



A Review of Energy Efficiency Strategies in Smart Buildings: Integrating Occupant Comfort, HVAC Optimisation, and Building Automation

CHINEDU C. ONWEH

AMIN AL-HABAIBEH

EMMANUEL MANU

**Author affiliations can be found in the back matter of this article*

REVIEW

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ABSTRACT

The convergence of artificial intelligence and the Internet of Things technologies is transforming how smart buildings balance energy efficiency with occupant comfort. This systematic literature review synthesises research findings published between 2015 and 2025, drawing on 52 peer-reviewed studies alongside 26 additional authoritative standards and high-quality policy reports identified through a structured search across major academic databases, targeted journals, and grey literature. The synthesis examines reported approaches to heating, ventilation, and air conditioning system optimisation, building automation, digital twin technologies, and occupant-centred control strategies, with specific attention to cold climate contexts. Artificial intelligence and Internet of Things technologies such as model predictive control, deep reinforcement learning, adaptive comfort models, and integrated indoor air quality management have been reported to deliver measurable energy savings while sustaining or enhancing occupant comfort. The best performance is achieved when active AIoT-enabled systems are combined with passive measures appropriate for the climate. Persistent challenges include gaps in interoperability between systems, data governance issues, and the scalability of solutions in retrofitted buildings. The implications for professional practice highlight the need for interoperable, cyber-secure platforms aligned with retrofit standards such as the Publicly Available Specification 2035. Future research priorities include large-scale longitudinal validation, integration with renewable energy generation and district energy systems, refinement of personalised comfort control algorithms, and the development of user engagement strategies. By mapping the current evidence base and associated challenges, this review provides a reliable foundation for accelerating the adoption of artificial intelligence and Internet of Things technologies in smart buildings, supporting the pursuit of net-zero carbon emissions while enhancing occupant wellbeing.

CORRESPONDING AUTHOR:

Amin Al-Habaibeh

Director Product Innovation
Centre, School of Architecture,
Design and Built Environment,
Nottingham Trent University,
UK

amin.al-habaibeh@ntu.ac.uk

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1. INTRODUCTION

Buildings account for a significant amount of global energy consumption, with the building sector responsible for approximately 40% of total energy use and related carbon emissions worldwide (UNEP, 2020). Improving energy efficiency in buildings is therefore critical to achieving climate goals and sustainable development towards NetZero. However, traditional energy management approaches often struggle to balance energy savings with occupant comfort, which is essential for user satisfaction and productivity (ASHRAE-55, 2017). The increasing complexity of building systems and occupants' behaviour demand innovative, data-driven solutions that can dynamically optimise energy use while maintaining indoor environmental quality.

The integration of Artificial Intelligence (AI) and the Internet of Things (IoT), collectively referred to as AIoT, offers a promising pathway to address these challenges. AIoT enables real-time data acquisition, advanced analytics, and automated control of building systems, particularly Heating, Ventilation, and Air Conditioning (HVAC), which is the largest energy consumer in buildings (Simpeh, et al., 2022; Carlsson, 2024). By leveraging sensor networks, machine learning algorithms, and cloud computing, AIoT systems can predict occupants' need, detect system faults, and dynamically optimise energy consumption (Devaraj, 2023; Gowda, et al., 2024). Furthermore, digital twin technologies allow for virtual simulation and performance assessment, enhancing decision-making for both new constructions and retrofits (Rutkowski, et al., 2024).

This literature review aims to synthesise recent research on AIoT-enabled energy efficiency strategies in smart buildings, focusing on three interconnected pillars: occupants' comfort, HVAC optimisation, and building automation. It critically examines how these technologies contribute to energy savings and occupants' satisfaction, identifies current challenges such as data privacy and system interoperability, and highlights future research directions. Special attention is given to the cold-weather context, where cold climates and stringent energy policies shape unique requirements for smart building solutions (Hajian, 2024).

The following is how the paper is organised: In Section 2, pertinent frameworks and standards for energy management and thermal comfort are reviewed. Section 3 explores AI and IoT technologies applied in smart buildings. Section 4 discusses energy efficiency strategies enabled by AIoT, including HVAC optimisation and digital twins. Section 5 addresses occupant comfort and behavioural adaptation. Challenges and future research directions are described in Section 6. Finally, Section 7 concludes with key insights and recommendations.

1.1 METHODOLOGY

This systematic review adheres to rigorous standards in line with established methodologies for evidence synthesis in built environment research. The approach follows the guidance of Denyer and Tranfield (2009) and conforms to the PRISMA 2020 reporting framework, which emphasises transparency, reproducibility, and methodological rigor. The review includes all key stages of a systematic literature review: (1) formulating clear research questions, (2) comprehensive literature searching using multiple databases, (3) applying predefined inclusion and exclusion criteria for study selection, (4) data extraction and synthesis organized by thematic areas, and (5) reporting findings comprehensively to support replicability (Smith, et al., 2017; Masi, Day and Godsell, 2017; Page, et al., 2021).

1. Formulating the Research Questions

The review commenced with the formulation of a focused, answerable set of research questions to guide the evidence gathering process. Following best practices, the questions were designed to be sufficiently specific to enable a meaningful and manageable review, but broad enough to cover the multifaceted nature of AIoT enabled energy efficiency strategies in smart buildings. The primary research question was:

- How do artificial intelligence and IoT-based strategies advance energy efficiency and occupant comfort in smart buildings, especially in cold climates?

Auxiliary research questions included:

- What methods and technologies are reported?
- What gaps and limitations exist in current approaches?
- What implementation contexts, performance metrics, and case study evidence are presented?

To further enhance focus, a Problem Intervention Context Outcome (PICO) framing was considered during question development, ensuring the review addressed both technical interventions and contextual factors (building types, climates, policy regimes).

2. Locating the Literature

A comprehensive search strategy was developed and documented following the "building blocks" Boolean approach, with careful synonym mapping for each key concept (e.g. "AI", "machine learning", "artificial intelligence"; "IoT", "Internet of Things", "AIoT"). British/American spelling variations, truncations (e.g. "comfort*", "optim*"), and acronyms were accounted for wherever feasible.

Databases and Sources

To ensure robust literature coverage, searches were conducted in at least four major, multidisciplinary academic databases:

- Scopus
- Web of Science (WoS) Core Collection
- IEEE Xplore
- ScienceDirect

Targeted searches were also performed in sector relevant databases and repositories, including Energy Catalyst, Global Decarbonisation, and Green Technology & Innovation. Grey literature (e.g. technical standards, authoritative policy documents, standards such as ASHRAE, [PAS 2035](#)) was reviewed to complement peer reviewed sources.

Search Period

All searches covered publications between January 2015 and June 2025, with no language or document type restriction applied in the initial search; limits were then subsequently applied as inclusion/exclusion criteria.

The literature search was limited to publications from January 2015 through June 2025. This timeframe was chosen to capture the most recent and relevant advances in AI and IoT technologies for smart buildings, reflecting the period when AIoT applications became more prominent and applicable in this domain. Earlier studies prior to 2015 were excluded to focus analysis on contemporary evidence aligned with recent technological developments and policy evolution.

Search String Construction

Boolean search strings were tested iteratively (trial and error and snowballing), with each string validated for known relevant results and comprehensiveness (example in supplementary material). Synonyms, regional terminology, and truncation operators were included following the SLR checklist.

Example string:

("Artificial Intelligence" OR "AI" OR "Machine Learning" OR "Deep Learning" OR "Reinforcement Learning") AND ("Internet of Things" OR "IoT" OR "AIoT") AND ("HVAC" OR "Thermal Comfort") AND ("Smart Building" OR "Building Automation") AND ("Energy Efficiency" OR "Energy Management")

All search terms, combinations, and rationales for selection are reported in supplementary material per SLR guidance.

3. Selecting and Evaluating the Literature

All located records were imported into reference management software (RefWorks), with duplicates

automatically and manually checked. The study followed a two stage selection protocol:

- Stage 1: Title/abstract screening according to predefined inclusion/exclusion criteria, aligned with research questions and following PRISMA guidance. Inclusion: Peer reviewed articles, conference papers, high quality policy reports, technical standards focused on AIoT for energy efficiency and/or occupant comfort; English language; published 2015–2025; full text available. Exclusion: Non English, unavailable full texts, topics outside AIoT or built environment, insufficient methodological detail, duplicates.
- Stage 2: Eligibility confirmed via full text review. Precise rationales for inclusion/exclusion recorded for each rejection (outside scope, not AIoT relevant, pre-2015, insufficient detail), as recommended.

Where subjectivity was unavoidable during eligibility assessments, any disagreements were resolved through discussion and consensus between reviewers or were transparently documented to ensure auditability. The final dataset was structured following PRISMA guidelines and standard systematic review data management practices, including detailed fields for bibliographic metadata, inclusion/exclusion coding, and reviewer comments, supporting transparency and reproducibility.

During the initial screening phase, automated tools were used to identify and remove duplicates and records deemed ineligible. In this review, no records were excluded due to automation tool screening or other pre-screening removal reasons, and no reports were unretrievable, reflecting the thoroughness of the search and data management process. Transparency of all exclusion categories, including those with zero counts, is maintained to demonstrate completeness and support replicability.

A flow diagram following PRISMA 2020 guidelines [Figure 1](#) was completed to transparently report the number of records at each stage (databases searched, records identified, screened, excluded, and included in synthesis).

A total of 52 publications (including 44 primary research studies and 8 supplementary documents such as standards, policy reports, and technical guidelines) were included in the synthesis. The bibliography lists the 52 studies.

4. Analysing and Synthesising the Evidence

For all the studies included in the review, data extraction was done carefully and clearly. The information collected included the type of technology or intervention, the AIoT methods used, the building and climate type, performance measures like energy savings and comfort, the study design (such as simulations or pilot projects), geographic and sector contexts, as well as the key findings and any limitations. To analyse this information, a mix of techniques

was used: content analysis helped find common themes, descriptive synthesis summarised trends and methods, and when suitable, scientometric mapping tools like Excel and VOSviewer were applied. A majority voting system was used to ensure the main patterns identified were reliable and to reduce bias in the synthesis.

5. Reporting Review Results

The findings of the review are presented following PRISMA 2020 guidelines. The methodology is fully described, covering all steps, reasons, tools, and how data were managed. The results are organised by themes such as HVAC optimisation, occupant comfort, and building automation, with clear information about the types of studies, existing trends, and research gaps. The synthesis draws direct connections between the evidence found and the conclusions made. Limitations and directions for future research are openly discussed, following best practices for systematic reviews.

As illustrated in the PRISMA flow diagram [Figure 1](#), a total of 442 records were identified, of which 24 duplicates were removed. No records were excluded due to automation tool screening or other preliminary removal reasons (both $n = 0$), and all reports sought were successfully retrieved ($n = 0$ report retrieval failures). Among records excluded after full-text assessment ($n = 167$), reasons included: 68 outside scope, 28 lacking AIoT relevance, 12 published before 2015, and 7 for insufficient methodological detail.

2. BACKGROUND TO ARTIFICIAL INTELLIGENCE AND INTERNET OF THINGS (AIoT)

The overall integration of AIoT technologies, building automation, and occupant-centric strategies in smart buildings is illustrated in [Figure 2](#). Key components

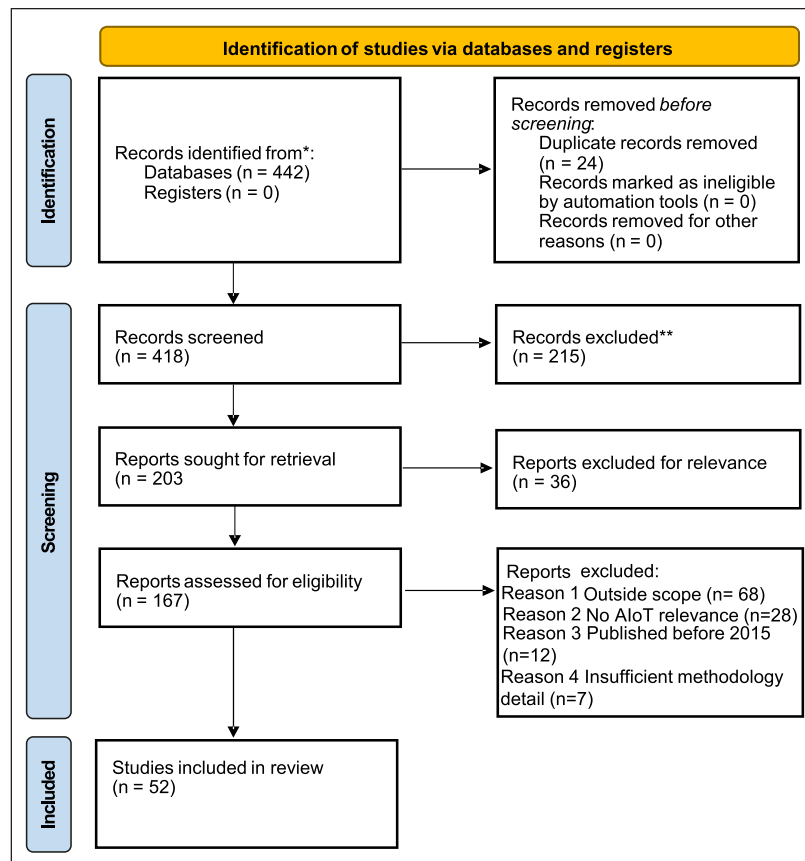


Figure 1 PRISMA flow diagram (Adapted from the PRISMA 2020 statement <https://www.prisma-statement.org/prisma-2020>).

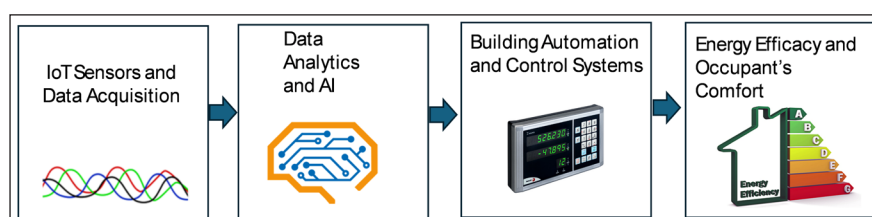


Figure 2 Conceptual framework illustrating the integration of AIoT, HVAC optimisation, occupant comfort, and building automation in smart buildings (adapted from [\(Himeur, et al., 2023\)](#)).

include the Building Automation System (BAS), Internet of Things (IoT) sensors, and Heating, Ventilation, and Air Conditioning (HVAC) systems.

In this paper, key terms such as Machine Learning (ML), Deep Reinforcement Learning (DRL), Fault Detection and Diagnosis (FDD), and Carbon Dioxide (CO₂) sensors are frequently used. ML involves algorithms that learn from data to optimise building operations. For adaptive HVAC control, DRL integrates reinforcement learning with deep learning. FDD techniques detect and diagnose system faults to improve maintenance, while CO₂ sensors monitor indoor air quality and occupancy for dynamic ventilation control.

2.1 OVERVIEW OF RELEVANT STANDARDS

Achieving both energy efficiency and occupants' comfort in buildings would require compliance with established standards and guidelines. The ANSI/ASHRAE Standard 55-2017 specifies the thermal environmental conditions for human occupancy, defining acceptable ranges for temperature, humidity, air speed, and personal factors to ensure comfort for most occupants (ASHRAE, 2020b). This standard is widely recognised and forms the basis for evaluating and designing HVAC systems in both new and existing buildings. Complementing this, the ASHRAE Handbook-Fundamentals provides detailed methodologies for thermal comfort assessment and energy calculations (ASHRAE, 2020a). In the UK and Europe, the PAS 2035/2030:2023 framework by the British Standards Institution offers a holistic approach to retrofitting dwellings for improved energy efficiency, emphasizing a whole-building perspective that integrates occupant needs (British Standards Institution, 2023).

2.2 BUILDING AUTOMATION AND ENERGY MANAGEMENT FRAMEWORKS

Modern energy management in buildings is increasingly driven by building automation systems (BAS), which integrate sensors, controllers, and actuators to monitor and control HVAC, lighting, and other services (Ait Abdelouahid, Debauche and Marzak, 2021). Open communication protocols and interoperable platforms have made it possible to connect heterogeneous devices, facilitating seamless data exchange and coordinated control (Lohia, et al., 2019). Predictive analytics, real-time problem detection, and adaptive control strategies are now possible because of the confluence of AI with IoT technology, or AIoT. (Himeur, et al., 2023). These frameworks support demand-driven energy management, where systems dynamically respond to occupancy, environmental conditions, and user preferences.

2.3 IMPORTANCE OF BALANCING OCCUPANT COMFORT AND ENERGY EFFICIENCY

While improving energy efficiency is a primary objective, maintaining occupant comfort is equally critical.

Uncomfortable indoor environments can negatively impact health, productivity, and overall satisfaction (Bourikas, et al., 2021). Standards such as ASHRAE 55-2017 and CIBSE Guide-A explicitly emphasise the need to balance thermal comfort with energy-saving measures (Chartered Institution of Building Services Engineers (CIBSE), 2021). Advanced BAS and AIoT solutions now enable continuous monitoring of indoor conditions, learning occupant's preferences, and adjusting system operations to ensure both comfort and efficiency (Arsad, et al., 2023). The integration of personalised comfort models and adaptive control is increasingly recognised as an essential feature for the next generation of smart, energy-efficient buildings.

3. ARTIFICIAL INTELLIGENCE AND INTERNET OF THINGS TECHNOLOGIES IN SMART BUILDINGS

3.1 INTERNET OF THINGS DEVICES AND SENSORS

Smart building operation relies on deploying a diverse array of Internet of Things (IoT) devices and sensors for real-time monitoring and control. Occupancy detectors optimise HVAC and lighting schedules based on actual space usage (Kim, et al., 2023). Temperature and humidity sensors are critical for precise HVAC regulation and comfort maintenance, while CO₂ and volatile organic compound (VOC) sensors help ensure indoor air quality and trigger ventilation as needed (Bourikas, et al., 2021). Smart meters and sub-metering devices provide detailed information about energy consumption patterns, aiding in identifying inefficiencies and assessing retrofit options (Gupta and Kotopouleas, 2018). The strategic placement and integration of these sensors are critical to achieving a holistic and responsive building management system.

The deployment of diverse IoT sensors particularly occupancy, environmental, and energy metering devices underpins real time smart building operation. As summarised in Table 1, these technologies vary in data granularity, installation complexity, and integration flexibility. Notably, machine learning based controls and digital twins not only monitor but also predict building performance, offering greater adaptability compared to reactive systems.

3.2 ARTIFICIAL INTELLIGENCE TECHNIQUES FOR DATA ANALYTICS, PREDICTIVE CONTROL, AND FAULT DETECTION

The vast amounts of data generated by IoT devices in smart buildings are harnessed through advanced artificial intelligence (AI) techniques. Machine learning (ML) algorithms are widely used for predictive analytics, enabling the forecasting of energy demand, occupancy patterns, and indoor environmental quality (Aguilar, et al., 2021; Lin, et al., 2022). In particular, deep

TECHNOLOGY	APPLICATION AREA	FUNCTIONALITY	REFERENCE
Occupancy Sensors	HVAC/Lighting Control	Detect presence, optimise schedules	(Kim, et al., 2023)
Temperature/Humidity Sensors	Environmental Monitoring	Maintain thermal comfort	(ASHRAE, 2020a)
CO ₂ /VOC Sensors	Indoor Air Quality	Trigger ventilation	(Bourikas, et al., 2021)
Smart Meters	Energy Management	Track consumption, identify savings	(Gupta and Kotopouleas, 2018)
Machine Learning	Predictive Control	Forecast demand, optimise setpoints	(Markowitz and Drenkow, 2024)
Digital Twins	Performance Simulation	Real-time monitoring & optimisation	(Rutkowski, et al., 2024)

Table 1 Overview of key AIoT technologies and their applications in smart building energy management.

learning models and deep reinforcement learning (DRL) have shown significant promise in optimising HVAC operations by dynamically adjusting setpoints and control strategies to balance energy efficiency with occupant comfort (Himeur, et al., 2023; Markowitz and Drenkow, 2024). AI-driven fault detection and diagnostics (FDD) systems can identify anomalies or inefficiencies in building systems, often before they escalate into significant issues, thus supporting proactive maintenance and reducing downtime (Chen, et al., 2023). The integration of digital twin technology, which creates a virtual replica of physical building systems, further enhances predictive control and performance optimisation by allowing real-time simulation and scenario analysis (Rutkowski, et al., 2024; Elghaish, et al., 2024).

3.3 ARTIFICIAL INTELLIGENCE AND INTERNET OF THINGS ARCHITECTURE AND INTEGRATION CHALLENGES

The convergence of AI and IoT, often referred to as AIoT, has led to the development of sophisticated architectures that combine edge computing for real-time responsiveness with cloud platforms for large-scale analytics and storage (Márquez-Sánchez, et al., 2023). Despite these advancements, several integration challenges persist. Interoperability remains a significant barrier, as smart buildings typically comprise heterogeneous devices and systems using different communication protocols such as BACnet, Zigbee, or LoRaWAN, necessitating middleware solutions for seamless integration (Lohia, et al., 2019; Ait Abdelouahid, Debauche and Marzak, 2021; Inthasuth, Kaewjumras and Sahapong Somwong, 2025). Data security and privacy are also critical concerns, as the increased connectivity and data exchange in AIoT systems can expose buildings to cyber threats if not properly managed (Kumar, et al., 2021; Hussain, et al., 2021). Moreover, the scalability of AIoT solutions can be limited by the need for retrofitting legacy infrastructure and the energy overhead associated with continuous sensor operation (Hou, et al., 2023; Márquez-Sánchez, et al., 2023). Addressing these challenges is essential for realising the full potential of AIoT in delivering energy-efficient, comfortable, and resilient smart buildings.

4. ENERGY EFFICIENCY STRATEGIES ENABLED BY ARTIFICIAL INTELLIGENCE AND INTERNET OF THINGS

4.1 HEATING, VENTILATION, AND AIR CONDITIONING OPTIMISATION METHODS USING ARTIFICIAL INTELLIGENCE AND INTERNET OF THINGS

Passive and hybrid cooling techniques continue to play a pivotal role in sustainable building design. As highlighted by Çüce (2025), evaporative cooling evolved from ancient passive methods to modern AI-optimised systems offers significant efficiency benefits in arid and semi-arid climates, and its integration with AIoT monitoring platforms can mitigate operational inefficiencies and water-use constraints.

Heating, ventilation, and air conditioning (HVAC) systems are typically the largest energy consumers in buildings, making their optimisation a priority for energy efficiency initiatives. The integration of AI and IoT has enabled the development of advanced control strategies that dynamically adjust HVAC operation based on real-time data and predictive analytics. AI-driven control approaches, such as model predictive control (MPC) and deep reinforcement learning, have demonstrated significant potential in reducing energy consumption while maintaining thermal comfort (Himeur, et al., 2023; Markowitz and Drenkow, 2024). Computational fluid dynamics (CFD) modelling, when combined with AI algorithms, allows for the simulation and optimisation of airflow and temperature distribution, leading to more efficient HVAC designs and operations (Carlsson, 2024). These methods enable the continuous adaptation of system parameters in response to changing occupancy and environmental conditions, resulting in both energy savings and improved occupant's satisfaction.

4.2 OCCUPANCY BASED CONTROL AND PRESENCE SENSING FOR DYNAMIC ENERGY MANAGEMENT

Occupancy-based control is a cornerstone of smart building energy management, leveraging IoT sensors to detect the presence and movement of occupants. By

BUILDING TYPE	AIoT SOLUTION	MAIN OUTCOME	REFERENCE
Smart Home	Cloud-integrated AIoT	18% energy savings	(Gowda, et al., 2024)
Multi-family	Intelligent EMS	15% reduction in HVAC use	(Amma Oforiwaa Ampomah-Asiedu and Wepea Adamwaba Buntugu, 2024)
Apartment	Occupancy Sensing	20% HVAC energy savings	(Pang, et al., 2024)
Multi-family	Digital Twin	Improved performance tracking	(Rutkowski, et al., 2024)
Server Room	AI-driven CFD	Optimised airflow, reduced energy	(Carlsson, 2024)

Table 2 Selected exemplary case studies of AIoT-enabled energy efficiency strategies in smart buildings (adapted from (Dankan Gowda et al., 2024; Pang et al., 2024; Rutkowski et al., 2024).

integrating data from occupancy, temperature, CO₂, and humidity sensors, AIoT systems can adjust lighting, HVAC, and ventilation in real time, minimising energy use in unoccupied spaces (Azizi, et al., 2021; Kim, et al., 2023). Machine learning models further enhance these systems by predicting occupancy patterns and proactively managing building systems to align with user behaviour (Jia, Srinivasan and Raheem, 2017). Field studies have shown that occupancy-based control can achieve substantial reductions in HVAC energy consumption, especially in commercial and multi-family residential buildings (Pang, et al., 2024; Amma Oforiwaa Ampomah-Asiedu and Wepea Adamwaba Buntugu, 2024).

4.3 USE OF DIGITAL TWINS AND SIMULATION FOR ENERGY PERFORMANCE ASSESSMENT

Digital twin technology is increasingly being adopted in the building sector as a means of simulating, monitoring, and optimising energy performance. A digital twin is a virtual representation of a physical building, continuously updated with real-time sensor data to reflect actual operating conditions (Rutkowski, et al., 2024). This technology enables detailed scenario analysis, predictive maintenance, and the identification of inefficiencies or faults before they impact performance (Elghaish, et al., 2024). Simulation tools, such as EnergyPlus and IDA ICE, are often integrated with digital twins to evaluate the impact of various retrofitting strategies and control algorithms on energy use and occupant comfort (Al-Habaibeh, Sen and Chilton, 2021; Markowitz and Drenkow, 2024). The use of digital twins supports data-driven decision-making and continuous commissioning, contributing to the realisation of net-zero energy buildings.

4.4 CASE STUDIES AND FRAMEWORKS FROM RECENT LITERATURE

Recent evidence from Suman, et al. (2025) demonstrates that passive cooling strategies such as natural ventilation, shading, and material selection, when tailored to climatic conditions in rapidly growing megacities, can substantially reduce HVAC energy demand. These findings reinforce the importance of combining AIoT-enabled active control with context specific passive measures to maximise efficiency gains.

Recent literature provides numerous examples of AIoT-enabled frameworks and case studies that demonstrate the effectiveness of these strategies. For instance, (Gowda, et al., 2024) presents a cloud-integrated AIoT framework for smart homes that achieves notable energy savings through adaptive control and real-time analytics. Similarly, (Amma Oforiwaa Ampomah-Asiedu and Wepea Adamwaba Buntugu, 2024) describes an intelligent energy management system that leverages AIoT to optimise energy use in multi-family buildings, resulting in measurable reductions in both energy consumption and operational costs. Studies by (Azizi, et al., 2021; Pang, et al., 2024) highlight the benefits of occupancy-based control, while (Rutkowski et al., 2024; Elghaish et al., 2024) showcase the application of digital twins for performance assessment and optimisation. These cases collectively highlight the transformative potential of AIoT in advancing energy efficiency, occupant comfort, and operational resilience in smart buildings.

Recent studies demonstrate the effectiveness of AIoT-enabled strategies in various building types. Table 2 highlights a few chosen case stories, emphasising the building type, AIoT solution used, and important results.

4.5 COLD CLIMATE CONSIDERATIONS IN AIoT STRATEGIES

Smart building energy management in cold climates presents distinct operational challenges. Higher heating demand reduced solar gain, and stringent requirements for insulation and building envelope performance necessitate strategies that differ from those used in temperate or hot climates. AIoT enabled HVAC optimisation in these regions must prioritise adaptive setpoint management, predictive pre-heating, and integration with high performance insulation materials. For example, recent work demonstrates that climate responsive measures in high density urban contexts such as adaptive heating control and integration of passive design solutions can achieve both comfort and notable energy savings, illustrating reductions of up to 25% in annual heating energy demand (Suman, et al., 2025).

Multiple studies highlight that climate and occupancy patterns significantly dictate the success of both passive

and active energy saving strategies. Applications in colder regions increasingly rely on heat recovery ventilation and real time occupancy sensing to prevent unnecessary heating and avoid overheating when spaces are partially occupied. Moreover, hybrid solutions, such as evaporative cooling and AI-monitored ventilation are emerging as effective strategies for improving indoor air quality and thermal comfort even in challenging low temperature settings (Suman, et al., 2025; Çüce, 2025).

Future research should explore the integration of AIoT enabled heating systems with renewable energy sources such as heat pumps combined with district heating as well as the critical role of user behaviour for comfort maintenance during extreme winter events. This approach supports both energy savings and occupant wellbeing, aligning with global decarbonisation and building sustainability goals.

5. OCCUPANT COMFORT AND BEHAVIOURAL ADAPTION

5.1 MODELLING OCCUPANT BEHAVIOUR AND ADAPTIVE COMFORT IN ENERGY MANAGEMENT

Building comfort and energy efficiency are greatly influenced by occupant behaviour. Traditional energy management systems often overlook the variability and unpredictability of human behaviour, leading to suboptimal energy use and occupant dissatisfaction (Jia, Srinivasan and Raheem, 2017). To address this, recent research emphasises the integration of occupant behaviour modelling into building energy management frameworks. Adaptive comfort models, which account for occupants' ability to adjust to varying thermal environments through behavioural and physiological changes, offer a more realistic basis for HVAC control strategies (Gauthier and Shipworth, 2015; Zhao and Yang, 2022). These models consider factors such as clothing insulation, activity levels, and individual thermal preferences, enabling dynamic adjustment of indoor conditions that better align with occupant expectations and reduce unnecessary energy consumption (Bourikas, et al., 2021).

5.2 TRADE OFFS BETWEEN ENERGY SAVINGS AND OCCUPANT'S SATISFACTION

Balancing energy savings with occupant's comfort presents a complex challenge. Aggressive energy reduction strategies can lead to discomfort, negatively impacting productivity and wellbeing (Simpeh, et al., 2022). Conversely, prioritising comfort without constraints can result in excessive energy use. Studies have documented this trade-off, highlighting that occupant's satisfaction often declines when indoor conditions deviate from preferred comfort zones, even if energy savings are achieved (Zhao and Yang, 2022;

Pang, et al., 2024). This necessitates the development of control systems that optimise for both objectives simultaneously. Multi-objective optimisation approaches and reinforcement learning algorithms have been employed to navigate these trade-offs, seeking to maximise comfort while minimising energy consumption (Markowitz and Drenkow, 2024; Hajian, 2024).

5.3 ARTIFICIAL INTELLIGENCE DRIVEN PERSONALISED COMFORT MODELS AND THEIR IMPACT ON ENERGY USE

Indoor air quality (IAQ) is an equally important dimension of occupant comfort. Tapia-Brito and Riffat (2025) present the MopFan multi-stage air purification system, which combines high efficiency particulate air (HEPA) filtration, photocatalytic oxidation, and bio-aerogel materials to significantly reduce concentrations of volatile organic compounds (VOCs) and formaldehyde in indoor environments. By integrating these IAQ focused technologies with building control platforms enabled by artificial intelligence (AI) and the Internet of Things (IoT) referred to as AIoT facility managers can create a more holistic strategy for optimising both comfort and wellbeing for occupants. Incorporating IAQ interventions alongside energy efficiency measures supports healthier, adaptive building environments that respond dynamically to occupant needs and environmental challenges.

Artificial intelligence has enabled the creation of personalised comfort models that tailor building operations to individual occupant preferences. Machine learning algorithms analyse data from wearable sensors, environmental monitors, and occupant feedback to predict comfort levels and adjust HVAC settings accordingly (Melo, da Graça and Panão, 2023; Osamudiamen and Ugboaga, 2024). Such personalised control has been shown to improve occupant satisfaction significantly while maintaining or even reducing energy consumption compared to traditional uniform control strategies (Devaraj, 2023). Moreover, AI-driven systems can learn occupant routines and preferences over time, enabling proactive adjustments that anticipate needs and prevent discomfort (Gowda, et al., 2024). These advances represent a paradigm shift towards occupant-centric energy management, where comfort and efficiency are no longer competing goals but integrated outcomes.

6. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

6.1 DATA QUALITY, PRIVACY, AND SECURITY CONCERNS IN ARTIFICIAL INTELLIGENCE AND INTERNET OF THINGS SYSTEMS

When AIoT systems are implemented in smart buildings, a wide variety of sensors and devices produce enormous volumes of data. Ensuring the

quality, reliability, and accuracy of this data is critical for effective energy management and occupant comfort (Calabrese, et al., 2022). However, real-world implementations often face challenges such as sensor drift, data loss, and inconsistencies arising from device heterogeneity or communication failures (Lu, et al., 2020; Márquez-Sánchez, et al., 2023). In addition to data quality, privacy and security are major concerns, as the interconnected nature of AIoT systems increases the risk of cyberattacks and unauthorised data access (Kumar, et al., 2021; Hussain, et al., 2021). Sensitive information about occupant's behaviour and building operations must be protected through robust encryption, secure authentication, and privacy-preserving data analytics (Abraham, et al., 2022). Developing standardised protocols and security frameworks tailored to the unique needs of smart buildings remains an ongoing research priority.

6.2 BARRIERS TO REAL WORLD DEPLOYMENT AND SCALABILITY

Despite the promising results demonstrated in pilot projects and simulations, the large-scale deployment of AIoT-enabled energy efficiency solutions faces several barriers. Legacy building infrastructure often lacks the compatibility required for seamless integration of modern sensors, controllers, and communication protocols, necessitating costly retrofits (Abuimara, et al., 2021; Hou, et al., 2023). Interoperability between devices from different manufacturers remains a persistent challenge, often resulting in fragmented systems that limit the effectiveness of holistic energy management (Lohia, et al., 2019; Ait Abdelouahid, Debauche and Marzak, 2021). Furthermore, the scalability of AIoT solutions is constrained by the need for ongoing maintenance, skilled personnel, and reliable network infrastructure, particularly in older or resource-constrained buildings (Márquez-Sánchez, et al., 2023; Amma Oforiwa Ampomah-Asiedu and Wepea Adamwaba Buntugu, 2024).

6.3 EMERGING TRENDS: INTEGRATION WITH SMART GRIDS, SECTOR COUPLING, AND POLICY IMPLICATIONS

Looking forward, the integration of smart buildings with smart grids and other energy sectors is an emerging trend with significant potential for enhancing energy flexibility and resilience. Sector coupling-linking buildings with transportation, heating, and renewable energy systems-can enable demand response, load balancing, and optimised use of distributed energy resources (International Energy Agency (IEA), 2023). Policy frameworks and regulatory standards are evolving to support these developments, with initiatives such as the UK's Net Zero Strategy and PAS 2035/2030:2023 providing guidelines for holistic retrofit and energy management

(Department for Business, Energy & Industrial Strategy (BEIS), 2021; British Standards Institution, 2023). However, aligning technological innovation with policy and market structures remains a complex challenge, requiring collaboration across disciplines and sectors.

6.4 KNOWLEDGE GAPS

A number of research gaps are identified in the literature that call for additional study. Firstly, there is a need for more robust, real-world validation of AIoT-enabled energy efficiency strategies, particularly in diverse building types and climatic contexts (Abuimara, et al., 2021; Elghaish, et al., 2024). Secondly, while AI-driven personalised comfort models show promise, their long-term impact on energy consumption and occupant wellbeing remains underexplored (Bresa, 2024; Osamudiamen and Ugboaga, 2024). Thirdly, the development of standardised, interoperable platforms for data sharing and analytics is still in its infancy, limiting the scalability and replicability of successful case studies (Ait Abdelouahid, Debauche and Marzak, 2021; Márquez-Sánchez, et al., 2023). Finally, the intersection of AIoT with social, behavioural, and cultural factors in building energy use is an area of significant importance for interdisciplinary research (Gauthier and Shipworth, 2015).

7. CONCLUSION

This review synthesised recent developments reported in the literature on artificial intelligence and Internet of Things enabled strategies for improving energy efficiency and occupant comfort in smart buildings, drawing on international standards, documented case studies, and peer reviewed research.

AIoT approaches including model predictive control, deep reinforcement learning, occupancy based optimisation, digital twins, and advanced indoor air quality management have consistently delivered measurable reduction in HVAC energy use while sustaining or improving comfort. The evidence shows that best performance is achieved when these active control strategies are combined with climate appropriate passive measures, supported by interoperable platforms that integrate sensing, analytics, and adaptive control.

For effective deployment, AIoT systems should be designed for real time responsiveness, predictive decision making, and seamless integration with existing building automation systems. In cold climate contexts, technical best practice includes adaptive heating control, heat recovery ventilation, and pre heating strategies to enhance performance and occupant comfort. Operationally, ensuring interoperability, robust cybersecurity, and reliable data governance is critical to scalability.

Occupant comfort is maximised when personalised HVAC control and IAQ management are integrated within AIoT systems.

Policy frameworks should prioritise interoperability, secure data governance, and alignment with standards such as PAS 2035 to accelerate the adoption of AIoT technologies in the building sector.

Looking forward, several future research priorities have been identified. First, there is a need for large-scale, longitudinal field studies of AIoT enabled smart building systems across diverse building types and climatic contexts. Such studies will provide robust evidence regarding the performance, reliability, and occupant satisfaction of these systems over time.

Research into the integration of AIoT control platforms with distributed energy generation technologies such as photovoltaic systems, thermal storage, and district heating and cooling is important to optimise renewable energy use and improve the overall sustainability of buildings.

Further, extended evaluations of personalised comfort control models are needed to better understand the long term trade-offs between occupant comfort and energy efficiency, facilitating the development of adaptive algorithms that maintain a balance between these objectives.

Developing secure, interoperable frameworks that enable real-time data sharing across building systems while safeguarding occupant privacy is crucial. Future research should focus on the establishment of standardised protocols that support seamless cross-platform interoperability.

Lastly, research into behavioural integration is essential. This includes exploring strategies for occupant engagement, behaviour change interventions, and implementing feedback loops to influence the adoption and ongoing performance of AIoT solutions, ensuring that technologies effectively complement human factors in building energy management.

DATA ACCESSIBILITY STATEMENT

No new datasets were generated or analysed during the current study. All data supporting the findings of this review are available in the cited peerreviewed literature, technical standards, and other referenced sources as listed in the References section.

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COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR CONTRIBUTIONS

Conceptualisation: Chinedu C. Onweh.

Methodology: Chinedu C. Onweh, Amin AlHabaibeh, Emmanuel Manu.

Investigation: Chinedu C. Onweh.

Writing – original draft preparation: Chinedu C. Onweh.

Writing – review & editing: Amin AlHabaibeh, Emmanuel Manu.

All authors have read and approved the final manuscript.

AUTHOR AFFILIATIONS

Chinedu C. Onweh  orcid.org/0009-0007-0405-9922

PhD Student, Product Innovation Centre, School of Architecture, Design and Built Environment, Nottingham Trent University, UK

Amin Al-Habaibeh  orcid.org/0000-0002-9867-6011

Director Product Innovation Centre, School of Architecture, Design and Built Environment, Nottingham Trent University, UK

Emmanuel Manu  orcid.org/0000-0002-9002-3681

Department of Construction Management, School of Architecture, Design and Built Environment, Nottingham Trent University, UK

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