



Net Zero Energy Buildings for low-carbon cities: Progress, challenges, and future directions

Qi Li¹, Rui Ma², Mo Yang³, Wei Wang³, Jiayu Chen^{4,*}

¹Department of Architecture and Civil Engineering, City University of Hong Kong, Kowloon, Hong Kong, China.

²School of Management, Zhengzhou University, Zhengzhou 450001, Henan, China.

³School of Architecture, Southeast University, Nanjing 210096, Jiangsu, China.

⁴Department of Construction Management, School of Civil Engineering, Tsinghua University, Beijing 100084, China.

***Correspondence to:** Jiayu Chen, Department of Construction Management, School of Civil Engineering, Tsinghua University, Beijing 100084, China. E-mail: jiayuchen@tsinghua.edu.cn

Received: July 27, 2025 **Accepted:** September 25, 2025 **Published:** September 30, 2025

Cite this article: Li Q, Ma R, Yang M, Wang W, Chen J. Net Zero Energy Buildings for low-carbon cities: Progress, challenges, and future directions. J Build Des Environ. 2025;3:202559. <https://doi.org/10.70401/jbde.2025.0014>

Abstract

Net Zero Energy Buildings (NZEBS) offer a transformative pathway for decarbonizing the built environment by integrating energy-efficient design, renewable energy systems, and smart grid interaction. This review positions NZEBs as critical enablers of low-carbon cities, highlighting their ability to balance annual energy demand through both passive strategies and active technologies. Evidence from the literature shows that advanced envelope materials can reduce heating and cooling loads by up to 18.2%, window retrofits lower thermal loads by 15.5%, and rooftop photovoltaic systems can supply up to 70% of household energy demand in certain regions. The review traces the evolution of NZEBs from early solar integration to contemporary climate-responsive designs aligned with global sustainability frameworks. It also identifies persistent challenges, including high upfront costs, climate-dependent performance variability, and retrofitting difficulties in dense urban contexts. Future directions are suggested in the areas of advanced materials (e.g., aerogels, phase-change composites), urban-scale microgrids for energy sharing, and policy harmonization to strengthen grid resilience. Successful deployment of NZEBs will additionally require interdisciplinary collaboration, standardized international codes, and financial incentives to overcome existing barriers.

Keywords: Net zero energy buildings, integrated renewable systems, passive design, energy storage, intelligent control, green buildings

1. Introduction

1.1 Overview

Sustainable development in cities and societies has attracted increasing attention in recent years, reflecting a global commitment to balancing economic growth, environmental stewardship, and social equity. One prominent trend is the emergence of smart cities, where technologies such as the Internet of Things (IoT), artificial intelligence, and big data are leveraged to enhance urban efficiency and improve quality of life^[1]. Smart grids, intelligent transportation systems, and automated waste management solutions exemplify this transition^[2]. Another important trend is the growing emphasis on green infrastructure and urban resilience^[3]. Cities are increasingly adopting urban greening initiatives, including rooftop gardens, urban forests, and green corridors, to reduce pollution and mitigate the urban heat island effect^[4]. Within both trends, buildings play a central role in sustainable development due to their substantial environmental, economic, and social impacts. As the primary spaces where people live, work, and interact, buildings are fundamental to urban life. Their design, construction, operation, and eventual decommissioning exert significant influence on energy consumption, resource utilization, and environmental sustainability^[5]. Globally, buildings account for a considerable share of energy use and greenhouse gas emissions, primarily through heating, cooling, lighting, and appliance operation.

1.2 Net Zero Energy Buildings (NZEBS)

Energy-efficient buildings that incorporate advanced insulation, energy-saving appliances, and efficient heating, ventilation, and air conditioning (HVAC) systems can significantly reduce energy consumption^[6]. In recent years, the integration of renewable energy has become another cornerstone of sustainability efforts. Decentralized energy systems, such as community solar projects and local wind farms, help reduce dependence on centralized power grids^[7]. Additional efficiency measures, including the adoption of advanced appliances and industrial processes, have further contributed to lowering energy use^[8]. Policy support in the form of subsidies and



incentives is also accelerating the widespread deployment of renewable energy technologies^[9]. A critical innovation in this context is the integration of energy generation systems with building energy demand, leading to the development of NZEBs. NZEBs represent a progressive architectural and engineering concept that emphasizes the creation of structures capable of producing as much energy as they consume over a defined period^[10]. Energy neutrality is achieved by combining energy-efficient design with on-site renewable energy generation^[11]. As vital components of sustainable development, NZEBs reduce greenhouse gas emissions, decrease reliance on nonrenewable energy sources, and support global climate change mitigation.

1.3 Research gap and objectives

Despite their potential, NZEBs continue to face considerable scientific and practical challenges. These challenges include high upfront costs, performance variability across different climatic conditions, and complexities associated with integration in urban contexts. Moreover, notable research gaps remain in areas such as long-term performance monitoring, adaptability to future climate extremes, and socio-economic barriers to widespread adoption. Accordingly, this review aims to summarize recent advances in NZEB research, highlight critical challenges encountered by both scientific and professional communities, and outline potential future directions. Particular attention is given to innovative materials and technologies, the development of urban-scale microgrids, and policy frameworks that can facilitate NZEB deployment. Ultimately, the objective is to provide a comprehensive overview that integrates technical, environmental, and policy perspectives, thereby supporting broader adoption of NZEBs as a pathway toward low-carbon and resilient urban environments.

2. Process of NZEB Literature Analysis

2.1 Review process and literature collection

Scopus, as one of the most widely used databases for peer-reviewed literature, enables transparent and reproducible searches based on specified keywords. In this study, Scopus was employed to collect publications on NZEBs from 2005 to 2025. The literature search workflow is illustrated in Figure 1. The initial step involved a broad search using the terms “Net Zero Energy” OR “Zero Energy” OR “Zero Net Energy” OR “NZEB” OR “ZEB” OR “ZNE” in the titles, abstracts, and keywords of articles published within the specified period, yielding 13,232 records. In the second step, the search was refined to the building sector by combining the previous keywords with “Build*” OR “Hous*” OR “Construction*” using the Boolean operator “AND”. Truncation operators (e.g., “Build*”, “Hous*”) were applied to ensure comprehensive retrieval of relevant word variants, as stemming is not always automatic in Scopus. This step excluded 6,057 articles, retaining 7,175 publications. To further focus on NZEBs, exact keyword matching was applied to remove 4,400 articles with low relevance. Finally, the selection was narrowed to journal and conference papers within the “Engineering” subject area and written in English, resulting in a final set of 1,655 articles deemed most relevant for detailed analysis.

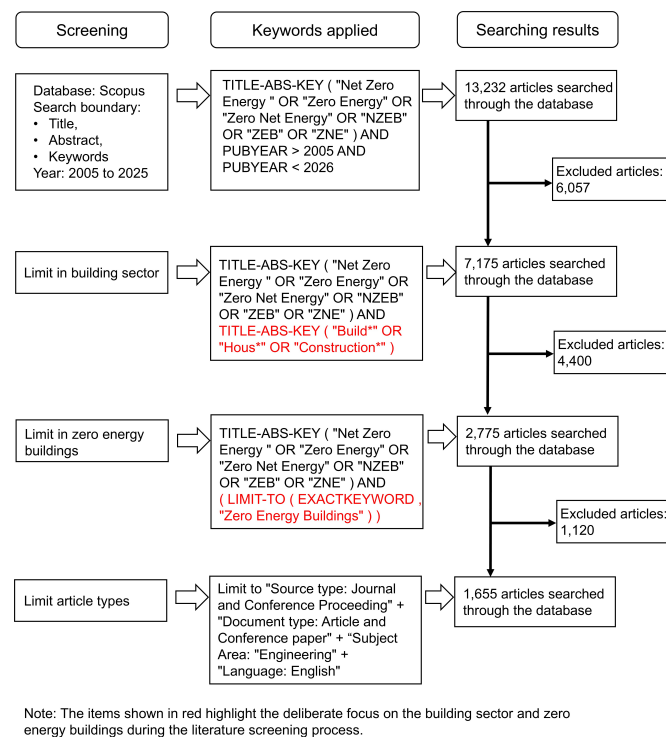


Figure 1. The workflow of the relevant literature search based on Scopus.

2.2 Bibliometric analysis

To capture the research dynamics of NZEB studies, a bibliometric analysis was conducted to examine publication trends, geographic distribution, and collaborative networks, providing an overview of the field’s evolution over the past two decades. Figure 2 illustrates the annual publication trend of NZEB-related studies, which can be divided into three main periods: the growth period (2005–2014), the peak period (2015–2019), and the stable period (2020–2025). During the growth period, only a limited number of NZEB studies were published, with the maximum annual output below 30. In 2015, the Paris Agreement was negotiated by 196 parties to address global climate change^[12]. Motivated by carbon emission reduction targets, NZEB-related publications increased dramatically from 2015 to 2019, reaching a peak of 327 articles in 2019. Thereafter, the field entered a stable period, maintaining a high annual average of approximately 176 publications.

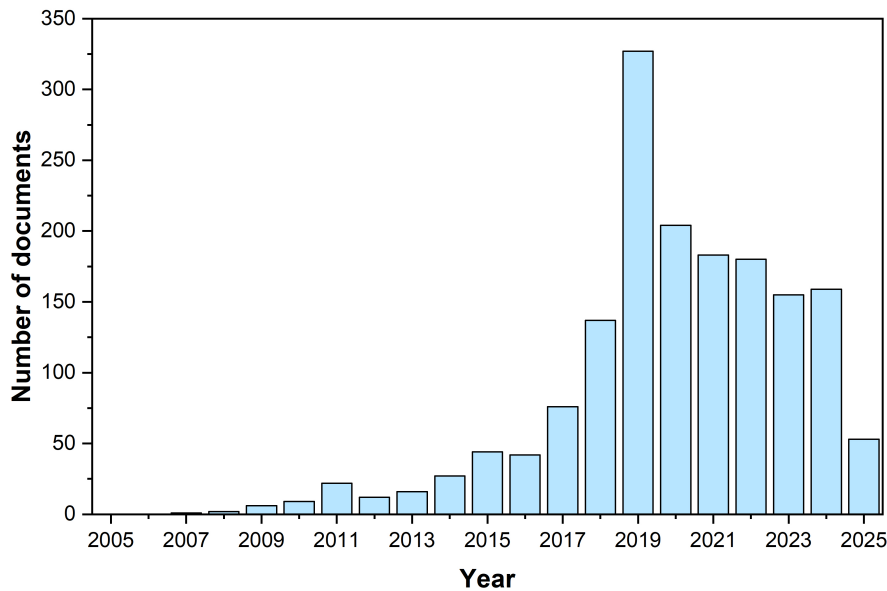


Figure 2. Annual publication trend of NZEBs from 2005 to 2025. NZEBs: net zero energy buildings.

Figure 3 presents the top 10 countries or regions in terms of NZEB publication output. Italy leads with 272 articles, followed by China with 238 publications and the United States with 183 publications over the past two decades. Spain, Canada, the United Kingdom, South Korea, Greece, Hong Kong, and India also represent major contributors to NZEB research.

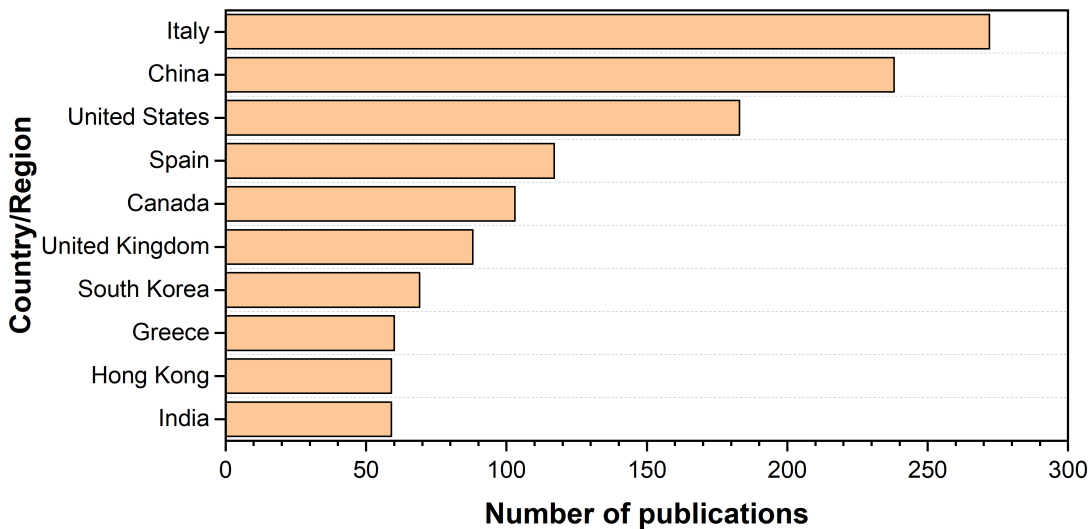


Figure 3. Top 10 countries or regions for NZEBs publications. NZEBs: net zero energy buildings.

The contribution of journal articles and conference proceedings to NZEB research is presented in Figure 4, along with their respective counts. The top five sources with the highest number of publications are *Energies* (199 articles), *Energy and Buildings* (182 articles), *IOP Conference Series: Materials Science and Engineering* (132 articles), *Journal of Building Engineering* (81 articles), and

Applied Energy (75 articles), collectively accounting for approximately 50% of the total publications. Other notable contributors include *Energy*, *ASHRAE Transactions*, *Sustainable Cities and Society*, *Building and Environment*, *Building Simulation Conference Proceedings*, *Journal of Cleaner Production*, and *Buildings*, each contributing less than 5% individually.

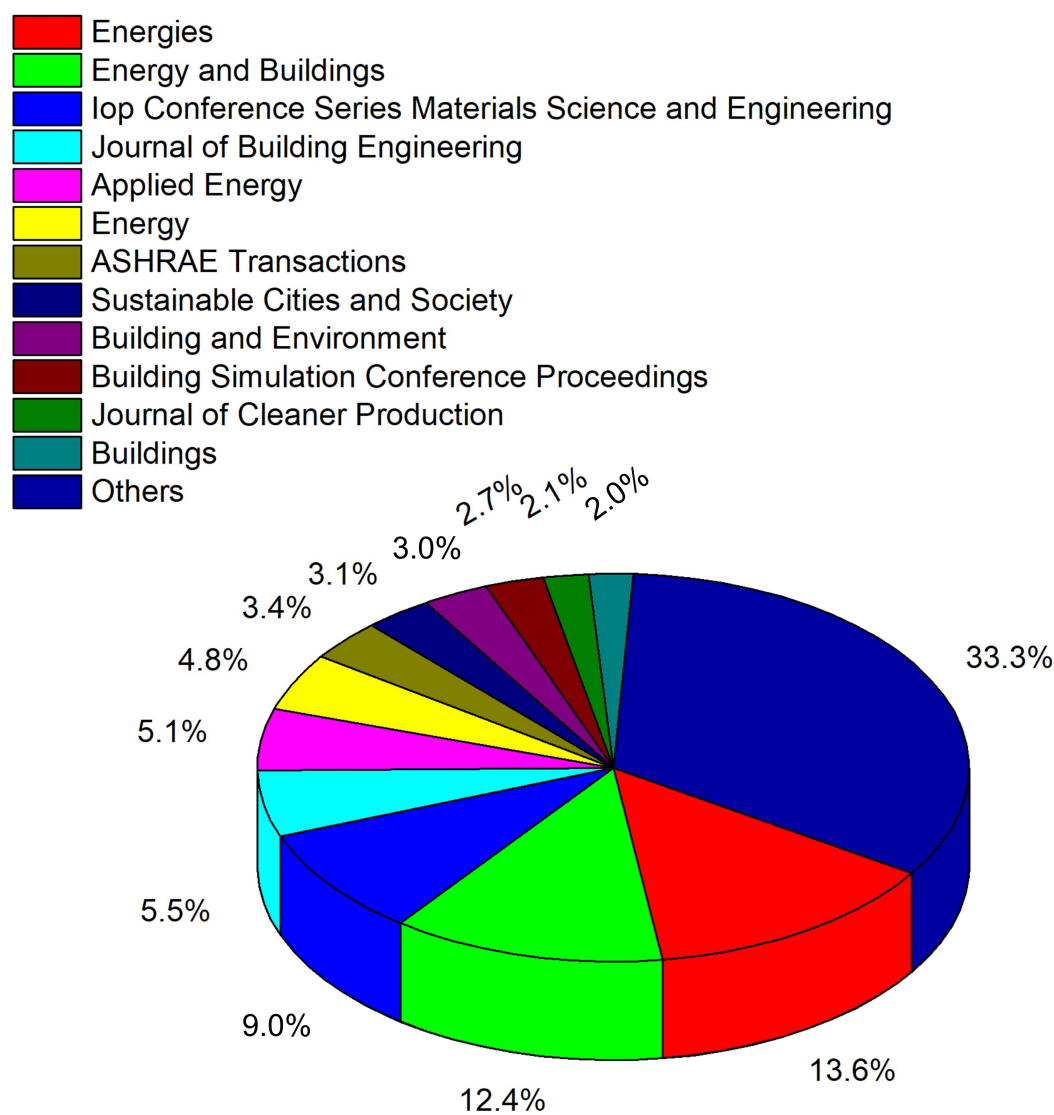


Figure 4. Contributions of publication sources.

Bibliometric mapping and visualization were conducted using VOSviewer, enabling the construction of co-authorship and keyword co-occurrence networks. The co-authorship network, shown in [Figure 5](#), illustrates collaborative relationships among researchers in the field of NZEBs. Applying a threshold of at least five publications per author, the analysis identified 130 authors grouped into 32 distinct clusters. Node size represents the number of publications per author, while line thickness indicates the strength of collaborative relationships. The network analysis reveals a central hub of strong collaboration among four key clusters: the red cluster (Wang, S., Hong Kong), the green cluster (Liu, Z., Mainland China), the light blue cluster (Sun, Y., Hong Kong), and the earthy yellow cluster (Attia, S., Europe). These interconnected clusters highlight particularly robust research collaboration between European and East Asian scholars. In contrast, three Italian-dominated clusters, the purple cluster (Asdrubali, F.), the blue cluster (Ascione, F.), and the light red cluster (D’Agostino, D.), exhibit more localized collaboration patterns, suggesting that NZEB research in Italy tends to operate with greater independence from international networks. Temporal trends in collaboration are further illustrated in [Figure 6](#), where an overlay of publication years indicates intensified partnerships in East Asia after 2020. This surge aligns with China’s “dual carbon” policy announcement, emphasizing the impact of national sustainability agendas on research collaboration dynamics.

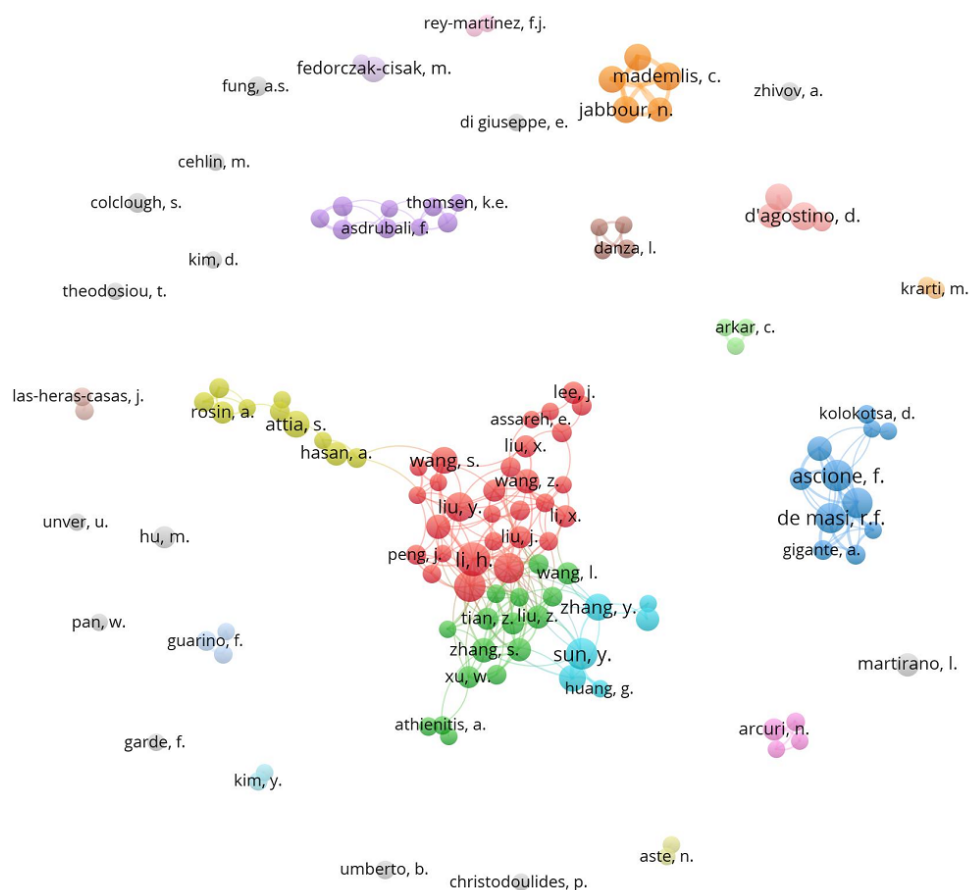


Figure 5. Visualization of co-authorship network.

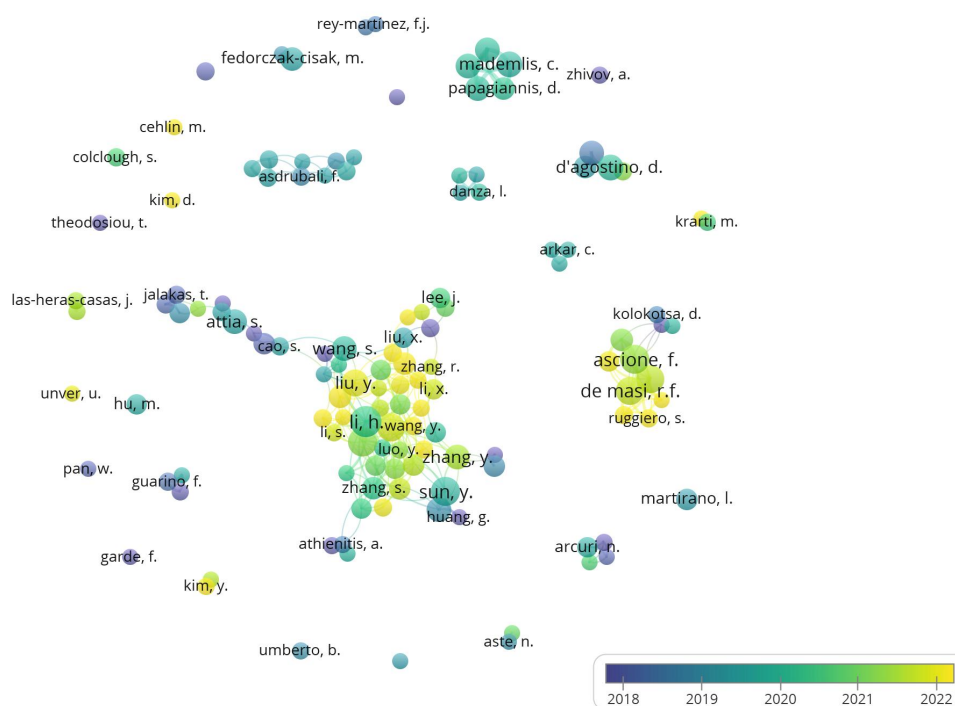


Figure 6. Co-authorship network overlaid with the publication year.

The keyword co-occurrence network is shown in Figure 7, comprising the 50 most frequently used keywords in NZEB research, and four major clusters were identified. Cluster 1 relates to the motivation for NZEBs, including keywords such as “carbon”, “climate change”, and “renewable energy”. Cluster 2 focuses on the characteristics of NZEBs, encompassing “cost effectiveness”, “energy performance”, and “energy efficiency”. Cluster 3 represents energy efficiency strategies, including “thermal insulation”, “ventilation”, and “architectural design”. Cluster 4 primarily concerns renewable energy applications in NZEBs, including “solar energy”, “solar power generation”, and “photovoltaic”. Figure 8 presents the keyword co-occurrence network with a publication year overlay, revealing temporal trends: early studies emphasized NZEB concepts and contributions, followed by research on design strategies, and the most recent works focus on renewable energy utilization.

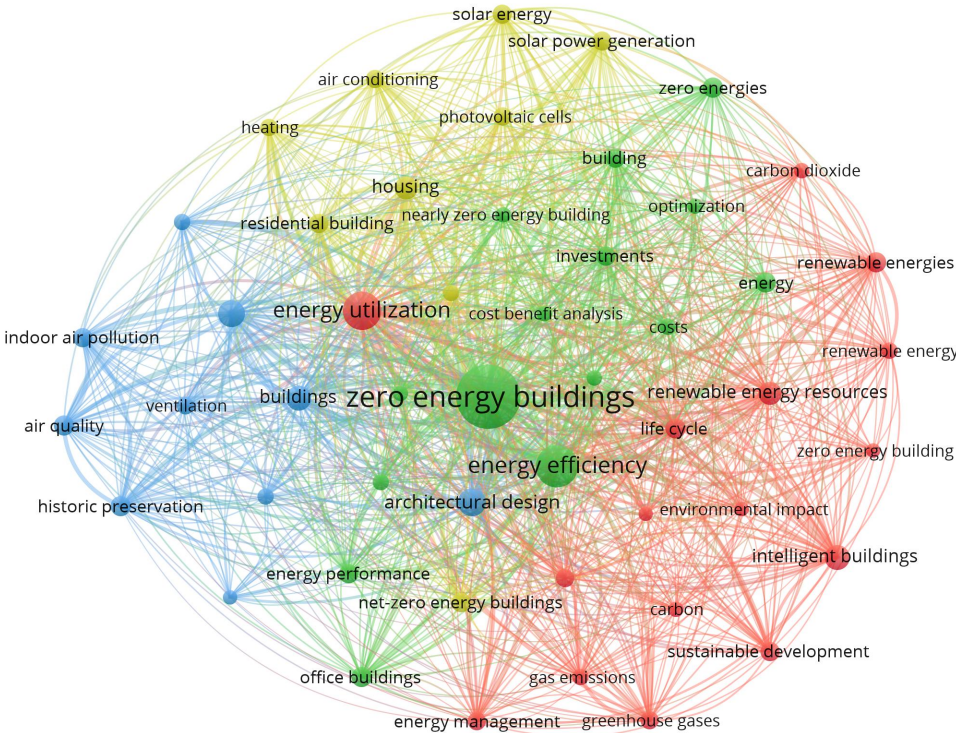


Figure 7. Visualization of keyword co-occurrence network.

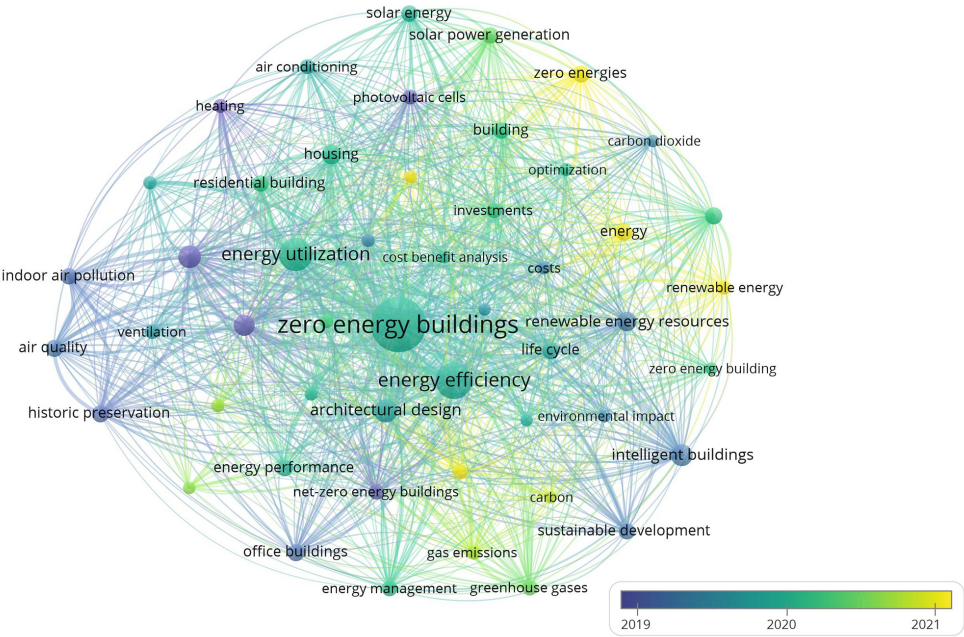


Figure 8. Keyword co-occurrence network overlaid with the publication year.

Based on this bibliometric analysis, the remainder of the paper is organized as follows. [Section 2](#) introduces the fundamental concepts of NZEBs. [Section 3](#) examines their key technical characteristics, while [Section 4](#) analyzes critical design strategies for NZEB implementation. [Section 5](#) synthesizes the principal tools and technologies employed in NZEB development. Finally, [Section 6](#) and [Section 7](#) discuss current challenges and future research directions in the field of NZEBs.

3. Summary of NZEB Literatures

3.1 Characteristics of NZEBs

NZEBs are designed to minimize energy demand through innovative architectural designs and advanced technologies. Features such as high-quality thermal insulation, energy-efficient windows, and state-of-the-art HVAC systems help reduce energy loss^[6]. Passive design strategies, including optimal building orientation and strategic window placement, further enhance the use of natural light and thermal energy^[13]. Renewable energy generation is another defining aspect of NZEBs^[14]. To achieve net-zero energy status, these buildings integrate renewable energy systems such as solar photovoltaic (PV) panels^[9], wind turbines^[15], or geothermal energy installations^[16], which generate clean energy to offset building energy consumption. While onsite renewable energy production is ideal, some NZEBs may also rely on offsite renewable sources, particularly in urban areas where space is limited. [Figure 9](#) illustrates a typical NZEB system, including integrated renewable energy systems (PV panels and wind turbines), battery-based energy storage, building-grid interactions, and intelligent energy management systems that optimize HVAC performance to achieve energy balance and resilience.

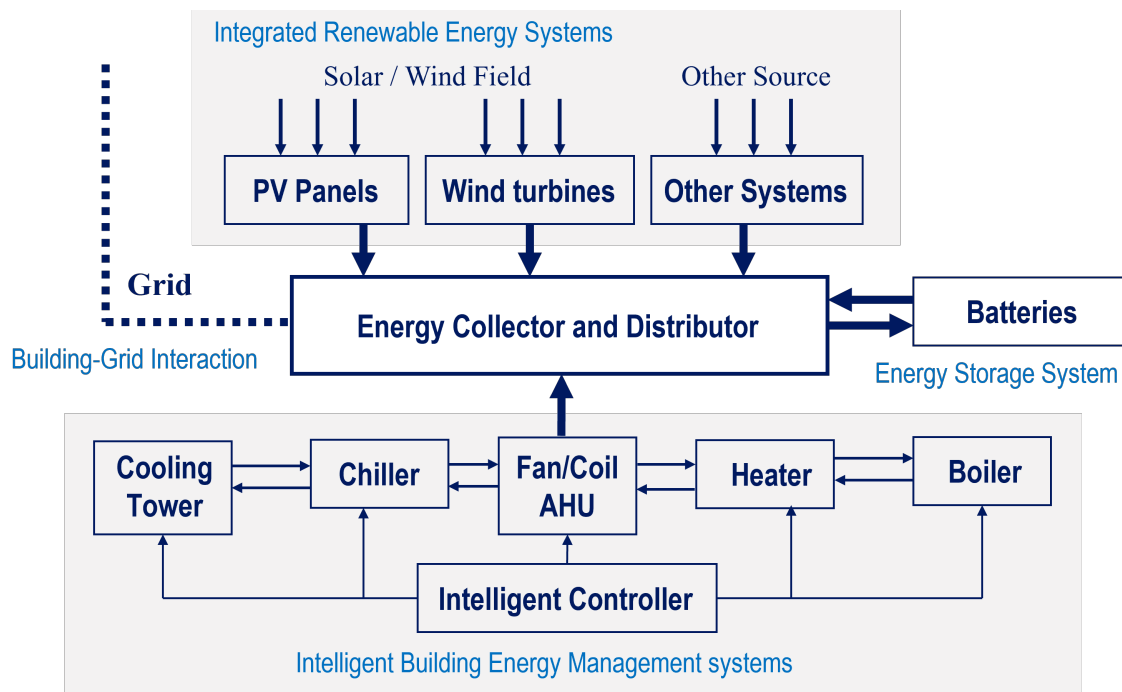


Figure 9. Typical system structure of NZEBs. NZEBs: net zero energy buildings.

Compared with conventional buildings, NZEBs are distinguished by several key features: (1) they prioritize minimizing energy demand through advanced building techniques and technologies^[10]; (2) onsite renewable energy production is preferred, although offsite sources can also be utilized^[17]; (3) advanced control systems and real-time monitoring enable efficient energy management, identifying inefficiencies, ensuring proper operation, and optimizing overall building performance^[8]; (4) despite higher initial costs, NZEBs offer long-term economic benefits through reduced energy bills and maintenance costs^[18]; (5) they enhance energy resilience by reducing dependence on centralized grids, which is particularly advantageous in areas prone to power outages or fluctuations^[1]. Overall, these life cycle benefits ensure that NZEBs provide more energy-efficient, accessible, and affordable housing. This study summarizes the main technical characteristics of NZEBs into four categories: improving energy efficiency, deployment of onsite renewable energy, energy balance, and energy storage and smart grid integration ([Figure 10](#)). [Figure 10](#) presents an integrated framework of NZEB technologies, highlighting that energy efficiency can be enhanced through passive design, advanced building envelopes, HVAC systems, efficient lighting, and occupant behavior. Renewable energy sources, including photovoltaics, wind, geothermal, hydropower, and biomass, are coupled with energy storage and smart grids to balance energy generation and consumption. Based on these four core characteristics, the study will further discuss the history of NZEB development, energy efficiency strategies, onsite renewable energy utilization, and energy balance within grid systems.

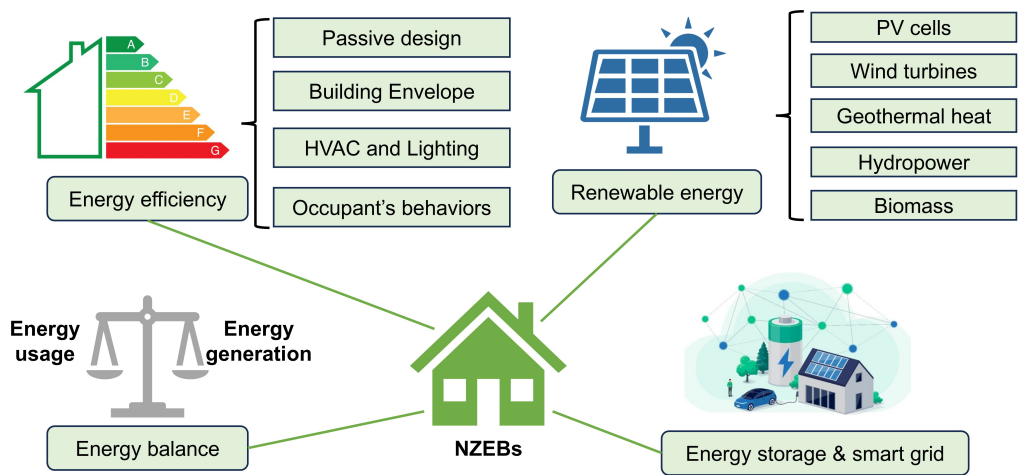


Figure 10. Main technical characteristics of NZEBs. NZEBs: net zero energy buildings; PV: photovoltaic; HVAC: heating, ventilation, and air conditioning.

3.2 History of NZEB development

The concept of NZEBs has evolved over several decades, driven by advancements in architectural theory, energy technologies, and environmental awareness. Its development can be traced through key historical milestones (Table 1), reflecting changing priorities and an increasing understanding of energy efficiency, sustainability, and climate change mitigation.

Table 1. The major milestones of NZEBs in history.

Time	Milestone	Strategies
Mid-20th Century	Energy Efficiency and Passive Design	• Passive strategies, such as building orientation, thermal mass, and natural ventilation • Development of building codes and standards focused on energy conservation
1970s-1980s	Solar Energy Integration	• Advances in photovoltaic technologies • Emerged theoretical frameworks for energy balance
1990s-2000s	Green Building Movements and Certification Systems	• Certification systems such as LEED* and BREEAM* • the Kyoto Protocol propelled sustainable building practices
2000s-2010s	Technological Advancements and Policy Integration	• Innovations in PV efficiency, battery storage, and smart building systems • The rise of global collaboration, with organizations like IEA
2010s-Present	Context of Climate Action	• The Paris Agreement of 2015 underscored the need for drastic reductions in carbon emissions • Combining both operational energy and embodied energy to address the building's life cycle environmental impact

LEED: Leadership in Energy and Environmental Design; PV: photovoltaic; BREEAM: Building Research Establishment Environmental Assessment Method; IEA: International Energy Agency; NZEBs: net zero energy buildings.

NZEBs embody a transformative approach to the built environment. By integrating energy efficiency measures with renewable energy generation, they establish a benchmark for sustainable construction and urban development. As global efforts to achieve carbon neutrality and mitigate climate change intensify, NZEBs are expected to play an increasingly important role in shaping a sustainable future. Despite their advantages, NZEB adoption faces challenges such as higher upfront costs, the need for specialized design expertise, and variability in renewable energy availability. Policymakers and stakeholders are addressing these barriers through incentives, subsidies, and technological advancements, aiming to make NZEBs more accessible and cost-effective.

3.3 Improving energy efficiency

Energy-efficient design is fundamental for achieving net-zero energy usage, as it minimizes building energy demand through both passive and active strategies^[5]. Passive design strategies typically focus on optimizing architectural components, including building orientation, shape, and envelopes^[19]. Properly designed orientation and building form can reduce internal load demands from

systems such as HVAC and lighting. Building envelopes, which separate the interior from the outdoor environment, significantly affect heat transfer and account for more than 50% of heat and energy loss in buildings^[20]. Enhancing exterior wall insulation, air tightness, and window glazing is widely adopted to reduce substantial heat gain and loss^[21]. Active design strategies aim to improve the efficiency of HVAC systems, lighting, and other building services^[22]. For instance, low-efficiency devices can be replaced with LED lighting, energy-efficient heat pumps, and optimized mechanical ventilation systems^[21]. Beyond technological solutions, occupant behavior is a key factor influencing energy consumption. Actions such as adjusting thermostats, operating windows, managing lighting, and modifying water usage routines directly affect building energy demand^[23]. Ouyang *et al.* reported a 10% reduction in electricity usage resulting from increased occupant energy-saving awareness^[24]. Evidence from Iran indicates that routine practices, including window opening, curtain use, and heating operation in residential complexes, can create significant gaps between simulated and actual energy consumption, highlighting the need to integrate culturally specific behaviors into building models^[25]. Similarly, research on low-income housing in India identifies distinct occupant archetypes shaped by appliance usage, thermal comfort preferences, and socio-economic constraints, which directly influence energy demand and comfort outcomes^[26]. These findings emphasize that incorporating behavioral diversity across cultural and economic contexts is essential for improving the reliability and inclusivity of NZEB design and operation. Overall, achieving consistent and inclusive NZEB performance requires an integrated approach that combines optimized design strategies with culturally and behaviorally informed energy models.

3.4 Deployment of on-site renewable energy

In addition to reducing energy demand, NZEBs require on-site renewable energy generation to offset their energy consumption. The most widely applied renewable energy source is solar energy, with PV cells commonly installed on roofs and walls to convert solar radiation into electricity^[9]. Solar thermal collectors are also employed to provide hot water and space heating^[27]. Wind energy can be harnessed through turbines, providing electricity to compensate for low PV output during nighttime or cloudy conditions^[28]. However, the main limitation of wind energy is its variable yield due to fluctuations in wind availability^[15]. Geothermal energy, generated and stored within the earth's crust, is independent of climatic conditions such as solar radiation or prevailing wind^[16]. By exchanging heat with the ground, geothermal systems can reliably supply HVAC energy throughout the year^[29]. Hydropower, produced by the movement of water (e.g., waves, tides, or river flows), is another important renewable source, generating 1.6 times more energy than nuclear power in 2021^[14]. In NZEBs, rainwater collected in rooftop reservoirs can drive turbines to generate electricity. Biomass is also a dependable renewable energy source, providing stable power output as long as feedstock is continuously available^[30]. Biomass feedstock includes food and paper residues, agricultural by-products, and sewage sludge^[31], with bioenergy generated through thermochemical processes (producing heat) or biochemical processes (producing biogas or biohydrogen)^[31]. Overall, the integration of diverse renewable energy sources, including solar, wind, geothermal, hydropower, and biomass, provides NZEBs with complementary and reliable options to balance energy supply and demand throughout the year.

3.5 Energy balance of grid systems

NZEBs with high energy efficiency aim to balance energy demand and renewable energy supply over a defined period, typically one year. In general, there are two main approaches to achieving “net-zero” energy: (1) reducing energy load through energy-efficient design, and (2) generating sufficient on-site renewable energy to cover the load. In most NZEBs, energy-efficient design is particularly important because options for on-site renewable energy are limited, such as the restricted roof area of high-rise buildings for PV installation^[32]. Renewable energy generation is inherently variable, often resulting in mismatches between energy supply and demand^[33]. To achieve net-zero status, smart energy management systems are integrated to optimize energy load, combining different energy efficiency strategies to align with real-time renewable energy generation^[18]. Energy storage systems and smart grids further help balance load demand by storing surplus on-site renewable energy or feeding it back to the grid^[34].

Energy storage and smart grid technologies are the two primary solutions for addressing the mismatch between renewable energy supply and building operation load. Energy storage systems provide a buffer to store excess renewable energy, which can be used when on-site generation is insufficient^[35]. Peaks in renewable energy production can be stored and later utilized to meet peak building demand^[1]. This approach converts intermittent on-site renewable energy into reliable and stable energy resources, dynamically balancing NZEB energy use. Smart grids complement this process by distributing excess renewable energy to the grid in an optimized manner. By synchronizing building energy status with grid demand, surplus NZEB power can be delivered to the grid, alleviating pressure on the system. Buildings can also purchase electricity at lower prices during periods of low grid demand, reducing wasted energy from the grid^[2]. In summary, integrating energy-efficient design with energy storage and smart grid technologies is essential for NZEBs to overcome renewable energy intermittency and reliably achieve an annual net-zero energy balance.

4. Design Strategies of NZEBs

After defining NZEBs and describing their main characteristics, this section summarizes their design strategies, addressing the second research question. Table 2 presents the main types and methods of design strategies, and the following sections provide detailed explanations.

Table 2. Summary of design strategies of NZEBs.

Design type	Method	Sources
Passive design	1. Optimizing building's orientation	[36,37]
	2. Optimizing building's shape	[13,38,39]
	3. Optimizing building group's layout	[40-43]
Building envelope	1. High-quality insulation	[44,45]
	2. Thermal resistance of window	[46-50]
	3. Radiative properties	[51-54]
HVAC and lighting	1. High-efficiency HVAC	[6,55-58]
	2. Efficient lighting	[59-62]
Renewable energy systems	1. PV	[11,63-65]
	2. Wind turbines	[66-68]
	3. Biomass	[69,70]
Grid interaction	1. Demand response optimization	[34,71]
	2. Inter-building micro-grid	[72,73]

NZEBs: net zero energy buildings; HVAC: heating, ventilation, and air conditioning; PV: photovoltaic.

4.1 Passive design

Passive design optimizes building orientation, shape, and layout, leveraging interactions with the local environment to reduce energy demand. Its specific impacts are illustrated as follows: (1) Orientation: Optimized building orientation reduces artificial lighting demand by maximizing natural sunlight. It also affects heat gain from solar radiation, thereby decreasing HVAC energy requirements. For example, Abanda and Byers investigated the effect of orientation on energy consumption in a small-scale building. Simulations using Revit and Green Building Studio indicated energy savings equivalent to £878 over a 30-year lifetime^[36]. Khan *et al.* analyzed both residential and commercial buildings using 360-degree rotation at 45-degree intervals. Autodesk Insight 360 simulations showed that orientation optimization can achieve an average energy saving of 18%^[37]. (2) Shape: Building form interacts closely with the local wind environment. Properly designed shapes can enhance passive ventilation and reduce cooling load^[38]. Xie *et al.* evaluated the natural ventilation cooling potential of four building forms, including open area, street canyon, semi-closed courtyard, and courtyard, based on year-long field measurements^[39]. Results indicated that the courtyard form provides the best energy-saving performance by increasing night-time ventilation cooling. Zoure and Genovese simulated hourly airflow for ten building forms and found that the “H” shape achieved the highest natural ventilation efficiency, resulting in 14.9% cooling energy savings^[13]. (3) Layout: The spatial arrangement of building blocks significantly influences natural ventilation and solar shading Yang *et al.* reported that shading from surrounding buildings can reduce cooling demand by approximately 20%^[40]. Krüger *et al.* evaluated the effect of aspect ratios (building height to street width, H/W) on cooling loads in hot, dry climates and found that higher H/W ratios enhance mutual shading and reduce cooling demand^[41]. Nikkho *et al.* quantified the wind sheltering effect of surrounding obstacles, showing a 5% decrease in total energy consumption in a cold-region case study^[42]. Deng *et al.* analyzed different building block layouts and demonstrated that staggered arrangements effectively enhance natural ventilation, reducing cooling loads^[43]. In summary, orientation, form, and spatial layout collectively highlight the critical role of passive design as a foundational strategy for minimizing energy demand in NZEBs.

4.2 Improved building envelope

Building envelopes, which form the barrier between indoor and outdoor environments, are key determinants of building energy efficiency. Previous studies reported that heating and cooling demands caused by building envelopes account for more than 50% of total operational energy consumption in buildings^[74]. Therefore, enhancing the energy performance of building envelopes is crucial for NZEBs. Typical approaches focus on improving insulation, thermal resistance, and radiative properties of the envelope. These improvements can be achieved through the following measures:

(1) High-Quality Insulation: Effective insulation reduces heat flow into buildings during summer and limits heat loss in winter. Huang *et al.* developed an aerogel super-insulation material with a thermal conductivity of 0.014 W/(m·K) for exterior walls. Simulations of a typical office building in a subtropical climate showed reductions in annual cooling and heating loads by 7.5% and 18.2%, respectively^[44]. Zhang *et al.* investigated five different insulation layers on exterior walls, finding that annual heat load could be decreased by approximately 30% on average^[45]. Emerging bio-based insulation materials, such as hemp, cork, straw, recycled cotton, and agricultural residues, are increasingly considered as alternatives to conventional petrochemical products^[75]. These materials

offer low embodied energy, favorable hygrothermal properties, and carbon sequestration potential, making them promising for NZEB envelopes^[76]. For instance, bio-based phase change materials, such as sheep-tail-fat stearin, demonstrate effective thermal storage and passive indoor comfort regulation, reducing operational energy demand and associated greenhouse gas emissions^[77].

(2) Windows and Thermal Mass: Improving the thermal resistance of windows is another common strategy. Mohammad and Ghosh examined high-insulation aerogel windows in the UK, which reduced heat load by 15.5%^[46]. Thermal mass, which refers to the ability of building elements to absorb and store heat, does not reduce total thermal gain but can delay and decrease indoor peak temperatures, thereby mitigating HVAC cooling loads^[47]. Zilberberg *et al.* modeled the impact of thermal mass in hot semi-arid climates, finding that heavyweight opaque vertical walls reduced operational energy consumption by 3%^[48]. In Poland, Kuczyński and Staszczuk reported that replacing lightweight frame walls with cellular concrete increased thermal mass, lowered indoor temperatures, and achieved 75% cooling energy savings at a set point of 26 °C^[49]. Costanzo *et al.* investigated the integration of phase change materials into opaque envelopes, showing that latent heat exchange during solid-liquid transitions compensates for thermal inertia and reduces peak cooling load by more than 10%.

(3) Radiative Properties: Modifying the radiative properties of building envelopes has emerged as an effective strategy for NZEBs. High solar reflectance and mid-infrared emittance coatings, also known as cool coatings, can reject solar heat gain and radiate energy to the outer environment^[51]. A case study on two hot islands reported annual energy savings of 21.7 kWh/m²/year in Silicy and 188 kWh/m²/year in Jamaica due to cool roof coatings^[52]. Xu *et al.* analyzed the use of cool materials on building facades, finding that annual energy savings for low-rise buildings could reach 3.4%^[53]. Solar radiation through windows is a major source of heat gain. Wang *et al.* implemented thermochromic windows that block excess solar heat, achieving up to 12.13% energy reduction in an office building^[54].

In summary, enhancing insulation, optimizing thermal properties, and modifying radiative characteristics of building envelopes collectively reduce heat transfer and solar gain, thereby improving NZEB energy efficiency and operational performance.

4.3 High-efficiency HVAC and lighting

HVAC systems account for more than half of the annual energy consumption of a building^[10], making the development of high-efficiency HVAC systems with updated hardware and control strategies critical for achieving energy savings in NZEBs. For instance, Wu *et al.*^[6] implemented heat recovery ventilators and energy recovery ventilators, reducing HVAC energy consumption by 13.5% and 17.4%, respectively. When integrating a dehumidifier with an air-source heat pump, the HVAC system achieved an additional 7.3% energy reduction. Behzadi and Sadrizadeh^[55] proposed an advanced smart HVAC system using borehole thermal energy to replace conventional machinery or heat pumps, resulting in a 28.5% reduction in space heating and cooling loads. Papadopoulos *et al.* applied multi-objective optimization to tune cooling and heating setpoints, achieving up to 60% annual HVAC energy savings in office buildings located in mild climates^[56]. Soleimani *et al.* developed a deep neural network to predict building thermal conditions, achieving 30% cooling energy reduction by adjusting the supply air temperature of the air handling unit^[57]. Bai and Tan designed an HVAC control framework based on deep reinforcement learning to mitigate disturbances from internal and external environmental factors such as weather and occupancy, achieving an 8% reduction in energy consumption compared with conventional strategies^[58].

In addition to HVAC systems, artificial lighting represents a significant portion of electricity consumption, accounting for nearly 20% of global electricity use^[78]. Installing more efficient lighting, such as LEDs, can substantially improve NZEB energy performance. Doulos *et al.* compared energy use between fluorescent lamps and LED lighting in a public school, finding that annual lighting energy consumption decreased from 90.5 kWh_p/m² to 0.55 kWh_p/m²^[59]. Cruz *et al.* investigated replacing fluorescent luminaires with LED lighting, which resulted in an energy saving of 2,475 kWhh/(m²/year)^[60]. Lighting control strategies also contribute to energy efficiency. Wagiman *et al.* proposed a visual comfort metric model that integrates artificial lighting and daylighting, achieving a 6% reduction in energy use^[61]. Aussat *et al.* developed a self-calibrating lighting control system that responds automatically to daylight and occupancy, reducing energy consumption by 40% compared with conventional LED systems^[62].

Overall, advancements in HVAC technologies and intelligent lighting solutions play a central role in reducing building energy consumption, reinforcing their importance in achieving the energy efficiency targets of NZEBs.

4.4 Integrated renewable energy systems

Among various renewable energy sources, electricity generated by PV systems is the most prominent choice for NZEBs due to low costs and zero pollutant emissions^[79]. Since rooftops are frequently exposed to solar radiation, installing PV panels on rooftops is the main strategy across different climatic zones^[80]. For example, Agathokleous and Kalogirou^[63] investigated the potential of rooftop PV in Mediterranean islands, showing that a 3 kW roof PV system could fully cover the electricity load of the domestic sector for 70% of existing residential stock. D'Agostino *et al.* analyzed the feasibility of PV roof systems for multi-story NZEBs in Italy^[11]. Sun *et al.* optimized the structure of building-integrated PV roofs and found that an air gap of 68 mm and PV panel spacing of 30 mm increased electricity generation by 2.49%^[64]. Building facades can also provide PV installation areas, although shading from surrounding buildings can significantly reduce energy generation efficiency^[65].

Wind turbines are often adopted in NZEBs to supplement PV panels^[65]. For buildings with limited roof areas for PV installation, wind turbines can effectively enhance energy supply^[66]. Ge *et al.* investigated the combination of wind and PV power, reporting that up to 45% of energy could be supplemented by wind power in a case study in Hangzhou, China^[67]. Zhang *et al.* applied a genetic algorithm to optimize a solar-wind energy system, and a case study on an island showed that an optimized configuration with two sets of 6,000 W wind turbines could meet 96% of the equipment load^[68].

Hydrogen-based energy storage is increasingly considered for NZEBs because of its potential to address daily and seasonal variability in renewable energy supply. Bellos *et al.* analyzed a zero-energy residential building in Athens and demonstrated that integrating photovoltaics with hydrogen storage in a power-to-hydrogen-to-power design enabled year-round energy autonomy without relying on grid electricity^[81]. Mehrjerdi *et al.* studied a NZEB with a hydrogen storage system to balance seasonal and daily variations in power production, showing that an optimized configuration of 73 kW solar panels, 39 kW hydropower, and a hydrogen storage unit could reduce annual CO₂ emissions by nearly 39,500 kg while lowering total costs by about 50%^[82].

Integrating biomass energy into NZEB systems can further mitigate the intermittency of PV and wind generation. For example, a biomass-fueled waste-to-energy trigeneration system has been shown to produce 541kW of electricity, 2,052 kW of heating, and 2,650 kW of cooling^[69]. Shirazi integrated a biomass-fired system into a building in a cold climate, demonstrating that the biomass heater was 36% more efficient than a PV panel and heat pump combination^[70].

Artificial intelligence (AI) is also becoming instrumental in improving the resilience and efficiency of renewable energy systems. Assareh *et al.* developed an AI-based multi-objective optimization framework using artificial neural networks to enhance the efficiency of geothermal cogeneration systems and reduce costs, achieving an optimal exergy efficiency of 63.79% and a cost-effectiveness of \$57.82 per hour^[83]. Mobayen *et al.* applied a neural network-based multi-objective optimization to a hybrid energy system integrating wind power and gas turbines in a NZEB, achieving an energy efficiency of 33.69%, exergy efficiency of 36.95%, and operating cost of \$446.04 per hour^[84]. These examples demonstrate that integrating renewable energy systems with AI-driven operational strategies can enhance reliability, cost-effectiveness, and scalability in NZEBs.

Overall, combining diverse renewable energy sources with advanced storage solutions and AI-driven optimization strengthens the reliability, efficiency, and sustainability of NZEB energy systems.

4.5 Building-grid interaction

Due to the intermittency and uncertainty of on-site renewable energy generation, NZEBs are often connected to the grid, serving both as energy consumers and producers. This arrangement allows NZEBs to purchase electricity from the grid when on-site renewable generation is insufficient and to feed surplus energy back to the grid. However, such interactions can cause grid imbalances, leading to issues such as voltage flicker and grid instability^[85]. To address these challenges and reduce the waste of renewable energy, demand response optimization has been proposed to lower energy usage during peak periods^[86]. By employing high-precision real-time monitoring of energy consumption, electricity prices can be adjusted to incentivize consumers to shift their load patterns^[86]. For example, Liang *et al.* developed a physically consistent neural network-based model predictive control to enhance building self-sufficiency, achieving a 30% reduction in load demand through real-time pricing^[34]. Wamalwa and Ishimwe proposed a mixed-integer non-linear programming model integrated with a smart appliance scheduler to minimize grid energy usage and peak demand, resulting in a 37.5% reduction in system peak and a 21.8% reduction in the building's peak grid demand^[71]. Although most research on urban microgrids is simulation-based, emerging field-validated systems provide valuable empirical data. For instance, Fan *et al.* reported a real-world microgrid integrating wind and PV generation in an urban context, with measured power generation and storage performance validating model predictions under variable conditions^[87]. These empirical deployments are crucial for confirming simulation accuracy, refining control strategies, and ensuring operational resilience in urban NZEB frameworks.

Inter-building microgrids offer another approach to stabilizing on-site energy systems. Fan *et al.* proposed a collaborative control strategy for renewable energy sharing among NZEBs, which reduced grid energy imports and exports and achieved daily cost savings ranging from 5% to 87.5%^[72]. Gebremariam *et al.* applied a game-theory-based optimization method for renewable energy exchange within building-to-building grids, showing daily peak-hour energy cost reductions of 2.15% to 6.37%^[73]. In summary, optimizing building-grid interactions enables more efficient utilization of variable renewable energy and mitigates potential adverse effects on local grid stability.

5. Tools and Technologies of Deploying NZEBs

5.1 Energy simulation tools

Building Performance Simulation (BPS) is a cornerstone of NZEB design. It enables architects and engineers to optimize energy efficiency and environmental performance throughout a building's lifecycle. By leveraging advanced computational tools, BPS facilitates multi-objective analysis, including energy consumption prediction and thermal comfort assessment, serving as a critical driver for carbon reduction in the built environment. BPS tools can be broadly categorized into three types based on their integration

level and functionality^[88]: (1) simulation plug-ins for computer-aided design (CAD) platforms, (2) simulation engines with graphical user interfaces (GUIs), and (3) standalone simulation packages. The first type is designed for mainstream CAD platforms such as Rhinoceros, SketchUp, and Revit. These plug-ins, including OpenStudio and Ladybug, interface with external simulation engines such as EnergyPlus to streamline design optimization. Their user-friendly interfaces make them ideal for early-stage design iterations, although they may be less robust for complex projects. The second type includes concise visual GUIs, such as DesignBuilder and N++, which are based on EnergyPlus, and the optimization tool Beopt, which is based on DOE2 and TRNsys. These tools reduce operational complexity and help users perform simulations more efficiently. The third type consists of standalone simulation platforms, such as IESVE, which integrate proprietary engines and offer high precision for large-scale or specialized simulations.

Building energy simulation tools provide indispensable support throughout the building lifecycle, enabling architects and engineers to make informed decisions based on detailed performance predictions and operational insights. Early-stage simulations can prevent mechanical system overdesign, leading to significant cost savings, while resilience planning capabilities allow designers to test building performance under future climate scenarios. Emerging technologies, including AI-assisted modeling^[89] and digital twin integration^[90], are enhancing the accuracy and utility of performance predictions. During the design phase, these simulation tools facilitate a performance-driven approach, supporting environmental performance analysis such as daylighting optimization^[90,91] and thermal comfort assessment^[92]. On the energy performance front, they provide accurate heating and cooling load calculations and energy use intensity predictions^[93,94], enabling proper sizing of mechanical systems and informing optimal renewable energy integration strategies. Validation studies further demonstrate their reliability. For instance, Lin and Chen compared simulated results with measured data from a NZEB during its first year of operation, finding only a -1.41% difference in total energy use, indicating high simulation accuracy^[95]. Similarly, a Norwegian office building case study reported that actual PV electricity generation was approximately 1% higher than simulated values, confirming the capability of well-calibrated models to predict on-site renewable performance^[96]. As buildings transition from design to operation, simulation tools evolve to support performance validation and continuous improvement. They facilitate energy benchmarking by comparing predicted and actual consumption, enable fault detection through advanced diagnostic algorithms, and support retrofit planning by evaluating upgrade scenarios. Tools such as OpenStudio exemplify this practical value by streamlining energy audits through model simplification techniques, reducing simulation times from days to two to four hours while maintaining accuracy. As simulation tools continue to advance, their role in achieving and maintaining net-zero performance will become increasingly critical, establishing them as essential components of sustainable building practice.

5.2 Building Integrated Photovoltaics (BIPV) systems

Solar energy is the most abundant clean energy resource on the planet, and BIPV systems represent one of the most widely applied technologies in NZEBs^[97]. In the building sector, there are two main approaches for deploying PV panels to capture solar energy: building-attached photovoltaics (BAPV) and BIPV^[98]. BAPV systems are typically mounted on the surface of existing building structures, such as roofs^[17]. In contrast, BIPV systems replace parts of building components (e.g., walls or roofs) with solar-integrated materials. These materials not only generate electricity but also serve as functional building envelope elements, providing structural support, thermal insulation, and light transmission.. Kong *et al.*^[99] provided a detailed comparison between BAPV and BIPV, highlighting the advantages of BIPV in aesthetics and thermal performance, while also noting current limitations and potential development directions. The evolution of roof-based BIPV demonstrates a trend from localized PV panel installations to complete solar roof systems, in which PV modules cover the entire roof. This integration not only enhances architectural aesthetics but also minimizes potential structural damage to the roof^[100]. For large or irregularly shaped roofs, solar shingles or solar films can be employed as alternatives to traditional shingles. These technologies are highly adaptable^[101] and can be installed using methods similar to conventional roofing materials. PV films, in particular, are lightweight, convenient, and suitable for mass production, combining high energy efficiency with economic scalability. On building facades, BIPV modules can be integrated into the exterior envelope to maintain structural integrity, safety, and aesthetics, while simultaneously supplying power. Façade BIPV systems are generally categorized as warm façades or cold façades. Warm façades incorporate insulating glass PV modules to reduce heat transfer and noise, thereby contributing to energy savings^[102]. Cold façades, in contrast, create a ventilated cavity between the PV panels and the building surface, improving summer cooling performance and enhancing PV efficiency by dissipating excess surface heat^[103]. Exterior window BIPV systems can take the form of shutter-type or window-type photovoltaic applications. In such systems, glass photovoltaic panels replace conventional windows or curtain walls, integrating PV films and wiring to combine transparency with energy generation^[104].

Despite rapid advances in BIPV technology, several challenges remain. The energy generation efficiency per unit area of BIPV is generally lower than that of BAPV, as BIPV modules are embedded within building components^[105]. In addition, factors such as reduced sunlight exposure, shading, extreme panel temperatures, and dust accumulation often limit their energy capture capacity, leading to reduced power generation efficiency^[106]. Moreover, the cost of BIPV remains considerably higher than that of conventional solar energy solutions, such as BAPV, due to the complexity of design, manufacturing, installation, and maintenance^[107].

In summary, BIPV systems offer strong potential for integrating renewable energy generation with building functions and aesthetics.

However, their large-scale adoption is still restricted by lower conversion efficiency, higher costs, and site-specific performance constraints.

5.3 Energy storage systems (ESS)

ESS play a crucial role in bridging the gap between intermittent renewable energy generation and consistent energy demand. ESS not only stabilize energy supply but also enhance grid resilience, enabling buildings to act as dynamic energy nodes within urban energy networks^[108]. Electrochemical and thermal storage technologies dominate current applications^[109], each offering distinct advantages tailored to different architectural and operational contexts.

Electrochemical energy storage includes battery energy storage (BES), electric vehicle (EV) energy storage, and hydrogen energy storage (HES). BES and HES are the most commonly applied in buildings. BES is frequently integrated with building photovoltaic systems due to its rapid power delivery, high efficiency, relatively low installation and maintenance costs^[110], and fast commercialization^[111]. Lai *et al.*^[112] provided an overview of BES technologies suitable for photovoltaic integration, including dye-sensitized cells, perovskite cells, organic cells, and QDC. HES, while traditionally applied in the transportation and engine sectors, is increasingly explored for building applications as the technology matures.

Thermal energy storage (TES) captures and stores excess heat for later use. TES technologies are categorized into sensible heat storage (SHS), latent heat storage (LHS), and thermochemical heat storage (TCHS). (1) SHS stores thermal energy by raising the temperature of a storage medium without phase change. SHS media include liquids and solids, such as water^[113], molten salts^[114], rocks^[115], concrete^[116], and certain metals. SHS is widely used in buildings due to the abundance, affordability, and durability of these materials. Solid SHS, such as concrete integrated into building structures, provides reliable performance at high temperatures and pressures^[117]. Typical applications include domestic hot water storage and space heating. (2) LHS leverages phase change materials to store thermal energy. LHS offers higher energy storage capacity per unit volume compared to SHS^[118], requires less storage space^[119], and exhibits lower sensitivity to temperature fluctuations^[120]. LHS also enables faster heat discharge^[121], making it suitable for efficient building heating and cooling applications. (3) TCHS stores and releases thermal energy via reversible chemical reactions^[122]. TCHS can be implemented as open or closed systems. In open systems, chemical reactions require a continuous supply of reactants, such as adsorbent materials that absorb reactants during heat absorption and release them during exothermic reactions, providing continuous heating or cooling^[123]. Closed systems, in contrast, operate with a fixed quantity of reactants, which often also act as the adsorbent. The chemical reactions occur in a confined space without requiring continuous reactant input, allowing controlled absorption and release of heat.

5.4 Intelligent Building Energy Management (IBEM) systems

IBEM systems leverage the support of IoT and AI technologies, employing smart meters, diverse sensors, and big data analytics to monitor, manage, and predict the energy production, storage, and consumption of buildings in real time. By dynamically adjusting building energy use, IBEM systems can enhance operational efficiency across almost all types of buildings^[124]. For instance, smart meters allow power utilities to remotely access a building's electricity usage, store surplus energy during off-peak hours, and use it during peak hours to alleviate grid load^[125]. These systems can also detect faults or outages remotely and automatically resolve certain issues that previously required manual intervention^[126]. In residential applications, IBEM systems enable predictive maintenance and energy optimization through IoT devices, which centrally monitor appliances such as lights, air conditioners, refrigerators, televisions, and water heaters. This enables devices to respond more intelligently to occupant needs Yang *et al.* demonstrated that home IBEM systems can reduce total household energy consumption by 15%^[127]. Mature smart control systems currently include intelligent lighting, HVAC, smart meters, smart plugs, and connected appliances^[128]. For example, advanced lighting systems can move beyond simple automatic switching or daylight adjustment to area-specific adaptive illumination, achieving energy savings while enhancing user comfort^[129,130]. By integrating AI, IBEM systems can learn occupant temperature preferences across different spaces and times, enabling more personalized and efficient climate control. Among occupant-related data, occupancy information is the most direct factor influencing building energy load.

Accurate capture of occupancy patterns can guide IBEM operation to support net-zero performance. Nord *et al.* studied 31 scenarios of occupant behavior in Norwegian NZEBs and found that occupant behavior could cause grid stress ranging from -5% to +13%^[131]. Berg *et al.* analyzed appliance usage across 564 households, showing that clothes dryers have the largest potential for demand reduction, followed by dishwashers and washing machines^[132]. Shi *et al.* proposed a deep reinforcement learning framework that considers occupant metabolic rate and clothing level, achieving 4.8%-39.58% reduction in HVAC heating load^[133]. Ala *et al.* simulated the effect of increased occupant energy-saving awareness, resulting in a 24.3% reduction in annual energy consumption^[134]. Zhang *et al.* developed an occupant-oriented energy-use regulation method incorporating thermal comfort, energy preferences, specific activities, and stochastic behaviors, which achieved a 12.12% reduction or shifting of peak energy load^[135]. Akbari and Haghighat extracted household daily occupancy patterns to support customized load-shifting and energy-saving strategies for IBEM implementation^[136].

In summary, IBEM systems, combined with energy generation and storage technologies, empower NZEBs to operate more efficiently

while enhancing self-sufficiency and supporting carbon neutrality. **Figure 11** illustrates the most widely used tools and technologies for NZEBs. Energy simulation and design tools, including graphical interfaces, EnergyPlus plug-ins, and standalone software, support performance verification and optimization. Building-integrated photovoltaics on roofs, façades, and windows enable electricity generation while maintaining envelope functionality. Advanced energy storage systems, both electrochemical and thermal, ensure stable energy supply and regulation. Finally, intelligent energy management systems optimize HVAC, lighting, and appliance operation, improving overall efficiency and occupant comfort. By integrating these technologies, NZEBs can achieve efficient operation, enhanced energy self-sufficiency, and significant progress toward carbon neutrality.

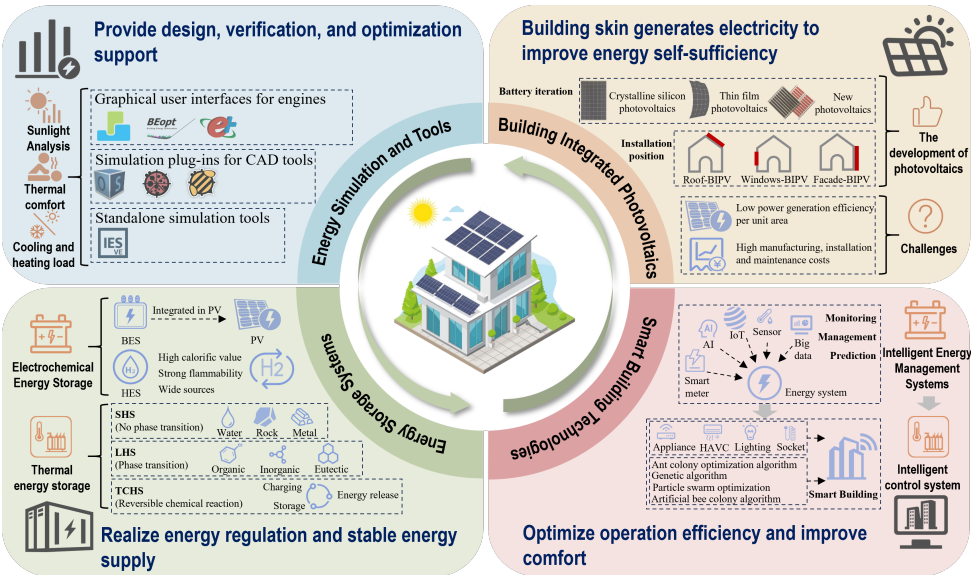


Figure 11. Tools and Technologies for NZEBs. NZEBs: net zero energy buildings; BES: battery energy storage; PV: photovoltaic; HES: hydrogen energy storage; SHS: sensible heat storage; LHS: latent heat storage; TCHS: thermochemical storage; IoT: Internet of Things.

6. Challenges Towards NZEB Implementation

Despite the growing global interest in NZEBs, several challenges remain in their practical implementation. This section addresses the final research question. **Table 3** summarizes the main categories of challenges in the NZEB field, and the following paragraphs provide a detailed discussion of these issues.

Table 3. NZEBs implementation challenges.

Category	Challenges	Source
Initial costs and financial feasibility	1. High upfront costs	[137]
	2. Long payback period	[138,139]
	3. Limited financial support	[140,141]
	4. Economic uncertainty	[142]
Energy availability and intermittency	1. Intermittency and reliability	[4,143]
	2. Energy storage	[22]
	3. Urban space constraints	[144]
	4. Grid and infrastructure	[145]
Climate and location considerations	1. Energy generation	[145,146]
	2. Localized design	[3]
Integration with existing infrastructure	1. Structural and technical limitations	[3,147]
	2. High costs and logistical barriers	[144]
Code and standards	1. Lack standardized definitions	[148]
	2. Compliance Burdens	[133]

NZEBs: net zero energy buildings.

6.1 Initial costs and financial feasibility

One of the major challenges in implementing NZEBs is the substantial upfront costs associated with planning, construction, and integration of green energy technologies. Realizing NZEBs requires numerous advanced insulation materials, multiple high-efficiency HVAC systems, additional solar panels, and specialized energy storage solutions, each of which entails considerable initial expenses^[137]. Comparative evidence from different regions highlights the economic trade-offs of NZEB variants over their full service life. In Denmark, studies show that NZEBs with integrated photovoltaics and advanced HVAC systems generally demand higher upfront investment than conventional designs, but these costs are offset by substantial operational savings over 20–30 years^[149]. A 50-year life-cycle cost analysis in Indonesia demonstrates that, despite higher construction and end-of-life costs, NZEBs can achieve nearly 48% lower operational expenses and an overall 10.8% reduction in life-cycle costs compared to baseline buildings^[150]. In Italy, a 30-year analysis of school retrofits revealed that meeting minimum regulatory standards alone is insufficient for cost-effectiveness, and only carefully selected combinations of active and passive measures provide cost-optimal solutions under future climate scenarios^[151]. These findings confirm that while NZEBs often require higher initial investment, their long-term economic viability strongly depends on contextual factors such as building type, design strategy, and projected climate conditions. This underscores the importance of life-cycle cost analysis in evaluating NZEB pathways. Although energy savings and government incentives can offset initial costs over time, many investors and contractors remain hesitant due to extended payback periods^[138]. The integration of smart grid technologies and automated energy control systems further increases capital costs, limiting widespread adoption^[139]. Long-term performance degradation is another concern. Global analyses indicate that crystalline silicon PV modules degrade by approximately 1% per year on average^[152], with some systems losing around 30% of total output over 22 years^[153]. Without harmonized benchmarking and longitudinal field data, NZEBs risk underperforming over their service life and failing to deliver promised sustainability outcomes. Moreover, the embodied carbon footprint of renewable system components, such as PV modules, inverters, and batteries, remains underexamined. Life-cycle assessments of crystalline silicon PV systems report average CO₂ emissions of 28–100 g CO₂-eq/kWh, covering manufacturing, installation, and end-of-life stages^[154]. Peng *et al.* reviewed photovoltaic systems and found that thin-film PV technologies have energy payback times of 0.75–3.5 years and life-cycle GHG emission rates of 10.5–50 g CO₂-eq/kWh^[155]. These findings emphasize that achieving true net-zero performance requires holistic lifecycle assessments encompassing both operational and material-phase emissions. Material availability also poses a challenge. The rapid expansion of photovoltaics raises concerns about the supply of critical minerals. Thin-film PV technologies such as cadmium telluride face constraints due to key element supply risks. Helbig *et al.* reported that indium and gallium face relatively high long-term supply risks, while cadmium and copper are less critical, suggesting that material availability and geopolitical concentration could limit large-scale deployment unless recycling, substitution, and diversified supply chains are strengthened^[156]. Government policies and subsidies are critical for promoting sustainable construction, but financial viability remains a significant hurdle, particularly in developing countries with limited incentives^[140]. Even in regions with well-established support mechanisms, challenges persist regarding financing models. Banks and financial institutions often lack appropriate frameworks to evaluate the long-term benefits of NZEBs^[141]. Economic assessments must also consider the costs and potential depreciation of green energy technologies, which can significantly affect overall financial feasibility^[142].

Overall, the long-term success of NZEB deployment depends not only on overcoming high upfront costs and ensuring reliable operational performance, but also on addressing material supply risks, embodied emissions, and financing barriers through integrated technical, economic, and policy frameworks.

6.2 Energy availability and intermittency

The integration of renewable energy in NZEBs presents significant challenges, primarily due to the variable availability and intermittency of energy sources. Solar photovoltaics and wind energy, the main renewable sources for NZEBs, are inherently dependent on fluctuating climatic conditions, which raises reliability concerns^[143]. This intermittency can compromise energy security, highlighting the need for efficient storage solutions, such as battery systems or thermal storage, to stabilize supply^[4]. However, current storage technologies remain costly and subject to efficiency losses, which can undermine overall NZEB performance^[22]. The challenge is further exacerbated in urban environments, where limited space restricts large-scale renewable installations, increasing dependence on grid connectivity^[144]. While smart grid integration and demand-response strategies offer opportunities to optimize energy use, persistent issues such as aging infrastructure, grid instability, and regulatory constraints continue to impede reliable operation^[145]. Addressing these gaps requires future research to focus on hybrid renewable systems, advanced predictive energy management models, and innovative battery technologies to mitigate intermittency and enhance NZEB resilience^[157]. Clustered NZEBs also introduce specific risks of local grid congestion. High densities of residential PV systems exporting electricity simultaneously can exceed feeder capacities, causing reverse power flows, voltage rises, and frequency fluctuations. For instance, simulation studies in Ghana demonstrate that dense PV penetration in low-voltage networks can trigger severe reverse flows and overload distribution lines, necessitating reinforcement or control interventions^[158]. Similarly, case studies in South Australia report that increased PV penetration substantially raises the frequency of over-voltage events and reverse flows, often resulting in inverter disconnections and forced curtailment of solar output^[159]. In summary, ensuring reliable integration of renewable energy in NZEBs requires holistic solutions that address intermittency, storage inefficiencies, spatial and regulatory

limitations, and local grid congestion. Such approaches are essential for achieving resilient, scalable, and effective net-zero transitions.

6.3 Considerations of location and climate

The operational effectiveness of NZEBs is strongly influenced by geographical and climatic conditions. In regions with limited solar exposure or pronounced seasonal variations, achieving net-zero energy targets becomes more challenging due to reduced potential for renewable energy generation^[146]. Colder climates, for example, impose high heating demands, placing considerable pressure on energy efficiency. In such contexts, advanced solutions such as high-performance insulation materials and high-efficiency heating systems, including geothermal heat pumps, are essential to offset energy demands^[145]. A case study in northeastern China demonstrated that integrating photovoltaic-thermal collectors with a ground source heat pump system not only reduces annual carbon emissions and life-cycle costs but also improves soil thermal balance and the contribution of renewable energy, bringing buildings closer to true zero-energy operation^[160]. In cold and near-arctic regions of Canada, urban-scale studies indicate that achieving net-zero energy relies on a combination of electrification, targeted efficiency retrofits, and solar integration. Case studies in British Columbia have shown substantial energy savings across residential and commercial districts^[161]. By contrast, tropical regions face dual challenges: elevated humidity increases cooling requirements and complicates indoor air quality management. Experiments in Malaysia's first NZEB revealed that conventional fan coil units could maintain temperature but were ineffective at controlling humidity, whereas a desiccant cooling system achieved improved comfort with approximately 38% lower energy consumption^[162]. Passive design strategies, such as natural ventilation and adaptive shading, can help mitigate cooling loads, but their effectiveness depends on regional climate conditions. Evidence from Singapore further highlights the importance of advanced control systems and energy flexibility for reliable cooling performance in tropical NZEB offices^[34]. In Sub-Saharan Africa, the transition to NZEBs is limited by high upfront costs and diverse climatic conditions. Effective strategies require robust energy codes and standards, targeted stakeholder training, innovative financing and incentives, development of local supply chains, and pilot projects that demonstrate feasibility and build confidence for broader adoption^[10]. Rising global temperatures have increased the frequency, intensity, and duration of heat waves over the past decade, with projections indicating further worsening^[163]. Power outages often coincide with heat waves, restricting the availability of active cooling systems^[164]. Recent studies suggest that passive strategies in NZEBs, such as natural ventilation, cool roofs, and solar shading, are insufficient to mitigate heat exposure during prolonged blackouts^[165]. To enhance resilience, Luo and Cao proposed integrating building batteries, electric vehicles, and wave energy converter storage into a coastal NZEB. This hybrid approach increased outage resilience from 83% to over 99% while nearly eliminating CO₂ emissions and dependence on diesel backup^[166]. Similarly, Japan has advanced the deployment of PV-battery-equipped NZEBs to maintain basic household functions and thermal comfort during emergencies, illustrating how locally adapted strategies can improve NZEB resilience under frequent extreme climate events^[167]. To ensure NZEB adaptability across diverse environments, future research should prioritize localized design frameworks, hybrid renewable energy integration, and climate-responsive building systems capable of dynamically adjusting to environmental stressors^[3]. In summary, achieving reliable NZEB performance under varying and evolving climatic conditions requires design strategies that are localized, resilient, and adaptive, balancing efficiency, reliability, and affordability.

6.4 Integration with existing infrastructure

Retrofitting existing buildings to achieve net-zero energy performance presents unique challenges compared with designing new constructions, where energy efficiency can be prioritized from the outset. Retrofitting requires navigating structural constraints, such as outdated building envelopes, spatial limitations, and legacy HVAC systems, which complicate both thermal improvements and renewable energy integration^[3]. These technical barriers, combined with high upfront costs and logistical complexities, often discourage property owners from pursuing NZEB retrofits^[147]. In urban settings, retrofits must also align with existing infrastructure, including electrical grids and district heating networks, necessitating collaboration among utilities, policymakers, and building owners. This multi-stakeholder process can introduce regulatory friction and technical mismatches, especially in aging urban systems^[144]. The structural considerations of installing rooftop renewable systems, particularly photovoltaic panels, require careful evaluation in retrofit projects. Additional dead loads on roof slabs may compromise waterproofing membranes and reduce long-term serviceability^[168]. Moreover, the orientation and tilt of PV arrays can significantly increase wind uplift forces, generating dynamic loads that could threaten rooftop integrity if not properly addressed in design^[169]. These challenges underscore the importance of comprehensive structural load assessments to ensure the safe and durable integration of rooftop renewable systems in both new and existing buildings. To overcome these barriers, future research should focus on scalable retrofit frameworks, modular renewable technologies adaptable to older structures, and digital tools, such as AI-driven analytics, to optimize energy performance in retrofitting projects.

6.5 Code and standards

The global policy landscape for NZEBs remains fragmented, with inconsistent codes and standards across regions. While some countries have implemented stringent NZEB mandates, others lack standardized definitions or enforcement mechanisms, resulting in disparities in energy performance criteria^[148]. Net-zero definitions vary across climates and jurisdictions, ranging from source energy

to delivered energy, and from annual energy balance to seasonal metrics, which complicates reliable comparisons and regulation of NZEB outcomes. This regulatory inconsistency hinders meaningful evaluation of NZEB initiatives worldwide and complicates assessments of their effectiveness in promoting broader sustainability goals. Compliance with existing NZEB requirements often involves resource-intensive processes, including exhaustive documentation, third-party certifications, and inspections, which impose financial and logistical burdens on stakeholders^[143]. In historic urban districts, NZEB deployment is often restricted by preservation and zoning regulations. Limitations on modifying façades, window designs, or rooftops can constrain the adoption of high-performance envelopes and renewable energy systems, such as photovoltaic installations^[170]. Additionally, implementing district heating networks is challenging due to space limitations and the fragility of masonry in terraced houses, which can be easily damaged during installation^[171]. Shortages of skilled labor and weak quality assurance remain significant barriers to NZEB adoption. Construction audits frequently identify recurring issues, including improper insulation installation, inadequate thermal bridge treatment, and insufficient airtightness testing. Structured training programs for craftsmen and site managers are generally lacking^[172]. In Southern Europe, these challenges are exacerbated by the misapplication of high-performance components designed for heating-dominated climates, where insufficient training results in persistent construction quality issues and slows NZEB uptake^[173]. Conflicting regulatory frameworks between municipal and national levels further complicate NZEB deployment. National standards may set stringent energy performance requirements, while municipal codes impose heritage preservation, zoning, or urban density restrictions that limit envelope retrofits or renewable integration. In several European cities, rooftop PV systems mandated by national targets have encountered resistance at the municipal level due to aesthetic controls and land-use regulations, causing delays in permitting and inconsistent compliance pathways^[174]. Similarly, in India, national initiatives such as the Jawaharlal Nehru National Solar Mission set ambitious solar PV targets, but fragmented implementation at the state and municipal levels, including varying Renewable Purchase Obligations, permitting procedures, and land-use constraints, has often slowed NZEB and PV deployment^[175]. To address these challenges, future policy frameworks should focus on harmonizing international NZEB standards, streamlining bureaucratic procedures, and integrating digital monitoring platforms to enable real-time compliance verification.

7. Future Research

7.1 Advancements in building materials

Recent developments in construction materials have significantly improved the energy efficiency and sustainability of NZEBs. Researchers are focusing on high-performance insulation materials, such as aerogels, phase-change materials, and vacuum insulation panels, which combine high thermal resistance with low conductivity to substantially reduce heating and cooling demands^[176]. These innovations are complemented by bio-based and recyclable insulation alternatives that minimize embodied carbon emissions while enhancing overall energy performance^[140]. Breakthroughs in self-healing concrete embedded with nanomaterials are also enhancing structural longevity and energy efficiency. These materials autonomously repair micro-cracks, reducing maintenance requirements and extending building lifespans^[146]. Smart building envelope technologies are further transforming NZEB design. Dynamic glazing systems, including electrochromic windows, adjust their transparency in response to sunlight, optimizing solar heat gain and indoor thermal comfort^[4]. BIPV and high-performance facades synergize energy generation with insulation, often enabling net-positive energy outcomes. Beyond insulation and glazing, accelerated research into high-strength, lightweight composites, such as carbon-fiber-reinforced polymers, is reducing material consumption without compromising structural integrity^[177]. Engineered wood products, including cross-laminated timber, are gaining attention for their carbon-sequestration potential and favorable thermal properties. When combined with modular construction and adaptive façades, these materials can significantly enhance energy efficiency^[7]. Emerging smart coatings, including hydrophobic and thermochromic layers, further improve envelope performance by mitigating moisture infiltration and seasonal heat transfer^[144]. The source of materials also plays a critical role in achieving NZEB performance across the entire lifecycle. While globally sourced high-performance components can enhance operational efficiency, they often carry higher carbon footprints due to long supply chains and energy-intensive manufacturing processes^[178]. Life-cycle assessments of housing typologies in West Africa indicate that reliance on imported high-embodied carbon materials increases emissions, whereas local biogenic and geogenic alternatives can reduce environmental impacts when combined with improved building density, passive design strategies, and renewable energy integration^[179]. Collectively, these innovations highlight a shift toward materials that balance energy efficiency, durability, and environmental sustainability in NZEBs.

7.2 High-level integration of new renewable technologies

The viability of NZEBs depends on advancements in on-site renewable energy generation technologies. BIPV are central to this effort, combining energy production with architectural design to reduce reliance on external grids^[176]. Innovations such as perovskite solar cells and bifacial panels are improving efficiency and adaptability, enabling higher energy yields even in dense urban environments^[180]. Transparent solar panels, for example, can now be integrated into windows and façades, generating electricity without compromising aesthetics^[142]. Complementing solar technologies, building-integrated wind turbines, particularly in high-rise structures, are emerging as viable urban energy sources. When combined with microgrids, these systems optimize energy distribution and storage, balancing supply with demand^[181]. Hybrid configurations that integrate solar, wind, and geothermal energy further enhance resilience, ensuring reliable power under diverse climatic conditions^[182].

To address the intermittency of renewable sources, effective energy storage solutions are essential. Advances in solid-state and flow batteries are expanding storage capacity, enabling NZEBs to achieve greater energy autonomy^[146]. Hydrogen storage systems coupled with fuel cells also show potential for long-term energy reserves, particularly in large-scale applications^[140]. Concurrently, AI-driven energy management systems are transforming load forecasting and demand-side optimization, dynamically aligning energy use with generation patterns. Collectively, these developments highlight a holistic approach to NZEB design, integrating generation, storage, and intelligent management to realize self-sufficient and resilient buildings.

7.3 Development urban districts and net zero communities

The evolution of NZEBs is extending into net-zero energy districts, where interconnected buildings share renewable resources through smart grids. Leading this transition, peer-to-peer (P2P) energy trading platforms enable buildings to dynamically exchange surplus renewable energy, fostering decentralized, community-driven energy ecosystems^[7]. At the same time, district heating and cooling systems that integrate geothermal energy and industrial waste heat recovery are emerging as effective tools to enhance energy efficiency at the community scale^[141]. Effective urban planning is crucial for realizing net-zero communities. Strategic implementation of green infrastructure, such as urban forests and green roofs, along with passive cooling strategies, including reflective pavements and shaded walkways, helps mitigate urban heat island effects and directly reduces cooling demands^[139]. AI-powered urban simulations further support this objective by enabling data-driven city layouts that optimize building orientations for solar gain and balance energy distribution networks.

7.4 Suitable policy and regulation

Policy frameworks are essential for accelerating the adoption of NZEBs. Governments worldwide are implementing measures such as mandatory net-zero building codes, carbon pricing mechanisms, and financial incentives, including tax rebates and grants, to encourage NZEB construction^[143]. At the same time, regulatory bodies are standardizing performance metrics and improving transparency through energy labeling systems, enabling more reliable benchmarking of NZEB efficiency^[183]. Despite these initiatives, persistent barriers such as high upfront costs, workforce skill gaps, and inconsistent policy enforcement continue to limit widespread NZEB implementation^[176]. Public-private partnerships are emerging as key enablers to overcome these challenges. By sharing investment risks and fostering cross-sector collaboration, such partnerships bridge financial gaps and stimulate innovation in scalable NZEB solutions. These developments highlight the importance of adaptive, multi-stakeholder policy frameworks to support the broader uptake of net-zero energy buildings^[7].

8. Conclusion

This study systematically reviewed the development, design strategies, and implementation challenges of NZEBs. By examining technical characteristics, passive and active design measures, renewable energy integration, and emerging technologies, the paper highlights the critical role of NZEBs in advancing energy efficiency and decarbonization within the building sector. Key pathways to achieving net-zero performance include passive design strategies, high-performance building envelopes, energy-efficient HVAC systems, renewable energy generation, and intelligent energy management. Additionally, tools such as artificial intelligence and occupant-centered regulation demonstrate potential for optimizing energy use and enhancing resilience.

Despite these advancements, several limitations and challenges remain. High upfront costs, long payback periods, and insufficient financial mechanisms continue to impede large-scale adoption. Technical barriers, including the intermittency of renewable energy, storage inefficiencies, and integration with existing infrastructure, further constrain performance. Geographical and climatic variability adds complexity, as strategies effective in one region may not be directly applicable to others. Moreover, many studies focus primarily on operational energy, while the embodied energy and life-cycle environmental impacts of NZEB components remain underexplored. Long-term system degradation and limited availability of critical materials for renewable technologies are also often overlooked, raising concerns about sustainability at scale.

In conclusion, NZEBs offer substantial potential to transform the building sector toward sustainability. Realizing this potential requires holistic consideration of financial, technical, and contextual factors. Future research should emphasize comprehensive life-cycle assessments, locally adapted design frameworks, and innovative financing and policy mechanisms to overcome existing barriers and accelerate the global transition to NZEBs.

Declarations

Authors contribution

Li Q: Writing-original draft, methodology, formal analysis, data curation, visualization.

Ma R, Yang M: Writing-original draft, formal analysis, visualization.

Wang W: Writing-review & editing, supervision, conceptualization.

Chen J: Writing-review & editing, supervision, methodology, conceptualization.

Conflicts of interest

Jiayu Chen is an Editorial Board member of *Journal of Building Design and Environment*. The other authors declare no conflicts of interest.

Ethical approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

Not applicable.

Funding

None.

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