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Smart and Sustainable Buildings: Integrating IoT, Renewable Systems, and Energy Efficiency Measures for Net-Zero Goals

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Abstract

This study investigates strategies, technologies, and challenges related to improving energy efficiency in buildings, particularly in the context of climate change and the European Green Deal. It highlights the importance of Energy Efficiency Measures, which include passive, active, and renewable-based systems, in achieving nearly zero-energy targets. The integration of Internet of Things and artificial intelligence into building operations is examined as a transformative approach for real-time energy monitoring and optimization. Simulations and practical applications, such as building-integrated photovoltaics and thermal energy storage, demonstrate quantifiable reductions in carbon dioxide emissions and operational costs. The study also identifies barriers to effective renovation, socio-economic factors influencing residential energy use, and the potential impact of advanced technologies like hydrogen-based storage and intelligent energy management systems. The research provides a broad analysis of the technical and behavioral aspects of transitioning toward energy-efficient buildings, offering valuable insights for policy development and implementation in sustainable urban environments.

1. Introduction

Climate change is one of the most pressing global environmental issues today and is directly linked to energy production and consumption. Approximately 40% of total global energy consumption occurs in buildings, making them a primary focus for energy efficiency interventions. The European Union, among other nations, has prioritized the widespread implementation of energy-efficient buildings as a strategic pathway toward achieving carbon neutrality by 2050.

In this context, various directives and regulatory frameworks have been enacted to enhance the energy performance of new buildings and to support the transformation of the existing building stock through integration with renewable energy systems. At the same time, advancements in digital technologies have increased the feasibility of deploying Internet of Things (IoT) and Artificial Intelligence (AI)-based solutions in building energy management systems.

The aim of this study is to examine the technical, economic, and environmental aspects of passive, active, and renewable-based Energy Efficiency Measures (EEMs); to evaluate the applicability of technologies such as heat pumps, battery storage, and hydrogen storage; and to analyze the impact of IoT-based systems on building energy performance. The research seeks to contribute to sustainable construction policies within the framework of net-zero energy building (nZEB) targets.

2. Energy efficiency in buildings

Improving the energy performance of buildings plays a fundamental role in achieving the energy efficiency targets set by the European Commission (EC) [1]. In this context, the Energy Performance of Buildings Directive (EPBD),

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which came into force in 2002 and was last updated in 2018, aims to ensure that new buildings meet performance-based efficiency standards and that existing structures are renovated to enhance energy efficiency. This includes the integration of Internet of Things (IoT) and Artificial Intelligence (AI) technologies into HVAC systems, in line with the European Green Deal's objective of achieving carbon neutrality by 2050 [2]. 85% of EU buildings were built before 2000 and 75% have poor energy performance. Improving the energy performance of existing buildings is therefore key to saving energy, reducing bills for citizens and enterprises, and achieving a zero-emission and fully decarbonised building stock by 2050. Yet the annual energy renovation rate remains very low at 1% [2]. The data presented in the table 1 indicate a steady decline in Sweden's greenhouse gas (GHG) emissions per capita over the past decade. In 2010, emissions stood at approximately 5.6 tonnes of CO_2-equivalent per person, gradually decreasing to 5.0 tonnes in 2015. By 2020, the value had dropped further to around 4.3 tonnes per capita, before a temporary increase to 5.0 tonnes in 2021, likely linked to post-pandemic economic rebound effects. Nevertheless, in 2022 Sweden recorded a significant reduction, achieving 4.0 tonnes of CO_2-equivalent per capita.

When compared to other European Union (EU) member states, Sweden consistently demonstrates the lowest per capita emissions. The EU average in 2022 was approximately 8 tonnes of CO_2-eq per capita, meaning Sweden's level is around half of the EU average. This highlights the country's effective climate policies, high share of renewables (particularly hydropower and bioenergy), and strong energy efficiency measures across both industry and households.

Table 1. Sweden – Net GHG Emissions per Capita ($t\ CO_2$-eq) [82]

Year	Net GHG Emissions ($t\ CO_2$-eq per capita)	Source
2010	5.6 (OECD, trend estimate)	OECD (2025 Review)
2015	5.0 (OECD, trend estimate)	OECD (2025 Review)
2020	4.3	SCB, Environmental Accounts
2021	5.0	SCB, Environmental Accounts
2022	4.0	EU/EEA Factsheet

Energy Conservation Measures (ECMs) can be classified into three main groups [3]:

- Passive ECMs: Insulated glazing, external shading systems
- Active ECMs: Energy-efficient HVAC systems, low-consumption lighting solutions
- Renewable energy ECMs: Solar collectors, photovoltaic panels, geothermal heat pumps, and wind turbines

For example, in a study by Weglarz and Narowski, it was recommended to use 25 cm of mineral wool in walls and 35 cm on roofs with XPS to achieve a balance between thermal comfort and cost in residential buildings [4]. Kisilewicz et al. demonstrated that placing a special concrete layer with embedded pipes in front of external walls could reduce heat loss by up to 63% [5]. Cholewa et al. found that by using heat pumps in older apartment buildings, savings in domestic hot water supply ranged from 56.7% to 70.5%, and the addition of PV systems further reduced the cost [6-7].

Energy Efficiency Measures (EEMs) encompass a wide array of strategies aimed at reducing the energy demand in buildings during their design, construction, operation, and maintenance phases. EEMs are crucial in lowering operational costs, enhancing energy efficiency, and minimizing environmental impacts [8-9]. The implementation of EEMs is both essential and primary to prompt the realization of Zero Energy Buildings (ZEBs).

EEMs utilized in ZEBs include optimized building envelope designs; the application of phase-change materials (PCM), which aim to reduce thermal loads; and efficient heating, ventilation, and air conditioning (HVAC) systems, as well as occupant behavior, which focuses on improving the energy efficiency of electric systems. High-performance envelope designs or the retrofitting of the building envelope are universally adopted; in addition, passive shading and natural ventilation are also utilized. Methodologies like high-efficiency HVAC systems, energy-efficient materials, and occupant control of the equipment are also widely used [10].

Key operational strategies proposed to reduce energy demand in buildings include energy audits [11], energy management systems [12], smart control systems, and green building certifications [13].

The most common green building certifications are:

- BREEAM (United Kingdom)
- LEED (United States)
- Energy Star [14]

The nZEB (Nearly Zero Energy Buildings)

standard, developed under the EPBD, mandates that public buildings constructed after 31 December 2018 and all new buildings from 2020 onwards must comply with this criterion [15]. This standard was updated in December 2021 with the Zero Emission Buildings (ZEB) target, stipulating that all new buildings must meet ZEB criteria as of 1 January 2030 [16].

Studies show that the main barrier to implementing energy efficiency practices is often not the lack of regulations but the insufficiency of implementation [17]. Research conducted by Blasch [18] and Boogen [19] has shown that awareness campaigns and energy certificates encourage users to engage in energy-saving behaviors.

Users still exhibit hesitation when it comes to investing in energy-efficient buildings. Green building labels are often perceived as offering only theoretical benefits, and doubts persist regarding whether these buildings truly deliver the promised energy savings in practice. Previous studies have revealed that some certified green buildings consume more energy than anticipated [20].

Although current energy consumption estimation methods generally rely on engineering calculations, simulation models, and statistical approaches, the inability to accurately measure variables such as number of occupants and heating habits, as well as data obsolescence and behavioral differences, complicate these estimations. Furthermore, due to variability in physical parameters such as CO_2 emissions and solar radiation duration, the reliability of such models is limited [21-22].

Further analysis of the spatial distribution of ZEB research across countries revealed that, between 2013 and 2023, China produced the largest number of publications with 327, followed by Italy with 277 and Spain with 161. These results indicate a higher level of interest in ZEB research among researchers in China, Italy, and Spain [10].

2.1. Challenges encountered during the renovation process

Renovation efforts aimed at improving energy efficiency in buildings represent a complex process involving technical, economic, and social dimensions [23-24]. Similar challenges have been reported in studies conducted across various countries [25-26]. For instance, Alam et al. categorized the main barriers encountered during the renovation of public buildings in Australia into four major groups [25]:

- **Lack of information**: Insufficient awareness, skills, and motivation
- **Administrative barriers**: Bureaucracy, slow decision-making processes, and difficulties in obtaining stakeholder approval
- **Social barriers**: Environmental factors and operational disruptions
- **Financial barriers**: Lack of incentives and the redirection of investment priorities to other areas

2.2. Factors affecting household energy consumption and the case of Norway

A study as seen on table 2 conducted in Norway examined the changes in household energy consumption between 1970 and 2019. According to the findings, the rate of consumption increase significantly slowed after 1990. If the trend from 1970 to 1990 had continued, the energy consumption in 2019 would have reached 86.4 TWh; however, the actual value was only 45.9 TWh. This indicates that the annual growth rate, which was 2.4% during the 1970–1990 period, declined to 0.15% between 1990 and 2019 [27].

Table 2. Household Energy Consumption in Norway (1970–2019)

Period	Annual Growth Rate (%)	Expected 2019 Consumption (TWh)	Actual 2019 Consumption (TWh)
1970–1990	2.4	—	—
1990–2019	0.15	86.4	45.9

2.3. Factors influencing changes in energy use: per capita residential area

Hille et al. [28] stated that the primary determinant of the change in energy use around the year 1990 was the per capita residential area. Two main factors were identified as influencing the change in this indicator [27]:

- Increased immigration to Norway from non-European countries and the rise in real estate prices,
- The aging population's preference for smaller dwellings.

Moreover, according to a study conducted in 2013, the per capita living space of immigrants from Africa, Asia, and South America was 43% smaller compared to that of native Norwegians [29].

2.4. Heat pump

Heat pumps are increasingly being used to reduce energy consumption and CO_2 emissions in residential buildings. These systems contribute not only to emission reductions but also offer lower operating costs compared to other heating solutions [30].

Heat pumps are classified into two main categories:

- **Ground Source Heat Pumps (GSHPs)**: Utilize the stable temperature of the Earth's crust to supply heat
- **Air Source Heat Pumps (ASHPs)**: Use ambient outdoor air as the heat source

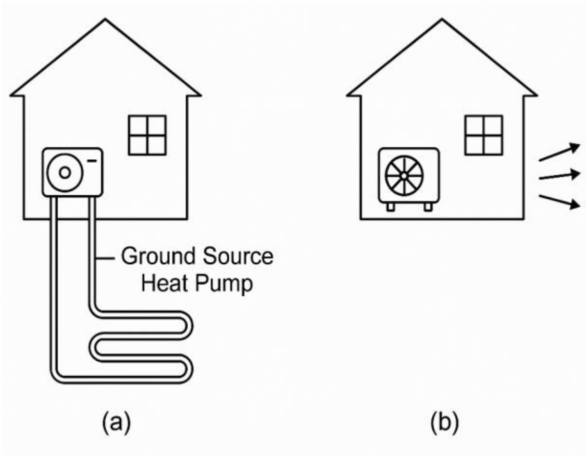

Figure 1. (a) GSHP (b) ASHP [Generated by AI]

System performance varies depending on numerous factors, including outdoor air temperature, soil characteristics, access to groundwater, architectural design, and economic constraints. The efficiency of a heat pump increases as the temperature difference between the heat source and the indoor environment decreases. Therefore, low-temperature systems such as underfloor heating or low-temperature radiators are recommended [31].

In a study by Yılmazer et al., it was found that a heat pump system with underfloor heating achieved 36% lower annual operating costs compared to a natural gas boiler system [31].

Although initial investment costs are high, these costs are expected to decrease as the technology advances, and such systems are projected to become more widespread, particularly in temperate climate regions.

According to Temel's research [32], air source heat pumps are preferred due to their low initial investment cost; however, in regions where winter temperatures fall below -5 °C, performance decreases, making ground or water source systems more suitable. In the Black Sea, Marmara, Aegean, and Mediterranean regions, where both heating and cooling needs are high, the use of ASHPs is considered efficient.

Gaur et al. [33] also stated that the efficiency of air source systems declines in colder climates, and ground/water source systems are more appropriate. Furthermore, in areas with high solar radiation, integrating heat pumps with solar energy systems enhances performance.

2.5. Energy storage in buildings

Within the framework of combating climate change, residential users are being encouraged to shift from fossil fuels to renewable energy sources (RES) and to adopt the concept of zero energy buildings [34]. In this regard, not only new constructions but also the existing building stock must be integrated with renewable energy systems and supported by energy storage solutions, which play a critical role in reducing environmental impacts.

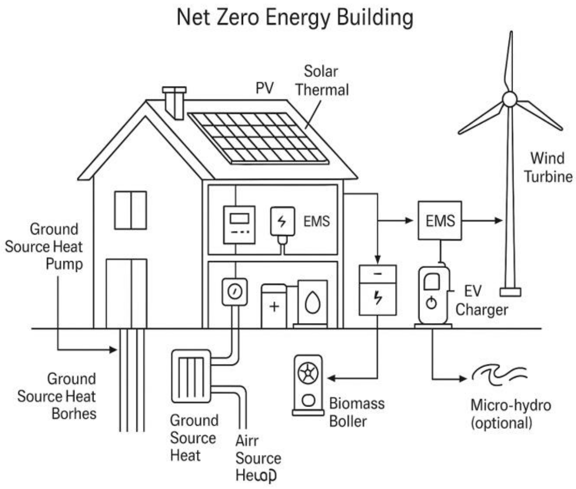

Figure 2. Nzeb [Generated by AI]

2.6. Battery-Based energy storage

The decreasing cost of solar panels and rising energy prices have led households to increasingly adopt solar energy systems [35]. The use of these systems also offers secondary benefits, such as extending the lifespan of roof components. Building-integrated photovoltaic (PV) systems are generally categorized into two main types: off-grid and on-grid. Off-grid systems are further divided into battery-based and non-battery systems. Although battery-based systems entail higher initial installation costs, they provide a solution to the intermittent nature of solar energy by enabling energy to be stored for use when needed [36–37].

While economic analyses primarily focus on residential users, the implementation of battery-based systems in public and commercial buildings is also on the rise [38–39]. According to projections based on current electricity prices, battery-based PV systems may achieve payback within seven years [71]. In contrast, non-battery PV systems are estimated to have an average payback period of approximately 2 years and 3 months [81].

2.7. Battery-based hybrid energy generation system

Buildings capable of meeting their annual energy consumption through self-generation are defined as Net Zero Energy (NZE) buildings. Numerous studies have been conducted on hybrid systems that combine solar and wind energy to achieve this target [40]. Although solar and wind systems are widely adopted individually, their combined use is often limited by high costs. Moreover, in distributed generation systems based on renewable sources, the real-time injection or withdrawal of energy from the grid can increase grid load. Therefore, aligning energy supply with demand is crucial for ensuring the sustainability of the system [41-42].

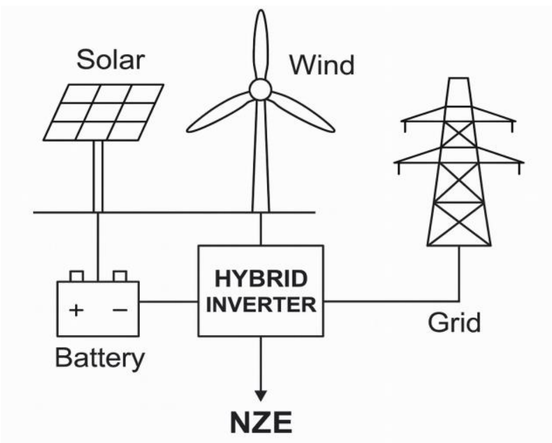

Figure 3. Battery-Based Hybrid Energy Generation System [Generated by AI]

Otherwise, excessive or insufficient generation may increase energy losses in transmission lines and reduce voltage stability and power quality [43-44]. The most effective solution to these issues is the integration of battery storage (BS) systems. This not only enhances system reliability but also reduces the dependence of net zero energy buildings on the grid [43- 45- 46]. Furthermore, research indicates that hybrid systems require lower battery capacity compared to single-source systems [47-48].

2.8. Thermal energy storage (TES)

Advancements in technology and decreasing installation costs have accelerated the adoption of thermal energy storage (TES) solutions in buildings [49]. The primary objective of TES is to minimize mismatches arising from time, temperature, power, and spatial differences between energy generation and consumption [50].

To ensure the societal adoption of TES, greater promotion of its benefits is required [51-52]. In addition to economic gains, increased energy efficiency offers positive impacts on the environment, public health, and sustainable development [53].

Key advantages of TES highlighted in the literature include the following [50, 54, 55]:

- Enhancing the efficiency and reliability of energy systems
- Reducing investment and operational costs
- Reducing pollutant emissions [56-57]
- Decreasing CO_2 emissions
- Improving indoor air quality (particularly when used with HVAC systems)
- Supporting biodiversity through integration with green roofs and façades [53, 58-59]

Furthermore, TES can be utilized alongside building-integrated photovoltaic (BIPV) systems. Thermal energy generated in excess during the day can be stored and used during peak demand periods in the evening or in the winter season. This reduces the amount of energy drawn from the grid [60-61].

As an example, a study by Amini et al. [35] examined the renovation of a residential apartment building constructed in 1985 in Italy (Figure 1a), as part of the Horizon 2020 HEART [62] project. The study investigated the integration of photovoltaic systems and air-to-water heat pumps with TES systems in the building (Figure 3b).

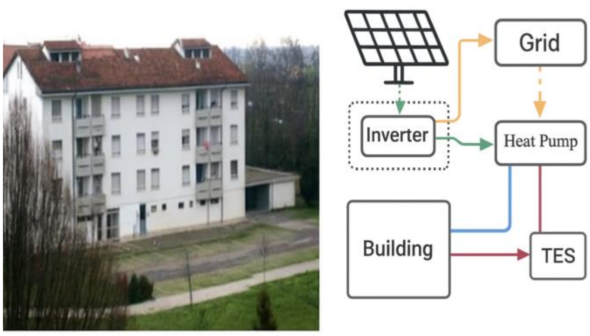

Figure 1. a) Family apartment in Italy, b) Diagram of the system integrated into the building

During the renovation process, the CO_2 savings provided by the building-integrated photovoltaic (BIPV) system and the thermal energy storage (TES) unit were modeled using EnergyPlus software, based on the annual energy consumption data for space heating, cooling, and domestic hot water. Three scenarios were analyzed within the scope of the study:

- **Scenario 1**: Grid-connected building only (no BIPV or TES).
- **Scenario 2**: A 10 kW capacity BIPV system is integrated into the building.
- **Scenario 3**: In addition to BIPV, a TES system is also installed.

The simulation results showed that Scenario 3, which involves the combined use of photovoltaic and thermal storage systems, achieved the highest efficiency. In this scenario, a total of 34.77 tons of CO_2 emissions was avoided over a 30-year period. This represents a 21.42% reduction compared to the conventional setup (Scenario 1). Moreover, the environmental payback period of the system was estimated to be approximately 15 years [35].

2.9. Hydrogen-based energy storage

A study conducted across 20 cities in Canada aimed to reduce greenhouse gas emissions by integrating hydrogen-based energy storage systems into buildings. It was estimated that an average investment of 122,686 Canadian dollars could prevent the emission of 10 tons of CO_2 annually [63]. In another study by Mehrjerdi et al., a system combining hydraulic power, solar energy, and hydrogen storage was found to reduce CO_2 emissions by 50% [64].

One of the main challenges in Canada is the uncertainty caused by seasonal variability due to the country's high-latitude location. This creates a need for high-density and long-term energy storage [65]. Compared to batteries, which have low energy density, hydrogen storage systems are considered a suitable option for residential use due to their higher energy density and lower leakage risk [66].

Solar energy–integrated hydrogen storage systems (SESH2ES) contribute to meeting net-zero emission building (NSEB) standards in new constructions [67]. However, the widespread adoption of these systems also introduces new challenges, such as the requirement for storage space and safety concerns [68]. Particularly in regions lacking integrated infrastructure, Liquid Organic Hydrogen Carriers (LOHC) enable the safe transport of hydrogen.

LOHC systems stand out for their high storage density and low operational cost, offering an economically viable solution for residential applications [69]. For example, according to Knosala et al., the use of LOHC in rural buildings can be 76–80% more economical compared to high-pressure storage systems [70]. In a study conducted by Teichmann and his team in Bavaria, it was calculated that 3.2 MWh of hydrogen could be stored in 2,000-liter fuel tanks [71].

2.10. Internet of things and smart buildings (IoT)

The Internet of Things (IoT) enables the collection of large volumes of data, which are processed in cloud-based or local systems and transformed into meaningful information. When visualized and analyzed through artificial intelligence (AI) tools, these data provide comprehensive insights into source systems. Basing decisions on this data-driven information not only enhances problem-solving capabilities but also contributes to cost reduction [72].

The concept of smart buildings relies on sensor systems that detect environmental changes in real time and inform the user or management units accordingly. Through the integration of IoT technologies into building infrastructures, user behaviors can now be consistently monitored. This enables the development of building-specific solutions in terms of energy consumption and carbon footprint [73].

2.11. Iot and thermal comfort

Studies conducted in public buildings have identified temperature ranges that ensure user comfort without compromising energy efficiency: 17–21 °C in winter and 26–27 °C in summer [74]. Although conventional insulation solutions (e.g., insulated glazing) contribute to comfort, their high embodied energy values can lead to increased costs. In contrast, IoT systems offer an economical and environmentally friendly solution due to their low installation and operating costs.

Thanks to temperature data collected from sensors placed at various points in buildings, areas that are over- or under-heated can be identified, as well as issues related to thermal insulation. For example, in a study conducted on four office buildings in Australia, data obtained from IoT-based environmental monitoring systems allowed real-time control of HVAC systems, thereby achieving optimal thermal comfort for employees [75].

2.12. IoT and building management systems

With the advancement of digital infrastructure and growing awareness of energy consumption, IoT technologies and Building Management Systems (BMS) have become two prominent fields of research in recent years. However, the most significant barrier to their widespread joint implementation is the perception of high cost by end users [76].

Ouedraogo et al. [77] developed a system that allows real-time monitoring of power generation in hybrid solar-wind energy systems via mobile devices with an additional investment of only 30 dollars. This cost is significantly lower than that of similar alternatives, which range from 100 to 600 dollars [78–79].

In a pilot study, a hybrid system was integrated into a building equipped with high-energy-consuming devices such as air conditioners, refrigerators, washing machines, and dishwashers. The following outcomes were reported [77]:

•**34% reduction** in electricity bills,
•**4% increase** in thermal comfort level,
•**53% reduction** in peak power demand.

These findings indicate that even in public buildings and schools lacking advanced power control infrastructure, low-cost energy management systems can be effectively implemented to improve energy efficiency.

3. Results and recommendations

3.1. Results

This study highlights that improving the energy efficiency of buildings is essential not only for reducing operational energy consumption but also for achieving broader environmental targets, such as those set by the European Green Deal. The integration of Energy Efficiency Measures (EEMs)—including passive insulation, active HVAC systems, and renewable energy technologies—substantially contributes to reducing CO_2 emissions. Simulation studies show that combining Building-Integrated Photovoltaics (BIPV) with Thermal Energy Storage (TES) systems can reduce emissions by over 20% over a 30-year period.

In addition, the use of Internet of Things (IoT) technologies and AI-based building management systems (BMS) enables real-time monitoring and optimization of energy consumption patterns, providing significant energy savings even in public and institutional buildings. The study also finds that heat pump technologies, particularly when integrated with PV systems, offer both economic and environmental advantages, particularly in temperate climate zones. Hydrogen storage and hybrid renewable systems are shown to be promising for long-term energy autonomy but still face practical constraints related to cost, safety, and infrastructure.

4. Recommendations

1. **Policy Integration**: Governments should enforce stricter building energy codes and offer financial incentives for retrofitting existing structures with energy-efficient and renewable technologies.
2. **Technological Adoption**: Stakeholders should prioritize the integration of BIPV, TES, and IoT systems during both design and renovation phases to maximize energy efficiency gains.
3. **Public Awareness**: Awareness campaigns and transparent energy certification schemes are critical to fostering behavioral change among building users and investors.
4. **Research and Development**: Further interdisciplinary research is needed on low-cost, high-efficiency hydrogen and battery storage solutions suitable for urban and rural buildings.
5. **Data-Driven Decision Making**: Building management systems should leverage IoT and AI tools for real-time control, predictive maintenance, and user-based comfort optimization.
6. **Customized Solutions**: Renovation strategies should be adapted to building typologies, local climate conditions, and user profiles to ensure optimal performance and economic feasibility.
7. **IoT technologies:** IoT are not merely supplementary but foundational components of next-generation energy-efficient buildings. Their integration enables a dynamic, user-centric approach to sustainability, bringing us closer to the realization of net-zero energy goals.

In conclusion, advancing toward net-zero energy buildings requires a holistic approach that incorporates innovative technologies, user-centered design, and supportive policy frameworks to drive sustainable transformation in the built environment.

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