sustainability

Review

Pathway to Sustainability: An Overview of Renewable Energy Integration in Building Systems

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Abstract: Decarbonizing the building sector is crucial for mitigating climate change, reducing carbon emissions, and achieving an energy production–consumption balance. This research aims to identify key design principles and strategies to enhance energy savings and analyze the integration potential of renewable energy sources (RES) such as solar, wind, geothermal, and biomass, providing in-depth technical exploration and evaluating current building developments. Moreover, the study also examines recent developments, explicitly focusing on integrating hybrid renewable energy systems, energy storage solutions, and AI-based technological innovations. Through comprehensive analysis and critical evaluation, this research provides valuable insights and practical recommendations for achieving building sustainability and advancing the transition towards a low-carbon built environment.

Keywords: solar integration; wind integration; geothermal integration; biomass integration; hybrid renewable energy systems; energy storage; building sustainability

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1. Introduction

1.1. Background

Traditional energy sources, such as coal, oil, and natural gas, are finite and face depletion. With the global concern over climate change and the limited nature of traditional energy resources, there is a critical need to transition towards more sustainable and eco-friendly energy solutions, especially within the built environment [1]. Scientific consensus indicates that human activities, including the combustion of fossil fuels for energy, contribute significantly to the rise in greenhouse gas emissions, leading to climate change. Buildings significantly contribute to these emissions due to their energy consumption for heating, cooling, lighting, and other operational needs [2]. The building sector's energy demand intensifies as urbanization and population growth continue. The global shift towards sustainable practices and the increasing awareness of climate change have intensified the focus on renewable energy technologies in the design and construction of modern buildings [3]. According to the targets set by the Paris climate agreement, only 27 years remain to reach global net-zero emissions. To limit warming, the emissions from buildings globally are to be halved by 2030 to reach net zero life-cycle emissions for all buildings by no later than 2050 [4]. This has given traction to the net-zero energy buildings in global markets. Reducing carbon emissions in the building sector is crucial for addressing climate change, given that this sector accounts for 40% of global energy consumption and contributes to 37% of total greenhouse gas emissions worldwide (Refer to Figure 1) [5,6].

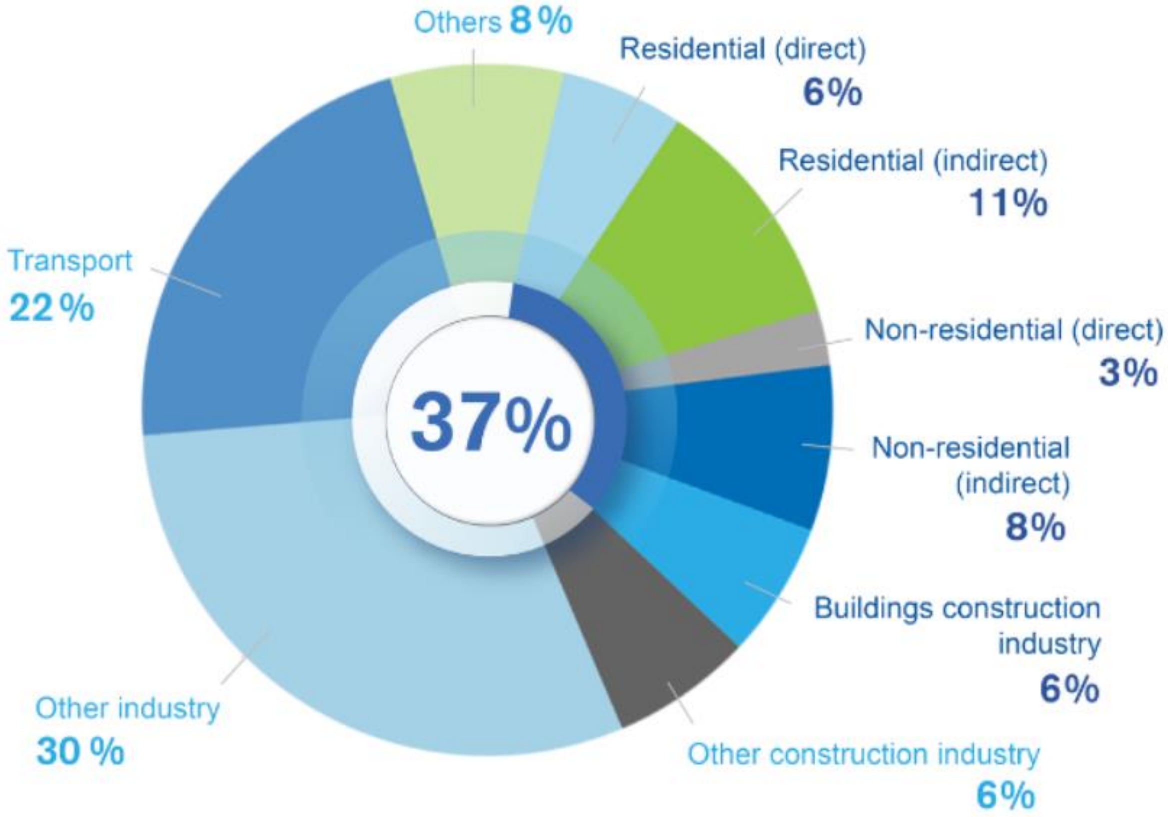

Figure 1. Global building sector energy-related CO_2 emissions in 2021 [7,8].

The emphasis is on sustainable development, reflecting the growing demand for energy-conscious building practices. Numerous critical elements and functions are essential to the functioning of present-day residential buildings. These include, but are not limited to, lighting, refrigeration, space heating and cooling, ventilation, domestic appliances, water heating, electronics, and mechanical systems. The scientific background of integrating sustainable technologies into a building lies at the intersection of environmental science, engineering, and sustainable architecture. Integrating renewable energy technologies aims to reduce this carbon footprint and mitigate the impact of buildings on climate change. Integrating renewable energy technologies is essential for addressing the impending scarcity of non-renewable resources and ensuring energy security for future generations [9]. Incorporating renewable energy technologies into building systems, including but not limited to HVAC (heating, ventilation, and air conditioning) and electrical systems, is essential to address the varied energy requirements of structures. Solar and geothermal energy are critical players in this integration, harnessed through technologies like PV panels, ground source heat pumps (GSHPs), and solar thermal collectors. While these technologies have made notable strides, the field is transitioning, with vast potential awaiting application and implementation [10]. The ongoing evolution of energy collection and storage technologies and advancements in materials enhancing heat transfer and storage further highlight the need for comprehensive research in this domain. The future of construction lies in combining these approaches to create buildings that are not just ecologically responsible but also regenerative and carbon-neutral, contributing positively to the global sustainability effort. Many developers begin this process by reducing their CO_2 emissions as much as possible during construction before investing in offset programs. Within the construction industry, initiatives are being undertaken to offset the equivalent quantity of CO_2 emitted through activities in their supply chains by investing in “carbon sinks”, which effectively absorb carbon dioxide [11]. The decision-making process for building construction necessitates carefully considering diverse technical, financial, and environmental factors, thereby validating the application of multi-criteria decision analysis methods in net-zero energy building designs [12].

1.2. Research Gap

The various specific gaps in existing research within the context of the current study are as follows:

The current state of the literature emphasizes the significance of renewable energy in building integration. Still, it lacks an in-depth exploration of the evolving technologies and materials that could further enhance energy collection, storage, and distribution within the built environment. While the literature provides a comprehensive overview of the urgency to transition towards sustainable building practices, a research gap exists in addressing the specific challenges and opportunities associated with integrating renewable energy technologies into various building systems. Moreover, there is a need for more detailed insights and comparisons of renewable energy technologies and their integration potential across multiple building types and climates.

1.3. Novelty Statement

This research aims to fill the identified gap by comprehensively exploring the evolving landscape of renewable energy technologies in the building sector. The focus extends beyond the established roles of solar and geothermal energy to incorporate advancements in materials and technologies related to energy collection and storage. The study seeks to evaluate, implement, and optimize the untapped potential of integrating renewable energy in buildings. Additionally, it aims to provide valuable insights, new perspectives, and practical recommendations for achieving regenerative, carbon-neutral buildings that align with global sustainability goals.

1.4. Objective of the Review

The objectives of this manuscript are:

- to comprehensively explore the concepts of decarbonizing buildings, providing a comprehensive understanding of their key features and pathways. This includes, but is not confined to, design aspects of building, advanced energy efficiency methods, and intelligent energy monitoring for optimization;
- to investigate and examine the spectrum of studies on innovative renewable energy technologies applied to buildings, particularly in the context of energy-efficient and green structures. This encompasses a range of topics, such as renewable energy applications, solar, wind, bio energy, geothermal energy systems, advanced energy storage, and hybrid energy strategies within the built environment,
- to address the challenges and opportunities in integrating renewable energy sources in buildings.

1.5. Structure and Scope of the Review

The structure and scope of the review are shown in Figure 2. The organization of this paper unfolds as follows. Section 2 provides the critical focus areas that support zero-energy building; moving forward, Section 3 comprehensively explores the various renewable energy options that can be integrated into a building. Section 4 deals with the challenges and opportunities of integrating renewable energy sources in buildings. Finally, in Section 5, the discussion outcomes are presented, accompanied by future avenues of exploration within this field. The paper concludes with future predictions and provides actionable recommendations for policymakers, builders, and stakeholders.

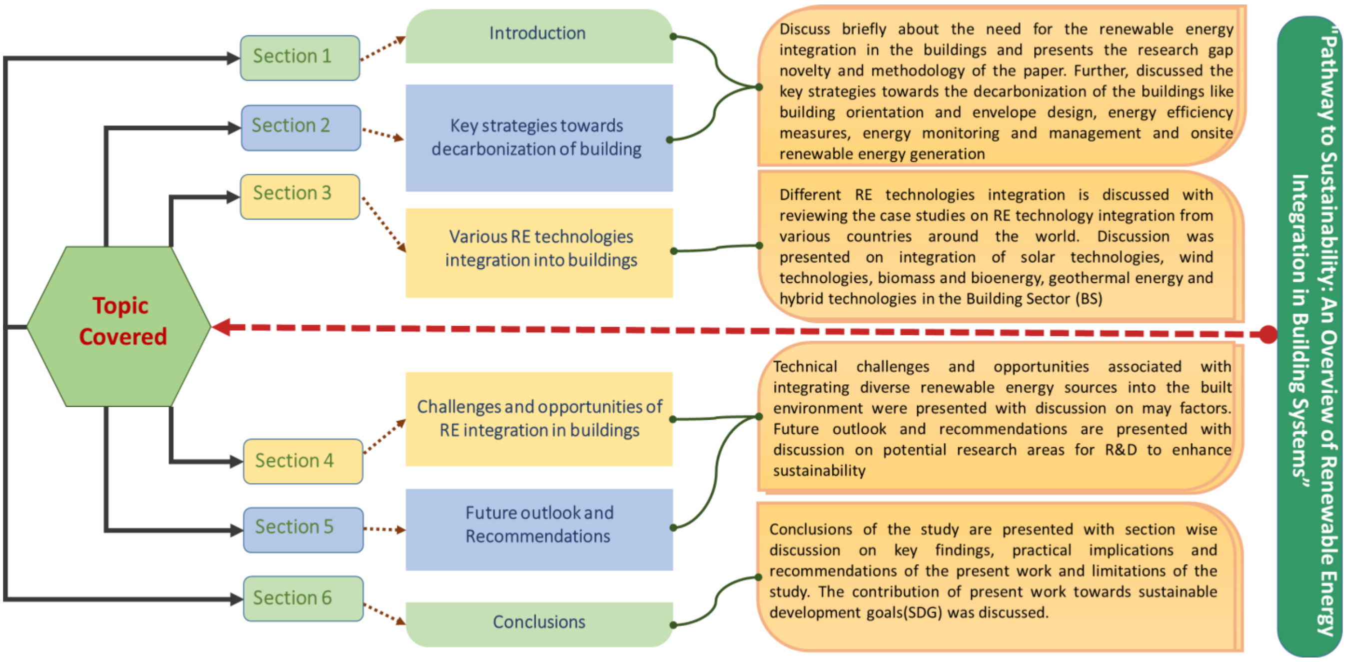

Figure 2. Pictograph showing the structure and scope of the review.

1.6. Methodology

A systematic search was carried out to identify relevant literature to investigate the viability of integrating sustainable energy sources for the decarbonization of the building sector. Distinct sets of keywords were formulated for each research objective to ensure precision:

Objective 1: "Energy-efficient building", "energy monitoring and management", "building design".

Objective 2: "buildings", in conjunction with "solar", "wind", "geothermal", "hybrid", "bioenergy", and "sustainability".

Objective 3: "opportunities and challenges" in combination with "building", "renewable technologies", and "energy storage".

The search was conducted across reputable electronic databases, including Google Scholar, Scopus, and Web of Science. Stringent filters were applied, confining the search to publications within the past decade, focusing on peer-reviewed articles, conference proceedings, and technical reports. This meticulous approach aimed to capture the latest and most reliable information available.

Our investigation involved a comprehensive analysis and case studies of various building-integrated renewable energy systems, such as solar energy, wind energy, biogas plants, geothermal energy, and hybrid renewable energy systems (HRES). Each renewable energy system was subjected to a thorough evaluation, weighing the potential advantages and disadvantages of its integration. This systematic methodology ensured a comprehensive understanding of the diverse renewable energy options available for decarbonizing the building sector, thereby contributing valuable insights to the broader discourse on sustainable building designs.

2. What Are the Key Strategies for Decarbonizing the Building Sector?

Modern buildings are progressively anticipated to fulfill elevated and intricate performance standards [13].

1. Emphasize sustainability as a critical criterion.
2. Strive for zero-net energy consumption.
3. Promote a healthful and comfortable indoor environment for occupants.
4. Align with grid-friendly principles.
5. Ensure economic feasibility in both construction and maintenance.

The most successful approaches for decarbonizing residential buildings encompass several key concepts, including building orientation and design, energy efficiency, energy monitoring and management, and onsite renewable energy [14]. Green buildings prioritize energy efficiency through advanced architectural and engineering practices. This includes superior insulation, efficient HVAC systems, and using natural light to reduce energy consumption [15]. Automation and intelligent technology are crucial in optimizing energy usage. These systems regulate lighting, heating, and cooling based on occupancy and weather conditions, ensuring minimal waste of energy [16]. Choosing sustainable and eco-friendly building materials and construction methods that minimize waste contributes to a building's overall sustainability [17]. To maintain an uninterrupted energy supply, energy storage systems, such as advanced batteries, store surplus energy for later use, particularly during periods of low energy production [18]. Sustainable buildings also focus on water conservation through low-flow fixtures, greywater recycling, and rainwater harvesting [19]. Continuous monitoring and management systems help building owners and operators track energy usage, identify inefficiencies, and make necessary adjustments to maintain a net-zero energy balance [20].

2.1. Building Orientation and Envelope Design

The orientation and design of a building can significantly impact its energy performance. Net-zero energy buildings (NZEBs) are commonly designed to maximize natural light and ventilation while minimizing energy losses through the building envelope [21]. In NZEB design, the task is to identify the most practical combination of design strategies to address the building's energy performance challenges. Numerous design principles and guidelines have been suggested for these characteristics. Utilizing geometric orientation and incorporating nature and climate-centric local designs within a global framework offer more suitable criteria for NZEBs [21–23]. The design principles for NZEBs can be summarized as follows:

- Prioritize design for comfort and functionality.
- Establish an airtight building enclosure.
- Implement controlled ventilation strategies.
- Utilize insulation surpassing current energy code requirements.
- Ensure effective control of water and moisture movement within the building enclosure.
- Optimize building orientation for maximum renewable energy production.
- Choose energy-efficient mechanical equipment.
- Opt for efficient lighting, plumbing fixtures, and appliances.
- Employ energy modeling to project total energy consumption and size of on-site renewables.
- Develop project plans that facilitate coordination and commissioning of systems.
- Incorporate passive design strategies.
- Design a high-performance building envelope.
- Specify energy-efficient HVAC systems, lighting, and appliances.
- Install on-site renewable energy sources.
- Implement proper offsetting measures.

For a more extensive exploration of the impact of building design, encompassing the building envelope, refer to the section on building design. Diverse design elements, such as building type, layout, and external structure, directly influence the energy requirements of the building, as well as its capacity to integrate solar technologies to generate sustainable energy [9]. The architectural layout of a structure plays a pivotal role in influencing its energy efficiency, resilience to climate events, and susceptibility to energy disruptions. By incorporating a range of climate-responsive features and passive architectural design elements such as shading strategies, light shelves, and solar chimneys, the effective utilization of solar energy for heating, cooling, and daylighting can be optimized [24]. This approach reduces reliance on local energy grids. These passive architectural features apply to various building types, including residential, office, and commercial structures, enhancing their adaptability to energy interruptions [23]. Building elements in the design, including improved insulation, a meticulously sealed building envelope, and well-optimized window systems featuring a suitable window-to-wall ratio (WWR), play a substantial role in shaping a building's energy demands. The region's specific building codes and rigorous energy performance standards influence the window-to-wall ratio [25]. High-performance windows include windows with thermochromic glazing and windows integrated with photovoltaic technology, whether ventilated or non-ventilated [26]. Such advanced window technologies diminish the requirements for heating and cooling, simultaneously improving visual and thermal comfort. This reduces the need for extensive mechanical equipment and extends a building's self-sufficiency without dependence on electricity for these operations [27].

The configuration of a building and its outer covering significantly impacts its interaction with solar radiation, where the orientation and tilt angles of these surfaces play crucial roles [28]. Figure 3 portrays the design of buildings for enhanced solar potential. Thoughtful geometric design and strategic site selection for the building envelope can optimize the reception of incident solar radiation on these surfaces, leading to increased electricity and thermal energy generation.

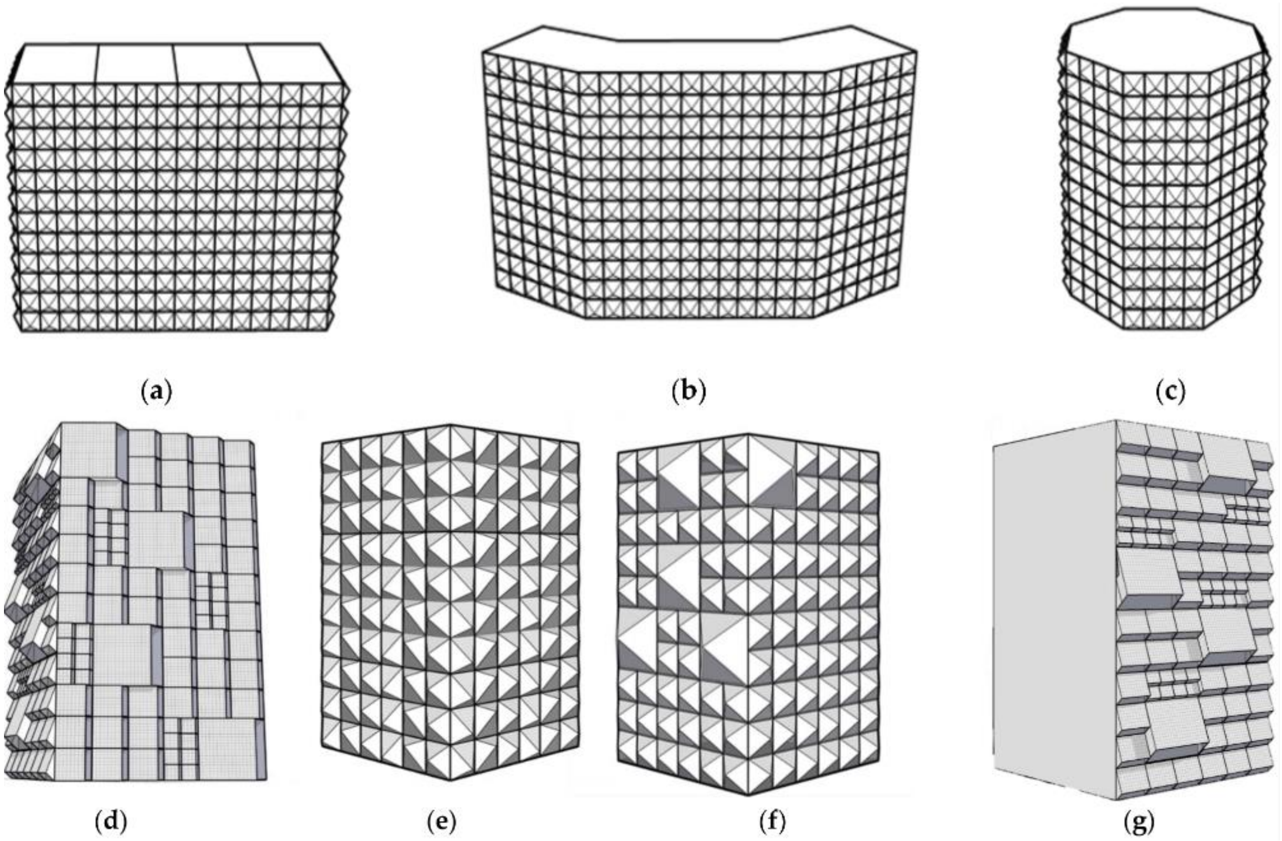

Figure 3. Architectural planning for increased solar efficiency: (**a**–**c**) arrangement of structures, (**d**–**g**) exteriors of the buildings [29].

A building's envelope design is crucial to integrate renewable energy systems like photovoltaic (PV) and photovoltaic–thermal systems (PV/T), thus enhancing their resilience against power interruptions. While placing PV technologies on the roofs is optimal for low-rise buildings, the facades of multi-story buildings present advantageous surfaces for integrating PV systems. This is due to the expanded surface area resulting from the increased height of multi-story buildings compared to the open roofs [30]. Fine-tuning the tilt and orientation angles of particular building surfaces can lead to enhanced electricity production and extended durations of peak energy generation. Complex geometries significantly improve the energy generation potential of both roofs and facades. These design considerations offer an innovative integration of photovoltaic (PV) systems, making them architecturally attractive and visually harmonious with the overall building design [29].

Using sustainable materials in construction will reduce the environmental impact and increase energy efficiency [31]. Recycling and reusing demolished debris could lower waste generation in construction and contribute to sustainable buildings [32]. The crushed bricks produced from demolishing old buildings are used to replace coarse aggregates and fine aggregates in making concrete sustainable materials. The addition of 0–50% bricks as coarse aggregates in cement increased the compressive strength of concrete at ages (7,28) days by 9.7% and 7% with a reduction in weight by 11%, whereas the fine aggregates of 0–75% added to cement increased the compressive strength by 59% and 61% for ages (7,28) days respectively with a weight reduction of 2% [32]. Using eco-friendly and sustainable building materials and waste-reduction techniques during construction influences a building's overall sustainability. Table 1 discusses the studies related to the building orientation and envelope design aspects, which results in the effective decarbonization of the buildings.

Table 1. Studies on building orientation and envelope designs for net-zero buildings.

Author	Building Aspect	Objective	Major Findings
Fereidoni et al., 2023 [21]	Building envelope design	Tradeoff between embodied and operating energy	Parametric analysis of how various envelope design elements affect the building's operational and embodied energy consumption. Parameters: Wall assembly, glazing type, glazing ratios for the southern and northern walls. The inside and outside insulation material, thickness, and the outermost layer material are wall assembly design variables.
Barrutieta et al., 2021 [22]	Hollow cylindrical shape building	Real performance data analysis of carbon-neutral building	Provides actual performance data for a near-zero energy building (NZEB) situated in a low-carbon neighborhood, boasting environmental design certifications such as LEED Gold and BREEAM Excellent.
Santos-Herrero et al., 2021 [23]	Modeling, simulation, and control tools for a net-zero building	Passive ventilation and heating	Employing a multidisciplinary method to attain energy efficiency in buildings. Significant opportunities for optimizing energy consumption by effectively combining Building Energy Performance Simulation (BEPS) tools for modeling and simulation with Model Predictive Control (MPC) for control strategies. Ability to manage heating, ventilation, and air conditioning (HVAC) systems using renewable energy sources (RES).
Dumitraşcu et al., 2020 [24]	Thermo-energetic envelope configuration	Evaluation, simulation, and optimization of a single-family house (Romania) through BIM methodology.	Examining in-depth climate data and identifying the most effective passive measures suitable for the specific locale. The primary energy value is 107.89 kWh/m^{2}a, while CO$_2$ emissions are recorded at 2.59 kg/m^{2}a. The building aligns with Romanian standards, showcasing low environmental impact and minimal energy consumption.
Chiesa et al., 2019 [25]	WWR (window-to-wall ratio), level of insulation, orientation	Optimize the expected energy needs based on different aspects like cooling, heating, lighting, design choices.	An algorithm was developed to allow a changing occupation rate based on random behavior. Simulations under consistent occupancy rates indicate an optimal Window-to-Wall Ratio (WWR), which achieves the lowest annual energy requirement by balancing the three energy uses mentioned above, of approximately 30% for both locations.

2.2. *Energy Efficiency Measures*

Integrating energy-efficient design principles, particularly in buildings with high-performance envelopes, enables passive building performance, ensuring habitability without heavy dependence on mechanical systems. Efficient heating systems have achieved significant energy savings and emission reductions in the building sector. Still, challenges arise when upgrading technologies for greater efficiency, potentially causing greenhouse gas emissions without achieving essential long-term decreases [33]. Energy efficiency is crucial in managing demand, especially during peak grid demand [34]. Diverse passive strategies can reduce the influence of external weather conditions, such as extreme heat or cold, on the indoor environment. The design of net-zero energy buildings (NZEBs) prioritizes high energy efficiency, integrating advanced insulation, high-performance windows, and efficient lighting and HVAC systems [10,35].

From the standpoint of energy efficiency in NZEBs, there are two primary categories: lessening the building load and more effectively addressing the load. Examples of load reduction encompass improved building designs (envelope, layout, orientation, etc.), solar shading, and encouraging efficient occupant behaviors (such as opening windows during favorable outdoor conditions, turning off HVAC when not in use, aligning domestic hot water (DHW) draw profiles with heat pump water heater (HPWH) production capacity, etc.) [36]. Achieving load requirements with reduced energy input entails choosing efficient mechanical systems (such as HVAC and DHW) and energy-efficient equipment, controls, and building appliances (lighting, refrigerators, washing machines, dryers, etc.) [37]. Enhancing energy efficiency involves optimizing efficient mechanical systems and controls and building envelope advancements. Although other factors like layout and geometry, internal gains, occupancy, and location and climate are less commonly optimized, this could be attributed to these parameters often being established earlier in the design process before energy designers are consulted. It is important to highlight that occupancy, location, and climate are typically not optimized for residential buildings [38]. Regarding optimization criteria in NZEB design, focus can be placed on energy consumption, cost analysis, comfort, carbon emissions, lighting, ventilation, and indoor air quality. A holistic consideration of life cycle analysis and carbon footprints can be integrated into the overall assessment. While the shift to zero carbon fuels is transitioning, the effective utilization of fossil fuels remains valuable for carbon reduction. However, in the long run, fossil fuels become outdated within a zero-carbon energy system, no matter how efficiently they are employed. Consequently, directly and indirectly, relying on fossil fuel-dependent energy efficiency will not suffice as a pathway to eliminate greenhouse gas (GHG) emissions [39].

The reconsideration of the benefits of energy efficiency has evolved, with a shifting emphasis on various outcomes. In recent years, energy efficiency advocates have predominantly focused on reducing carbon emissions. It is essential to recognize that energy efficiency is not inherently valuable but derives its worth through delivering social benefits, including enhanced energy security, economic efficiency, and diminished environmental impacts [40]. Systems and controls have been identified as the most intricate and dynamic design parameters, underscoring the critical importance of design optimization [41]. In the design of the building envelope for energy-efficient buildings, multiple criteria must be taken into account. Figure 4 outlines various energy efficiency measures applicable to net-zero energy buildings. A notable challenge lies in addressing building thermal loads. This challenge can be alleviated by implementing enhanced thermal insulation, improved thermal capacitance, increased airtightness measures, optimized orientation and shape, appropriate window-to-wall ratios, enhanced window glazing, solar shading, passive solar technologies, and other strategies [42].

Increasing insulation thickness and implementing "continuous insulation" to reduce thermal bridging are advisable in regions prioritizing heating concerns. Windows, especially in heating-dominated climates, should have a commendable R-value and maintain air- and water-tightness. Utilizing window shading strategies can minimize solar gains in the summer when the sun is higher and allow more significant improvements in the winter when the sun is lower. Emphasizing the reduction of space heating loads through well-insulated and airtight envelopes proves more advantageous than relying solely on less insulation and a larger renewable energy system. The efficiency of HVAC systems is crucial for overall energy efficiency and can be described in terms of ventilation, dehumidification, and heat pump options [43].

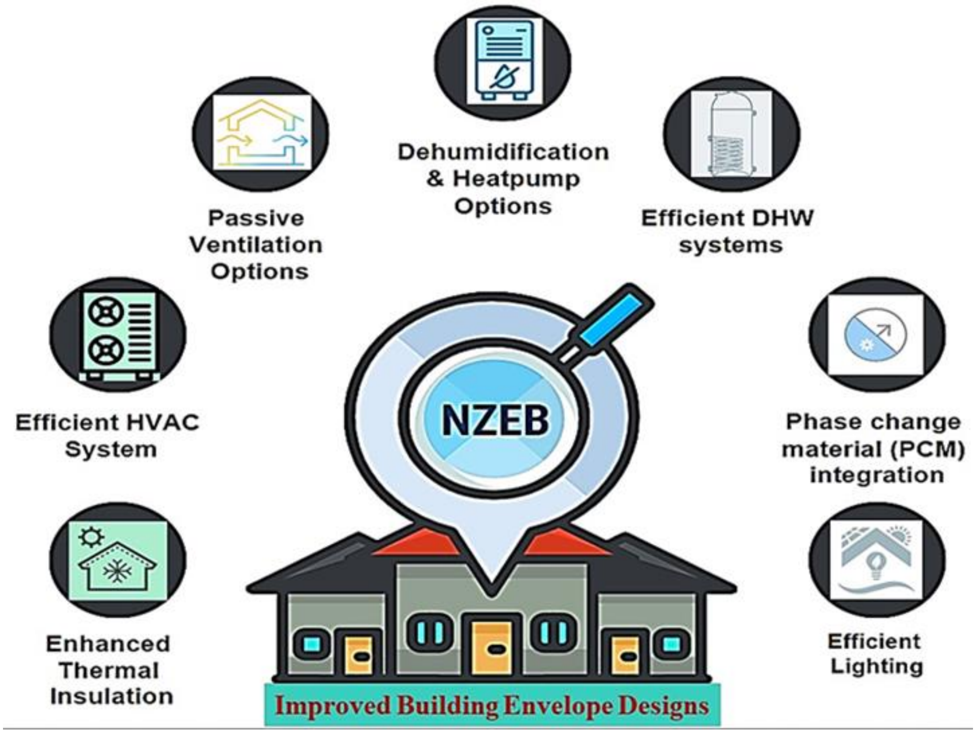

Figure 4. Energy efficiency measures for a net-zero energy building.

Heat-recovery systems provide a mechanism to transfer both sensible and latent heat from exhaust air to outdoor air, effectively reducing the thermal load introduced by outdoor air. While lower outdoor air ventilation rates can decrease energy consumption, they might elevate indoor contaminant levels. On the contrary, higher outdoor air ventilation rates could challenge achieving the net-zero energy target due to increased energy consumption. Passive concepts, including natural ventilation driven by wind or buoyancy, have also been explored in NZEBs [44]. Though natural ventilation reduces energy demand, it may lead to an uneven temperature distribution within the building. Through enhanced architectural designs and strategies, NZEBs relying solely on natural ventilation for cooling can attain satisfactory thermal comfort, even in warmer months, without mechanical cooling. An efficient ventilation approach involves the direct exchange of heat between the air and the ground; earth-to-air heat exchangers can precondition outdoor air or recondition indoor air for heating and cooling purposes [40]. Phase change materials (PCMs) are commonly utilized for thermal energy storage at low temperatures, typically ranging from −20 °C to 200 °C. Incorporating PCMs in buildings presents significant potential for enhancing thermal comfort in the future. Technologies associated with thermal energy storage provide a solution to the mismatch between the timing and capacity of energy supplied by renewables and the demand from buildings. The adoption of PCMs offers dual advantages to HVAC systems: firstly, it allows for a reduction in heat pump capacity as the PCM can complement the HVAC capacity, and secondly, the PCM can be charged during more favorable outdoor air temperatures [45,46]. PCMs can also be incorporated into various building components like walls [47], windows, and construction materials as thermal insulation to increase the energy efficiency of the buildings [48].

In the context of operational perspectives for energy efficiency, the mindset and attitude of citizens towards energy efficiency, along with conscientious consumption and usage of energy, play pivotal roles. Promoting proper awareness regarding efficient use and providing timely maintenance advice is crucial. Consultants should educate owners about the significance of adopting these design strategies and technologies in buildings. This awareness can lead to increased implementation of NZEB systems, overcoming potential hesitations due to their moderately high initial costs. NZEBs are designed for energy efficiency, integrating advanced insulation, high-performance windows, and efficient lighting and HVAC systems [37,43]. Table 2 discusses the studies that presented energy-efficient measures for decarbonizing buildings.

Table 2. Studies on energy-efficient measures for decarbonizing buildings.

Author	Energy-Efficient Measures	Objective	Major Findings
Gaarder et al., 2023 [49]	Thermal insulation thickness	Optimization of thermal insulation thickness pertaining to embodied and operational GHG emissions	Optimal insulation thickness calculations are fundamental to low energy emission factor value. Operational emissions dominated energy emission factors above 25–30 g CO_2 eq/kWh. Due to climate change, the optimal insulation thickness for Norwegian inland may reduce to 75–100 mm towards 2071–2100.
Delac et al., 2022 [36]	Building envelope and the HVAC system	Integrated optimization of the building envelope and the HVAC system in building refurbishment	Water-to-water heat pump system using seawater as the heat source and sink (170.2 kWh/m^2) when cooling energy prevails over heating energy use, an air-to-water heat pump system is the suitable solution (176.4 kWh/m^2). Optimal solutions are when the HVAC system size matches the design load.
Hamburg et al., 2020 [44]	Air handling units, heating coils and DHW (domestic hot water) systems	Energy performance targets of an old apartment building.	Measured heating energy consumption is 1.6 times higher due to the higher indoor and supply air temperature, window airing, and higher ventilation airflow rates. The measured energy needed for DHW is 4.4 times higher because of the real use profiles and the unexpected performance of the solar collector and sewerage heat recovery system.
Fedorczak-Cisak et al., 2019 [50]	Lighting and heating systems	Influence of Lighting and Air Heating on the Comfort Conditions	Slightly more than 73% of the respondents consider illuminance at a desk at the 500 lux level recommended. A potential for lower energy consumption and simultaneous improvement of people's comfort by providing local lighting control at the level of individual workstations, allowing adaptation of the illuminance to the individual preferences.
Durakovic and Halilovic 2023 [47]	PCM solar wall	Thermal performance analysis of PCM solar wall	During the heating season, the wall had the potential to maintain the temperature of the test cell above 20 °C up to 7 h, while in the cooling season, the wall keeps room temperature for about 17 h within the comfort range. Analysis was carried out in the area of Sarajevo, Bosnia.

2.3. Energy Monitoring and Management

To ensure sustained optimal results over the long term, strategically managing systems such as thermal systems and climate control is imperative. The efficacy of energy-saving measures implemented in the new design must be demonstrated to maintain performance. Establishing generalized criteria for monitoring and managing NZEBs is quite challenging, primarily due to variations in climate conditions, energy requirements, primary energy factors, ambition levels, and calculation methodologies [51]. A valuable instrument for monitoring the market shift towards NZEBs is establishing a building focused on typical practices [52]. Ensuring that a building functions according to its design and construction necessitates a sophisticated combination of processes, tools, and services [53]. Effective management, ongoing monitoring, and optimized maintenance are crucial for greater energy and cost savings.

Enhancing our understanding of the building stock, improving the effectiveness of energy policies, and facilitating the intelligent management of dynamic loads are essential objectives [33,54]. Monitoring a building's dynamic energy performance typically relies on yearly, monthly, weekly, and daily data. However, it would be more beneficial to reference real-time data to adapt the building's behavior to climate change. Furthermore, extended sets of monitoring data spanning several years could contribute to a more profound comprehension of NZEBs. This understanding would encompass real-time varying boundary conditions, thermal storage efficiency in walls, the regulation of plant functions, and other building characteristics [36]. The monitoring system can identify the operational issues in the equipment to achieve the zero-energy objective. However, maintaining the proper functioning of the systems throughout the building's use is essential. A more comprehensive assessment of the integrated energy performance of buildings can be attained by employing multiple techniques, which, when combined, provide a thorough understanding of the entire building [55]. The data acquired through extended monitoring, coupled with the regulatory criteria for thermal equipment and the establishment of environmental set-points, can serve as valuable assistance in validating design decisions and refining plant management techniques. Despite individual technologies not being novel or unfamiliar, the necessity for collaborative use of multiple systems underscores the importance of acquiring further knowledge regarding achievable outcomes.

Monitoring the building and its systems has to be carried out to streamline decision-making processes towards more energy-efficient operating modes. This includes assessing the variation between predicted and measured data, optimal strategies, and technical choices based on the local climate. The engagement of occupants and their awareness of the building's energy performance, influenced by individual behavior, are crucial factors in augmenting energy savings. Studies focused on analyzing occupant behavior have shown that furnishing real-time feedback on electricity consumption, facilitated by smart meters and sensors, aids citizens in optimizing their energy consumption patterns [54]. Automation and NZEBs are closely interconnected in sustainable and energy-efficient building design and operation. Automation serves as a crucial component of energy monitoring and management. It entails leveraging technology to oversee and control various systems within a building, optimizing performance, improving efficiency, and enhancing occupant comfort. This encompasses the automation of lighting, HVAC (heating, ventilation, and air conditioning), security, and other building systems [43]. Integrating sensors, actuators, and control systems enables real-time occupancy, temperature, and natural light adjustments. Automation substantially contributes to energy savings by ensuring that building systems operate at their most efficient levels. In the overarching concept that strives to minimize the energy consumption of buildings, achieve a balance between energy demand and renewable energy supply, and reduce the carbon footprint and reliance on non-renewable energy sources, energy monitoring and measurements play a pivotal role.

Energy optimization is the primary strategy in NZEB. Automation systems can continuously monitor and adjust building systems to optimize energy consumption. For example, sensors can detect occupancy levels, and the HVAC system can adjust airflow accordingly. Lighting systems can be programmed to dim or turn off lights in unoccupied areas. Automation allows buildings to participate in demand response programs, where they can adjust their energy usage based on external signals, such as electricity prices or grid demand [42]. This can lead to cost savings and more efficient use of energy resources. Automation can also control and monitor renewable energy systems like solar panels or wind turbines. It ensures that the building maximizes the use of on-site renewable energy and minimizes reliance on traditional energy sources. Automation enables buildings to integrate and interact with intelligent grids, allowing for more dynamic energy management. Buildings can adjust their energy consumption based on real-time data from the grid, contributing to overall grid stability and reliability. Automation systems can enhance occupant comfort by changing environmental conditions based on individual preferences and real-time needs [56]. Support of IoT and AI will enhance the residents' comfort and satisfaction level and improve their ease of living and quality of life. Integrating automation and NZEB principles is a powerful approach to creating sustainable and energy-efficient buildings. It involves leveraging technology to optimize energy use, maximize renewable energy generation, and enhance overall building performance while ensuring occupants' comfortable and productive environment [57]. Incorporating passive heat strategies with practical IoT and AI-based control mechanisms has become crucial for analysis and implementation. The foundation of such initiatives lies in designing an appropriate renewable energy generation system, whether solar, wind or any other renewable source. Energy literacy is vital in optimizing efficient use to achieve net-zero targets. Conducting system analysis using industry-standard software provides an economic advantage for these project implementations.

Simultaneously, monitoring real-time electricity consumption patterns for each connected load, ranging from heavy-duty to household appliances, is essential. Any deviations in the design of connected loads alert the user to faults in household loads, enabling informed decisions to upgrade energy-efficient requirements. This precise monitoring prevents energy wastage more effectively and cost-effectively [58,59].

During the competition, successful energy usage recording and monitoring were achievable due to implemented initiatives and design strategies involving AI, IoT connectivity, and an automation-based energy monitoring system. Integrating Artificial Intelligence (AI) and the Internet of Things (IoT) offers advantages in understanding automation-based energy monitoring and controlling net-zero buildings to achieve net-zero energy consumption. Controlling and monitoring loads are crucial steps in successfully implementing this concept, reducing stress on the generating system and saving energy. In implementing NZEBs, the strategy for real-time data monitoring of energy consumption is often overlooked [60]. Table 3 provides the various studies on smart systems integrated into net-zero buildings.

Table 3. Studies on smart systems integrated into net-zero buildings.

Author	Smart Techniques	Objective	Major Findings
Ahmed et al., 2023 [56]	IOT and AI	Internet of Things (IoT) and Artificial Intelligence (AI) are used to monitor a building to understand energy savings and methods to combat usage.	Avoid, Minimize, and then Generate (AMG) is to be followed in energy optimization aligned with net-zero practices. Techniques, including trackable blinds, photoelectric daylight sensors, and occupancy sensors, to name a few, are to be used effectively. Application of AI in the management and maintenance of intelligent meters and display board monitoring helps educate the users on energy conservation.
Magrini et al., 2022 [52]	Energy smart management	The need to adapt the home automation management systems to the actual use of the building	The project and monitoring data have been compared with internal and external thermo-hygrometric conditions. Smart energy management can significantly reduce the actual consumption compared to the estimated one. The study can be done using effective environmental thermo-hygrometric control systems and accurate regulation and operation of the machines. The energy behavior defines the building as a PEB rather than a NZEB.
Pernetti et al., 2021 [53]	Spreadsheet as a support tool	Analyzing an nZEB cost spreadsheet as a support tool for the design.	An effective tool for producing the nZEB spreadsheet, including all the main indicators for analyzing in detail the performances. A shared and operative LCC methodology, including boundary conditions, reference values, normalization factors and sensitivity analysis and a comprehensive database with detailed building Life Cycle Cost evaluation and energy evaluation represent the strategic references for a broader implementation of LCC analyses, providing useful benchmarks for comparison and increasing the reliability of LCC.

Table 3. *Cont.*

Author	Smart Techniques	Objective	Major Findings
Marinova et al., 2021 [60]	Internet of Things (IoT) technology	IoT-based approach of the administrative buildings in the Port of Durres, Albania for the control and improvement of environmental conditions and energy efficiency	The optimization of energy consumption of HVAC systems in buildings will lead to about 20% saved energy. Including a Photovoltaic System and a Battery Storage Block with an optimized BSB schedule will save approximately another 30% of energy. Considering the "energy-aware" behavior of buildings users, the reduction of energy consumption could exceed 50%. The IoT-based plan and further development and refinement of the virtual buildings model based on accurate data can transform the considered buildings into smart ones. The IoT solutions proposed will also be implemented in other buildings to achieve a green transformation of the port.
Causone et al., 2019 [54]	Data-driven simulation	Data-driven procedure to model occupancy and occupant-related electric load profiles in residential buildings energy simulation	The procedure is applied to the case study of a multi-residential building in Milan, Italy. Study showed a substantial improvement in the reliability of building energy simulation, and that occupant-related load profiles may account for about 8% of the building's energy need for space heating.

2.4. Onsite Renewable Energy Generation

To meet their energy needs, NZEBs typically incorporate on-site renewable energy generation, such as solar panels or wind turbines. Advanced technologies harnessing renewable and alternative energy sources for power and heat production offer robust backup solutions for communities [61,62]. These technologies encompass diverse on-site power generation methods, including building-integrated photovoltaics (BIPVs), solar thermal collectors, geothermal heating, micro wind turbines, often integrated with microgrids, hybrid energy systems, and more. Strategically planning and deploying these technologies can benefit entire communities, especially critical facilities like hospitals and accommodation for vulnerable populations, such as retirement homes. Notably, combined heat and power systems and microgrids ensure continuous operation, not limited to emergencies, making them reliable energy supply options.

Photovoltaic (PV) systems paired with batteries: Photovoltaic systems, renowned for their resilience during extreme weather events, serve as backup power sources for buildings and critical facilities, enhancing community resilience. These PV systems can be tailored to provide essential functions to residences during power outages, ensuring their survival [63].

Micro wind turbines: Small-scale urban wind turbines, encompassing both building-integrated and stand-alone options, contribute to energy generation in urban settings. Building-integrated wind turbines can operate either grid-tied or off-grid, requiring battery storage for energy retention [64].

Micro combined heat and power (micro-CHP): Micro combined heat and power (micro-CHP) systems, specifically designed for single or multi-family houses and small office buildings, simultaneously generate electric power and thermal energy for space heating and hot water through waste heat recovery [61]. These systems can be configured to align with a building's energy demands, supplying heat or electricity as needed. This may result in surplus electricity or heat, necessitating methods for managing excess power, including energy storage solutions. Under normal conditions, any excess electricity can be fed back into the grid. While many micro-CHP systems utilize natural gas for heat and power generation, their overall greenhouse gas emissions are lower than those of alternative heat generation methods, such as condensing boilers. When connected to the grid, micro-CHP systems, including micro-CHPs, can operate independently, strengthening a building's resilience against power interruptions [39].

Fuel cell technologies present a promising avenue for clean power generation, yielding electricity and heat as valuable by-products. Operating through the chemical reaction of hydrogen and oxygen to produce water, fuel cells typically employ fossil fuels to generate hydrogen. Nevertheless, fuel cells emit significantly fewer pollutants than most other fossil fuel-based generators [62]. Fuel cells have applications in powering vehicles and supplying energy to various types of buildings, utilities, and communities. Use cases include backup power generation for hospitals, office buildings, schools, remote villages, campgrounds, temporary facilities like shelters, and construction sites. Fuel cells are pivotal in advancing distributed energy initiatives, providing electricity and heat while reducing vulnerability to disruptions in the central power grid [65].

The combination of various heat and power generation systems remains a central point for improving the efficiency of renewable and alternative energy resources. For example, investigations into integrating a fuel cell (FC) micro-cogeneration device, a heat pump (HP), and thermal storage have showcased an optimal solution for managing electrical and thermal storage, curbing energy consumption, and preventing excess energy production [66]. Fuel cell-based combined heat and power (CHP) systems can be customized to align with the energy requirements of individual buildings. Separate research delves into integrating heat pumps, photovoltaic (PV) systems, and local grid connections, underscoring their efficiency in multi-story buildings [67].

The essential strategies highlighted in this session emphasize the significance of a thorough and integrated approach to building design, construction, and operation. Adopting renewable energy sources, energy-efficient technologies, and sustainable building practices becomes imperative in addressing the intricate challenges of climate change and energy security. The synergy between advanced technologies, such as solar panels and intelligent building management systems, coupled with implementing energy-efficient materials and construction methodologies, constitutes the foundation of net-zero's objectives. The comprehensive integration of these strategies mitigates the environmental impact of buildings and elevates their overall performance, resulting in structures that actively contribute to a low-carbon future.

Crucially, the success of net-zero initiatives hinges on the collaboration between policymakers, industry stakeholders, and the wider community. Figure 5 provides the various renewable energy options for integration in buildings. Supportive policy frameworks, financial incentives, and public awareness campaigns are integral to fostering an environment conducive to sustainable building practices. By aligning interests and mobilizing resources, we can accelerate the transition to NZEBs on a global scale. The journey towards net-zero energy buildings transcends individual structures; it embodies a collective commitment to mitigating climate change and fostering a more sustainable built environment. Energy-oriented design envelope parameters, renewable energy efficiency, energy monitoring and automation with intelligent sensors and IoT, and on-site integration of renewable energy systems are the significant drivers toward zero-energy concepts in residential buildings. As technology evolves and awareness grows, implementing these key strategies provides a roadmap for architects, engineers, policymakers, and citizens alike to contribute meaningfully to a greener and more energy-efficient future. The quest for NZEBs is not just a technological challenge but a shared vision that requires continued dedication, innovation, and collaboration to realize a world where our built environment harmonizes with the planet's ecological balance. In conclusion, integrating renewable energy sources in the buildings represents the way forward to net-zero energy consumption in buildings.

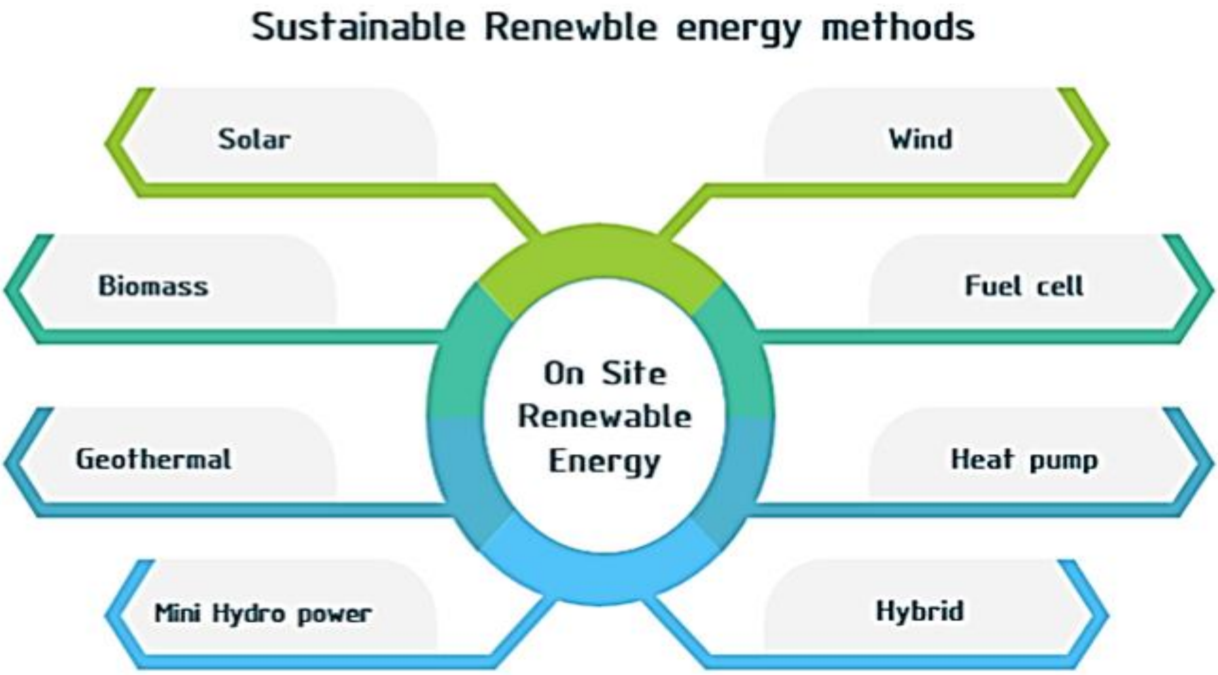

Figure 5. Various renewable energy options for integration in buildings.

3. How Can Sustainable Energy Technologies Such as Solar, Wind, Biogas, Geothermal, and Hybrid Systems Be Integrated into the Building?

Integrating innovative energy technologies into building structures has become paramount in pursuing a sustainable and resilient future. This is one of the critical structures of NZEBs. On-site energy generation mitigates environmental impact and enhances energy efficiency, fostering a harmonious relationship between the built environment and the ecosystem. This study has to go through the present scenario to explore critical sustainable energy technologies tailored for seamless integration into buildings, shaping a landscape where structures consume and contribute to generating clean and renewable energy. From solar photovoltaic systems and wind turbines to advanced building design and energy storage solutions, the following discussion focuses on a spectrum of cutting-edge technologies that redefine the role of buildings as active participants in the global transition towards a more sustainable energy paradigm. In addition to solar power, renewable energy sources such as wind turbines, biomass, geothermal, and hybrid systems are integrated into the building's energy infrastructure to reduce reliance on non-renewable energy sources.

3.1. Integration of Solar Technologies in the Building Sector (BS)

The installation of solar panels on various parts of the building design is a cornerstone of net-zero energy buildings. Figure 6 describes the different integration points of solar within the built environment or building infrastructure. The primary pathways of integrating solar power into the building envelope can be grouped into three categories: roof, facade, and external integrated devices [68]. Solar PV in roof areas may be utilized in continuous roofs, discontinuous roofs, and atriums. The second integration category is a facade, including rainscreen facades, double-skin facades, curtain walls, windows, and masonry walls. The third category comprises external integrated devices, representing elements and systems of the building envelope in contact only with the outdoor environment, including parapets, canopies, balustrades, and solar shading [69]. Building integrated photovoltaics (BIPV) offers a significant advantage, allowing solar panels to serve a dual purpose [70]. For instance, when crystalline solar panels are incorporated into a wall, they generate electricity and function as part of the wall structure. In contrast, placing solar panels on a rooftop involves only the additional installation cost. Various forms of BIPV exist, each with its unique approach to integrating photovoltaic systems [71].

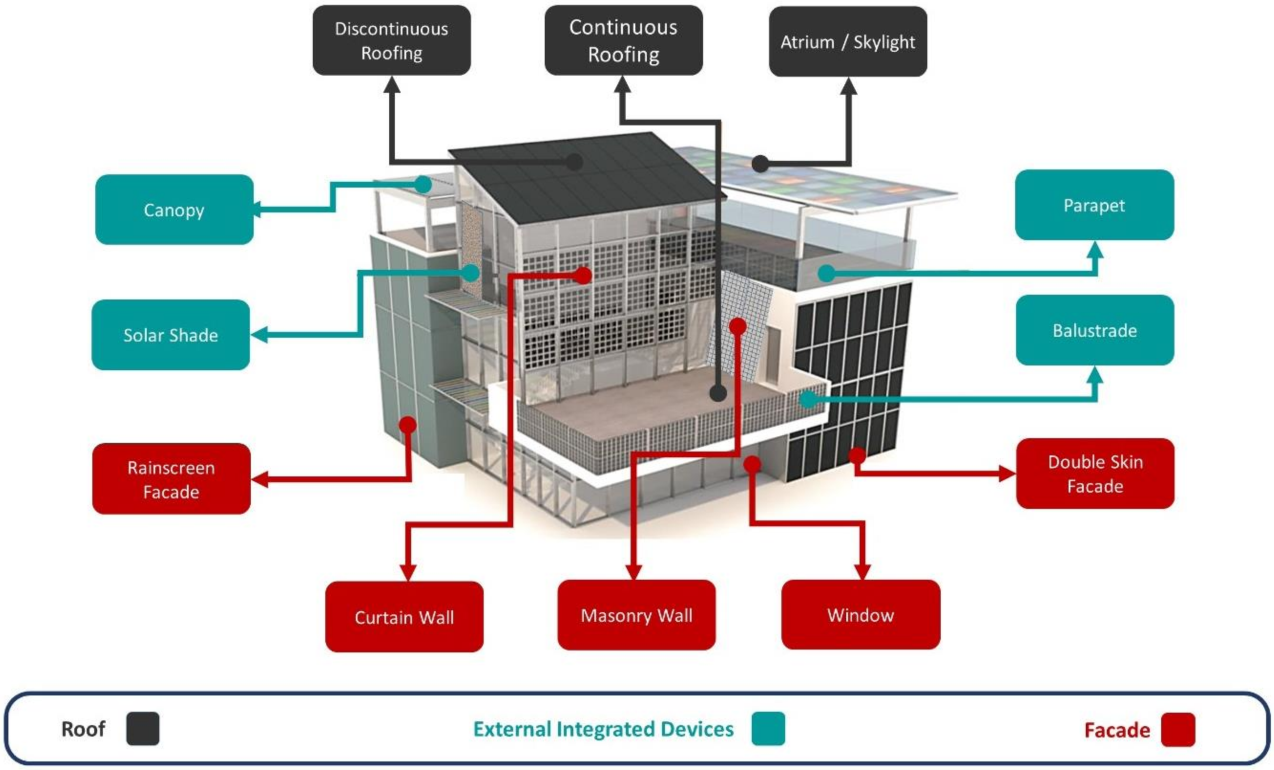

Figure 6. Solar integration in a building.

BIPV presents a notable drawback: it can only be implemented in newly-constructed buildings. While there is an alternative in the form of BAPV (building applied photovoltaics), the cost of BAPV tends to be considerably higher due to the absence of cost offsets related to the building materials, which is a primary advantage of BIPV. Furthermore, there is a lack of standardization in construction and installation within the BIPV industry [72]. In contrast, rooftop PV systems benefit from established standards, using crystalline silicon panels and standardized mounting systems. This standardization offers economic advantages through economies of scale and a smoother learning curve for the industry. However, the BIPV market is characterized by various technologies (including C-si, A-si, CIGS, CdTe, Dye-sensitized, and Organic Solar) competing for market share, each with unique installation standards [73].

However, C-Si has distinct drawbacks, including:

- Lack of transparency: C-Si cannot be installed in glass or windows.
- Less desirable aesthetics and low versatility: C-Si is not flexible in adapting to building designs.
- Relatively low performance under low light or partially shaded conditions.

In recent times, thin film technology has gained popularity, offering significant advantages in flexibility, transparency, and building aesthetics. Various thin-film technologies include:

- Copper indium gallium selenide (CIGS): CIGS cells are well-suited for BIPV due to their physical flexibility, aesthetics, relatively high efficiency, and good performance in diffuse light conditions. However, they tend to be less cost-efficient.
- Cadmium telluride (CdTe): CdTe is the only more cost-efficient technology than C-Si. However, First Solar, the dominant player in the CdTe market, has shown little interest in the BIPV market. Additionally, the toxicity of cadmium is a significant concern.
- Amorphous silicon (A-Si): A-Si is a reasonable alternative to C-Si as it is flexible and performs better in diffuse sunlight. It is cheaper than C-Si but significantly less efficient. Improving its efficiency remains a challenge.

- Dye-sensitized solar cells (DSC): DSC cells offer variability in color and transparency, making them a perfect solution for glass BIPV. However, their prices remain high, and overall efficiency is low, primarily because it is a relatively new technology.

BIPV presents a promising solution for urban development and is on the rise. In the pursuit of the second revolution in solar power, cost-effective and straightforward methods for installing PV systems on existing buildings have emerged, marking a significant breakthrough in the form of BAPV solutions. BIPV offers a viable solution for contemporary urban structures, especially considering the constraints of limited roof area relative to the number of stories in a building and the corresponding energy demands [74]. Table 4 illustrates the various case studies of solar integration in Buildings.

Table 4. Summary of various case studies on solar integration in buildings.

Author	Country	Type of Solar Integration	Remarks/Major Findings
Zhao et al., 2023 [63]	Swansea University, UK	BIPV with Li-ion battery energy storage	Studied the economic analysis of integrating Li-ion battery energy storage with BIPV for buildings in the UK. Results revealed that BIPV without battery storage turns profitable in a lifetime with the current electricity scenario, whereas BIPV with battery storage is not economically advisable.
Broers et al., 2023 [75]	Netherlands	BIPV	Case study covers the research gap on intermediaries that help in the multistage decision process on utilizing BIPVs in the Netherlands.
Jahangiri et al., 2023 [76]	Eight cities in Iran	BIPV	Techno-economic and energy analysis of BIPV for various cities of Iran carried out using HOMER 2.81. Jask city was found suitable, and Ramsar city was the least ideal for BIPV out of the eight Iranian cities analyzed.
Khan et al., 2023 [77]	Kuantan, Pahang, Malaysia	BIPV for residential and electric vehicle charging	Explored three cases of BIPV for Malaysian houses: grid integration without battery storage and with battery storage (75% and 100% battery storage). BIPV grid integration without battery storage was viable with 8.05 MWh energy generation and better greenhouse gas reductions.
Mangkuto et al., 2023 [78]	Bandung, Indonesia	BIPV for vertical facades	Explored optimum orientation for 105 Wp monocrystalline silica PV placement for tropical buildings based on three different objective functions. 179–186 kWh high annual energy yield was observed for north-oriented BIPV, but south orientation was found as optimum in this study for placing BIPV.
Shono et al., 2023 [79]	Tokyo, Japan	BIPV on large-scale building facades	Presented a model for estimating hourly PV potential for a commercial building in Tokyo. The generated power is enough to meet 15–48% of the annual electricity needs of the building. Negative impacts of large-scale BIPV on power systems are a reduction in asset utilization and an increase in the need for flexibility.
Yang et al., 2023 [80]	Three different climate zones/cities in Australia	BIPV double skin facades (BIPV-DSF)	Study on optimizing the design solutions of BIPV-DSF to office modules in three different climates of Australia. The other two parameters optimized were two different ventilation modes and four directions. The optimum parameters were different for different cities or climatic zones.

Table 4. *Cont.*

Author	Country	Type of Solar Integration	Remarks/Major Findings
Feng et al., 2023 [81]	Eight cities in China	Residential BIPV	Studied and proposed the research framework to access the potential of BIPV for residential buildings in different regions of China. Rooftop BIPVs are the best choice, followed by south facades in high latitude cities, then east and west facades.
Yang et al., 2023 [82]	Seven countries	BIPV	Studied fire safety requirements of BIPV in seven countries: Australia, UK, USA, China, Canada, and Singapore.
Uddin et al., 2023 [83]	Bangladesh	BIPV windows	Explored three configurations of semi-transparent CdTe combined BIPV windows for an office building. EnergyPlus-based model found CdTe combined BIPV windows can save 30–61% of annual energy consumption with 270 kWh electricity generation compared to conventional windows

Simulations showed that 30° was the most suitable angle for solar panels in Iran, and 90° was unsuitable for the Iranian climate based on analyzing four angles. Jask city was found to generate 39 MWh of annual solar electricity generation with a 30° angle-installed BIPV, priced at the low cost of 0.073 USD/kWh and reducing CO_2 emissions by 16.5 tons yearly with a return time of 11.7 years [76]. For the Malaysian study on BIPV utilization for buildings and electric vehicle charging, BIPV grid integration without battery storage was viable with better greenhouse gas reductions and 8.05 MWh energy generation at the rate of 0.16 RM/kWh and lower payback of 6 years with lower cost of EV charging of 2.08 RM/100 km [77]. The north-faced BIPVs integrated into building facades generated high electricity of 179–186 kWh annually for the Indonesian climate but with high uncertainty due to direct sunlight occurrence, whereas south-faced BIPVs were better with low uncertainty [78]. A case study on building stock in Japan suggested that facade BIPV could provide 33%, and PV modules on the rooftop could contribute to 15% of buildings' electricity needs by 2050 and considerably reduce carbon emissions [79]. A case study in China reported that rooftop PV is better at generating electricity than facade-integrated PV [81]. A Bangladesh case study found that PV-integrated windows can generate 270 kWh of electricity and contribute 30–61% annual energy savings for buildings [83]. In the present scenario from a case study across the UK, BIPV without battery storage is advisable for UK conditions [63].

In conclusion, solar energy is an excellent resource for reaching net-zero energy goals in buildings through efficient heating and cooling solutions. Solar energy, other energy-efficient technology, and renewable energy sources can drastically reduce a building's carbon footprint while providing year-round comfort.

3.2. Integration of Wind Technologies in the BS

Wind power, in particular, makes an appealing case because of its abundance, scalability, and low environmental impact on building applications. Clean electricity production is commonly performed by installing macro wind turbines deployed in large spaces far away from urban areas [84]. Large space requirements for these traditional wind turbines make them unsuitable for installation in urban locations where buildings occupy most of the available space. Integrating wind turbines, or BIWT, has come to light as a possible solution. Compared to large-scale wind energy systems, these systems are more advantageous in several ways, including reduced dependency on grid-connected power, longer transmission lines, and lower costs [85].

3.2.1. Wind Integration in Buildings

BIWTs can generate clean electricity for buildings using on-site micro wind turbines installed on the roofs of the buildings or spaces nearby or integrated into the architecture of the buildings (Figure 7). Two conventional kinds of wind turbines can be integrated into buildings, which are different based on their axis of rotation [86]. They are vertical-axis wind turbines (VAWT) and horizontal-axis wind turbines (HAWT) [87]. In areas characterized by low-density buildings and ample open space within the built environment, stand-alone wind turbines, specifically medium-scale horizontal axis wind turbines (HAWTs), are deployed for electricity generation. Conversely, a high-density built environment presents different challenges, leading to the consideration of small-scale vertical-axis wind turbines (VAWTs) explicitly designed for retrofitting existing buildings.

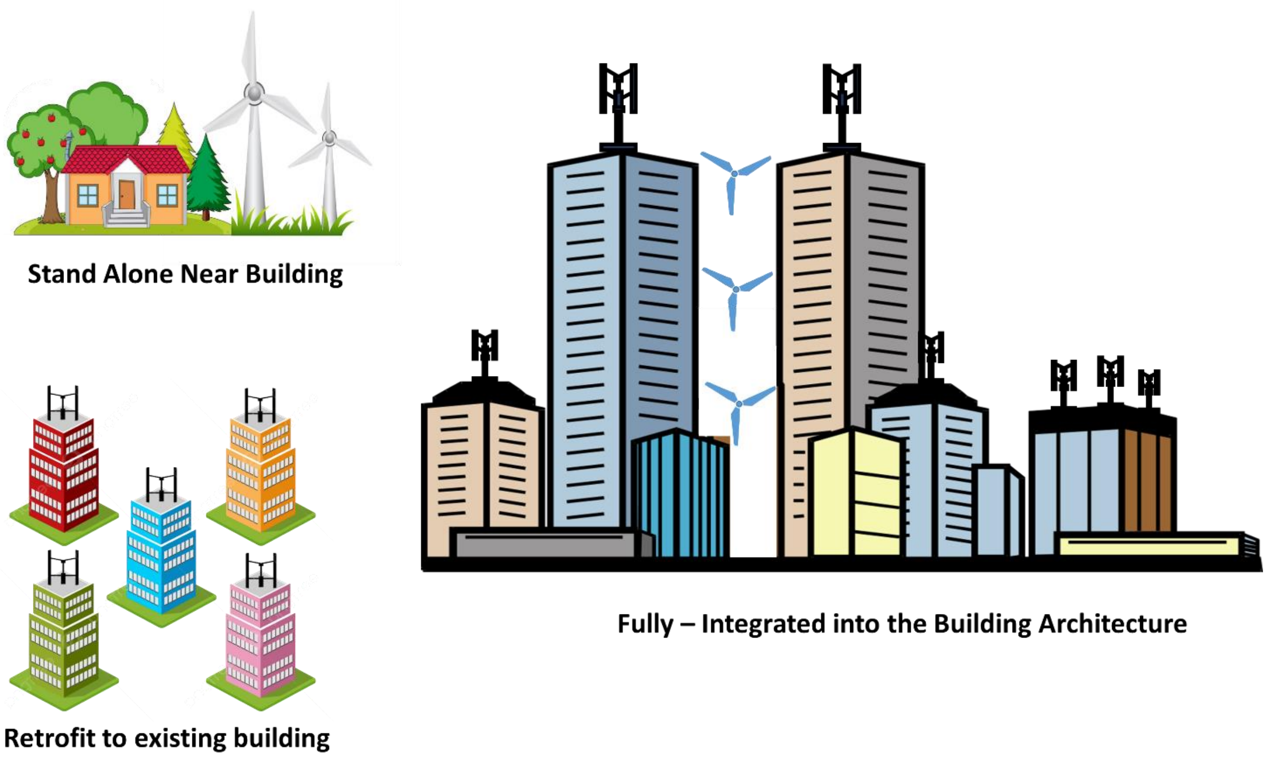

Figure 7. Wind integration of wind turbines in buildings [88,89].

3.2.2. Horizontal Axis Wind Turbines (HAWT)

The HAWT, with its more typical propeller-like shape, has a horizontally spinning rotor. While large-scale wind farms are typical, smaller ones are suited for urban incorporation. The difficulty with HAWTs in urban environments is their sensitivity to wind direction, which necessitates precise installation to improve effectiveness.

3.2.3. Vertical Axis Wind Turbines (VAWT)

The VAWT has a rotor that revolves around a vertical axis. This design is practical in metropolitan areas where the wind direction might be changeable and turbulent. BIWT can be put on building rooftops, facades, or standalone structures. Because of the vertical position, the design is more compact and aesthetically beautiful. Darrieus and Savonius wind turbines are the two types of VAWT. Savonius wind turbines function according to the drag force, whereas Darrieus wind turbines function according to the lift force [90,91].

The inability of these designs to fully utilize wind energy has prompted ongoing advancements in the construction of integrated wind turbines. Consequently, the duct-augmented wind turbine (DAWT) was developed, which includes ducts or diffusers that gradually increase the wind turbine's power coefficient [85,92]. With growing attention over power generation through wind energy, wind turbines with various designs, like cross-axis wind turbines and induced vibration technologies, are emerging for BIWT applications [85].

The major disadvantage of integrating small wind turbines into buildings is that they generate noise and vibrations when operating [84]. It affects the overall comfort and well-being of the building's occupants and birds. Addressing noise and vibration issues may necessitate additional steps and materials, increasing the final cost. The incorporation of BIWTs into buildings may provide structural and architectural design issues, as well as aesthetic concerns. Accessing and servicing BIWTs can be more complex than large wind turbines. Building codes and zoning regulations may make installing BIWTs difficult. Getting around these regulatory obstacles might add complexity and time to the project. Factors such as building height, shape, roof configuration, building location, and the spacing between buildings are pivotal in influencing wind flow patterns, consequently impacting the choice of turbine type, efficiency, and power output. These drawbacks limit the spread of wind turbine integration into buildings, and future research to address these issues could make BIWTs viable shortly [85]. Table 5 summarizes the various case studies of wind integration in buildings.

Table 5. Summary of various case studies on wind integration in buildings.

Author	Country	Type of Wind Integration	Remarks
Diaz et al., 2023 [93]	32 provinces of the Dominican Republic	Urban wind energy with small building integrated wind turbines	Evaluated the wind energy potential of 32 provinces in the Dominican Republic and factors influencing it. Five cities were found favorable for harnessing wind energy with average wind speed in the range of 4.83–6.63 m/s with predominant wind direction north east between 60°–90°.
Tawfik et al., 2023 [94]	Port of Alexandria, Egypt	Solar and wind energy for port buildings	DesignModeler 17.1 software was used for solar energy and ANSYS tool for wind energy simulations on port buildings. Small- to medium-vector axis wind turbines are the best choice for wind power generation.
Murshed et al., 2023 [95]	Lubbock, West Texas, USA	Distributed wind turbines to use wind power for household utilization	Carried out the design, economics, and analysis of a 6-kW distributed wind turbine utilization for power generation. The average wind speed for the location was 11.6 m/s
Tzen et al., 2023 [96]	Greece	Small-scale wind energy in urban areas	Fundamental overview of small wind turbines for small-scale energy generation in urban areas of Greece.
Tominaga, 2023 [97]	Niigata Institute of Technology, Japan	Small vertical axis wind turbine (VAWT) for wind power	Accuracy of CFD prediction of total power generation from VAWT installed on the university campus at wind turbine site 4 m above the ground. The study was conducted for the snowy winter, not throughout the season.
Abdelsalam et al., 2023 [98]	Guangzhou, China	Wind turbine integrated within building tunnel for wind power generation	Performance evaluation of a Savonius rotor integrated within the building. Savonius rotor installed in duct attained higher performance than free stream rotor.
Zhang et al., 2023 [99]	Newzeland	Wind power generation	Compare seven types of mainstream wind energy storage technologies for New Zealand. Analyzed the feasibility of using small wind turbines for household power needs and found they have notable power generation capability in the long term.
Deltenre et al., 2019 [100]	Brussels, Belgium	Rooftop PV and rooftop wind turbines	Considering an average wind speed of 5 m/s, roof-mounted wind turbines produce more power than roof-mounted PVs. Techno-economic comparison shows 3.2 kW and 5.2 kW turbines compete with PVs only in power generation terms.

In the Dominican Republic case study, five cities out of 32 provinces were found favorable for harnessing wind energy with an average wind speed of 4.83–6.63 m/s with a predominant wind direction northeast between 60°–90° [93]. Small to medium vertical axis wind turbines are reported as the best choice for wind power generation in port buildings of Alexandria, Egypt [94]. A case study in Lubbock, USA, showed that the city has great potential to generate wind power with a wind speed of 11.6 m/s, and 6 kW distributed wind turbines can reduce greenhouse gas emissions by 50% annually [95]. From a case study on wind turbines in building tunnels in a Chinese city, it was reported that the Savonius rotor installed in a duct attained higher performance than the free stream rotor [98]. A New Zealand case study showed that small-scale wind turbines can generate wind power in the long term compared to large-scale wind turbines. A case study in Brussels, Belgium, suggested that small-scale wind turbines with 3.2 kW and 5.2 kW capabilities can compete with PV panels in power generation but are not economical, whereas 10 kW wind turbines can compete economically with PV panels [100].

In conclusion, wind energy is an excellent resource for reaching net-zero energy goals in buildings through efficient heating and cooling solutions. When combined with other energy-efficient technology and renewable energy sources, wind energy can drastically reduce a building's carbon footprint while providing year-round comfort.

3.3. Biomass and Biogas Energy for Buildings

Biomass can be used as a direct heat source by burning it to produce heat directly. The other way of using biomass for building energy is by generating biogas. Biogas is a renewable energy source generated from the anaerobic digestion of agricultural waste, animal waste, food and human residues [101,102]. Biowaste is collected and added to a digestor along with water. The digestor is then sealed, and the biowaste added will undergo a series of biochemical reactions in the absence of air with the help of microorganisms, giving rise to biogas that contain predominantly methane [102]. The biogas produced using anaerobic digestion is helpful for domestic heating and cooking and is used as a fuel for power generation. Biogas production helps in organic waste management, and the residue produced from biogas production could be used as fertilizer. Biogas generation is favorable mainly for buildings in rural areas due to the abundant availability of agricultural and animal waste. Figure 8 illustrates the concept of biogas integration in buildings. Table 6 provides the summary of various case studies on biomass-based energy integration in buildings.

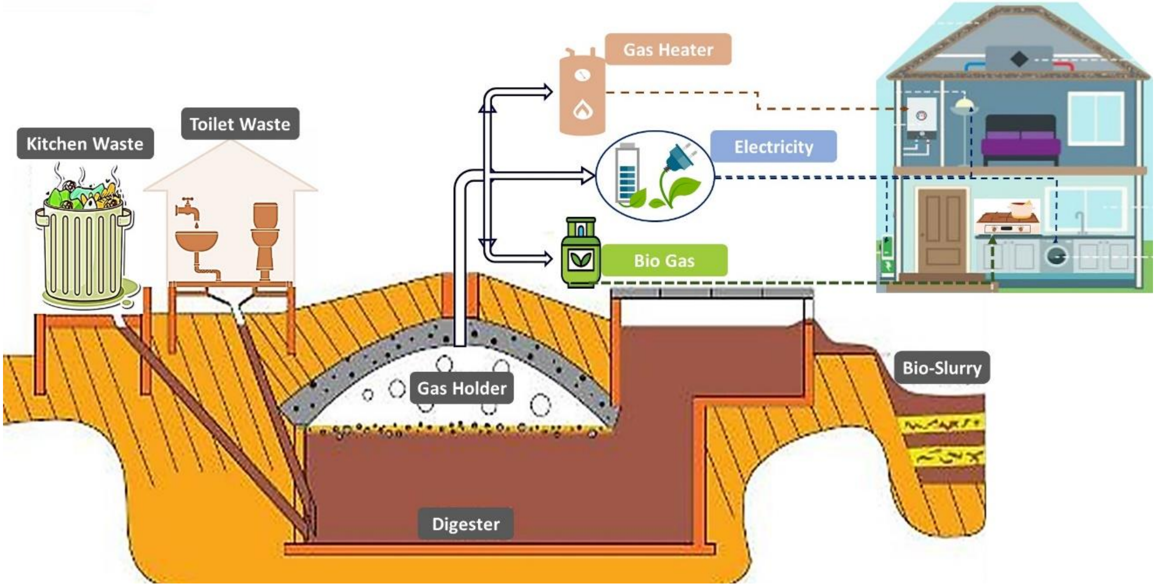

Figure 8. Biomass-based energy integration in buildings.

Table 6. Summary of various case studies on biomass-based energy integration in buildings.

Author	Country	Biomass-Based Energy Integration	Remarks
Ebrahami-Moghadam et al., 2023 [103]	Mashhad, Iran	Optimization of biomass-driven plant for combined heat, cold and power	The system produced 541 kW of electricity, 2052 kW of heat, and 2650 kW of cold at optimum operating conditions.
Huang et al., 2023 [104]	Chongqing city, China	Kitchen waste-based bio energy plant optimization	A surplus renewable energy feed-in district energy system produces a minimum of 9457 kWh/day and a maximum of 16,793 kWh/day.
Shebanina et al., 2023 [105]	Ukraine	Economics of agriculture-based bioenergy plant	Bioenergy plants could help in producing electricity irrespective of pre-war or war conditions.
Liu et al., 2023 [106]	Kuala Lumpur, Malaysia	Comparison study of grid-electrified and biogas-based cooling systems	The district cooling system fueled with biogas-generated electricity comes at MYR 1.004 million/year and reduces CO_2 emissions by 41.1 kt eq. CO_2/year.
Furubayashi et al., 2021 [64]	Koriyama city, Japan	Analysis of woody biomass energy in district heat systems for residential buildings and commercial sectors	Producing heat with biomass reduced CO_2 emissions more than having electricity or combined heat and power.
Picardo et al., 2019 [107]	Atlantic and continental regions of Spain	Analysis of district heating system utilizing biogas generated from water treatment plants to supply heat and hot water to the municipality	With an investment of EUR 2854 million, CO_2 emissions of 1.8 Mt per year could be reduced
Santoli et al., 2015 [108]	Bari airport, Italy	Comparison of building-integrated bioenergy production with three green sources	Bioenergy generated using wood chips was more sustainable than biodiesel and farm waste.

The production of heat utilizing biomass was more eco-friendly than using it for power generation or combined power and heat generation [64]. The Iranian case study showed that the designed sustainable municipal solid waste-based trigeneration system, i.e., a combined heating, cooling, and power system, could provide 541 kW of electricity, 2052 kW of heat, and 2650 kW of cold at optimum operating conditions to the buildings with the levelized electricity generation cost of 0.083$/kWh [103]. The China-based case study in which a kitchen waste feed-based biogas plant was integrated with a district energy system generated 9457–16,793 kWh/day with surplus feed-in mode operation [104]. In the Malaysian case study, the district cooling system was fueled with biogas-generated electricity, priced at MYR 1.004 million/year, and CO_2 emissions were reduced by 41.1 kt eq. CO_2/year [106]. Biogas could be generated from the waste treatment process, which could be used to supply hot water and heat to the municipality. The Spain-based case study suggests that investing EUR 2854 million into utilizing biogas from wastewater treatment for domestic heat and hot water supply will reduce emissions by 8 Mt/year CO_2 emissions [107]. The best local bioenergy generated using wood chips was found to be most sustainable compared to biodiesel and farm waste for the case study at Bari airport in Italy [108].

In conclusion, biomass-based energy generation is an excellent resource for reaching net-zero energy goals in buildings through efficient heating and cooling solutions. Biomass-based energy, when combined with other energy-efficient technology and renewable energy sources, can drastically reduce a building's carbon footprint while providing year-round comfort.

3.4. Geothermal Energy in Buildings

Geothermal systems are sustainable and energy-efficient solutions that can be integrated into buildings for heating, cooling, and sometimes hot water supply by harnessing the Earth's natural thermal energy. Heat pumps are typically used to enhance the efficiency of these systems by compressing and transferring heat [109]. The integration involves connecting the geothermal system to the building's heating, ventilation, and air conditioning (HVAC) system. The system can be designed to work seamlessly with the building's existing infrastructure, providing a comfortable indoor environment while minimizing energy consumption and environmental impact.

GSHP (ground source heat pumps): Ground source heat pumps, often known as geothermal heat pumps, are a common technique for net-zero building heating and cooling. They exchange heat with the structure by taking advantage of the generally constant temperature of the Earth below the frost line (usually approximately 50 °F to 60 °F or 10 °C to 15 °C). The system collects heat from the ground and provides it to the building during the winter, releasing heat from the building into the ground during the summer. This highly efficient technique can minimize heating and cooling energy usage. There are various types of geothermal systems, including vertical, horizontal, closed-loop, and pond-loop systems, each with its characteristics and applications.

Vertical geothermal systems: Vertical geothermal systems involve drilling boreholes into the ground to access the Earth's heat. Pipes are inserted into these boreholes, and a heat transfer fluid circulates. This type is suitable for areas with limited horizontal space, making it a viable option for urban environments or sites where the land area is restricted [110].

Horizontal geothermal systems: In horizontal geothermal systems, pipes are laid horizontally in trenches dug at a relatively shallow depth beneath the Earth's surface. The pipes contain a heat transfer fluid that absorbs or releases heat. This system is ideal for larger plots of land where horizontal space is more readily available. It is a common choice for residential applications and small commercial buildings [111].

Closed-loop geothermal systems: Closed-loop geothermal systems circulate a heat transfer fluid (usually a mixture of water and antifreeze) through a closed system of pipes. Sometimes, closed-loop geothermal heat exchangers can be built vertically or horizontally in the ground near the building to exchange heat. The fluid absorbs heat from the environment in winter and releases heat into the ground in summer. They are commonly used in residential and commercial buildings due to their efficiency and minimal environmental impact. Although less efficient than GSHPs, these systems can provide significant energy savings for net-zero buildings [112].

Pond loop geothermal systems: Pond loop systems utilize a body of water, such as a pond or lake, as a heat exchange source. Pipes are submerged in the water, and a heat transfer fluid circulates through them, transferring heat to or from the water. This system is suitable when a water source is available nearby. It is often chosen in areas with accessible bodies of water and is considered environmentally friendly. The geothermal energy systems that could integrate into buildings are shown in Figure 9.

The following are some examples of geothermal integration towards net-zero buildings [113]:

Geothermal systems for direct use: Direct-use geothermal systems can provide room heating and even energy generation in places with access to hot geothermal reservoirs. These systems are more widespread in areas with active geothermal resources, such as Iceland and the United States.

Thermal energy storage: In addition to geothermal energy, thermal energy storage devices can be used. A net-zero building can heat or cool a thermal storage system when there is excess renewable energy (for example, from solar panels or wind turbines). When renewable energy production is low, the stored thermal energy can be used later.

District geothermal systems: In metropolitan locations, district geothermal systems can be developed to provide centralized geothermal energy to several buildings. Because it uses economies of scale, this strategy can be more cost-effective and efficient.

Reduced greenhouse gas emissions, stable energy costs, and improved energy resilience are all advantages of using geothermal energy in net-zero buildings. On the other hand, the practicality and effectiveness of geothermal energy consumption depend on elements such as geological conditions, local climate, and building design. Proper design, installation, and maintenance are required to reap the full benefits of geothermal systems in net-zero buildings. Table 7 provides a summary of the integration of geothermal energy systems in buildings.

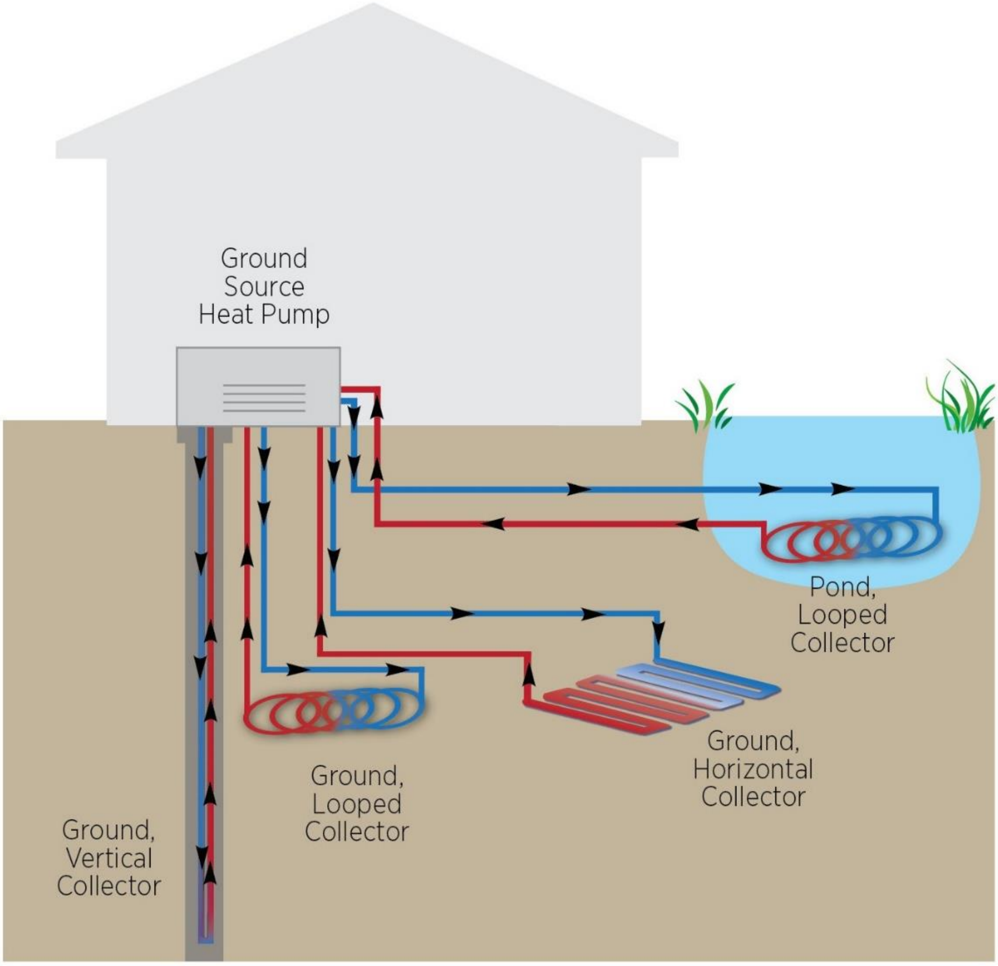

Figure 9. Geothermal integration in a building [114].

Table 7. Summary of various geothermal energy systems' integration in buildings.

Author	Country	Type of Geothermal System	Remarks
Vargas-Payera et al., 2023 [66]	Patagonia, Chile	Social and cultural aspects of adopting GHPS for educational spaces replacing wood-burning heaters	Lack of information regarding GHPS technology and perception of it as untouchable elegant technology stopping the adoption of GHPS.
Abed et al., 2023 [115]	Iraq	Geothermal energy-based air conditioning	With an air velocity of 4 m/s, the designed system reduced the air temperature by 10–16 °C.
Kljajic et al., 2020 [116]	Serbia	Geothermal heat pump system (GHPS) for district cooling	The designed system could reduce primary inlet energy consumption by at least 30%
Piselli et al., 2020 [117]	Italy	Ground source heat exchangers coupled with adsorption heat pumps for buildings	GHEX-coupled adsorption heat pumps could increase historic buildings' energy and environmental performance.
Senova et al., 2022 [118]	Slovakia	Geothermal energy for building heating	Adopting geothermal energy for building heating could reduce the consumption of natural gas or coal.

Table 7. *Cont.*

Author	Country	Type of Geothermal System	Remarks
Han et al., 2023 [119]	Mei County, China	Mid-deep ground water heat pumps for clean energy into buildings	The optimized geothermal-based system could save an electricity bill of RMB 392,000 per heating season.
Li et al., 2023 [120]	Melbourne, Australia	Ground source heat pump for high-performance buildings	An integrated framework simulation showed results close to the experimental conditions, a 0.92% difference in inlet temperature and 2.2% in gross thermal energy production
Erkan et al., 2023 [121]	Thrace Basin, Turkey	Potential of geothermal energy production for the future	Bottom hole showed 45–64 °C at 1 km depth, 99–136 °C at 3 km depth, and 155–208 °C at 5 km depth.
Ahmed et al., 2023 [122]	Poland	A comparison study on the performance of borehole heat exchangers to fuel-based systems	GSHP system could reduce CO_2 emissions by 58% compared to coal-based systems.
Korhonen et al., 2023 [123]	Central Budapest, Hungary	A model developed for estimating the technical potential of shallow geothermal energy in urban areas separated in less space	100 m deep independent boreholes produce 14.20 MWh/annum, whereas the infinite borehole field model predicted it would be 7.80 MWh/annum from holes spaced with 20 m.

An earth cooling system based on ground source heat exchange in Iraq was found to reduce air temperature from AC outlets by 10–16 °C when the air flows with 4 m/s velocity inside the ground source heat exchange system [115]. In Serbia, using a district heating geothermal heat pump would reduce the primary inlet energy consumption by 30% as the air can be heated using ground heat [116]. In a case study on Mei County, China, it was reported that the region has excellent geothermal resources and recoverable heat from geothermal sources is 1.3×10^{14} kJ/year, and mid-deep groundwater heat systems can reduce the electricity bill of RMB 392,000 per heating season using geothermal heat sources [119]. A case study in Turkey showed that boreholes at 1 km depth had 45–64 °C, at 3 km depth 99–136 °C, and at 5 km depth 155–208 °C temperatures that could be utilized as potential geothermal resources [121]. The Poland case study proved that a geothermal-based heating pump system could generate 58% fewer carbon emissions when compared to a conventional coal-based system [122]. A case study in Hungary studied the potential of using geothermal energy in urban areas. It showed that the energy generated is 7.8 MWh from the holes spaced 20 m in urban areas [123].

In conclusion, geothermal energy is excellent for reaching net-zero energy goals in buildings through efficient heating and cooling solutions. Geothermal energy can drastically reduce a building's carbon footprint while providing year-round comfort when combined with other energy-efficient technology and renewable energy sources.

3.5. Hybrid Energy Systems for Buildings

Hybrid energy systems may be a viable option for sustainable development in this industry to meet the energy requirements of buildings and meet the NZEBs. These systems comprise a few subsystems that work together as an integrated system. These systems have the following benefits: delivering all forms of energy (such as hot water, space heating and cooling, and electricity) inside a monolithic system; (2) lowering energy losses during operations and so conserving fuel; (3) lowering CO_2 emissions; and (4) saving money. These systems use a variety of energy sources as their primary input, including geothermal, biomass, wind and solar energy [103]. The complete renewable source-based energy utilization will reduce costs and improve environmental friendliness. The hybrid renewable systems integrated with renewable energy sources and storage systems for the buildings are shown in Figure 10. Table 8 provides a summary of various hybrid energy system integrations in buildings.

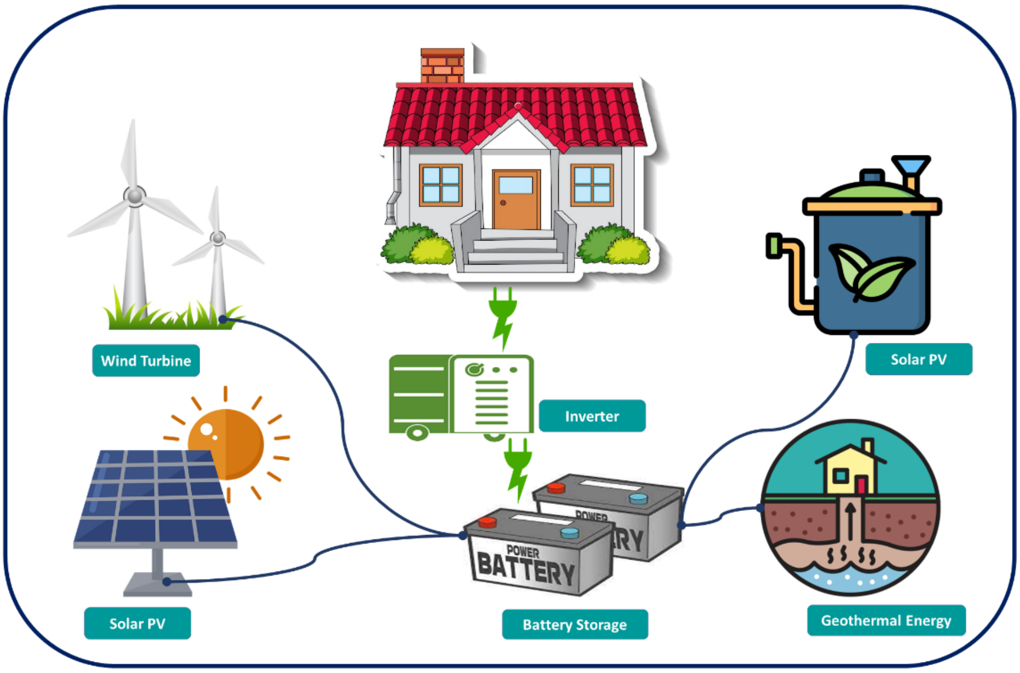

Figure 10. Hybrid integration of renewable energy systems into a building.

Table 8. Summary of various hybrid energy systems' integration in buildings.

Author	Country	Types of Hybrid Energy Systems	Remarks
Luo et al., 2023 [67]	Chongqing, China	A polygeneration system integrated with a ground source heat pump and anaerobic digester for rural areas.	Integrated systems saved 21.6% and 32.2% of primary energy compared to individual technologies.
Liu et al., 2023 [124]	Xilin Hot, Inner Mongolia	Hybrid heating system with solar, biogas and phase change thermal energy storage	The hybrid system showed stable supply and demand with good economic benefits and a payback period of 4.15 years.
Temiz et al., 2023 [125]	USA, Turkey, Canada, and Germany	Hybrid system integrated with solar and geothermal energy for heat, cold and power, along with domestic hot water for residential buildings	Turkey was found to be self-sufficient by using a building surface area with 495 kWp BIPV and 90 kW rooftop PV.
Khalil et al., 2023 [126]	Canada, South Africa, Netherlands Denmark	Integrated system with solar, wind and biomass energy for various applications	The hydrogen generated was 307, 232, 399, and 487 tons for Canada, South Africa, Netherlands, and Denmark.
Zhang et al., 2023 [127]	Stavanger, Norway	Biogas fueled micro gas turbine and borewell heat exchanger or pump for seasonal thermal energy storage for 4-floor hotel building.	Design and optimization studies were carried out for the integrated system for the whole lifetime, and the energy consumption of the system was found to be 15,106,125 kWh
Abdelhady 2023 [128]	Egypt	Hybrid renewable energy systems for hotel buildings contain PV, wind, and biogas systems.	The present cost of the hybrid system is k$ 388, and the electricity cost after generation is charged as 2.1₵/kWh whereas conventional electricity is charged at 6.9 ₵/kWh
Mendecka et al., 2021 [129]	United States	Biogas-solar-based hybrid off-grid power plant with storage for commercial buildings	A power plant can operate with 100% renewable procurements if the bio-digester produces 6000 to 9500 std m^3/y and the battery is fully charged at the start of the year.

A case study on hotel buildings suggested that the electricity generated from the hybrid energy system containing 143 kW PV, 20 kW wind with a hub height of 18 m was cheaper than conventional electricity [128]. An integrated energy system consisting of a ground source heat pump and biogas from anaerobic digestion in rural China showed 21.6% and 32.2% more savings on primary energy than individual energy systems [67]. Hybrid energy systems are cost-intensive but can provide a stable supply compared to individual energy systems [124].

4. What Are the Technical Challenges and Opportunities Associated with Integrating Diverse Renewable Energy Sources into the Built Environment?

The drive for a net-zero energy-built environment is a target for many countries worldwide. Renewable energy integration in buildings presents a compelling array of opportunities, though it is not devoid of challenges [130].

4.1. Opportunities

Cost savings: Renewable energy integration in buildings is a beacon of energy efficiency, significantly reducing energy costs for building owners and occupants. Furthermore, these buildings generate their energy on-site, acting as a safeguard against the volatility of energy prices [131].

Environmental stewardship: Incorporating renewable energy into buildings is crucial for addressing climate change by reducing greenhouse gas emissions. The self-sustained production of renewable energy minimizes reliance on fossil fuels and non-renewable energy sources [132].

Enhanced indoor air quality: Thanks to meticulous insulation and airtight design, renewable energy integration in buildings prevents external pollutants from infiltrating indoor spaces. State-of-the-art ventilation systems are often integrated, supplying a continuous fresh air flow, ultimately promoting healthier indoor environments [12].

Improved comfort: Integrating renewable energy into buildings ensures year-round comfort by maintaining a consistent temperature, humidity, and air quality. This approach enhances occupant comfort and contributes to increased productivity [9].

Resilience: Renewable energy integration in buildings is engineered for superior strength compared to conventional structures. Their energy systems can endure power outages and grid disruptions, a particularly crucial attribute in disaster-prone regions.

Potential revenue streams: Excess energy generated by renewable energy integration in buildings can be fed back to the grid, allowing building owners to generate revenue.

4.2. Challenges

Upfront investment and cost: Realizing renewable energy integration in buildings requires substantial upfront investments in energy-efficient technologies like solar panels, insulation, and high-performance windows [133]. These technologies can be cost-intensive, making it challenging to justify the investment, particularly in regions with low energy costs. Achieving renewable energy integration in buildings demands a significant investment in time and financial resources despite the considerable progress in sustainable energy technology. While installing renewable energy solutions, like PV panels, can offset their initial costs through reduced operational energy expenses within a short timeframe, a comprehensive evaluation of expenses is crucial. It is imperative to recognize that high-performance buildings inherently incur lower long-term operational and maintenance costs.

Complex design: Renewable energy integration in buildings is a complex endeavor that requires meticulous attention to various factors, including building orientation, shading, insulation, ventilation, and energy generation technologies [134]. This intricacy can render the design process more time-consuming than conventional buildings. To ensure the efficient construction and maintenance of net-zero energy buildings (NZEBs), meticulous consideration must be given to every facet of a building's design, construction, and operation. This necessitates additional time and labor in the creation of NZEBs. Furthermore, the effectiveness of highly efficient strategies may be compromised due to insufficient training in proper installation techniques and a lack of knowledge about implementing new technologies.

Maintenance and operation: Maintaining a renewable energy system in a building can be more intricate than managing a traditional building [135]. Ongoing monitoring and upkeep of energy systems are vital to sustain peak efficiency. Occupants must also be educated on the effective use of these systems and encouraged to adopt energy-saving behaviors. Advanced IoT-based automation technologies can simplify this task.

Grid integration: Integrating surplus energy produced by renewable energy systems in buildings back into the grid requires meticulous coordination with the local electricity grid. The grid must accommodate the variability inherent in renewable energy sources, and building owners may need to negotiate with utilities to ensure fair compensation [136].

Climate and geographic considerations: Designs of renewable energy systems may require adjustments to align with local climate and weather patterns, presenting challenges for building owners and operators in various geographic locations [137]. In regions characterized by cold winters or hot summers, energy consumption tends to escalate, primarily driven by the necessity for substantial HVAC systems. In areas with high humidity, natural ventilation proves less effective. Conversely, relying solely on insulating materials is insufficient in the coldest climates without incorporating a heating system. Consequently, attaining net-zero energy (NZE) status by integrating renewable energy is contingent upon unpredictable weather conditions, further exacerbated by the uncertainties introduced by climate change.

Energy transition challenges: There are many obstacles to the switch to renewable energy in building construction. Widespread adoption of renewable technologies like BIPV and BIWT is hindered by reliability issues arising from current infrastructure constraints and the intermittent nature of renewable sources. Development is also hampered by a lack of uniform laws and resistance to change within conventional building techniques [138]. Workforce shortages are also a result of the transition's need for specialized workers for installation and maintenance. The ongoing evolution of storage technology complicates the smooth integration of intermittent renewable energy sources. A more seamless shift towards a sustainable and renewable future in building construction necessitates coordinated efforts in amendments to laws, financial incentives, technology innovation, and public awareness to overcome these challenges.

The opportunities are vast in integrating renewable energy systems in buildings. Still, navigating the associated challenges is essential to pave the way for a sustainable and energy-efficient future in the building sector [139]. Integrating renewable energy in the built environment presents formidable challenges, yet utilizing current materials, technology, and methodologies offers a promising avenue to overcome these obstacles.

5. Future Outlook and Recommendations

Achieving net-zero energy buildings poses challenges, such as the high initial cost of installing renewable energy systems compared to the total building cost. The technical feasibility of integrating solar energy into these structures and building owners' motivation to invest remains uncertain and challenging. Moreover, the limited availability of visually appealing building-integrated photovoltaic (BIPV) modules hampers the widespread adoption of net-zero energy buildings. Intelligent and sustainable technologies will likely shape how we design, construct, and manage the built environment. Predictions include the overall integration of advanced energy-efficient materials, the expansion of intelligent building automation systems, and the incorporation of innovative renewable energy solutions. The integration of renewable energy in buildings may evolve to become energy producers and dynamic contributors to grid resilience, leveraging sophisticated energy storage and management systems. A universal decision instrument for optimal design and operation is essential for the successful development of net-zero energy buildings. Builders and developers should prioritize sustainability in their projects, embracing eco-friendly materials, energy-efficient designs, and renewable energy solutions. Collaboration with technology providers can lead to integrating cutting-edge solutions into construction processes. Other stakeholders, including investors and consumers, can play a role by prioritizing sustainable projects and demanding transparency regarding the environmental impact of buildings and communities. Training programs can ensure that construction professionals are well-versed in the latest sustainable building practices.

Potential Areas for Research and Development to Enhance Sustainability

Research and development (R&D) efforts should focus on advancing technologies to enhance the built environment's sustainability. R&D in the built environment focusing on sustainability is crucial for addressing the challenges of urbanization, resource depletion, and environmental degradation. Here is a comprehensive discussion of various potential areas for R&D in the built environment from a sustainable perspective. This includes:

- Energy storage and management: Developing efficient energy storage systems can help address the intermittent nature of renewable energy sources, ensuring a stable and reliable power supply. Investigate ways to enhance building energy efficiency through improved insulation, intelligent energy management systems, and integrating renewable energy sources like solar and wind. Develop energy storage solutions to optimize the use of renewable energy.
- Advanced building materials: Research on innovative, eco-friendly materials with improved insulation properties and reduced environmental impact can contribute to energy-efficient building designs. Research can focus on developing eco-friendly materials with minimal environmental impact during production and use. Explore innovative construction technologies that reduce energy consumption and waste generation.
- Smart grid integration: Enhancing the integration of buildings with smart grids can optimize energy consumption, facilitate demand–response mechanisms, and improve overall energy grid resilience.
- Circular economy practices: Investigating circular economy principles in construction, such as recycling and reusing materials, can minimize waste and promote sustainable resource management.

6. Conclusions

This comprehensive review has offered a more thorough understanding and goes beyond a surface-level examination of various strategies for decarbonizing the built environment. The analysis has comprehensively examined diverse renewable technologies, encompassing solar, wind, biomass and geothermal. It has also explored integrating hybrid renewable energy systems for building applications. In conclusion, this paper has comprehensively analyzed the crucial role of decarbonizing residential buildings in achieving global climate goals.

6.1. Key Findings

- ➢ The successful attainment of decarbonization in buildings involves critical concepts such as strategic site selection, building orientation and design, energy efficiency, energy monitoring and management, and on-site renewable energy, thereby promoting healthful indoor environments.
- ➢ The holistic integration of BIPV and BAPV, combined with intelligent technologies, represents a forward-thinking approach to achieving net-zero energy consumption in modern buildings. However, limited developments in commercial BIPV products and the lack of skilled designers hinder the widespread adoption of net-zero energy buildings.
- ➢ The integration of solar technologies emerged as a prominent and viable option, offering a clean and abundant energy source. Wind technologies also showcased significant potential, especially in regions with favorable wind conditions. Additionally, incorporating geothermal, biomass plants, and hybrid renewable energy systems alongside the crucial integration of energy storage solutions demonstrated

diverse approaches to building decarbonization. However, successfully integrating these sustainable technologies into the building landscape presents challenges and complexities.

- Opportunities included reduced carbon emissions, energy independence, and economic benefits. However, challenges such as intermittency, upfront costs, grid integration complexities and regulatory barriers must be addressed for effective implementation.

6.2. Practical Implications & Recommendations

- Scientific advancements in materials science and engineering contribute to the evolving landscape of renewable energy integration in the building sector.
- The continuous development of innovative solutions, such as advanced solar panels, efficient geothermal systems, energy storage, and intelligent building technologies, provides exciting avenues for research and application in the building sector. Sustainable R&D efforts in the built environment involve innovative materials, smart technologies, urban planning strategies, and policy frameworks.
- The transformative potential of embracing present-day advancements to dismantle barriers and construct buildings capable of meeting future demands must be explored. Collaborative efforts among stakeholders, including building owners, local governments, industries, and communities, are essential to creating resilient, energy-efficient, and environmentally friendly environments for present and future generations to overcome challenges and seize opportunities. This involves a call for continued research and development, supportive policies, and public awareness initiatives. A multi-pronged approach is essential, encompassing effective policy frameworks, technological advancements, financial incentives, and public awareness campaigns.

6.3. Limitations of the Study

- The study findings are generalized to provide the global perspectives of the decarbonizing strategy. However, specific regions focused on different climates, policies, and building typologies are needed for effective implementation.
- The affordability and accessibility of different decarbonization strategies for buildings depend on socioeconomic factors such as diverse income levels and housing situations, which are not carefully analyzed in the manuscript.

6.4. Significant Contributions towards SDG

- The study aligns with specific sustainable development goals (SDGs) such as the integration of sustainable energy technologies (SDG 7), the development of more sustainable urban environments(SDG 11), reducing carbon emissions from residential buildings contributes to climate action (SDG 13), promoting inclusive and sustainable industrialization and fostering innovation (SDG 9), responsible energy consumption and production (SDG 12), potential positive effects on biodiversity and ecosystems on land(SDG 15), and importance of collaboration among various stakeholders (SDG 17).
- The article's content is aligned with several SDGs, including 7, 9, 11, 12, 13, 15, and 17, emphasizing the interconnected nature of sustainable development and the importance of integrating renewable energy technologies for a more sustainable and resilient future.

The future success of decarbonizing built environments lies in our ability to embrace innovation, foster collaboration, and implement supportive policies.

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