

# Renewable Energy Integration for Net-Zero Buildings: Challenges, Opportunities, and Strategic Pathways

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## Abstract

Buildings account for nearly 40% of global energy use and 36% of CO<sub>2</sub> emissions, positioning Net-Zero Energy Buildings (NZEBs) as vital for climate mitigation. However, large-scale adoption remains limited by technical, economic, and policy barriers. This study systematically reviews 1285 peer-reviewed articles (2015–2025) from Scopus and Web of Science, following PRISMA guidelines and thematic analysis to assess renewable energy integration and efficiency strategies. Results indicate that 70% of studies highlight emissions reduction and cost savings as key NZEB benefits, while 60% cite high storage costs and 45% report grid integration challenges. Only 30% of studies address policy dependency, revealing a research gap. Effective measures include passive solar design (up to 25% heating load reduction), high-performance envelopes (15–40% energy savings), and smart energy management (10–20% efficiency gains). Persistent obstacles involve high up-front costs, renewable variability, and rapid technological obsolescence. Achieving NZEB viability requires integrating energy-efficient design, affordable renewables, advanced storage, and coherent policy frameworks to accelerate the transition toward a sustainable, NZEB-built environment.

**Keywords:** net-zero energy buildings; renewable energy integration; energy efficiency; sustainable building design; hybrid energy systems; circular bioeconomic

## 1. Introduction

The urgency of climate change has placed unprecedented pressure on the global energy sector, with the building industry emerging as a critical area for emissions reduction. Buildings account for nearly 40% of global energy consumption and contribute significantly to greenhouse gas (GHG) emissions [1]. As a result, the transition toward sustainable energy solutions has gained traction, with energy buildings emerging as a viable strategy to mitigate environmental impact [2]. NZEBs are designed to balance their total energy consumption with on-site renewable energy generation, thus reducing dependency on fossil fuels and lowering carbon footprints [3]. Achieving this balance, however, presents a range of technical, economic, and regulatory challenges that must be critically examined. NZEBs rely on integrating renewable energy sources, such as solar photovoltaics (PV), wind energy, and geothermal systems, to meet their energy demands [4]. The effectiveness of these technologies varies depending on geographic location, climate conditions, and technological advancements [5]. Additionally, energy storage solutions and smart grid



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interactions play a vital role in ensuring the reliability of renewable energy in NZEBs [6]. Despite the potential of these systems, issues such as intermittency, efficiency losses, and integration complexities pose significant risks to their widespread adoption [7]. Understanding these challenges is essential for developing practical solutions that enhance the feasibility of NZEBs.

Economic and regulatory factors strongly shape NZEB adoption, as high upfront costs for renewable systems and efficient materials remain a barrier despite potential long-term savings and policy incentives [8,9]. Implementation also depends on regional variations in building codes, incentives, and energy policies, underscoring the need for a comprehensive assessment of these economic and regulatory dimensions [10]. Although previous reviews have discussed biomass-based energy systems, most focus on isolated technologies or overlook grid-connected configurations. This review addresses these gaps by offering an updated, comprehensive analysis of biomass systems with emphasis on grid integration, regional challenges, and modeling approaches. By consolidating recent advancements, it provides actionable insights for researchers, planners, and policymakers, guiding sustainable energy development and policy-making.

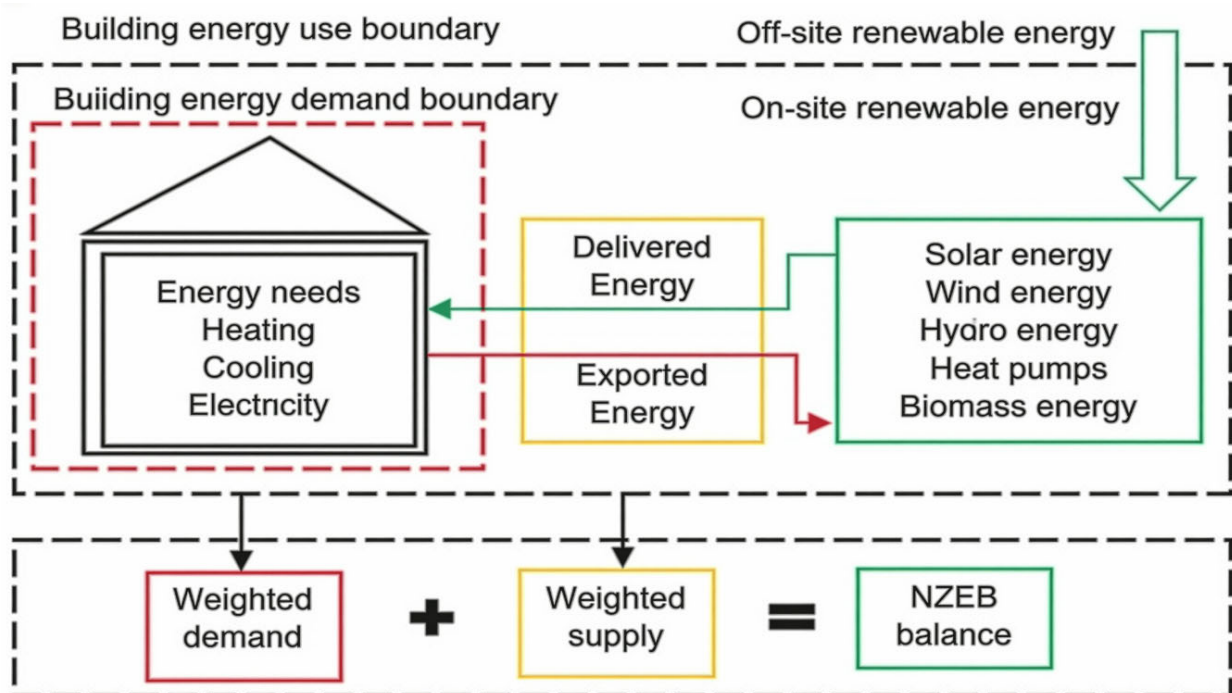
The novelty of this study lies in its holistic and quantitative evaluation of renewable energy integration in NZEBs. Unlike previous reviews that focus on isolated technologies, single regions, or narrow case studies, this work systematically analyzes 1285 peer-reviewed articles (2015–2025) across technical, economic, and policy dimensions. It offers measurable insights—for example, 70% of studies emphasize emissions reduction, while 60% identify storage costs as a major challenge—providing a more data-driven synthesis than earlier assessments. The study also acknowledges limitations, including its restriction to English-language peer-reviewed literature and the exclusion of grey sources such as industry reports and policy documents. Despite these boundaries, the review contributes a novel, multi-dimensional framework that identifies key advantages, challenges, and risks, and proposes actionable strategies for advancing NZEB adoption globally. Its objective is to evaluate the effectiveness of renewable energy systems in achieving NZEB performance by examining technical efficiency, economic feasibility, and regulatory influences. Subsequent sections assess major renewable technologies, integration challenges, financial and policy considerations, and design strategies for optimized NZEB deployment. Moving beyond descriptive summaries, this study integrates bibliometric trends with thematic analysis to reveal structural research gaps, underexplored risks, and emerging opportunities. This holistic, gap-oriented approach supports researchers, practitioners, and policymakers in navigating the evolving NZEB landscape and shaping a forward-looking research and development agenda.

## 2. Literature Review

Net-zero energy buildings (NZEBs) represent a key advancement in sustainable architecture, aiming to balance building energy consumption with on-site renewable energy generation. Growing interest in NZEBs reflects their potential to mitigate climate change, reduce dependence on fossil fuels, and lower energy-related emissions. NZEBs achieve this balance primarily through the integration of renewable energy technologies, such as solar and wind systems. Among their main advantages is the significant reduction in greenhouse gas emissions, as renewable energy integration substantially lowers the carbon footprint of building operations. Studies consistently identify solar energy as a practical and effective renewable electricity source for buildings, supporting improved energy efficiency and long-term sustainability [11,12]. This shift not only lessens reliance on conventional fuels but also aligns with global sustainability goals, as NZEBs help improve energy efficiency (EE) while maintaining comfort for occupants [3,13].

However, significant challenges persist in the development and implementation of NZEBs. High upfront investment costs for renewable energy technologies can deter stakeholders, particularly in regions with limited financial incentives or policy support [14]. Regulatory complexity and variations in building codes across jurisdictions further constrain adoption [15]. While advanced tools such as Building Information Modeling (BIM) can improve NZEB design and construction efficiency, they require specialized expertise and may increase initial costs [16]. Energy management systems (EMS) are also critical to NZEB feasibility, as they must operate under uncertainty in energy demand and renewable supply [17]. Recent studies demonstrate that advanced EMS solutions can enhance energy efficiency and system reliability across residential, commercial, and institutional NZEBs [7,18].

Figure 1 illustrates the energy balance concept for a Net Zero Energy Building (NZEB). It shows the interaction between a building's energy needs—such as heating, cooling, and electricity—and its energy supply sources. Energy is delivered to meet the building's demand, while excess energy can be exported. The supply comes from renewable sources like solar, wind, hydro, heat pumps, and biomass, primarily generated on-site. The balance between the weighted demand (energy consumed) and weighted supply (renewable energy produced) determines the NZEB status, aiming for NZEB energy consumption within the building energy use boundary [19]. Despite these challenges, the long-term benefits of adopting NZEB principles often outweigh the initial difficulties. For example, not only do NZEBs provide financial savings through reduced energy bills, but they also enhance the resilience of buildings against fluctuating energy prices and climate-related disruptions [20].



**Figure 1.** Energy Flow and Balance Concept for Net Zero Energy Buildings [19].

Furthermore, the promotion of NZEBs can stimulate local economies by fostering jobs in renewable energy sectors and sustainable construction practices, leading to broader community benefits and increasing public awareness of sustainability [21]. While the transition to Net-Zero Energy Buildings is fraught with challenges and risks, it offers substantial advantages for energy efficiency, emissions reduction, and economic viability from a long-term perspective. By comprehensively addressing the technological, regulatory, and investment challenges, stakeholders can harness the overall benefits of NZEBs, ultimately

contributing to a more sustainable future. Table 1 presents a systematic literature review of recent studies addressing the integration of renewable energy sources into (NZEBs), with a focus on technical and economic challenges. The reviewed literature spans peer-reviewed journal articles, conference papers, and book chapters published between 2020 and 2024. Key themes include energy storage, system modeling, policy and regulatory barriers, and the role of technologies such as hydrogen and solar photovoltaics. This synthesis supports further meta-analytical and bibliometric analyses to identify research gaps and inform future directions in NZEB development and renewable integration strategies.

**Table 1.** Challenges in Renewable Integration for NZEBs.

No.	Reference	Focus Area	Technical Challenges	Economic Challenges	Key Insights	Identified Research Gaps
1	[22]	NZEB integration	Intermittency of renewables; need for storage	High initial costs; regulatory complexity	Highlights the need for collaborative solutions for NZEB deployment	Lacks detailed strategies for scaling solutions across different climates and building types
2	[23]	Hydrogen storage + solar/wind	Electrolyser efficiency; storage; fuel cell performance	High initial cost of hydrogen tech; policy gaps	Emphasizes hydrogen's role in enhancing system resilience	Limited empirical demonstration of hydrogen systems in real NZEBs
3	[24]	Urban NZEBs	Advanced EMS; legacy infrastructure compatibility	High investment cost; policy/regulation barriers	Provides a roadmap for improving NZEB performance	Does not fully address retrofitting challenges in existing urban infrastructure
4	[25]	Integration of renewable energy in green buildings	Intermittency of solar/wind; grid integration	Upfront cost; lack of technical expertise	Underscores implementation barriers in developing contexts	Insufficient analysis of context-specific socio-economic barriers
5	[26]	System-level integration	Grid stability; storage limitations	Cost competition with fossil fuels; financing/policy	Focus on low-carbon transitions and incentives for renewables	Limited exploration of long-term storage and grid-interactive buildings
6	[27]	Multi-energy systems	Modeling, dynamic simulation, integration optimization	Life cycle cost and investment return	Advocates for multi-source systems and performance optimization	Gaps in validation of models with real-world building performance data
7	[28]	Solar energy for NZEBs	PV output prediction; uncertainty management	Minimize operational costs; system reliance reduction	Emphasizes energy management and optimization techniques	Needs integration of advanced AI-based forecasting methods
8	[29]	Solar energy assessment	Uncertainty in renewable output	Optimization to reduce grid reliance	Highlights gaps in detail; focuses on modeling approaches	Does not link modeling with actual building energy performance data
9	[30]	Residential NZEBs	Renewable energy variability; suitable tech	High capital/operational cost	Recommends strategic planning for placement and cost reduction	Insufficient focus on occupant behavior and socio-cultural adoption factors
10	[31]	CO <sub>2</sub> -neutral RE systems	Dynamics of solar/wind/hydrogen; system complexity	Need for multi-objective optimization	Calls for advanced modeling for balanced integration	Gap in holistic frameworks combining CO <sub>2</sub> -neutral targets with economic feasibility

### 3. Materials and Methods

The methodology for this systematic literature review follows a rigorous process to ensure comprehensive and reliable results. This section outlines the approach adopted to gather, analyze, and synthesize relevant studies on Net-Zero Energy Buildings (NZEBs). The review examines the advantages and challenges associated with NZEB implementation, as well as the risks related to renewable energy generation in these buildings. The study follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework [32], ensuring transparency, reproducibility, and methodological rigor through clearly defined inclusion and exclusion criteria and a structured analysis process.

#### 3.1. Search Strategy

The search strategy involves conducting a comprehensive search of multiple academic databases to identify relevant studies on NZEBs and renewable energy challenges. Two primary databases—Scopus and Web of Science—were selected due to their comprehensive coverage of peer-reviewed articles in the fields of engineering, environmental science, and renewable energy. These databases provide access to a wide range of studies that meet the required academic rigor for this review.

The keywords used in the search include:

- “Net-Zero Energy Buildings” (NZEBs)
- “Renewable energy challenges”
- “Energy efficiency in buildings”
- “Sustainability in construction”
- “NZEB performance”

Additional keywords focused on specific challenges and technological aspects, such as “solar energy integration,” “energy storage,” “geothermal energy for buildings,” and “economic feasibility of NZEBs,” were included to narrow down results relevant to the scope of the study. The search was limited to studies published between 2015 and 2025, as this period encompasses the most recent advancements and research on NZEBs. The rationale behind this time frame is to focus on contemporary literature that reflects current trends, technologies, and challenges in the field. Furthermore, the review was limited to English-language articles to ensure accessibility and consistency in the analysis. The details of the exact search strings used in Scopus and Web of Science are as follows:

##### Database 1: Scopus

- Date of search: 25 March 2025
- Search string: TITLE-ABS-KEY (“Net Zero Energy Building\*” OR “NZEB\*” OR “Zero Energy Building\*”) AND TITLE-ABS-KEY (“renewable energy” OR “solar” OR “wind” OR “geothermal” OR “energy efficiency” OR “energy storage”) OR “Renewable energy challenges” OR “Energy efficiency in buildings” OR “Sustainability in construction”
- Fields searched: Title, Abstract, Keywords
- Filters applied: Document type = “Article”; Language = English; Year = 2015–2025

##### Database 2: Web of Science (Core Collection)

- Date of search: 22 March 2025
- Search string: TS = (“Net Zero Energy Building\*” OR “NZEB\*” OR “Zero Energy Building\*”) AND TS = (“renewable energy” OR “solar” OR “wind” OR “geothermal” OR “energy efficiency” OR “energy storage”) OR “Renewable energy challenges” OR “Energy efficiency in buildings” OR “Sustainability in construction”
- Fields searched: Topic (Title, Abstract, Keywords)
- Filters applied: Document type = “Article”; Language = English; Year = 2015–2025

### 3.2. Inclusion and Exclusion Criteria

A total of 1285 studies were included in the review, following the application of specific inclusion and exclusion criteria as shown in Table 2. The criteria were designed to ensure that only the most relevant and high-quality studies were considered:

**Table 2.** Inclusion and Exclusion Criteria for Studies on NZEB.

Criteria	Inclusion	Exclusion
Type of Study	Peer-reviewed journal articles	Studies that were not peer-reviewed (e.g., conference proceedings, reports, opinion pieces)
Publication Period	Studies published between 2015 and 2025	Studies published outside of the 2015–2025 range
Focus of Study	Articles specifically focused on (NZEBs) or related topics (e.g., renewable energy integration, energy-efficient design, challenges of renewable energy systems in buildings)	Articles focusing on building energy performance without a clear link to NZEBs
Language	English language studies	Non-English language studies
Scope	Studies that are specifically related to NZEBs (including technical, economic, and policy aspects)	Studies focusing on residential or commercial buildings outside the NZEB scope

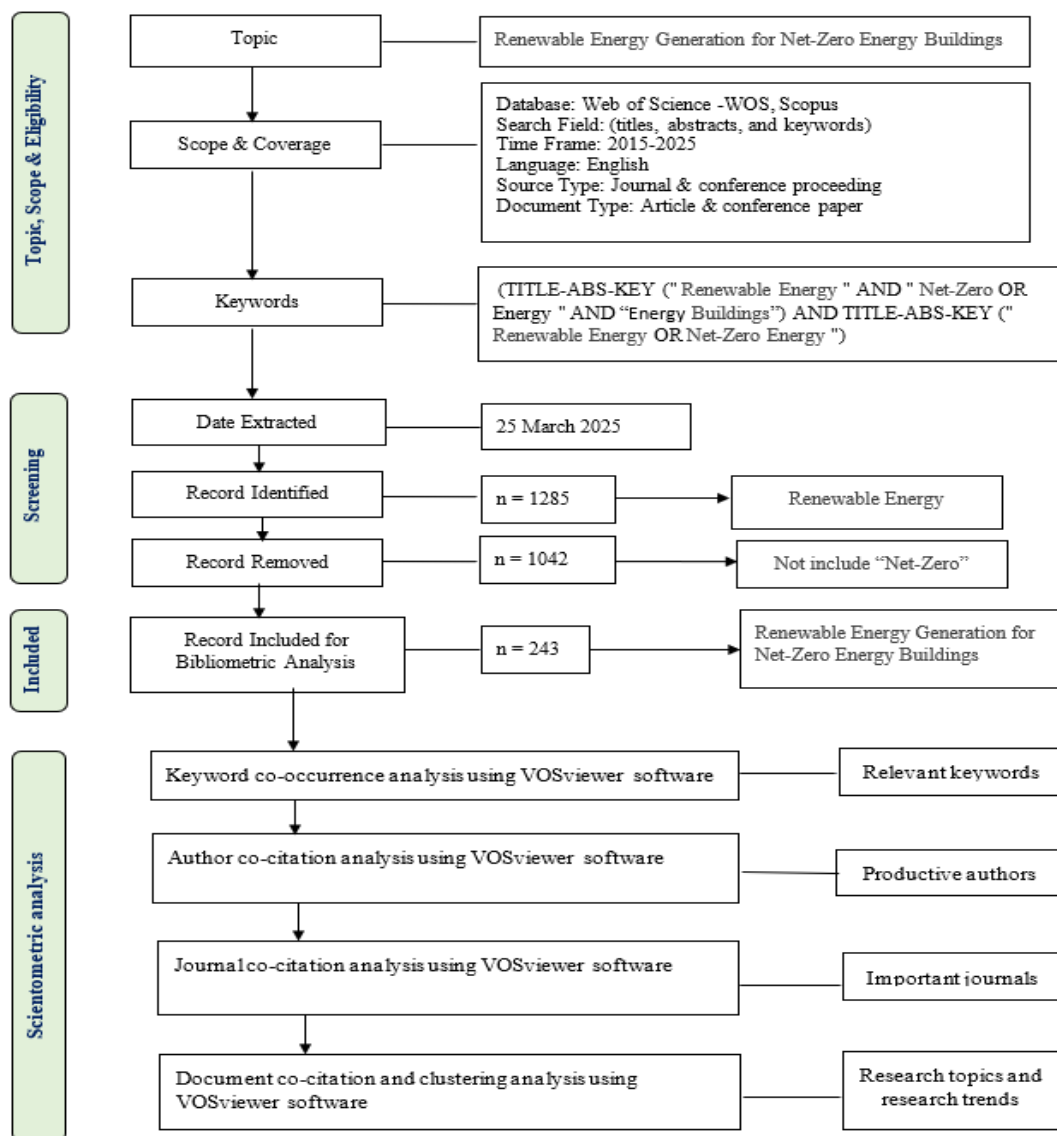
The inclusion of 243 peer-reviewed articles selected after applying the inclusion and exclusion criteria outlined in Table 2 to the initial set of 1285 studies ensures a broad yet focused dataset, encompassing a wide range of research on the technical, economic, and policy aspects of NZEBs. These 243 studies were carefully analyzed to identify common themes related to the advantages, challenges, and risks associated with NZEBs.

### 3.3. Data Analysis Process

The studies identified were subjected to thematic categorization, allowing for the systematic extraction of key information across various dimensions of NZEBs. These dimensions include:

- **Advantages:** The positive impacts of NZEBs, such as environmental benefits (e.g., carbon footprint reduction, sustainability), economic advantages (e.g., long-term cost savings, energy independence), and resilience (e.g., energy security, grid independence).
- **Challenges:** The technical, economic, and social challenges encountered in the implementation of NZEBs. This includes issues related to the intermittency of renewable energy sources, high upfront costs, storage limitations, public acceptance, and aesthetic concerns.
- **Risks:** Risks tied to policy changes (e.g., regulatory shifts, subsidy reductions), market volatility (e.g., material cost fluctuations), and technological obsolescence (e.g., the rapid pace of innovation in renewable energy technologies).

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram was employed to ensure transparency and traceability in the study selection process. The PRISMA diagram in Figure 2 illustrates how studies were identified, screened, and included, providing a clear visual representation of the systematic review process. The PRISMA 2020 checklist is provided as Supplementary Materials.



**Figure 2.** PRISMA-Based Methodological Framework for Bibliometric Analysis on Renewable Energy Generation in NZEB.

### 3.4. Quality Assessment

To ensure the reliability and credibility of the studies reviewed, a structured quality appraisal was conducted. We employed an adapted version of the Critical Appraisal Skills Programme (CASP) and the Joanna Briggs Institute (JBI) critical appraisal tools, which are widely used for evaluating qualitative and quantitative studies [33]. Five core criteria were applied:

1. Clarity of research objectives
2. Appropriateness of research design
3. Validity of data collection methods
4. Robustness of data analysis
5. Transparency and completeness of results reporting

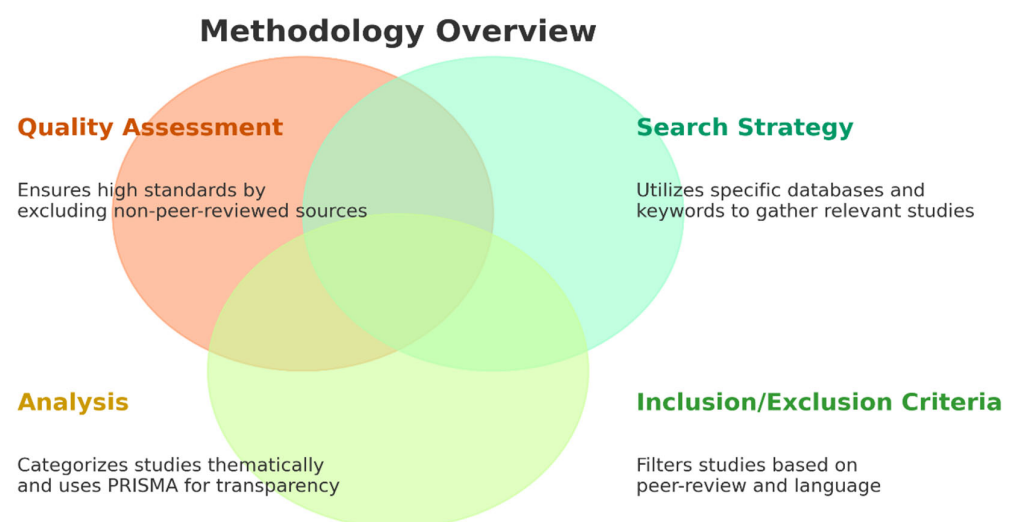
Each criterion was scored on a 0–2 scale (0 = not met, 1 = partially met, 2 = fully met), providing a maximum possible score of 10 points. Studies were categorized based on their total score as follows:

- High quality ( $\geq 7/10$ ): Fully included and weighted strongly in the synthesis.
- Moderate quality (5–6/10): Included but weighted less heavily in interpretation.

- Low quality (<5/10): Excluded from the review.

This appraisal process ensured that non-peer-reviewed sources, such as reports, unpublished theses, and opinion pieces, were excluded. Priority was given to studies published in leading peer-reviewed journals indexed in the Web of Science database and widely recognized for their relevance and citation performance in the NZEB and sustainable energy domains. These include Renewable and Sustainable Energy Reviews, Applied Energy, Energy Policy, Energy, Building and Environment, Journal of Cleaner Production, Energy and Buildings, Sustainable Cities and Society, Renewable Energy, and Applied Thermal Engineering. No specific numerical threshold (e.g., minimum Impact Factor value) was used to define “high-impact” journals; rather, classification was based on established academic reputation and field relevance. By systematically applying these quality criteria, the review enhances transparency, reproducibility, and methodological rigor while emphasizing robust and influential contributions to the field.

This systematic literature review employs a transparent, structured approach to gather and analyze studies on NZEBs, focusing on the challenges, advantages, and risks associated with renewable energy generation in these buildings. By adhering to rigorous inclusion and exclusion criteria and conducting a thematic analysis, this review provides a comprehensive overview of the current state of knowledge on NZEBs, as shown in Figure 3. The methodology ensures that the findings are robust, reliable, and based on high-quality peer-reviewed sources, contributing to the academic understanding of NZEBs and guiding future research and practice in the field. Bibliometric network analyses were conducted using [Software VOSviewer 1.6.20]. For network map construction, a minimum threshold of [5 occurrences] was set for inclusion of keywords (or items), ensuring that only the most relevant terms were considered. Clustering of nodes was performed using the [VOS clustering algorithm], and the [normalization method, association strength] was applied to standardize co-occurrence measures. Network maps were interpreted by examining cluster composition and the strength of links between nodes, in line with established bibliometric visualization practices.



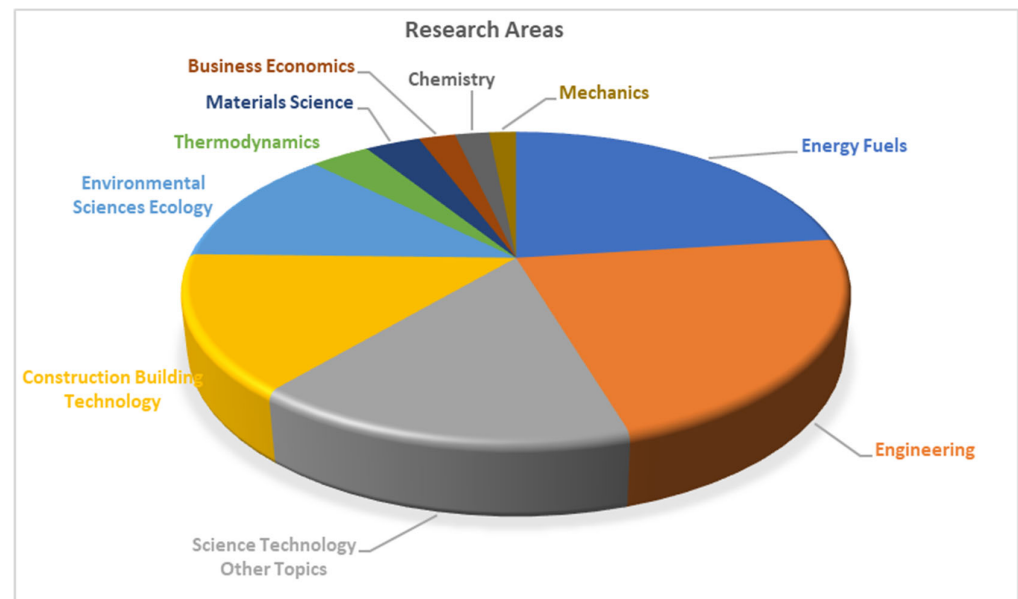
**Figure 3.** Visual Summary of Methodological Approach for Study Selection and Analysis.

## 4. Data Extraction and Analysis

### 4.1. Web of Science Categories

Figure 4 shows the disciplinary distribution of NZEB research based on Web of Science data, highlighting its interdisciplinary nature. The largest contributions come from Energy & Fuels (23%) and Engineering (22%), reflecting the strong technical focus on renewable

energy systems, building performance, and energy optimization. Science and Technology–Other Topics (16%) and Construction and Building Technology (14%) indicate substantial cross-disciplinary and practical implementation research. Environmental Sciences & Ecology (12%) emphasize sustainability and emissions reduction, while smaller shares from Thermodynamics (4%), Materials Science (3%), Business & Economics (2%), Chemistry (2%), and Mechanics (2%) reflect more specialized studies on energy processes, materials, structural behavior, and economic feasibility. Overall, the Figure demonstrates that NZEB research is dominated by engineering and energy disciplines, with growing integration of environmental and economic perspectives.



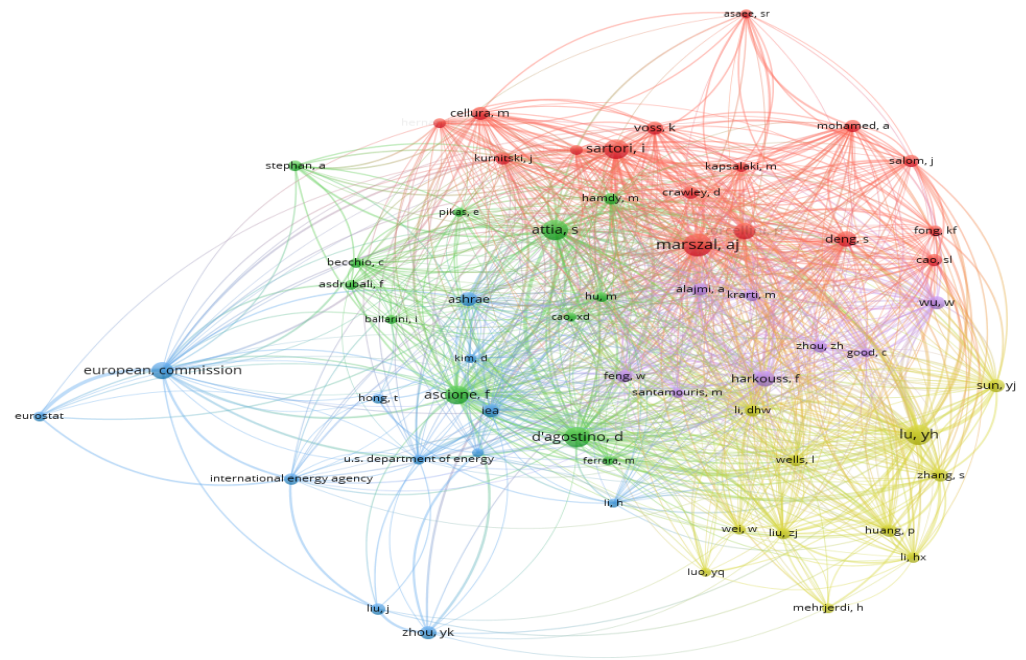
**Figure 4.** Research area categories.

#### 4.2. Keyword Co-Occurrence Network

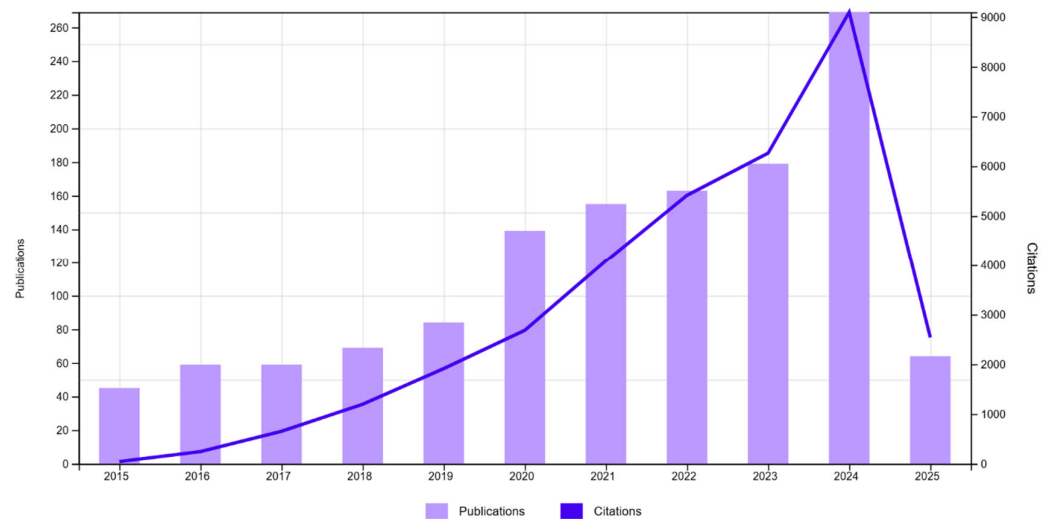
Figure 5 presents a keyword co-occurrence network for research related to (NZEBs), showcasing how frequently specific terms appear together across scientific publications. Each node (circle) represents a keyword, and its size indicates how often that term is used. The links (lines) between nodes represent co-occurrence relationships—how often two keywords appear together in the same documents—while colors signify different thematic clusters.

Figure 5 presents a keyword co-occurrence network that reveals the intellectual structure and dominant research clusters within the NZEB literature. Despite its density, several clear thematic clusters can be identified based on keyword proximity and linkage strength. The central cluster (blue/green) is anchored around “net zero energy building,” “energy efficiency,” and “renewable energy,” indicating the core focus of the field on balancing demand reduction with on-site generation. A technology-oriented cluster (yellow/red) groups keywords such as energy storage, optimization, genetic algorithms, Monte Carlo simulation, and uncertainty, reflecting modeling-driven research on system performance and reliability. A design and assessment cluster (orange) links life-cycle assessment, energy simulation, embodied carbon, and economic analysis, highlighting evaluation methods used to assess NZEB feasibility. Finally, a digital and systems integration cluster (light blue) connects BIM, digital twin, building information modeling, and simulation, indicating the growing role of digital tools in NZEB design and operation. Overall, the network demonstrates that NZEB research is structured around a central efficiency–renewables nexus,





**Figure 6.** Author co-citation analysis.



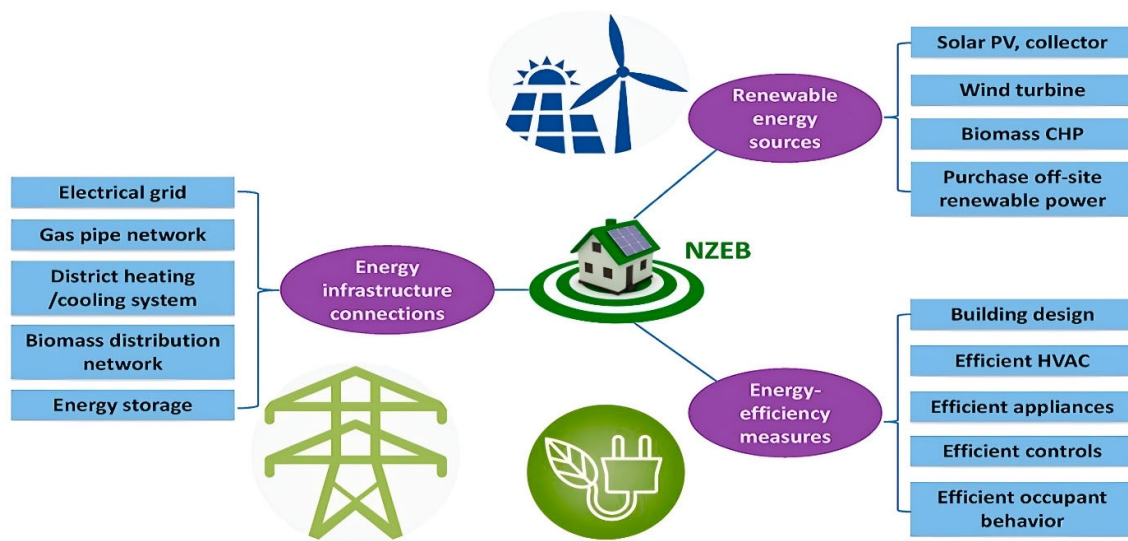
**Figure 7.** Documents and Citation Record Count (2015–2025).

#### 4.5. Journal Co-Citation Network

The journal co-citation network illustrates the interrelationships among academic journals frequently cited together in the field of (NZEBS). Each node represents a journal, with its size reflecting the frequency of co-citation—larger nodes indicate more influence. The network reveals several key clusters: the blue cluster is centered around Energy and Buildings, the most influential journal in the field, with strong connections to Building and Environment, Journal of Building Engineering, and Energy Policy. The red cluster, led by Applied Energy, includes journals like Energy, International Journal of Hydrogen Energy, and Renewable Energy, reflecting a strong focus on energy systems, performance, and integration. The green cluster involves interdisciplinary journals such as Sustainable Cities and Society and Sustainability, emphasizing urban sustainability and policy aspects. Meanwhile, the purple cluster, including Applied Thermal Engineering and International Journal of Refrigeration, leans toward technical studies in HVAC and thermal systems. These clusters showcase the multidisciplinary nature of NZEB research, spanning building



management systems, thus contributing significantly to achieving net-zero energy [36]. In regions where solar irradiance is high, solar energy becomes a particularly viable option due to lower installation costs and advancements in solar technologies [37].



**Figure 9.** Achieving Residential NZEB: A Systems-Based Approach [34].

### 5.1.2. Wind Energy

Wind energy represents another complementary source for NZEBs, especially in areas with favorable wind resources. Wind turbines can be installed on-site or in proximity to the building to harness kinetic energy from wind currents and convert it into electricity [38]. The assessment of wind installations must consider local climate conditions, building design, and regulations governing turbine placement to maximize efficiency and minimize potential noise disturbances [39]. Innovative approaches, like the combination of wind and solar energy systems, have been shown to enhance energy resilience and reliability. Such hybrid models allow buildings to take advantage of both energy sources, thus optimizing their overall performance throughout the year [40]. The complementary nature of wind and solar—where often when solar production is low, wind energy can compensate—cements their roles in the NZEB paradigm [41].

### 5.1.3. Biomass Energy

Biomass energy can be harnessed in NZEBs through various methods, including the use of biogas systems or biomass heating. Organic materials such as agricultural residues, wood waste, or dedicated energy crops can be transformed into biofuels or heat through anaerobic digestion or combustion processes, thereby generating renewable energy [42]. The feasibility of biomass systems within NZEB frameworks is greatly enhanced in regions with abundant organic waste resources, making them an attractive option for certain environments [43]. Biomass supports renewable energy generation while addressing waste management, aligning with NZEB sustainability principles. Lifecycle assessments show that sustainably managed biomass can deliver significant carbon reductions [44]. Its use has evolved from traditional combustion to advanced gasification, co-firing, and integrated bioenergy systems, increasingly applied in grid-connected settings under policy drivers such as the EU Renewable Energy Directive and global carbon neutrality goals. Key research gaps remain in smart-grid integration, lifecycle sustainability assessments, and harmonized policy frameworks. Future directions include hybrid systems with solar, wind, or storage, AI-driven optimization, and circular bioeconomy approaches, integrat-

ing biomass with waste-to-energy strategies and carbon capture, ensuring resilient and sustainable energy systems.

#### 5.1.4. Geothermal Energy

Geothermal energy is a lesser-utilized but potent renewable resource for NZEBs, particularly beneficial in areas with geothermal hotspots. This energy source relies on the consistent thermal energy from the Earth's crust. Geothermal heat pumps can effectively provide heating and cooling for buildings, significantly reducing energy consumption compared to conventional HVAC systems [44]. The primary benefits of utilizing geothermal systems include their high efficiency and consistent energy supply regardless of external weather conditions [45]. Recent studies have shown that integrating geothermal systems into the architectural design of NZEBs can further enhance the total energy performance, allowing buildings to achieve or exceed net-zero targets [46]. This integration not only supports energy efficiency but also contributes to reducing greenhouse gas emissions associated with conventional heating and cooling methods [47].

Figure 10 illustrates a building energy flow, showing how electricity, solar (PV and heat), biofuels, geothermal, and purchased fuels are converted and delivered to end uses such as space heating/cooling, water heating, refrigeration, and fuel-only systems. Energy flows through components like electricity, heat storage and combined heat and power (CHP) systems, with losses highlighted in red. The diagram also shows grid sales and savings from efficiency measures. Leveraging renewable sources and integrated energy management, NZEBs enhance performance, resilience, and energy independence, providing a framework for sustainable, low-carbon buildings [5].

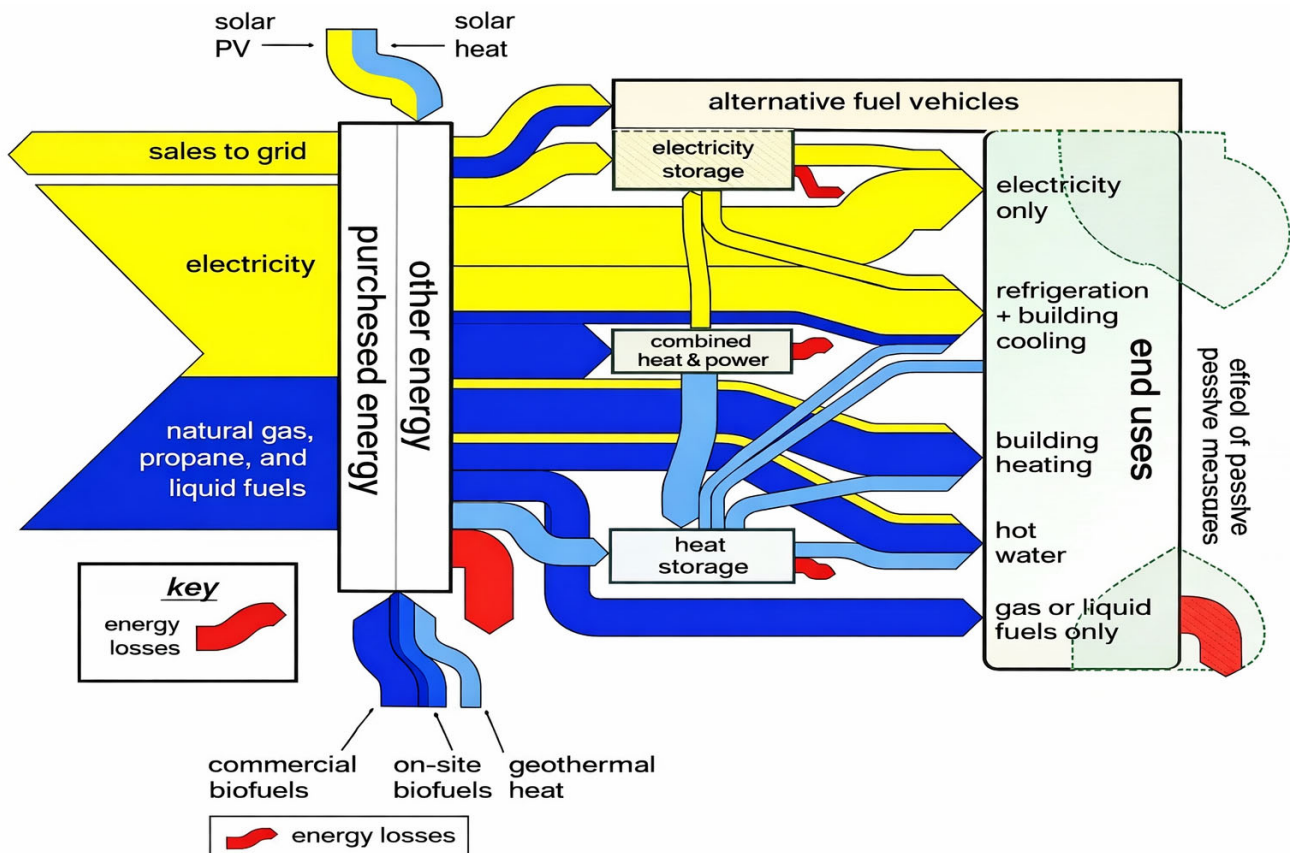


Figure 10. Comprehensive Energy Flow Diagram for Building Energy [48].

## 5.2. Advantages of NZEB

### 5.2.1. Environmental Benefits

NZEBs significantly reduce carbon footprints by minimizing reliance on fossil fuels. According to the International Energy Agency (IEA), buildings account for nearly 40% of global energy consumption and over 30% of greenhouse gas emissions. By incorporating renewable energy sources, NZEBs contribute to sustainability efforts and climate change mitigation. The UK's carbon emissions decreased by 4% in 2024, attributed partly to the expansion of renewable energy and the closure of coal-fired power stations [49]. Similarly, carbon-neutral neighborhoods like Bahnstadt in Heidelberg, Germany, have demonstrated substantial reductions in energy consumption, with buildings using 80% less energy for heating compared to conventional structures [18].

### 5.2.2. Economic Benefits

While the initial investment in NZEBs can be substantial, long-term cost savings are evident. For example, a London homeowner retrofitted their century-old house to a net-zero standard, resulting in their energy supplier paying them £69 over a year for surplus electricity generated [50]. Additionally, NZEBs reduce dependency on fluctuating energy markets, enhancing energy independence and reducing long-term operational costs. A study conducted by the U.S. Department of Energy found that NZEBs can lead to energy cost savings of up to 60% over their lifespan [30]. NZEBs can be understood as niche innovations within dominant fossil-based building regimes. Their diffusion depends not only on technological maturity but also on regulatory alignment, market structures, and institutional support, consistent with socio-technical transition theory.

### 5.2.3. Resilience and Energy Security

NZEBs enhance grid resilience by reducing dependence on external energy sources. The Bullitt Center in Seattle, Washington, exemplifies this by generating 60% more electricity than it consumes annually, ensuring operational continuity during grid outages [51]. Such resilience is particularly important in areas prone to extreme weather events, where power grid failures can have severe consequences. In California, for instance, homes with integrated solar and battery storage systems continued to operate during widespread blackouts caused by wildfires [52].

## 5.3. Challenges in Implementing NZEB

### 5.3.1. Technical Challenges

Integrating renewable energy sources like solar and wind presents issues of intermittency and storage limitations. Energy storage remains one of the most critical barriers to NZEB adoption, as lithium-ion batteries, the most common storage solution, are expensive and have a limited lifespan. The Pearl River Tower in Guangzhou, China, addressed these issues by incorporating vertical axis wind turbines and photovoltaic panels, achieving a 30% energy savings compared to baseline codes [53]. Moreover, spatial constraints in urban environments limit the installation of large solar arrays, necessitating innovative solutions such as building-integrated photovoltaics (BIPV).

### 5.3.2. Economic Challenges

High upfront costs and uncertain return on investment (ROI) can deter NZEB adoption. A feasibility study conducted for the National Western Center in Denver, Colorado, highlighted the need to optimize the levelized cost of energy (LCOE) and balance grid dependence to achieve economic viability [8,30]. The payback period for NZEBs varies widely, ranging from 10 to 30 years depending on factors such as energy prices, subsidies,

and financing options [54]. Government incentives, such as tax credits and net metering policies, play a crucial role in improving the financial attractiveness of NZEB projects [55].

### 5.3.3. Social Challenges

Aesthetic concerns and public acceptance can impede NZEB projects. In historic districts, for example, integrating modern solar panels into traditional architectural designs can face opposition from preservation committees. Retrofitting Edwardian social housing in Chelsea with ground source heat pumps demonstrated that preserving architectural integrity while implementing low-carbon solutions is achievable [56]. Additionally, public awareness campaigns and incentives for homeowners can help address misconceptions about NZEBs and encourage wider adoption [57].

### 5.4. Risks Associated with NZEB

NZEBs offer many environmental and economic benefits, but they also come with inherent risks that need to be carefully managed. These risks span across policy, market dynamics, technological advances, and geographic considerations. The following Table 3 summarizes the key risks associated with NZEBs, providing real-world examples to illustrate each risk and its implications.

**Table 3.** Summarizes the key risks associated with NZEBs.

Risk Category	Description	Example
Policy Risks	Regulatory changes and discontinuation of subsidies can impact financial planning for NZEB projects. Policy uncertainty can create instability for developers.	In the UK, energy-intensive companies benefit from exemptions in net-zero policies, which may change with shifts in government policy [58].
Market Risks	Volatility in material costs can affect the overall cost of NZEB construction. The prices of renewable energy components and sustainable materials fluctuate.	The Bullitt Center incorporated triple-paned windows and advanced insulation but faced cost fluctuations in these materials [51].
Technological Risks	Rapid technological advancements may render current systems obsolete, requiring ongoing adaptation and investment in emerging technologies.	Smart home technologies used in NZEBs must be upgraded regularly as newer, more efficient systems are developed [59].
Geographic Variability	The effectiveness of renewable energy systems varies based on location, requiring design adjustments according to regional energy resources.	The Pearl River Tower optimized energy generation based on local wind patterns, highlighting the importance of site-specific renewable energy strategies [53].

Achieving net-zero energy status requires both renewable energy integration and energy efficiency, including high-performance building envelopes, smart grids, and demand-side management. Widespread adoption, however, faces technical, economic, and policy challenges. NZEBs' viability can be affected by policy and market risks, as seen in the UK's Feed-in Tariff cuts, Italy's changing Superbonus 110 rules, and cost overruns at Seattle's Bullitt Center. These examples highlight that, beyond technical solutions, systemic risks—such as subsidy withdrawal, regulatory shifts, and financial uncertainties—critically influence the scalability and resilience of NZEB projects.

### 5.5. Building Design Measures for Minimizing Energy Waste in Achieving (NZEBs)

Achieving NZEB requires a comprehensive approach that focuses not only on generating renewable energy but also on minimizing energy waste through efficient building design. This involves a synergy of architectural strategies, passive design principles, high-

performance building envelopes, and smart technologies to ensure that energy demand is reduced before renewable systems are even considered. The following are key design measures that significantly contribute to minimizing energy waste in NZEBs.

#### 5.5.1. Passive Solar Design and Orientation

One of the most foundational strategies in NZEBs is passive solar design, which leverages the sun's energy for heating, cooling, and lighting. Proper orientation of a building ensures maximum solar gain in winter and minimal exposure in summer. For example, in the Northern Hemisphere, orienting the majority of windows and living spaces towards the south allows buildings to harness sunlight effectively during colder months. Additionally, the use of shading devices like overhangs, louvers, and pergolas helps prevent overheating in summer. Thermal mass—such as concrete floors or masonry walls—is also used to absorb, store, and gradually release solar heat, reducing the need for mechanical heating. Proper orientation combined with thermal mass can reduce heating energy demand by up to 30%, according to a study published in the journal *Energy and Buildings* [60].

#### 5.5.2. High-Performance Building Envelope

A well-designed building envelope is critical in controlling heat flow and minimizing energy loss. This includes insulation, windows, doors, and airtight construction. High levels of thermal insulation in walls, roofs, and floors reduce the rate at which heat escapes or enters the building, thereby reducing the need for heating and cooling systems. Windows should be double- or triple-glazed with low-emissivity (Low-E) coatings to minimize heat transfer while maximizing daylight [61]. Additionally, airtight construction is essential to prevent unwanted air infiltration and exfiltration, which can account for up to 20% of a building's heating and cooling load [62]. The use of continuous air barriers and meticulous sealing of gaps ensures that conditioned air remains inside the building.

#### 5.5.3. Natural Ventilation and Daylighting

Maximizing the use of natural ventilation and daylighting reduces reliance on mechanical systems. Strategically placed operable windows, vents, and atriums facilitate cross-ventilation, improving indoor air quality and reducing cooling loads. Stack ventilation, where warm air rises and exits through high-level openings, draws cooler air in through low-level openings, is another effective strategy [63]. Daylighting is enhanced through the placement of windows, skylights, and light shelves, which reflect light deeper into interior spaces. When effectively designed, daylighting can reduce electric lighting needs by up to 40% [64]. Moreover, combining daylighting with daylight sensors and dimmable lighting systems ensures consistent interior illumination while saving energy.

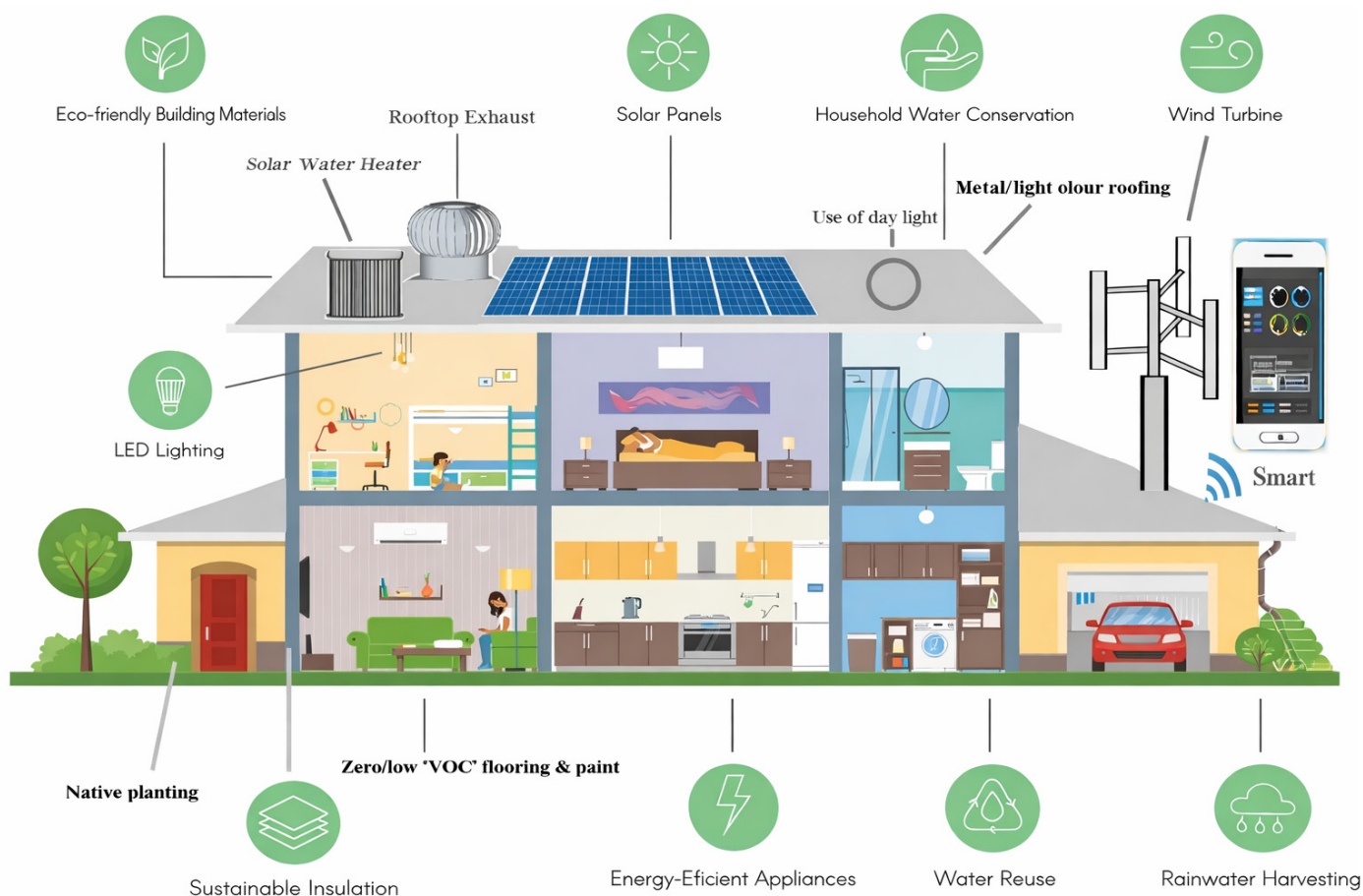
#### 5.5.4. Integrated Design and Building Information Modeling (BIM)

An integrated design process brings together architects, engineers, energy consultants, and stakeholders from the early stages of a project [65]. This collaborative approach ensures that all aspects of building performance are considered and optimized [16]. Building Information Modeling (BIM) tools allow teams to simulate energy performance, daylighting, thermal comfort, and HVAC loads, making it easier to evaluate the impact of design decisions [9]. Through BIM and simulation software such as EnergyPlus version 9.6.0 and DesignBuilder version 7.0, energy modeling can inform decisions on insulation levels, window-to-wall ratios, shading systems, and HVAC sizing. Integrated design can lead to energy savings of up to 25% compared to conventional design approaches, according to [15]. Emerging digital technologies are poised to play a transformative role in the future of NZEBs. Internet of Things (IoT) systems enable real-time monitoring of building

performance, providing granular data to optimize energy use. Artificial Intelligence (AI) and machine learning algorithms have shown promise in forecasting renewable energy production and enabling predictive control strategies that balance demand with intermittent supply. Building Information Modelling (BIM) and digital twins further enhance design and retrofitting by simulating system performance under varying conditions. These digital innovations not only improve operational efficiency but also reduce reliance on static energy models, thereby increasing resilience and adaptability. Future research should investigate the integration of IoT and AI in large-scale NZEB deployments, explore cybersecurity and data privacy implications, and evaluate how digital twins can accelerate retrofitting of existing building stock.

### 5.5.5. Energy-Efficient Systems and Appliances

While design strategies minimize energy demand, it is equally important to install energy-efficient systems and appliances. High-efficiency HVAC systems, LED lighting, low-flow water fixtures, and ENERGY STAR-rated appliances all contribute to reducing a building's operational energy use. In addition, smart thermostats and building automation systems can optimize energy usage by learning occupant behavior and adjusting systems accordingly [66]. Heat recovery ventilators (HRVs) and energy recovery ventilators (ERVs) help maintain indoor air quality without significant energy penalties by capturing heat from exhaust air to preheat incoming fresh air [67]. A Smart Eco-Friendly Home example is shown in Figure 11. An energy justice perspective reveals that NZEB benefits and risks are unevenly distributed. High upfront costs, limited access to financing, and weak institutional capacity constrain NZEB adoption in developing regions, raising concerns about procedural and distributive justice in the global energy transition.



**Figure 11.** Smart Eco-Friendly Home: A Sustainable Living Model [59].

### 5.5.6. Thermal Zoning and Compact Building Form

Designing buildings with thermal zoning—grouping spaces with similar heating and cooling needs—enhances energy efficiency by allowing targeted climate control. For instance, bedrooms can be placed on the cooler side of the building, while living areas can benefit from solar exposure. Compact building forms with low surface-to-volume ratios minimize heat loss through the building envelope [68]. Simple geometric shapes like cubes or rectangles are more energy-efficient than complex or sprawling layouts. A study published in *Renewable and Sustainable Energy Reviews* [69] found that compact building designs can reduce energy consumption by up to 15%. Minimizing energy waste through thoughtful design is the foundation of achieving NZEB performance. From passive solar orientation and high-performance envelopes to natural ventilation and integrated design tools, each measure contributes to lowering a building's energy demand [70]. Coupled with energy-efficient systems and smart technologies, these strategies not only reduce environmental impact but also pave the way for buildings that are cost-effective, comfortable, and future-ready. As innovation continues to evolve, adopting these best practices will be essential in the global effort to create a more sustainable built environment.

### 5.6. Case Study of NZEB: Longfor Guangnian Project

In the quest for sustainability, the Longfor Guangnian project in Qingdao, China, serves as a significant case study for demonstrating the implementation of (NZEBs). This project showcases innovative architectural design and the integration of renewable technologies aimed at achieving near-zero energy consumption and minimizing carbon emissions. Adopted as part of the broader initiative to align with China's "double-carbon" goals, the project exemplifies the practical exploration of NZEB technologies in a region with climatic challenges ranging from hot summers to cold winters. The Longfor Guangnian project, initiated in 2018, encompasses various building types including residential complexes, commercial spaces, and community facilities. The goal is to create a self-sustaining energy ecosystem that produces as much energy on-site as it consumes annually. The building area covers approximately 32,800 square meters, combining efficiency in design with renewable energy technology to address energy demands comprehensively [71].

#### 5.6.1. Renewable Energy Sources Used

1. **Solar Energy:** The project incorporates advanced Building-Integrated Photovoltaics (BIPV), which not only serve as energy-generating solutions but also as critical components of the building's façade. The installed solar panels generate approximately 400,000 kWh annually, covering around 50% of the total energy demand of the buildings [71]. Solar energy is especially pertinent in the context of the project, given the geographical advantage that allows for extensive sun exposure for a significant part of the year.
2. **Geothermal Energy:** Geothermal heat pumps are utilized for the heating and cooling systems, tapping into the earth's natural temperature stability. The system significantly reduces reliance on conventional heating methods, leading to an estimated 30% reduction in building energy requirements for thermal comfort [71]. The geothermal system is projected to save about 180,000 kWh per year, showcasing substantial energy efficiency and reducing carbon emissions.
3. **Passive Solar Design:** Utilizing design elements such as optimized orientation, strategic window placements, and thermal insulation, the Longfor Guangnian project minimizes its energy consumption for heating and cooling. These concepts are embedded into the building's architectural design and contribute significantly to the NZEB target by reducing the energy load while enhancing indoor comfort. However,

additional relevant studies specifically related to passive design principles in NZEBs are required to further substantiate this claim [71].

### 5.6.2. Energy and Economic Impact

The holistic implementation of renewable energy sources within the Longfor Guangnian project yields tangible economic and environmental benefits. The construction and operational protocols put in place result in operational energy expenditures expected to be 40% lower than traditional buildings within similar climatic conditions [71]. The project is not only a model of energy-efficient design but also serves a dual purpose by acting as an educational and community engagement tool, advocating for greater public awareness regarding sustainable practices in the built environment [72]. The projected payback period for the additional investment in renewable technologies is estimated to be between 7 and 10 years, highlighting an economically viable pathway for similar future developments [73]. Table 4 provides a summary of selected NZEB case studies, highlighting their key technologies, locations, capacities, storage solutions, cost estimates, payback periods, and the methods used for analysis.

**Table 4.** Summary of Selected NZEB Case Studies.

Study Ref.	Technology	Location	Capacity	Storage	Cost Estimate	Payback Period	Methods Used
[22]	PV + Battery	California, USA	50 kW PV	Lithium-ion (100 kWh)	\$180,000	10 years	Case study, monitoring
[23]	Hydrogen + Wind + PV	Germany	120 kW PV + 80 kW Wind	Hydrogen fuel cell (200 kWh equiv.)	€550,000	15–18 years	Techno-economic modeling
[24]	PV + Smart EMS	Singapore (urban)	40 kW PV	Minimal storage (grid-connected)	\$140,000	8–10 years	Simulation & optimization
[25]	PV + Solar Thermal	India	25 kW PV + 20 m <sup>2</sup> collectors	Battery (50 kWh)	\$95,000	12–14 years	Mixed-method assessment
[26]	Multi-source (PV + Wind + Biomass)	Denmark	150 kW PV + 40 kW wind	Thermal storage (200 MWh seasonal)	€1.2 million	14 years	System-level modeling
[30]	Residential NZEB	Canada	5 kW rooftop PV	Battery (10 kWh)	\$25,000	12 years	Simulation validated by field monitoring
[31]	CO <sub>2</sub> -neutral hybrid system	China	80 kW PV + 30 kW Wind + H <sub>2</sub>	Hydrogen + Li-ion hybrid	¥3.6 million	16 years	Multi-objective optimization

The Longfor Guangnian project stands as a landmark example of how the integration of multiple renewable energy sources can effectively lead to the realization of NZEB. Through the innovative application of solar technologies, geothermal systems, and passive design strategies, the project aligns with global sustainability goals while serving as an educational cornerstone for future buildings. By minimizing energy use and maximizing on-site energy generation, this project offers a replicable model for sustainable construction practices worldwide, demonstrating that NZEBs are indeed attainable. This detailed case study highlights the viability of NZEBs in reducing carbon footprints while addressing the inherent energy challenges faced by modern buildings. The Longfor Guangnian

project illustrates the tangible benefits of practical applications of advanced technologies in sustainable urban development.

Table 5 synthesizes representative, influential studies in the NZEB literature, highlighting what each contributed, where limitations remain, and how the present systematic review (243 papers, 2015–2025) fills the identified gaps. This comparison clarifies the incremental novelty of this work and shows how it builds a more integrated, quantitative, and risk-aware understanding of renewable integration in NZEBs.

**Table 5.** Synthesis of Key NZEB Studies, Limitations, and Addressed Gaps.

Study (Ref)	Main Contribution	Principal Limitation(s)	How This Review Addresses the Gap
[4]	Quantified energy flexibility of residential NZEBs and proposed hybrid storage/operation strategies.	Focused on modelling of flexibility for limited system configurations; limited cross-regional validation.	Synthesizes modelling studies across 243 papers and reports how flexibility results vary by climate and system architecture.
[5]	Detailed energy-matching analyses, showing methods for matching on-site generation to load.	Early work with limited inclusion of emerging storage tech and smart-grid interactions.	Integrates recent studies (2015–2025) including advanced storage and grid-interactive strategies, reporting measured/modelled distinctions.
[6]	Reviewed advances in thermal energy storage and NZEB greenhouse applications.	Narrow application domain (greenhouses); limited transferability to other building types.	Places thermal storage findings in broader NZEB context and quantifies how thermal vs. electrochemical storage performs across building types.
[8]	Combined technical, economic and policy analyses for smart PV blinds and NZEBs.	Case- or tech-specific; lacked systematic synthesis of relative importance of issues.	Provides quantitative distribution of concerns (e.g., 60% of studies cite storage costs), situating Koo et al.'s findings within broader evidence.
[10]	Empirical evidence on barriers from the SPARCS smart-city project.	Region- and project-specific; limited generalisation to other policy contexts.	Aggregates policy findings across countries, quantifies how often policy risk is addressed (30% of studies), contrasts regional policy impacts.
[71]	Large-scale demonstration (Qingdao): integrated BIPV, geothermal heat pumps and passive measures.	Project-specific; limited discussion on transferability and long-term monitoring data.	Uses Longfor as an empirical anchor and combines with other field studies to derive descriptive statistics and transferability constraints.
[51]	Demonstrates high-performance NZEB in practice and highlights material/upgrade cost issues.	Single iconic example; cost figures can be site- and specification-specific.	Places Bullitt Center evidence alongside multiple examples to derive generalized lessons on retrofit-cost variance.
Selected modelling studies (various refs)	Advanced multi-objective optimization approaches for multi-energy NZEB systems.	Often model-only; limited validation against measured building performance.	Identifies validation gap and recommends priorities for empirical studies and model benchmarking.

Recent advancements in energy storage systems (ESS) are crucial for integrating renewable energy sources and enhancing grid stability. Research highlights various ESS technologies, including battery energy storage systems (BSS) like lithium–ion, sodium–

sulfur, and zinc–air batteries, which offer high energy density and portability, despite challenges in cost, safety, and cycle life [74]. Hybrid systems combining batteries with hydrogen storage (HS) are also explored for improved efficiency and reduced reliance on single storage methods, particularly in off-grid and remote applications [75]. Furthermore, the application of deep convolutional neural networks (DCNNs) in power quality disturbance (PQD) classification demonstrates significant progress in smart grid management, achieving high accuracy even in noisy environments through ensemble techniques, which is vital for real-time grid monitoring and stability [76]. While most NZEB case studies originate from developed regions such as the EU, US, and China, significant barriers remain in developing countries that constrain global adoption. In South Asia, high capital costs combined with limited access to financing mechanisms discourage investment in renewable energy systems for buildings [54]. In sub-Saharan Africa, weak grid infrastructure and frequent power outages pose additional hurdles, as NZEBs often depend on hybrid systems that are not yet financially viable at scale [66]. Latin America faces regulatory fragmentation, with countries like Brazil and Mexico lacking consistent building codes or incentive schemes to standardize NZEB implementation. Furthermore, the scarcity of skilled professionals and limited awareness among policymakers and developers reduce the feasibility of large-scale NZEB deployment. Addressing these barriers requires tailored strategies—such as micro-financing, technology transfer, and capacity-building initiatives—that go beyond the frameworks successfully applied in developed regions [77].

## 6. Conclusions

This research explored the integration of renewable energy technologies and energy-efficient design measures for achieving (NZEBs). The findings highlight that achieving net-zero performance requires a holistic approach, combining building design optimization, energy efficiency improvements, and renewable energy integration. Key strategies such as passive solar design, high-performance building envelopes, efficient natural ventilation, and energy-efficient systems significantly reduce energy demand before renewable energy systems are considered. Case studies illustrate that these strategies can achieve substantial energy savings even in complex urban environments. Despite the potential of NZEBs, several challenges remain. High upfront costs, space constraints for renewable installations, intermittency of solar and wind resources, and the limited availability of cost-effective energy storage solutions continue to hinder widespread adoption. Policy frameworks and government incentives have facilitated NZEB implementation in regions like Europe, but adoption in developing nations remains constrained by regulatory and economic barriers.

To summarize the key findings and implications:

- Energy Efficiency First: Passive solar design, high-performance envelopes, and efficient systems reduce energy demand and operating costs.
- Renewable Integration: Incorporating PV, wind, and other renewables is essential but must be tailored to available resources and site constraints.
- Policy and Incentives: Clear building codes, financial incentives, and long-term strategies are crucial for NZEB adoption.
- Technological Limitations: Energy storage solutions need to become more efficient, scalable, and cost-effective.
- Climate and Regional Adaptation: Designs must consider diverse climates and regional renewable energy potential.
- Retrofitting Existing Buildings: Strategies for upgrading older buildings are critical for achieving net-zero targets at scale.
- Smart Grids and Demand Response: Integration with smart grids can optimize energy flows and reduce reliance on centralized generation.

- **Economic Modeling:** Full lifecycle cost analyses and consideration of societal benefits enhance financial viability and decision-making.

Addressing these technological, economic, and policy challenges, stakeholders can contribute to energy-efficient, sustainable, and resilient urban environments. NZEBs provide a practical pathway for reducing energy consumption, minimizing carbon emissions, and promoting sustainability. Achieving their potential requires a concerted effort across design, technology, and policy domains, ensuring a positive impact on both the environment and society.

### **Implications for Practice and Policy**

The design measures outlined above are crucial in guiding the development of (NZEBs). As energy demand continues to rise globally, the integration of renewable energy systems with energy-efficient building designs is becoming an essential component in reducing carbon footprints and enhancing sustainability in the building sector. The adoption of strategies like passive solar design, high-performance building envelopes, and energy-efficient systems can dramatically reduce energy waste and operating costs while supporting the transition toward low-carbon urban environments. From a policy perspective, governments must continue to incentivize the implementation of NZEBs through financial mechanisms, building codes, and long-term energy strategies. The successful examples of NZEB adoption in Europe, particularly in countries like Denmark and Germany, demonstrate the critical role that clear and supportive policy frameworks play in driving widespread adoption. Furthermore, the focus on energy efficiency and renewable energy integration within building codes should be expanded to include not only new construction but also retrofitting existing buildings.

Beyond its research contributions, this study also provides teaching utility by offering structured case-based learning components for classroom application. The systematic literature review and case study insights can help students understand the technological, economic, and policy challenges of deploying renewable energy systems in net-zero buildings, while also evaluating risks, trade-offs, and emerging solutions such as hybridization, digitalization, hydrogen pathways, and BECCS. To guide discussion, the study proposes open-ended questions on barriers to deployment, the role of AI and policy mechanisms, and strategies for integrating circular bioeconomic principles.

- What are the key barriers that hinder large-scale deployment of renewable energy systems in net-zero energy buildings?
- How can hybridization (biomass with solar PV, wind, or storage) help reduce intermittency challenges, and what risks remain?
- In what ways could digitalization and AI transform renewable energy management in the built environment, and what limitations should be considered?
- What role should policy instruments (carbon pricing, incentives, or bioenergy credits) play in accelerating adoption, and how do these vary regionally?
- How can circular bioeconomic strategies, such as BECCS or waste-to-energy, be integrated into urban building design to deliver long-term sustainability?

In addition, the paper suggests classroom applications such as modeling energy balances for hypothetical net-zero buildings, structured debates comparing renewable pathways, policy design workshops, and research gap mapping exercises. These elements ensure that the findings not only advance academic research but also serve as a practical and engaging resource for teaching and case-based learning.

## Limitations of Current Research

Despite significant advancements in NZEB design strategies, several limitations exist in the current body of research. Many studies focus on specific geographical regions with ideal conditions, such as temperate climates or areas with abundant solar resources. As such, the applicability of some design measures, particularly those dependent on renewable energy availability (e.g., solar PV or wind), may be limited in regions with less favorable climates. Furthermore, the integration of renewable energy technologies often assumes the availability of cost-effective, large-scale storage solutions, which remain a challenge in the current market. Another limitation lies in the financial aspect of NZEBs. While the long-term savings of energy-efficient designs are widely recognized, the high upfront investment costs of integrating renewable energy technologies can be a significant barrier for many developers and homeowners. Furthermore, the scalability of NZEB solutions in urban areas with limited space for renewable energy installations, such as solar panels and wind turbines, requires more research into space-efficient technologies like building-integrated photovoltaics (BIPV) and vertical wind turbines.

Despite the breadth of the review, certain scope limitations remain. First, restricting the dataset to peer-reviewed, English-language publications indexed in Scopus and Web of Science may have led to regional biases, with stronger representation from Europe, North America, and East Asia, and weaker coverage of Africa, Latin America, and the Middle East. This imbalance may influence the generalizability of findings, particularly in relation to policy effectiveness and socio-economic adoption factors. Second, the reviewed literature demonstrates a technology concentration on solar PV systems, while relatively fewer studies focus on wind, geothermal, biomass, or integrated multi-energy solutions in NZEBs. This technology-specific bias may overemphasize PV-related challenges (such as intermittency and storage) while underrepresenting issues unique to other renewables. Recognizing these scope limitations is essential in interpreting the findings: while the review provides a robust synthesis across 243 studies, its generalizability is constrained by both regional coverage and technological focus. Future work should integrate non-English sources, grey literature, and a more balanced range of renewable technologies to strengthen global applicability. The bibliometric analysis reveals that European countries, particularly Germany, Denmark, and Italy, dominate NZEB research output. This aligns with the thematic findings where supportive policy frameworks and financial incentives emerged as critical enablers of NZEB adoption. Similarly, the bibliometric trend showing the predominance of solar PV research corresponds to the identified technical challenge of intermittency and storage, while the growing focus on smart grids and storage solutions in recent publications mirrors the thematic finding that energy reliability remains a key barrier. By integrating bibliometric insights with thematic results, the analysis underscores how research trajectories reflect practical challenges in NZEB deployment, highlighting the centrality of policy support, technology innovation, and region-specific strategies.

## Recommendations for Future Research

The future of NZEBs will require continued research and innovation in several key areas:

1. **Improved Energy Storage Solutions:** Future research on NZEBs should focus on energy storage solutions with demonstrated potential in the literature, such as phase-change materials (PCMs) and seasonal underground thermal storage, which can improve self-consumption of on-site renewable energy and reduce peak grid demand. Specifically, studies should optimize PCM compositions for building-specific temperature ranges, integrate thermal storage with smart building management systems to coordinate heating and cooling with solar PV output, and evaluate hybrid systems

- combining short-term electrical storage with long-term thermal storage to address both daily and seasonal energy fluctuations.
2. **Climatic Adaptation and Regional Variability:** Future studies should explore how NZEB principles can be tailored to different climates and geographical contexts. This includes examining how regional renewable resources (e.g., geothermal, hydro, wind) can be optimally integrated into building designs, especially in areas with lower solar or wind potential.
  3. **Building Retrofitting:** As the existing building stock continues to grow, more research should focus on retrofitting older buildings to meet NZEB standards. This includes investigating cost-effective strategies for upgrading building envelopes, improving insulation, and integrating renewable energy technologies.
  4. **Smart Grid and Demand Response Integration:** The development of smart grids and demand response systems will play a key role in managing energy flows between buildings and the grid. Research into optimizing the interaction between NZEBs and smart grids will help reduce reliance on centralized energy generation and improve the overall efficiency of energy distribution.
  5. **Economic Models for NZEBs:** Future research should develop comprehensive economic models that account for the full life-cycle costs and savings associated with NZEBs. This includes the consideration of externalities, such as the environmental impact and public health benefits of reducing energy consumption in buildings.

Future development in biomass energy is likely to be shaped by several interlinked pathways that require deeper research and demonstration. One promising direction is the hybridization of biomass systems with solar PV, wind, or storage technologies, which can improve grid stability, reduce intermittency, and enhance overall efficiency. In parallel, fuel cells and hydrogen production pathways are emerging as critical frontiers, offering opportunities to diversify the role of biomass beyond electricity generation into transport and industrial decarbonization. Digitalization and AI will also play a transformative role, enabling optimization of biomass supply chains, predictive maintenance for conversion technologies, and more accurate demand forecasting to align supply with fluctuating market needs. Policy frameworks will remain pivotal, with carbon pricing, bioenergy credits, and regional incentives driving deployment and investment, especially in markets where biomass competes with other renewables. Finally, integrating biomass into circular bioeconomy strategies, such as waste-to-energy systems and bioenergy with carbon capture and storage (BECCS), will be essential for maximizing resource efficiency and delivering net-negative emissions, underscoring the importance of continued innovation and policy support. NZEBs represent a promising solution to reducing energy consumption and mitigating climate change. While design measures such as passive solar strategies, energy-efficient building envelopes, and the integration of renewable energy systems have proven effective in minimizing energy waste, challenges remain, particularly in regions with less favorable conditions for renewable energy generation. The limitations identified in current research highlight the need for continued innovation in energy storage, building retrofitting, and the integration of smart technologies. Future NZEB research should adopt systems-oriented and justice-informed frameworks to ensure that net-zero transitions are not only technically feasible, but also socially equitable and institutionally resilient.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/buildings16040879/s1>: PRISMA 2020 checklist. Reference [78] is cited in the Supplementary Materials.

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