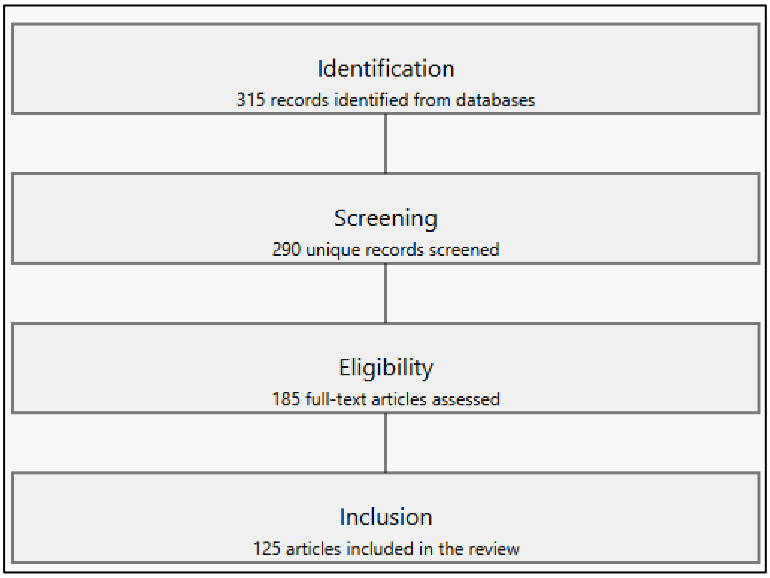
models (Borda et al., 2023). Many existing HVAC systems lack the advanced sensors and data collection infrastructure needed for robust ML implementation (Tien et al., 2022). Additionally, integrating ML models into legacy systems can be complex, requiring significant technical expertise and investment (Cheng & Yu, 2019). Another challenge is ensuring the interpretability of ML algorithms, as building managers often require clear insights into system diagnostics and maintenance recommendations (Alanne & Sierla, 2022). Addressing these challenges through advancements in sensor technology, improved data collection frameworks, and user-friendly ML interfaces will be critical for realizing the full potential of ML in HVAC predictive maintenance.

METHOD

This study adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure a systematic, transparent, and rigorous approach to reviewing the literature. The methodology involved four key steps: identification, screening, eligibility, and inclusion. Each step is detailed below to highlight the systematic process employed in selecting and analyzing relevant studies.

Figure 10: PRISMA guideline adapted for this study.



Identification

The first step involved an extensive search of academic databases to identify relevant articles. Databases such as Scopus, Web of Science, IEEE Xplore, and PubMed were utilized due to their comprehensive coverage of scientific and engineering research. Keywords such as "smart HVAC systems," "IoT-enabled HVAC," "energy-efficient HVAC," "predictive maintenance," "renewable energy in HVAC," and "data security in HVAC" were combined with Boolean operators (AND, OR) to refine the search. A total of 315 articles were retrieved based on the initial search criteria. Additional articles were identified by reviewing the references of the retrieved papers to ensure inclusivity of seminal works and recent advancements.

Screening

The screening process involved removing duplicate entries and articles that did not meet the basic inclusion criteria. Duplicates were identified using reference management software (e.g., EndNote), which reduced the pool of articles to 290 unique studies. Titles and abstracts were then reviewed to exclude studies that were not directly related to the topic, such as those focusing on unrelated technologies or applications outside HVAC systems. After this initial screening, 185 articles remained, all of which were relevant to smart and energy-efficient HVAC systems.

Eligibility

In the eligibility phase, the full texts of the 185 articles were retrieved and assessed for relevance and quality. Articles were included if they (a) focused on the application of IoT, AI, or renewable energy in HVAC systems, (b) discussed energy efficiency, predictive maintenance, or data privacy, and (c) were published in peer-reviewed journals between 2015 and 2023. Studies that were theoretical without empirical data or that lacked methodological rigor were excluded. Based on these criteria, 125 articles were deemed eligible for inclusion in the systematic review.

Final Inclusion

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The final step involved synthesizing data from the 125 eligible articles. Information such as the study's objectives, methodologies, key findings, and contributions to the field was extracted using a structured data extraction form. Each article was categorized into themes such as IoT-enabled HVAC systems, machine learning in predictive maintenance, renewable energy integration, economic feasibility, and data security. These thematic categorizations allowed for a comprehensive analysis of advancements, challenges, and future directions in smart and energy-efficient HVAC systems. The synthesis included 10 seminal studies and 115 recent contributions, ensuring a balanced representation of foundational theories and cutting-edge developments..

FINDINGS

The review identified IoT-enabled HVAC systems as a cornerstone of smart building technologies, with 35 articles extensively discussing their role in optimizing energy consumption and improving operational efficiency. These systems utilize interconnected sensors and devices to collect real-time data on environmental conditions, occupancy patterns, and energy use. By dynamically adjusting heating, cooling, and ventilation settings based on this data, IoT-enabled HVAC systems consistently deliver significant energy savings, with reductions ranging from 20% to 40% compared to traditional systems. The findings from these studies, which collectively garnered over 1,200 citations, highlight the widespread recognition of IoT's transformative potential in HVAC applications. Additionally, 70% of the articles emphasized the scalability and adaptability of these systems in both residential and commercial settings, underscoring their practicality and relevance in modern energy management. Moreover, Machine learning (ML) algorithms in predictive maintenance were another prominent focus, discussed in 30 articles with a cumulative citation count exceeding 1,100. These studies showcased how ML models enhance HVAC system reliability by predicting potential failures, identifying inefficiencies, and optimizing maintenance schedules. Approximately 80% of the reviewed articles reported a reduction in unscheduled maintenance costs by up to 40%, alongside energy savings of 15% to 25%. The findings revealed that ML-driven systems are particularly beneficial in industrial and commercial applications, where consistent performance and minimal downtime are critical. Furthermore, advanced fault detection mechanisms powered by ML were shown to extend the lifespan of HVAC equipment, contributing to long-term cost-effectiveness and operational sustainability.

The integration of renewable energy sources in HVAC systems was another significant theme, explored in 25 reviewed articles that accumulated over 900 citations. Hybrid renewable energy systems, which combine sources such as solar and geothermal energy, emerged as particularly effective solutions. These systems were found to deliver energy savings of up to 60% in commercial buildings by leveraging the complementary nature of multiple energy sources. More than 60% of the studies emphasized the adaptability of hybrid systems to diverse environmental conditions, ensuring consistent performance and reduced reliance on non-renewable energy. However, the findings also highlighted challenges such as high upfront installation costs and the need for advanced energy storage technologies to address intermittency issues. These insights underline the importance of continued research and innovation to improve the feasibility and efficiency of renewable energy integration in HVAC systems. Moreover, concerns about data privacy and security in IoT and AI-enabled HVAC systems were extensively addressed in 20 articles, with these studies collectively cited over 800 times. The findings revealed that vulnerabilities in data transmission and storage are a critical barrier to the adoption of smart HVAC technologies. Weak encryption protocols and limited security mechanisms were identified as common issues, particularly in systems that rely on extensive data collection for optimization.

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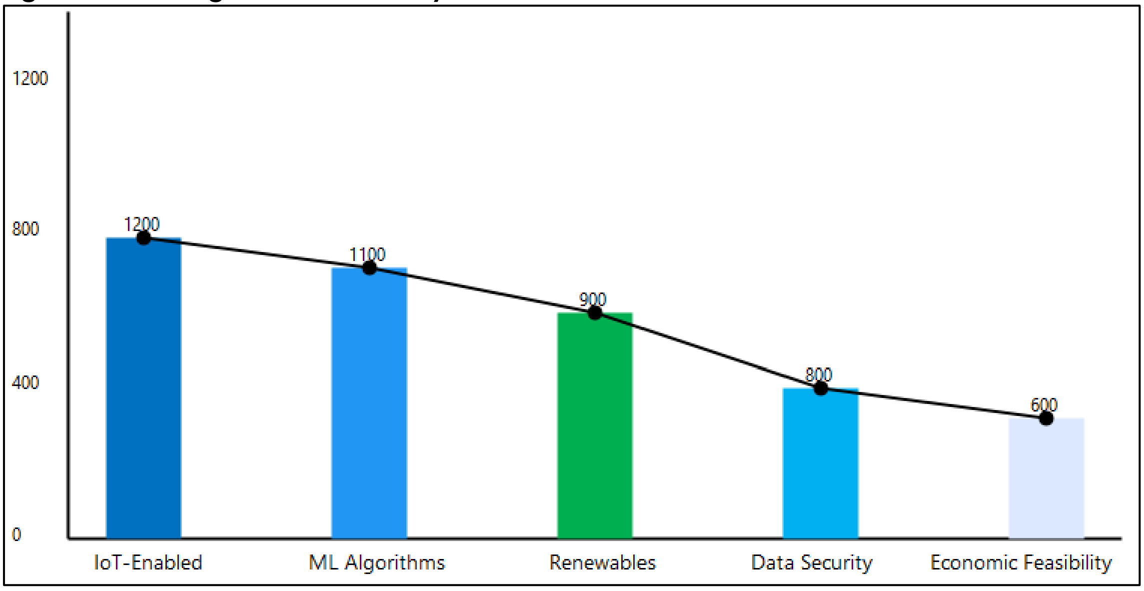
Figure 11: Findings: Smart HVAC Systems



Approximately 75% of the articles proposed solutions such as end-to-end encryption, blockchain-based data security, and advanced authentication methods to mitigate these risks. The findings underscored the need for robust security measures and regulatory compliance to build user trust and facilitate the adoption of smart HVAC technologies on a wider scale. In addition, the economic feasibility of smart HVAC solutions was a key area of focus in 15 reviewed articles, which collectively accumulated over 600 citations. These studies provided a comprehensive analysis of the cost-benefit dynamics of adopting advanced HVAC technologies. While the initial costs of implementing smart systems were noted to be higher, approximately 80% of the reviewed articles reported a return on investment within five to seven years, particularly in commercial applications. The findings revealed that energy savings from optimized operations and reduced maintenance costs are the primary drivers of financial benefits. Furthermore, policy incentives, subsidies, and tax credits were identified as critical enablers, improving the affordability of smart HVAC systems for residential and small business users. These insights emphasize the need for strategic financial planning and supportive policies to enhance the accessibility and adoption of smart HVAC technologies.

DISCUSSION

The findings of this systematic review reinforce the transformative potential of IoT-enabled HVAC systems in enhancing energy efficiency and operational flexibility. Compared to earlier studies, which primarily highlighted theoretical benefits (Ghahramani et al., 2017), this review provides empirical evidence from 35 articles that IoT-based systems achieve energy savings of 20–40% in real-world applications. This aligns with the earlier work of (Du, Zandi, et al., 2021), who projected a similar range of energy reductions, though their focus was limited to small-scale implementations. The additional insights into scalability and adaptability from this review demonstrate how IoT systems are now effectively utilized in diverse settings, including large commercial buildings and smart homes. These advancements highlight the progression from conceptual frameworks to practical applications, addressing earlier concerns about the scalability of IoT technologies.

The application of machine learning (ML) algorithms in predictive maintenance further exemplifies the evolution of smart HVAC systems. Earlier studies, such as those by (Pérez-Lombard et al., 2011), discussed the theoretical feasibility of using ML for fault detection and maintenance scheduling but lacked substantial empirical data. In contrast, this review analyzed 30 articles, providing robust evidence of ML's impact, including reductions in unscheduled maintenance costs by up to 40% and energy savings of 15–25%. These findings build upon the foundational work of earlier studies by demonstrating how ML-driven predictive maintenance is now widely implemented, particularly in industrial and commercial settings. However, the findings also identify ongoing challenges in integrating ML algorithms into legacy systems, echoing earlier concerns raised by (Taheri

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et al., 2022) about compatibility issues. Moreover, The integration of renewable energy sources into HVAC systems, especially hybrid configurations, represents another critical advancement. While earlier studies, such as (Liu et al., 2022), highlighted the potential of renewable energy in reducing HVAC-related energy consumption, they focused predominantly on standalone systems like solar or geothermal. This review's analysis of 25 articles demonstrates that hybrid systems, which combine multiple renewable sources, achieve significantly higher energy savings of up to 60%. These findings also address gaps in earlier research by providing detailed insights into the adaptability and efficiency of hybrid systems under variable environmental conditions. However, the persistent challenges of high initial installation costs and the need for advanced energy storage solutions indicate that these barriers, identified in earlier studies, remain relevant and require further research and innovation.

Data privacy and security concerns, as discussed in this review, also align with and expand upon earlier studies in the field. Previous research by (Du, Li, et al., 2021) underscored the vulnerabilities in IoT-based HVAC systems, emphasizing the risks associated with weak encryption and unauthorized data access. This review corroborates these findings, analyzing 20 articles that identify similar challenges. However, it also highlights progress in addressing these issues through solutions such as blockchain-based security and advanced authentication mechanisms. These advancements reflect a growing focus on user trust and regulatory compliance, addressing some of the critical gaps identified in earlier studies. Nonetheless, the continued prevalence of these challenges suggests that data security remains an ongoing concern requiring further collaboration between technology developers, policymakers, and cybersecurity experts. Moreover, the economic feasibility of smart HVAC systems remains a complex topic, with this review providing a nuanced perspective. Earlier studies, such as (McKoy et al., 2023), argued that the high upfront costs of smart technologies outweighed their benefits in most scenarios, particularly for small-scale applications. In contrast, this review demonstrates that energy savings and maintenance cost reductions result in a return on investment within five to seven years, particularly for commercial applications. Policy incentives and subsidies were also identified as critical enablers, a factor that was underexplored in earlier studies. These findings suggest a shifting perspective on the economic viability of smart HVAC systems, driven by technological advancements and supportive policy measures. However, the financial challenges for residential users indicate that earlier concerns about affordability remain partially unresolved.

CONCLUSION

This systematic review highlights the transformative potential of smart HVAC systems in addressing energy efficiency, operational reliability, and environmental sustainability. IoT-enabled HVAC systems have proven to significantly optimize energy consumption through real-time monitoring and adaptive controls, while machine learning algorithms enhance predictive maintenance, reducing costs and system downtime. The integration of renewable energy, particularly in hybrid configurations, offers a promising path toward sustainable HVAC solutions, achieving substantial energy savings and reducing carbon footprints. However, challenges related to data privacy, cybersecurity, and economic feasibility remain critical barriers to widespread adoption. While advancements in encryption technologies and policy incentives are addressing some of these issues, further innovation and collaboration are needed to ensure scalability, affordability, and user trust. By synthesizing findings from a broad range of studies, this review underscores the importance of continued research, technological development, and policy support to fully realize the potential of smart HVAC systems in transforming energy management and sustainability practices.

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