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The Role of Smart Houses in the Journey towards Net-zero: A Review

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Abstract
Achieving net-zero requires an integrated approach to energy efficiency throughout a building's life cycle. Energy consumption can be optimised and carbon emissions can be reduced when utilising smart technologies. This paper explores the role of smart home technology in achieving net-zero home goals, by synthesising existing literature on smart energy, user behaviour, and sustainable building strategies. A rapid evidence review is conducted to identify technologies that support net-zero through smart home systems. Key findings indicate that while smart homes can significantly contribute to reducing energy consumption and carbon footprints, challenges such as limited public awareness, data privacy concerns and policy barriers hinder their widespread adoption. The research demonstrates the need for further empirical studies on user engagement, cost-benefit models and policy frameworks to facilitate the integration of smart home technologies into decarbonising homes, therefore accelerating the transition to net-zero.

Keywords
Smart House, net-zero, adoption barriers, smart technology, energy efficiency

1 Introduction

The global demand for energy continues to rise, leading to significant environmental adversities. Buildings are among the largest contributors to this rising energy consumption (Chenari et al., 2016), with their impact on carbon emissions being widely recognised (Sajjadian, 2023). In the UK, carbon emissions from buildings are growing at a rate of 0.5 % (Pérez-Lombard et al., 2008). In Addition, 29 million UK homes account for 14% of the country's total energy consumption, highlighting the urgent need for action. It is crucial to build new energy-efficient homes and retrofit existing buildings to meet the UK's 2050 net-zero target (Sajjadian, 2023).

Smart home technologies can play a crucial role in enhancing building energy efficiency (Awwal et al., 2024). They facilitate the decarbonisation of heating and cooling systems by meeting energy needs through local renewable energy sources and energy management systems, thereby reducing energy consumption and optimising resource use (Furszyfer Del Rio et al., 2021). However, despite their significant potential, the relationship between design features of smart homes and their sustainability outcomes remains poorly understood. Furthermore, there are issues with user behaviour regarding technology adoption.

This paper aims to identify commonalities between smart home technologies and net zero home strategies. The literature synthesis identifies key challenges in the adoption of smart home technologies e.g. high initial cost, interoperability issues, data privacy concerns, user acceptance and the need for change in policies. The research presents limitations highlighting the need for further empirical research to validate findings. Nonetheless, the synthesis provides valuable insights to inform decision-making, facilitating the integration of smart home technologies to support net-zero goals.

2 Research Method

This study uses a Rapid Evidence Assessment (REA) framework (Simcock, 2023), with the following stages: (i) string development, (ii) review of topics, (iii) screening and study selection, (iv) data extraction, (v) knowledge synthesis, and (vi) output production and dissemination. The initial inclusion criteria for papers are: (i) Date: studies published post 2000 to account for time and resource considerations.; (ii) Language: limited to English language records; (iii) Type of studies: peer reviewed journal articles and grey literature reports; (iv) Study designs: all study designs; (v) Population: smart technology use to support net-zero and (vi) Phenomena of interest: use of smart technology in residential settings to achieve net-zero. The strings are below:

Table 1. String 1 – Phenomena of interest

Keyword(s)	Rationale
"Net-zero*"	Captures literature referring to net-zero home principles or adoption challenges
"Technology facilitated smart home" OR "NZEB"	Focuses on the integration of net-zero technology in smart home systems
"Energy efficiency""	Targets specific technologies aimed at improving energy performance

Final String 1:
Scopus: "net-zero*" OR "net-zero technology" OR "technology facilitated smart home" OR "NZEB" OR "energy efficiency"

Table 1. String 2 – Context

Context	Keyword(s)
Smart Home	"Smart home" OR "Smart house" OR "Smart building" OR "automated home" OR "digital home" OR "intelligent home"
Smart Technology	"Smart technolog*" OR "Connected smart devic*" OR "advanced technolog*" OR "digital intelligence" OR "IoTs" OR "Internet of Things"

Final String 2:
Scopus: "Smart home" OR "Smart house" OR "Smart building" OR "automated home" OR "digital home" OR "intelligent home" OR "Smart technolog*" OR "Connected Smart Devic*"

Final search string
("net-zero homes*" OR "net-zero technology" OR "technology facilitated smart home" OR "NZEB" OR "energy efficiency") AND ("Smart home" OR "Smart house" OR "Smart building" OR "automated home" OR "digital home" "intelligent home" OR "Smart technolog*" OR "Connected smart devic*")
The final search string was used to create a database for the selection of papers. PRISMA framework was applied for study selection (see Figure 1), resulting in a final sample of 46 papers for review, which are included in this paper's reference list.

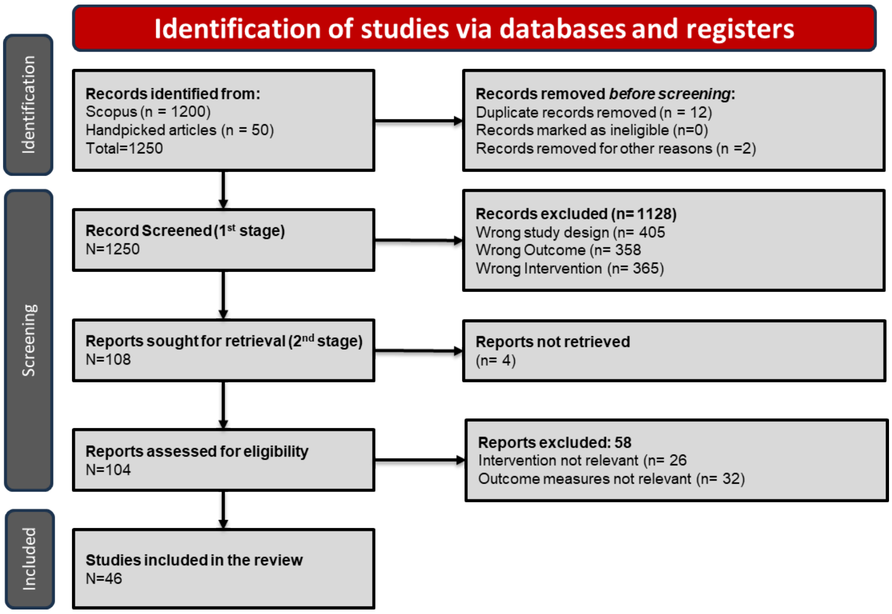

Figure 1. PRISMA Framework for review conducted in the research

Methodological Limitations

The limitations of the study are time constraints, inclusion and exclusion criteria. The inclusion criteria focused on keywords such as net-zero homes, smart home technology adoption, energy management system, and adoption barriers. Conversely, exclusion criteria filtered out studies with highly technical jargon such as blockchain, (ANN) artificial neural networks, regression analysis, and machine learning, as they were beyond the scope of the qualitative synthesis. The study primarily synthesises existing qualitative research focusing on value-adding functions and user requirements for smart home adoption. This paper reports on a limited number of papers. However, findings highlight research gaps in linking smart home technologies with net-zero strategies, especially in terms of user value and adoption challenges, suggesting the need for a larger systematic study. Additionally, future research is required for empirical validation to enhance the understanding of smart home technologies in achieving net-zero energy goals.

3 Literature Synthesis

The selected papers were analysed to identify: (i) strategies to achieve net-zero homes; (ii) design and use of environmentally beneficial smart home technologies; (iii) list smart home technologies; (iv) commonalities between smart home technologies and net-zero strategies and (v) challenges in adopting smart home technologies. The rationale for analysing the papers through these five objectives is to provide a holistic understanding of how smart home technologies contribute to net zero energy goals. These objectives are interconnected, portraying a progression from technological identification to real-life implementation challenges.

3.1 Net-zero Buildings

Understanding net zero buildings and strategies is essential to understand how smart home technologies can contribute to their achievement. Different Zero-Energy Building (ZEB)-related definitions exist, considering zero energy, zero carbon, and zero cost (Açikkalp et al., 2023). This paper focuses primarily on zero energy. The key argument is that net-zero buildings aim to balance energy consumption with renewable energy generation over a given period. While most papers present the fundamental concept, variations exist in how net zero is achieved and quantified. Some definitions, for instance, Jaysawal et al (2022) and Idrissi Kaitouni et al (2024) emphasised achieving a net-zero energy balance, the total annual energy consumption of the buildings being approximately equal to the renewable energy generated on-site. Omrany et al (2022) eexpandon this by stressing the role of commercially available renewable energy technologies and energy-efficient construction, where no fossil fuels are consumed. Kilkis (2007) introduced the idea of a total annual zero energy transfer accounting for all electrical and other forms of energy exchange over a specific period. Noguchi et al (2008) similarly stated that net-zero buildings use the same amount of energy as it generated during a certain period. These definitions illustrate that the overarching goal of net-zero buildings is widely accepted as net-zero energy balance. However, the inclusion of specific methods to achieve this differ. Table 3 presents key theoretical concepts and supporting literature on Net zero homes.

Table 3. Theoretical understanding and supporting literature of Net Zero Homes

Category	Key Concepts	Authors
Energy efficiency (zero energy concept)	• Energy efficiency through smart system integration in buildings • Balance energy use with renewable energy via smart management • Minimising carbon footprint by adoption of energy efficient technologies	(Habiba et al., 2024; Lazaroiu et al., 2024)
Smart energy management system	• Renewable energy sources and integration (PV Panels, and surplus energy systems through smart energy storage systems) • Reduce dependency on fossil fuels • Water conservation through rainwater harvesting and water reuse systems • Utilisation of solar, wind, geothermal, and biomass energy	(Jaysawal et al., 2022; Omrany et al., 2022;Habiba et al., 2024)
Renewable energy Integration	• Smart grids in reducing the carbon footprint of UK homes • Smart grid to reduce additional stress on the power infrastructure • Information and Communication Technology (ICT) and smart grids for energy management and optimised building operation	(Kolokotsa, 2016; Wilberforce et al., 2023)
Lighting and HVAC	• Integration of automatic shading systems into window construction • Light sensors built into the lighting system to reduce energy consumption • Occupant-centric control (OCC) for balancing occupant comfort with energy efficiency	(Jaysawal et al., 2022;Wilberforce et al., 2023;Habiba et al., 2024)
Building envelope (thermal efficiency	• Building envelope materials for insulation; eco-friendly materials • The techniques include shade, thermal bridge, design of air tightness, efficient ventilation, and lighting, coupled with high energy efficiency • The building's airtightness and thermophysical properties of the materials	(Jaysawal et al., 2022; Wilberforce et al., 2023)

Establishing a pathway to net-zero emissions is critical (Gatt et al., 2020). Smart home technologies have the potential to enhance energy efficiency (Furszyfer Del Rio et al., 2021). Therefore, a clear understanding of smart home technologies is essential for maximising its impact on energy savings and emissions reduction.

3.2 Smart Homes Technology

Building on the 'net-zero energy home' strategies, the identification of smart home technologies is essential to understand how these can be applied effectively. The term 'smart home technology (SHT)' defines services that provide occupants security, comfort, convenience, and energy efficiency (Shabha et al., 2021) . A smart home refers to a residence that is equipped with computing and information technologies to build better living environments (Aldrich, 2003). Three related concepts are: (i) Smart Building; (ii) Smart Systems and (iii) Smart appliances (Li et al., 2021;Habiba et al., 2024).

Smart building refers to modernised buildings equipped with data collection systems for intelligent building management (Li et al., 2021). Smart buildings were initially identified as the 'integration of complex and novel technologies in the fabric design and construction of a building'(Drewer and Gann, 1994). However, the concept evolved with a more comprehensive approach of emphasising user interactive roles and the social context to enhance quality of life. A smart building consists of innovative energy storage technologies, intelligent optimisation of self-consumption, situation-specific home automation, and integration of renewable technologies (Froufe et al., 2020). Energy management with building monitoring and fault detection is another recent focus in smart buildings (Aguilar et al., 2021). Smart building is defined as a human cyber-physical system, where data collection systems measure the physical built environment or human behaviour, and send data to computer algorithms for building operation control (Li et al., 2021).

Smart Systems refer to the integration of intelligent energy (IIE) systems, renewable energy technologies, and geothermal energy systems (Habiba et al., 2024). A smart home system offers occupants the convenience of remote control and automation of household systems, with one or more devices. The home gateway is responsible for connecting to all smart devices on the wireless channel and connecting to the service provider via a wired connection (Reisinger et al., 2023). In a smart home, various devices (smart devices) in the home can be remotely controlled through mobile terminals such as smartphones.

Smart homes offer a range of potential benefits, including:

3.2.1 Energy and financial benefits

Smart homes improve energy management, enabling reduced consumption and lower costs through demand response and real-time energy monitoring (Li et al., 2021). For instance, smart thermostats adjust heating and cooling by learning from user preferences (Wong et al., 2017). Energy efficient lightings controlled by motion sensors reduce overuse. Several studies have shown that integrated smart energy management systems reduce bills by 10-30%, contributing to longer term financial savings (Asadullah and Raza, 2016). Using energy-efficient technologies with smart energy management systems and renewable energy leads to a reduced carbon footprint (Gunawan et al., 2024).

3.2.2 Health Benefits

Smart homes can provide home-based healthcare services that support independent living and monitoring of health conditions (Li et al., 2021). Smart buildings can realise specific functions, such as those developed for indoor air quality (Zhang et al., 2023), and occupants with disability (Sovacool et al., 2021). Due to its intelligent and timely reaction to dangerous conditions, smart homes also have great advantages in reducing indoor risks for the elderly efficiently, and promoting safer residences (Zhang et al., 2023).

3.2.3 Enhanced quality of life

Smart homes offer convenience, security, and improved control over household environments that enhance the quality of life. For instance, pervasive computing allows unobtrusive monitoring of occupants' behaviour, generating data that can be used to analyse activity patterns (Dawadi et al., 2016). Smart home supports health and wellbeing and transforms the home into a responsive, efficient, and comfortable environment (Sovacool et al., 2021).

4 Integration of Smart Home technologies and net-zero targets

The design of smart homes has an important role in helping achieve net-zero targets by integrating advanced technology and sustainable practices that minimise energy consumption and carbon emissions (Peiris et al., 2023). Smart homes use interconnected systems, sensors, and automation. It can help reduce reliance on non-renewable energy sources and support sustainable energy goals (Kim et al., 2022). Figure 2 shows smart home technologies.

Smart home design supports net-zero goals primarily through intelligent energy management (Li et al., 2021). Smart thermostats, lighting, and appliances adjust automatically based on occupancy, weather conditions, and user preferences, optimising energy use (Awwal et al., 2024). For example, smart thermostats learn residents' schedules and adjust temperatures accordingly, avoiding unnecessary heating or cooling, which reduces energy consumption—a major source of energy use in residential buildings (Reisinger et al., 2023). Similarly, smart lighting systems use motion detectors and natural light sensors to turn lights on only when needed, which conserves electricity and reduces demand on the grid (Kim et al., 2022).

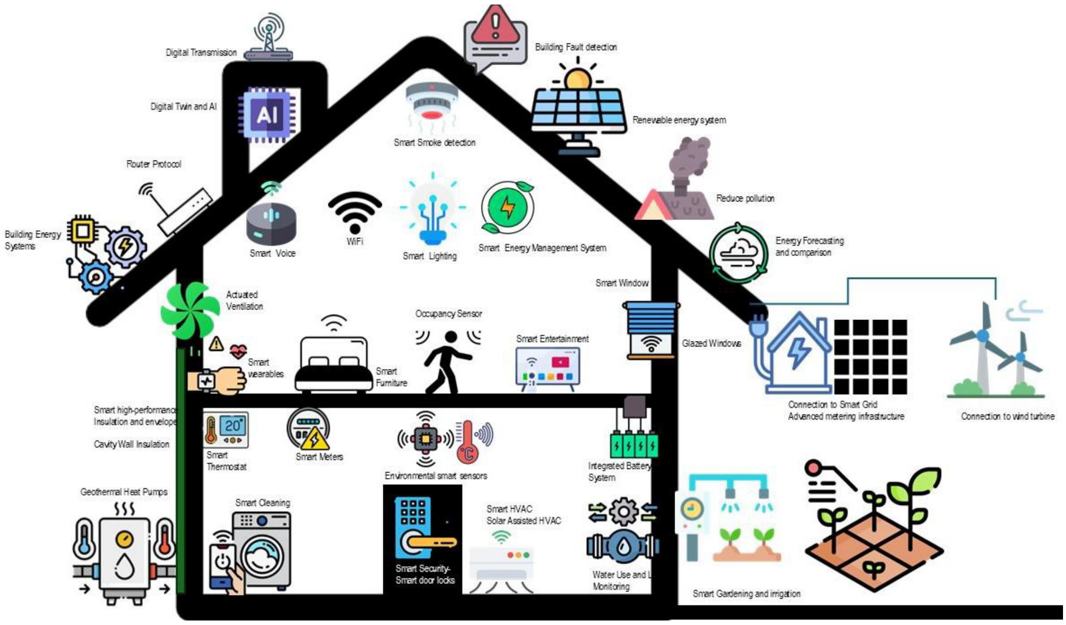

Figure 2. smart home technologies

Smart homes also facilitate the integration of renewable energy sources, such as solar panels and wind turbines, into the home's energy system (Kim et al., 2022). For instance, energy storage solutions like smart batteries enable excess energy generated during peak production times to be stored and used during high demand periods or when renewable generation is low . Smart home systems can also be programmed to shift energy use to times when renewable energy is more readily available, often during daylight hours for solar-powered homes (Lazaroiu et al., 2024).

Real-time monitoring and data analytics enable occupants to track and optimise energy performance continually. Dashboards and mobile apps provide insights into energy usage patterns, allowing for adjustments that align with net-zero goals (Gøthesen et al., 2023). Furthermore, many smart homes now include electric vehicle (EV) charging systems, encouraging the use of renewables and further reducing reliance on fossil fuels (Barman et al., 2023).

Water and waste management are intrinsically connected to energy saving in homes, as the process involves water treatment, distribution, heating and waste disposal, requiring significant energy inputs (Traven, 2023). Smart water systems can monitor consumption, detect leaks, and reduce water wastage. Greywater recycling systems help reduce overall water usage, supporting water conservation and reducing the energy required for water heating and treatment (Maktabifard et al., 2023).

Additionally, smart homes reduce carbon footprints by incorporating advanced materials and construction methods. Insulation and high-performance windows, coupled with smart ventilation systems, help maintain comfortable indoor conditions while minimising energy loss (Peiris et al., 2023). Building materials themselves are increasingly chosen based on sustainability and efficiency, such as recycled or carbon-neutral materials, which further support the building's net-zero status (Tazmeen and Mir, 2024).

Smart home design aids in achieving net-zero building targets through energy-efficient systems, renewable energy integration, resource management, and data-driven optimisation, creating comfortable and convenient homes aligned with a sustainable future. The commonalities between smart home technologies and net-zero strategies are presented in Table 4.

Table 4. Commonalities between net-zero and Smart Home Technologies

Net-zero	Smart Home Technologies	Commonalities	Authors
Net-zero refers to a balance between generating as much energy as is consumed through an energy-efficient design	Reducing energy demand using smart building technologies such as high-performance insulation, Smart HVAC and ventilation, smart lighting, and optimised BMS systems	Energy Efficiency	(Adeyeye, 2024; Borgentorp et al., 2023; Gunawan et al., 2024; Habiba et al., 2024; Jaysawal et al., 2022)
Energy is consumed in an efficient way, achieved through users' conscious energy-efficient behaviours and intelligent automation controls	Automated smart sensors and systems enhance householder experience and advanced control techniques to improve occupant comfort level	User Behavioural and controls	(Berry et al., 2014; Fakhabi et al., 2024; Habiba et al., 2024; Shabha et al., 2021)
Continuous tracking of energy usage and performance, enhancing system responsiveness and maintenance in buildings.	By integrating IoT systems with real-time monitoring, and renewable energy, buildings can enhance energy efficiency.	Real-time monitoring and data analytics	(Fakhabi et al., 2024; Peiris et al., 2023; Shabha et al., 2021)
Net-zero relies on integrating solar and wind energy to replace fossil fuels and reduce carbon emissions. It integrates through a smart grid connection and generates clean energy on-site	Smart homes are highly energy-efficient and cover its very low energy demand to a large extent by on-site or district-system-driven renewable energy sources	Renewable Energy Integration	(Gunawan et al., 2024; Habiba et al., 2024; Jaysawal et al., 2022; Kim et al., 2022; Peiris et al., 2023; Shabha et al., 2021)
Building materials comprise of insulation, thermal bridging prevention, airtight design, and efficient ventilation to attain thermal comfort	The integration of sustainable technologies and insulation, glazed windows, and automated shading control are integrated in Smart homes	Advanced materials and construction methods.	(Berry et al., 2014; Peiris et al., 2023; Tazmeen and Mir, 2024; Wilberforce et al., 2023)

4.1 Challenges in the adoption of smart home technologies

Despite the extensive benefits, there are several challenges in the widescale adoption. The key four themes identified from the synthesis are cost, privacy concerns, and user perception and policy barriers. These are widely recognised as significant obstacles in preventing the large-scale implementation of smart homes. These are further discussed below:

4.1.1 Cost of installation and affordability

Achieving net-zero buildings requires integrating smart technologies offer longer-term benefits (Jaysawal et al., 2022). However, the high installation cost of smart technologies presents a substantial barrier to widespread adoption (Habiba et al., 2024). Smart devices are expensive and complex to use, particularly challenging for elderly adults from lower socio-economic backgrounds, who may not recognise the immediate benefits of making such a large financial commitment (Lazaroiu et al., 2024). A common pattern is found in Gunawan et al (2024)'s research, where smart home technology is predominantly adopted in luxurious homes, with users showing little interest in the basic functions of these technologies. The adoption of smart home technology remains limited and largely confined to specific demographics (Gunawan et al., 2024; Lazaroiu et al., 2024).

4.1.2 Data Management and Privacy Concerns

Data Management issues are related to the integration of data sources with real-time decision-making. The significant challenge is accommodating varying occupant behaviours and preferences, such as thermal comfort needs, activity patterns, and levels of heat sensitivity. These variations complicate the design of smart technology and systems that balance individual comfort with energy efficiency (Habiba et al., 2024). Furthermore, cyber-physical systems and Internet of Things (IoT) systems collect sensitive user data, necessitating robust protocols to secure and manage (Furszyfer Del Rio et al., 2020). Ensuring secure communication between devices and user data are essential to fostering trust and enabling widespread adoption. However, trust remains a significant challenge as many users doubt the reliability, performance, and controllability of these smart devices (Sovacool et al., 2021). Thus, if users perceive the device as trustworthy, their adoption intention would be increased (Li et al., 2021).

4.1.3 User perceived benefits of smart home technology

There is a level of reluctance from the users in the adoption of smart home technology (Shabha et al., 2021). Wilson et al (2017)'s research stated that although occupants have positive perceptions of smart home technology installation in general, they are often unaware of the impact on energy once the technology is adopted. There is a mismatch between the functionality of smart home technology and user needs that are not captured (Shabha et al., 2021).Adeyeye (2024)'s research shows end users had scepticism on the long-term benefits of smart home technology. This issue worsens if the home occupants are elderly or vulnerable, who are often reluctant to complex technology installation (Sovacool et al., 2021) Value generation among users through knowledge sharing can be a focus rather than only technological innovation in implementing smart home technology (Gunawan et al., 2024)

4.1.4 Lack of public awareness and policy barriers

A lack of public awareness, understanding, and trust in smart home technology creates substantial barriers to its acceptance (Gunawan et al., 2024). Geographic location plays a significant role in the adoption with climate specific needs, where region specific design strategies are required (Jaysawal et al., 2022). Policy challenges underpin the need for an integrated approach combing smart technology with post occupancy performance to support social and market transformation within housing sector (Adeyeye, 2024). Moreover, a lack of comprehensive legislation establishing the standard for smart buildings presents policy barriers (Omrany et al., 2022). The deficiency of standardisation and inconsistent definitions complicate regulatory efforts and market estimation. The variety of business models reflects both opportunities and risks, especially in data-driven revenue models and the bundling of services that could lead to monopolistic practices by tech giants (Furszyfer Del Rio et al., 2020). Addressing these challenges is essential to foster a more inclusive smart technology integration.

5 Recommendations and future research

Smart home technology has the potential to play a significant role in achieving net-zero targets by optimising energy efficiency (Jaysawal et al., 2022), reducing waste through intelligent control system (Maktabifard et al., 2023) and integrating renewable energy sources (Peiris et al., 2023). Although smart home innovations offer substantial benefits in terms of energy savings, cost reduction and improved quality of life, there remains a gap in understanding their full potential. Future research is needed in user engagement, cost-benefit models, and policy changes to support widespread adoption. Research on behavioural intentions, user training and adaptive control systems are required in maximising energy efficiency and maintaining occupant comfort. Another key research area is data analytics and energy monitoring to improve real-time energy tracking and predictive maintenance. By overcoming these barriers, smart home technology can contribute to the transition toward a more sustainable and energy-efficient future.

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