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Review

Investigation of net-zero buildings: Architectural features and their efficacy in lowering pollution and energy consumption

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Abstract: The pressing global need for sustainable development has amplified the architectural emphasis on net-zero buildings, which aim to align energy use with renewable energy production while reducing environmental harm. This research examines the design elements of net-zero buildings and assesses their effectiveness in lowering pollution and energy use. Utilizing the literature review method, the study compiles academic literature, case studies, and technical documents to pinpoint essential design strategies such as passive ventilation, optimal building orientation, high-performance insulation, renewable energy integration, water recycling systems, and the incorporation of biophilic design principles. In addition, the review incorporates broader considerations related to advanced material innovations, smart-building controls, and climate-responsive architectural practices. The review also provides a more detailed discussion of performance outcome of these strategies across different climatic and urban settings, bringing to light both their success and the challenges associated with their implementation. The findings demonstrate that net-zero buildings substantially reduce operational energy requirements and contribute to lowering greenhouse gas emissions; however, issues such as economic feasibility, long-term maintenance demands, and context-specific adaptability continue to pose barriers. Furthermore, the study emphasizes the importance of multidisciplinary collaboration and continuous performance monitoring to ensure sustained efficiency. The research concludes by underscoring the need for integrated design processes, supportive policies, and ongoing technological advancements to achieve scalable, resilient, and environmentally responsible net-zero developments.

Keywords: architectural features; carbon emission; energy consumption; net-zero buildings; pollution

1. Introduction

Buildings and related construction sectors professionals are critical to reducing energy use and carbon dioxide emissions. However, concerns over climate change and global warming have turned sustainable architecture into a necessity [1]. Rising global temperatures and rapid climate change compel more than ever before the need for sustainable, energy-efficient construction techniques. Buildings and their associated construction supply chains are among the most significant contributors to global energy consumption and carbon dioxide emissions. The building sector as a whole is responsible for approximately 38% of global carbon emissions, while buildings in operation alone account for approximately 40% of the world's total energy consumption [2]. Projections indicate that, in the absence of transformative corrective action, rising demands for space heating and cooling will cause the building sector's cumulative carbon footprint to increase by as much as 55% by 2050 [3].

Sapna and Anbalagan [4] recorded that the use of modern technologies and processing of goods has resulted in environmental degradation, hence highlighting the need to pay attention to sustainable materials with minimal carbon emissions. Research suggests that material production worldwide accounts for 23% of human-caused greenhouse gas (GHG) emissions. A significant portion of these emissions is attributed to construction materials, particularly cement and steel, which together have been estimated to contribute nearly 14% of global CO_2 emissions caused by human activity and expected to double by 2060 [5]. These figures underline the vital character of the construction industry in global carbon emissions and demand swift steps toward adoption of sustainable, energy-efficient approaches [6]. Net-zero buildings (NZBs) offer a promising solution to mitigate climate change by reducing carbon footprints [7]. It also balances the total amount of energy used annually with the renewable energy produced on-site [8].

This approach minimises reliance on non-renewable energy sources, reducing electricity use and greenhouse gas emissions from the building sector [9]. Shirinbakhsh and Harvey [10], in their investigation of the feasibility of achieving net zero energy performance in high-rise residential buildings using solar energy, corroborated this sequential approach, reporting that the pathway to net zero status first requires the application of passive design strategies to reduce a building's intrinsic energy demand, after which renewable energy sources deployed within or immediately adjacent to the building's footprint are engaged to meet remaining energy needs. Their findings carry particular significance for high-density urban typologies, where the constrained ratio of roof area to total floor area limits the potential for on-site renewable generation, making the prior reduction of energy demand through passive design an even more critical precondition for achieving net zero performance.

However, achieving net-zero buildings faces obstacles such as legislative gaps, the need for a common definition in policies and regulations, and the potential for unintended consequences like demolishing buildings to replace them with new ones [1]. Realising the net-zero buildings in Nigeria's urban setting face critical obstacles, which include legislative gaps, the absence of common definitions in policies and regulations, and the unintended consequence of removing existing buildings to erect new ones. Karlsson et al. [11] opined that the idea of net-zero buildings has become important, stressing the need for decreasing energy use and incorporating renewable energy sources to reach carbon neutrality. This study sought to position net-zero buildings for widespread acceptance and use in Nigeria by reemphasising and pushing for the adoption of sustainable design approaches, renewable energy integration, and strategic policy frameworks.

The concepts discussed in this work are poised to guarantee the next generation of energy-efficient, environmentally responsible constructions in Nigeria's urban setting and reduce temperature gain by identifying these vital features.

2. Materials and methods

2.1. Defining net-zero buildings

The net zero building (NZB), referred to variously in the literature as a net-zero energy building (NZEB) or a Zero Carbon Building, is a highly energy-efficient structure in which the total quantity of energy consumed over a period of time, is balanced by an equivalent quantity of renewable energy generated on-site or procured from renewable sources [8,12,13]. This balance principle is what distinguishes net zero buildings from conventional high-performance or low-energy buildings: the aim is not merely a reduction in energy demand but the achievement of a measured net annual equilibrium between consumption and clean-source generation. As Jaysawal et al. [8] observe, this equilibrium minimises reliance on non-renewable energy sources while simultaneously reducing electricity consumption and greenhouse gas emissions from the building sector.

Definitions of NZBs vary considerably across regulatory jurisdictions, professional organisations, and research traditions. Torcellini et al. [14] proposed four principal definitional boundaries through which the net zero balance can be assessed. The first is site energy, measured directly at the building's utility meter and representing only the energy that enters and leaves the building itself. The second is source energy, which traces consumption back through the full upstream chain of extraction, processing, and transmission losses, thereby providing a more complete picture of the building's total energy impact on the wider energy system [15,16]. The third boundary is cost, which establishes financial equivalence between the energy purchased from and exported to the grid. The fourth is emissions, which frames the balance in terms of greenhouse gas equivalence rather than energy units.

Each of these boundaries produces a distinct set of design targets and performance benchmarks, which partly explains why terms such as zero energy, zero carbon, carbon neutral and zero emissions continue to be used interchangeably in both policy and practice, often with markedly different underlying meanings [17,18]. Whereas initial approaches to NZB focused primarily on operational energy performance, the discourse has progressively shifted towards greenhouse gas emissions as the primary metric of a building's contribution to global warming [19,20]. This has, in turn, given way to a broader whole-lifecycle framing that encompasses the embodied carbon associated with the production and transportation of construction materials, maintenance activities throughout the building's service life, and end-of-life demolition and disposal [21–23].

Hernandez and Kenny [23] gave formal expression to this development by proposing the Life Cycle Zero Energy Building (LC-ZEB) as a conceptual framework requiring that the sum of renewable energy generated over a building's entire service life equals or exceeds all energy consumed in its construction and operation. It is within this expanded and evolving conceptual frame that the present review situates its analysis of the architectural features of Net Zero Buildings and their efficacy in reducing both energy consumption and environmental pollution.

2.2. Net-zero concept strategy and architecture

The net-zero concept is fundamentally based on the important difference between "site energy" and "source energy". "Site energy" refers to the energy utilised within a building, as indicated by utility meters. However, relying solely on this metric does not provide a complete picture of a building's environmental consequences [15]. In contrast, source energy encompasses the entire energy lifecycle, considering the energy required for extracting, processing, and transporting primary fuels, as well as the energy losses incurred during thermal combustion at power plants and throughout transmission and distribution to the building site [16]. Reducing emissions to net-zero is crucial for mitigating climate change effects [19]. The Paris Agreement's targets of maintaining global temperature rise below 2 °C and aiming for a 1.5 °C limit necessitate achieving net-zero at the earliest opportunity.

After reaching net-zero, the average global surface temperature is expected to stabilize. Nevertheless, aiming for net negative emissions could lead to greater cooling of the planet, further diminishing climate-related risks [24]. For a long time, the regulatory focus was primarily on a building's energy performance, often based on primary energy use, with legal requirements to reduce GHG emissions being absent or just emerging [7]. This led to the emergence of a significant number of net-zero building approaches in the market. These early net-zero building targets primarily focused on the operational aspect of buildings. However, the discourse has now expanded, shifting from energy demand as a proxy to GHG emissions as the metric for a building's impact on global warming [20]. This evolution reflects a greater understanding of climate change mitigation and the importance of addressing GHG emissions directly [19].

Numerous professional organisations and government entities, such as the American Institute of Architects (AIA) [25] with its 2030 Commitment and ASHRAE through its Vision 2030, have adopted this objective, creating actionable standards and milestones for reaching net-zero emissions in the built environment [17]. Their decentralized energy systems and diminished reliance on the traditional power grid enhance energy reliability and provide increased resilience during power outages and natural disasters. This capability is becoming increasingly crucial amid unpredictable weather patterns. The combination of reduced long-term expenses, improved resilience, and enhanced occupant comfort fosters a positive feedback loop that encourages widespread adoption. Various sources highlight an increasing variety of terms, definitions, and approaches emerging worldwide for net-zero buildings [17].

Terms such as zero energy, zero carbon, or zero emissions are frequently used, but their meaning often remains unclear, specifically whether they refer to an "absolute zero" or a "net-zero" in terms of energy and emissions balance [18]. Fankhauser et al. [26] describe absolute zero GHG emissions in operation as that using zero emissions of fuel or electricity for operational needs, while absolute zero in the life cycle would additionally require zero-emission supply chains for construction materials, end-of-life management, transport, and construction. Achieving an "absolute zero" level is currently considered practically impossible if all upstream supply chains are included [27]. Consequently, the focus has largely been on net-zero emissions, which implies a balance between emissions produced and emissions avoided or compensated for [28].

NZBs target zero operational and embodied carbon during their entire life cycle, taking a leadership role in the decarbonisation of the construction sector. This signifies a move beyond just the energy consumed during a building's operation to include the carbon footprint associated with the materials used in its construction, maintenance, and eventual disposal [22]. To achieve Net-Zero targets, a combination of strategies is required, including reducing energy demand through energy-efficient measures (EEMs) and implementing renewable energy technologies (RETs) to meet the remaining demands [29]. Architects are viewed as integrators of technologies aimed at achieving a zero energy balance, requiring a radical shift from conventional building design approaches [30].

2.3. Sustainable design principles in modern architecture

Sustainable design principles in modern architecture represent a fundamental shift in the way buildings are conceived, designed, constructed, and operated, aiming to meet present needs without compromising the ability of future generations to meet their own [31]. This encompasses a holistic approach that considers not only environmental aspects but also social and economic factors [32]. Krarti and Dubey [33] pointed out that one of the core tenets of sustainable design is minimising energy consumption. This involves a two-pronged approach: first, reducing the need for energy through energy-efficient measures (EEMs) and passive design strategies, and second, meeting the remaining energy demands through the incorporation of renewable energy technologies (RETs) [34]. The importance of passive design strategies cannot be overstated, as they form a key element in achieving net-zero buildings and contribute significantly to reducing the building's overall energy balance [35].

Passive design strategies, aimed at minimising energy needs, and the integration of on-site or nearby renewable energy sources are crucial elements [36]. The concept has also expanded from individual buildings to considering net-zero neighbourhoods [37]. Another crucial principle is the selection of environmentally friendly and sustainable materials. This involves considering the embodied energy and carbon associated with material production, transportation, construction, maintenance, and end-of-life phases [38]. The focus is shifting towards a Cradle-to-Cradle assessment to comprehensively evaluate the entire life cycle of building materials, including recyclability and post-demolition waste [39]. This is particularly important as the reduction in operational energy in high-performance buildings means that embodied carbon can constitute a significant portion of the total carbon emissions [22].

Utilizing environmentally friendly products and prioritizing less energy-intensive materials are vital aspects of sustainable building classification systems [40]. The scholar also observed that water conservation is another key principle, emphasizing the efficient use of water resources within and around buildings. Mba et al. [41] added that sustainable site design also plays a significant role, aiming to maximize the site's potential while minimising environmental impact, considering factors like land use, ecology, and microclimate. Furthermore, sustainable design prioritizes enhancing indoor environmental quality. This includes aspects like natural day lighting, natural ventilation, thermal comfort, and air quality, all of which contribute to the health and well-being of building occupants [42]. The integration of these sustainable design principles into modern architecture is increasingly becoming mandatory rather than voluntary, driven by regulations.

This necessitates a strong formal relationship between the way a building is designed and its energy performance [43]. Mageed et al. [44], however, opined that the concept of sustainability in architecture extends beyond environmental performance to encompass social and economic dimensions. It considers the durability of buildings, the use of appropriate materials, and a sense of place, while also balancing environmental considerations with economic constraints. The goal is to create a sustainable green built environment that supports the natural environment with minimal damage [45]. The evolution towards net-zero building concepts, as discussed previously, is intrinsically linked to sustainable design principles [46]. Overall, a comprehensive approach to energy efficiency in building design involves a synergistic combination of passive design principles, energy-efficient technologies, smart controls, and renewable energy integration, tailored to the specific climate and occupancy of the building [35].

2.4. BIM and net-zero building

The development of net-zero buildings is a growing trend, and Building Information Modelling (BIM) plays a significant role beyond just a drafting tool in achieving these goals [47]. BIM serves as a collaboratively generated and maintained data-rich information source, particularly valuable for energy calculations [48]. The greatest architectural value derived from BIM in this context is the design of templates, such as one to calculate the number of photovoltaic panels needed to reach net-zero energy [49,50]. BIM is intended as a decision-support tool for incorporating energy simulation into the early architectural design process of net-zero buildings. This highlights the importance of integrating energy performance considerations from the initial architectural design stages, facilitated by tools like BIM [21]. The decision-making process for developing these buildings requires considering various technical, financial, and environmental factors [51].

While not explicitly detailing architectural forms or features, this classification and the need for multi-criteria analysis suggest that architectural design plays a crucial role in defining and achieving different types of net-zero energy performance [52].

2.5. Systematic barriers to net-zero building implementation

The review of existing literature indicates that the pursuit of net-zero buildings (NZBs) faces economic, policy, technical, and socio-behavioral obstacles that collectively impede widespread adoption [53]. **Table 1** highlights the barriers, descriptions and mitigation strategies. **Table 1** highlights economic issues; particularly, the high initial costs and a focus on short-term returns remain the most frequently cited limitations, while ambiguous policies and inconsistent definitions of NZBs create regulatory ambiguity and hinder the establishment of standards. Technical challenges including the ongoing discrepancy between designed performance and actual operation further undermine confidence among investors and stakeholders.

Table 1. Barriers and mitigation strategies to achieving net-zero energy buildings (NZEBs).

Reference articles	Barrier category	Description of barrier	Mitigation strategies
Eksi et al. [35], Arenas and Shafique [39], Menon and Porteous [53], Brown et al. [54]	Economic	High upfront capital costs hinder adoption, even with the promise of long-term operational savings. Investors often prioritize short-term returns rather than total life cycle benefits.	Shift financial metrics toward Total Resource Cost (TRC) and Life Cycle Cost (LCC) analyses to reflect long-term savings. Leverage financial incentives such as tax credits, green loans, grants, and Power Purchase Agreements (PPAs) to reduce initial investment burdens.
Tirelli, and Besana [3], Terblanche et al. [7], Jaysawal et al. [8], Noh et al. [9], Falana et al. [21], Borowiak et al. [24], Satola et al. [27], Tak Kit [28], Þórólfsdóttir et al. [29], Arenas and Shafique [39], Almasi [45], International Energy Agency [49]	Policy and Regulatory	The regulatory framework often lags behind innovation, creating a “legislative maze” and uncertainty due to the absence of standardized NZEB definitions.	Establish clear national or international NZEB definitions. Formulate integrated policies supporting holistic energy solutions rather than isolated technologies. Introduce government-backed financial support and compliance mechanisms.
Tirelli and Besana [3], Terblanche et al. [7], Jaysawal et al. [8], Noh et al. [9], Anyanwu et al. [15], Parkin et al. [16], Tak Kit [28], Eksi et al. [35], Mab et al. [41], Mageed et al. [44], Khassan et al. [47], Imoni et al. [48], Myint et al. [50], Brown et al. [54]	Technical	A “performance gap” often exists between the designed and actual energy performance of buildings due to poor installation, commissioning, or construction quality. NZEB achievement is particularly difficult for high-density or high-load buildings.	Strengthen contractor training and certification systems. Promote prefabrication and off-site construction to enhance quality control. Allow off-site renewable energy generation for projects with physical constraints.
Falana et al. [21], Myint et al. [50], Brown et al. [54]	Knowledge and Education	Many small and medium-scale building owners and developers perceive NZEB implementation as complex or unattainable due to limited technical awareness.	Enhance public and professional education on NZEB principles, design strategies, and available technologies. Provide operational training for facility managers to optimise building performance.
Brown et al. [54]	Attitude Toward Risk	Stakeholders often exhibit resistance to change, preferring proven solutions over innovative NZEB technologies due to perceived financial and performance risks.	Demonstrate the business viability of NZEBs through data-driven case studies and performance benchmarks. Highlight added benefits such as resilience, market value, and long-term economic and environmental gains.

Lack of awareness, insufficient professional education, and risk-averse mindsets among developers and clients exacerbate these difficulties, especially in developing regions. Individual interventions alone are inadequate; instead, holistic strategies that incorporate clear policy frameworks, long-term funding models, strong quality control processes, and extensive capacity-building initiatives are essential to address these gaps [54]. Future initiatives should prioritize empirical post-occupancy assessments, standardized performance metrics for NZBs, and comparative research that uncovers context-specific strategies for enhancing the implementation of NZBs across various climates and market environments.

2.6. Methodology

This study employed a systematic literature review to evaluate the architecture of net-zero buildings. Focusing on secondary resources, the methodology identified scholarly trends and architectural successes in energy performance, particularly focusing on passive/active design strategies and sustainable materials.

2.6.1. Study selection procedure

This study was undertaken between April 2025 and March 2026, comprising an electronic database search. Data sources include results from Scopus, Google Scholar, ScienceDirect, IEEE Xplore, and SpringerLink. Only publications from 2014 to 2026 were eligible to capture the most recent advancements in the field, except for a few older publications that spoke on the original concepts under investigation. To maintain high research validity, the study applied the following filters:

a) Inclusion Criteria: Peer-reviewed articles, conference papers, and industry reports (2014–2024) directly related to net-zero architectural design and energy integration.

b) Exclusion Criteria: Engineering-only solutions lacking architectural context, non-peer-reviewed content (blogs/opinions), and papers lacking supporting qualitative or quantitative data.

2.6.2. The results of the literature search

As presented in **Figure 1**, the initial search results yielded about 1,248 references. A closer look on papers relevant to the main issue under investigation yielded a total of 81 selected articles utilized in this review. The primary criteria for inclusion were that the papers retrieved must be peer-reviewed articles, conference papers, and industry reports directly related to net-zero architectural design and energy integration within 2014–2024. Of the 80 references identified by the search strategy, 58 were further extracted for more detailed evaluation based on analyzing the title, abstract and conclusion of each manuscript to include works that deal with passive design strategies (building orientation, building envelope, thermal mass, fenestration & glazing, shading devices, and daylighting) and active design strategies (high-efficiency HVAC systems with heat recovery, smart lighting systems, energy-optimised appliances and plug load management, on-site energy storage systems, storage systems, Combined Heat and Power (CHP) systems, biomass or biogas systems, performance monitoring and data management, management, and integrated net-zero design process), which met the inclusion benchmark of the final dataset.

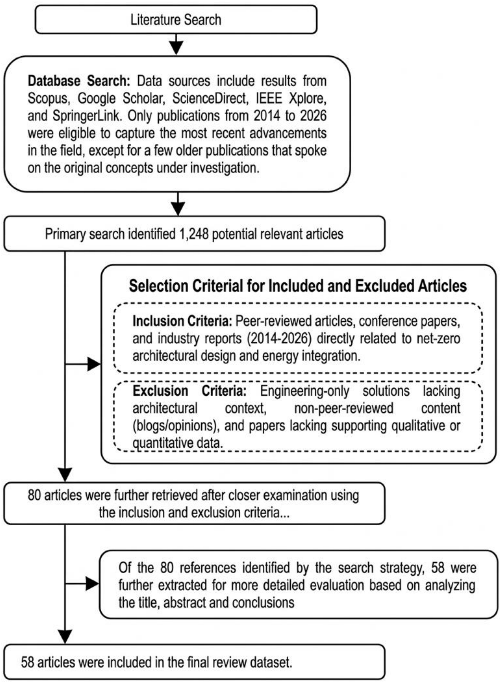

Figure 1. Literature review flow chart.

3. Findings

Synthesized findings and discussions are categorized according to the paper's three objectives of the study: identifying the architectural characteristics of net-zero buildings, evaluating the efficacy of design strategies, and uncovering systemic barriers to implementation. It links quantitative trends and qualitative findings by connecting theory and practice.

3.1. Passive design strategies

Passive design strategies (PDS) are the first steps in the design of net-zero buildings (NZBs). PDS's primary goal is to significantly minimize a building's energy demand by leveraging natural environmental conditions and architectural elements before resorting to mechanical systems or renewable energy generation to meet the remaining energy demand [55]. This approach is rooted in utilizing building physics through elements like window-to-wall ratios, insulation, shading, glazing, and orientation. In most cultures of the world, particularly in Africa, indigenous buildings employed passive design strategies [56] for energy reduction until capitalism and mass production of modernism suppressed them. It allows for a reduction in size and cost of subsequent active systems and renewable energy installations.

Building orientation and site planning are critical passive design considerations that profoundly impact energy consumption and the potential for on-site energy generation. Fadeyi et al. [57] addressed that a common strategy involves orienting the building along the east-west axis to simplify solar control on the southern façade for countries north of the equator and northern façade for countries south of the equator and mitigate challenges with intense low-angle sun on the east and west facades. The building's overall form (mass, shape, and aspect ratio) is also important site planning factor affecting energy performance [58]. Natural ventilation and daylighting are core passive strategies for reducing operational energy loads associated with mechanical cooling and artificial lighting [59].

Daylighting involves designing spaces to maximize the use of natural light, thereby decreasing the need for electric lighting. This includes careful consideration of window design, size, placement, and incorporating features like light wells or glazed interior doors to distribute light deep into the building plan [60]. Maximizing exposure to daylight is a common design rationale, often facilitated by shallow plan depths. Natural ventilation focuses on designing the building to promote airflow through openings. It can substantially lower air conditioning energy use, particularly in warmer climates [61]. Architectural features like light wells can also create passive stack ventilation effects, aiding both ventilation and daylighting. A high-performance building envelope is paramount for achieving energy efficiency [62].

Key elements of high-performing envelopes are thermal insulation, indoor comfort, and efficient HVAC systems [63]. Using glazing with low solar heat gain coefficient values and optimizing the window-to-wall ratio manages heat gain. Avoiding significant glazing on east/west facades helps reduce heat gain [62].

Upgrading from single pane to double-glazed windows is a common improvement.

Airtight measures prevent uncontrolled air leakage (infiltration) through the building fabric. Improving airtightness helps conserve heat and stabilize indoor temperature [64]. Solar shading, such as overhangs, awnings, and vegetation, is used to control solar gains by blocking direct sunlight and reducing energy consumption. Thermal mass materials (concrete or masonry) can store solar heat, releasing it later (night) to help regulate indoor temperatures [65]. High thermal mass envelopes can effectively collect, store, and radiate solar heat gained through glazing [66]. While passive design is crucial for minimising loads, achieving a Net-Zero goal ultimately requires meeting the residual energy needs through other means, often involving the integration of renewable energy sources and active systems. This can best be summarized in **Table 2**.

Table 2. Passive design strategies and their contribution to net-zero energy buildings.

Reference article	Passive design strategy	Mechanism in net-zero buildings	Performance/Efficacy metrics
Igbo and Ekeoba [6], Shirinbakhsh and Harvey [10], Lou and Hsieh [22], Alessandra et al. [30], Tungnung et al. [34], Arenas and Shafique [39], Chandra et al. [55], Gondal et al. [56], Juffle and Rahman [58], Ijahenda et al. [59], Xu et al. [60], Gil-Ozoudeh et al. [62], Anand et al. [63], Sharif et al. [64], Marro [66]	Building Orientation	Optimises solar exposure to maximize winter gains and minimize summer overheating; harnesses prevailing winds for natural ventilation, reducing reliance on mechanical systems.	Can reduce heating energy demand by up to 50% when effectively combined with thermal mass and optimised glazing.
Khadka [1], Sapna and Anbalagan [4], Igbo and Ekeoba [6], Lou and Hsieh [22], Alessandra et al. [30], Wang and Adeli [32], Zhou and Herr [38], Mohammed [40], Elnaklah et al. [43], Fadeyi et al. [57], Ijahenda et al. [59], Xu et al. [60], Gil-Ozoudeh et al. [62], Anand et al. [63], Marro [66]	Building Envelope (Insulation & Airtightness)	Enhances thermal resistance and minimizes unwanted air infiltration to maintain consistent indoor temperatures and reduce HVAC dependence.	Reduces overall heating and cooling energy needs by 10–20%, with a 5–8% reduction in heating/cooling loads.
Khadka [1], Sapna and Anbalagan [4], Tungnung et al. [34], Han et al. [65]	Thermal Mass	Stores and gradually releases heat, stabilizing indoor temperature fluctuations and reducing mechanical conditioning loads.	Enables thermal comfort for several hours post-HVAC operation; buildings with high thermal mass can remain cool during high outdoor temperatures through pre-cooling.
Zhou and Herr [38]	Fenestration & Glazing	Incorporates energy-efficient glazing and optimised window placement to balance daylighting and solar heat gain while minimising heat loss.	Can lower heating and cooling demand by 6–11% in moderate climates and 8–16% in hot climates; high-performance systems can achieve 8–26% energy savings.
Igbo and Ekeoba [6], Lou and Hsieh [22], Alessandra et al. [30], Wang and Adeli [32], Zhou and Herr [38], Mohammed [40], Chandra et al. [55], Gondal et al. [56], Fadeyi et al. [57], Juffle and Rahman [58], Xu et al. [60], Gil-Ozoudeh et al. [62], Anand et al. [63], Sharif et al. [64], Marro [66]	Shading Devices	Controls direct solar radiation through architectural elements (louvers, overhangs, screens), minimising unwanted heat gain.	Decreases mechanical cooling demand significantly by reducing solar heat gain through openings; allows use of cost-effective, high solar-heat-gain-coefficient (SHGC) glass.
Igbo and Ekeoba [6], Lou and Hsieh [22], Wang and Adeli [32], Mohammed [40], Chandra et al. [55], Juffle and Rahman [58], Anand et al. [63]	Daylighting	Maximizes use of natural light through window design, skylights, and light shelves to minimize artificial lighting needs.	Can reduce lighting energy consumption by 20–30%, and in optimised spaces, can nearly eliminate daytime lighting energy use.

3.2. Active design strategies

Active design strategies involve the integration of mechanical systems and technologies to meet the remaining energy needs and potentially generate energy on-site [67]. These strategies are seen as complementary to passive measures and are necessary because passive design alone is often not sufficient to fully implement NZB targets. Ali et al. [68] opined that both passive and active techniques are considered viable solutions for achieving net-zero buildings over their life cycle. Frequently identified active design strategies include efficient HVAC systems [69].

Advanced and efficient mechanical systems are still crucial for thermal comfort, especially in varying climates. Advanced technologies like solid desiccant dehumidifiers are also capable of handling cooling loads efficiently in NZBs [29]. Lighting systems and controls are other areas of active strategies that manage energy consumption from artificial lighting. Advanced shading like external roller shades and Venetian blinds is categorized as an active type of system. A critical element of active design is on-site renewable energy generation. Photovoltaic (PV) systems, which convert solar energy into electricity, are explicitly and frequently cited as an active technique in various literature. The sizing and selection of PV systems are crucial aspects of the design process and offsetting energy consumption or carbon emissions. This cumulative approach necessitates early integration of both passive and active systems in the design process [70]. It requires detailed analysis, often through simulation tools, to determine the most effective combination.

3.3. Sustainable material selection

UNEP [71] reported that materials used in a building's construction are crucial for defining its contribution to the net-zero concepts. Buildings become more energy efficient when the relative contribution of embodied carbon to the total life cycle emissions is considered [72]. Embodied carbon encompasses the greenhouse gas (GHG) emissions associated with the production, transportation, and installation of construction materials. Evaluating the environmental impact of material selection typically involves a Life Cycle Assessment (LCA). LCA is a method used to assess the environmental consequences across a product or structure's entire life cycle, from raw material extraction and manufacturing to transportation, assembly, use, and end-of-life management [73]. LCA can provide specific information on the embodied energy usage contributions of each material from the production stage to disposal. Hernandez and Kenny [23] extended this line of reasoning considerably, arguing that a building's net zero energy balance cannot be meaningfully assessed on an annual operational basis alone. Their proposal of the Life Cycle Zero Energy Building (LC-ZEB) as a more comprehensive analytical construct requires that the sum of renewable energy generated over the full life of the building equals or exceeds all energy consumed in its construction, operation, maintenance, renovation, and eventual demolition. This lifecycle framing carries direct implications for material selection decisions: in buildings where passive and active design measures have succeeded in reducing operational energy to very low levels, the embodied carbon of construction materials becomes the dominant component of total lifetime environmental impact, making low-carbon material substitution not merely desirable but essential to genuine net zero performance [22, 39, 72]. In the context of buildings, this helps quantify the carbon footprint associated with construction materials. Studies have shown that construction materials, such as concrete, structural steel, and PV panels, can contribute significantly to a building's overall environmental impacts [74].

Considering embodied carbon in the decision-making process requires assessing these emissions across the materials and building's entire lifecycle. Various strategies that focus on material selection to enhance net-zero buildings are utilizing low-carbon materials (rammed earth, compressed/stabilised earth blocks, bamboo, and wood), prioritizing locally available materials, integrating recyclable and reusable materials, exploring innovative and natural materials, and selecting efficient thermal insulation materials [75]. However, several challenges exist regarding sustainable material selection. There is a lack of comprehensive Life Cycle Inventory (LCI) data for many eco-resilient materials, which makes informed decision-making difficult, especially for emerging materials.

This data gap can hinder the prediction of complex material interactions. Achieving true net-zero building requires a comprehensive LCA that considers both operational and embodied emissions [76]. Adopting low-carbon materials sometimes incurs an increase in total cost compared to traditional materials, although long-term environmental benefits and potential cost savings should be considered. Building Information Modelling (BIM) tools are increasingly being used to evaluate embodied carbon and facilitate net-zero building design decisions during the early stages. BIM is recognized as a data-rich information source useful for energy calculation and integrating energy simulation into the early design process of net-zero buildings.

3.4. Smart technologies for net-zero buildings

Smart technologies represent a layer of intervention, complementing passive design and efficient active systems to achieve Net-Zero targets. Smart technologies involve integrating advanced control, monitoring, and responsive systems to optimise building performance and interaction with energy grids [18]. Smart building technology, alongside renewable energy systems and academic research, is making the construction of NZBs increasingly feasible. Several examples of smart technologies, like smart window (electrochromic and energy conversion devices) technology, contribute to net-zero goals. It manages solar gain through glazing elements, reduces operational energy use and improves occupant comfort. Advanced shading systems that respond to changing environmental conditions to optimise daylighting and solar heat gain are also identified as key façade technologies [70].

The disparity between a building's designed efficiency and its actual performance is often caused by a lack of proper installation training and is exacerbated by labour shortages and squeezed project timelines. This failure to achieve modelled results reinforces the misconception that NZEB is too risky or complex. This resistance to innovation, rooted in a lack of knowledge and a fear of complexity, limits opportunities for practical experience and knowledge transfer within the industry. The solution requires a collaborative effort to break this cycle through improved education, professional competency frameworks, and a reframing of the NZEB value proposition for a wider audience.

4. Discussion

Most buildings that will exist in 2050 have already been built. Consequently, transforming the existing building stock is a critical and necessary trend for the future. Deep retrofits, which involve comprehensive upgrades to insulation, air sealing, and mechanical systems, are considered essential for this task. Flores et al. [77] estimate that improving insulation and air sealing alone can reduce heating and cooling energy needs by 10–20%. Insights from the World Economic Forum indicate that deep retrofits have the potential to cut a building's operational carbon emissions by as much as 40% and total energy use by up to 60%. Beyond these substantial energy savings, retrofits improve occupant comfort, health, and productivity, while also extending the asset value of older properties and reducing vacancy risk. The future of NZEB design is characterized by a convergence of digital technology and material science that is fundamentally changing the entire value chain, from design to construction to operation. Similarly, recent studies highlight the use of technologies to optimise NZEB systems [78], as well as frameworks that suggest an integration of technologies, materials, and strategies [79].

Advanced and sustainable materials are also playing a critical role in reducing the environmental impact of construction. Materials such as mass timber, bendable concrete, and bamboo offer a viable substitute for traditional materials like steel and conventional concrete, which have a higher carbon footprint. These materials not only reduce embodied energy but also offer enhanced durability and resilience. Digital technologies like 3D printing and construction robots are set to revolutionize the construction process itself, reducing material waste, expediting production, and augmenting design flexibility.

In terms of operations, the increasing integration of battery energy storage systems (BESS) and microgrids is a critical trend for managing the variable nature of renewable energy sources like solar and wind. These systems enable a building to store surplus energy for later use, provide backup power during outages, and even operate autonomously when the main grid is strained. This holistic approach, which targets the entire building lifecycle from material sourcing and construction to operational energy and end-of-life is the next logical step in the evolution of sustainable construction. This study emphasizes that net-zero buildings are pivotal in mitigating climate change. By integrating passive and active strategies, prioritizing low-carbon materials, and addressing barriers, the construction sector can achieve net-zero buildings [80].

However, success hinges on interdisciplinary collaboration, robust policy frameworks, and societal commitment. net-zero architecture represents a paradigm shift in sustainable building design, combining passive ingenuity, active technical solutions (see **Table 3**), and renewable energy to eliminate operational emissions. This paper has identified the key architectural features, demonstrated the pivotal role of on-site renewables, and highlighted the multifaceted barriers to widespread adoption. Overcoming these challenges will require coordinated policy action, innovative financing, capacity building, and integrated design approaches. As global carbon targets tighten, scalable net-zero solutions will be essential to decarbonize the built environment and safeguard planetary health.

Table 3. Active and operational strategies for achieving and sustaining net-zero energy buildings.

Reference article	Net-zero building strategy	Core mechanism/function	Impact/Efficacy toward net-zero goals
Igbo and Ekeoba [6], Eksi et al. [35], Elnaklah et al. [43], Fadeyi et al. [57], Flores et al. [77], Wang et al. [78], George and Meng [79]	High-Efficiency HVAC Systems with Heat Recovery	Mechanical ventilation systems incorporate heat exchangers to recover thermal energy from exhaust air while supplying fresh air.	Reduces heating and cooling loads; enhances indoor air quality and overall energy efficiency. Can lower HVAC energy consumption by up to 30–40% in optimised systems.
Eksi et al. [35], Fadeyi et al. [57], Flores et al. [77], Wang et al. [78], George and Meng [79]	Smart Lighting Systems	Combines LED fixtures, occupancy sensors, and daylight dimming controls to minimize unnecessary lighting use.	Reduces electrical lighting energy by 20–40%; decreases internal heat gains, thereby lowering cooling demand.
Wang et al. [78], George and Meng [79]	Energy-Optimised Appliances and Plug Load Management	Employs high-efficiency appliances, power strips, and demand-response strategies to reduce non-regulated energy use.	Plug loads account for over one-third of total building energy use; active management can yield 10–25% total energy savings.
Jaysawal et al. [8], Noh et al. [9], Shirinbakhsh and Harvey [10], Lou and Hsieh [22], Eksi et al. [35], Brozovsky et al. [37], Gondal et al. [56], Fadeyi et al. [57], Musah et al. [61], Ali et al [68], Wang et al. [78], George and Meng [79]	On-Site Energy Storage Systems	Battery storage captures surplus renewable energy for later use, enabling load shifting and enhancing grid independence.	Improves reliability and ensures energy balance between generation and consumption; essential for consistent NZEB operation.
Jaysawal et al. [8], Noh et al. [9], Brozovsky et al. [37], Fadeyi et al. [57], Wang et al. [78], George and Meng [79]	Combined Heat and Power (CHP) Systems	Small-scale cogeneration units produce both heat and electricity simultaneously for local use.	Enhances overall system efficiency by 60–80%, especially in mixed-use or district applications; reduces dependence on external grid supply.
Musah et al. [61]	Biomass or Biogas Systems	Utilizes renewable organic fuels for heating and power, often integrated into community or district energy schemes.	Provides renewable heat and power; supports carbon neutrality at neighbourhood scale.
Terblanche et al. [7], Mba et al. [41], Mageed et al. [44], Vasudevan et al. [46], Khassan et al. [47], Imoni et al. [48], Wang et al. [78], George and Meng [79]	Performance Monitoring and Data Management	Continuous data collection, benchmarking, and optimization to verify modeled versus measured performance.	Addresses the performance gap; ensures long-term operational efficiency and occupant satisfaction.
Tirelli and Besana [3], Terblanche et al. [7], Jaysawal et al. [8], Noh et al. [9], Anyanwu et al. [15], Parkin et al. [16], Maloo [17], Lou and Hsieh [22], Satola et al. [27], Tak Kit [28], Brozovsky et al. [37], Wang et al. [78], George and Meng [79]	Integrated Net-Zero Design Process	Sequential approach: first reduce energy loads through efficiency, then maximize on-site renewable generation.	Ensures cost-effective pathway to net-zero energy balance; guided by advanced simulation and renewable yield modeling.

The investigation into the architectural features of net-zero structures reveals that their efficacy in lowering energy consumption and pollution is a multifaceted achievement, dependent on a rigorous, layered, and holistic design philosophy. The foundational principle of net-zero is not simply a technical goal, but a paradigm shift that demands a departure from incremental efficiency toward an absolute zero baseline. This begins with passive design, which is the most cost-effective and critical phase, leveraging a building's orientation, envelope, and fenestration to drastically reduce its energy load. The successful implementation of these passive strategies directly enables the effective use of high-efficiency active systems, such as geothermal heat pumps, by reducing the energy demand to a level that can be met by smaller, more efficient equipment.

The final energy balance is achieved through the integration of renewable energy sources, primarily solar and geothermal, which are becoming increasingly viable and cost-effective due to maturing technology and supportive policies.

5. Conclusion

This review has established that net zero buildings represent a technically viable and architecturally substantiated response to the building sector's disproportionate contribution to global energy consumption and greenhouse gas emissions. However, the widespread adoption of net-zero buildings is hindered by a number of significant barriers. The most prominent is the high upfront capital cost, which is often perceived as an insurmountable obstacle due to a widespread focus on short-term financial metrics. This economic barrier is exacerbated by a fragmented and non-standardized policy landscape that creates market uncertainty and makes it difficult to scale solutions. The "performance gap", the disparity between designed and actual energy use—is a major technical challenge that stems from a lack of knowledge and proper training in the construction industry, reinforcing a market-wide reluctance to embrace these innovative practices. Looking to the future, the industry is poised to address these challenges through a strategic focus on deep retrofits of the existing building stock and the adoption of emerging technologies.

The shift from a singular focus on new construction to the transformation of existing properties is essential to meeting global climate goals. The convergence of digital technologies, such as smart building systems and robotics, with advanced materials promises to fundamentally change the NZEB value chain, addressing not only operational energy but also the embodied energy and waste of the construction process itself. By tackling these issues, the building industry can move toward a more comprehensive, life-cycle-oriented approach to sustainability, making net-zero buildings not just a possibility, but a practical and necessary reality for the future of the built environment. To accelerate the transition toward net-zero buildings:

a. Policymakers must prioritize the development of harmonized international frameworks that standardize definitions, certification processes, and embodied carbon reporting in building codes.
b. Financial incentives, such as subsidies for renewable energy systems and tax rebates for low-carbon materials, should be introduced to mitigate high upfront costs and incentivize net-zero practices.
c. Architects and engineers should adopt an integrated design approach, leveraging passive strategies from the conceptual stage and utilizing BIM tools for energy modelling and material optimization.
d. Concurrently, educational initiatives are critical to bridge technical knowledge gaps among professionals and foster energy-conscious behaviours among occupants through smart technology interfaces.
e. Governments and industry stakeholders must also allocate resources to retrofit existing buildings, addressing aging infrastructure while advancing circular

economy principles for material reuse.

By aligning policy, practice, and public engagement, these measures can overcome the barriers and ensure the scalable adoption of net-zero building strategies.

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