https://gospodarkainnowacje.pl
GOSPODARKA I INNOWACJE
LABORATORIUM WIEDZY Artur Borcuch
Volume: 53 | 2024
Economy and Innovation
ISSN: 2545-0573
For more information contact : editor@gospodarkainnowacje.pl

ENERGY HARVESTING AND STORAGE SYSTEMS FOR NET-ZERO ENERGY BUILDINGS: A REVIEW OF RECENT ADVANCES AND FUTURE DIRECTIONS

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ARTICLEINFO.
Keywords
Polyvinyl chloride (PVC), Thermal stabilization, Thermo-oxidative stabilization, Product-T salts, Stabilizers, Thermogravimetric analysis (TGA), Differential scanning calorimetry (DSC), Thermal resistance, Oxidative stability

Abstract

This study investigates the thermal and thermo-oxidative stabilization of polyvinyl chloride (PVC) through the use of salts of Product-T, a complex stabilizer. The research explores the mechanisms of stabilizer interaction with PVC and assesses its effects on material properties under elevated temperatures and oxidative conditions. By analyzing the efficacy of various salts of Product-T in comparison with traditional stabilizers, the study provides insights into improving PVC's thermal resistance and durability. Results from thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) confirm the potential of Product-T salts as efficient stabilizers, capable of significantly enhancing PVC's thermal and oxidative stability.

INTRODUCTION

The built environment is one of the largest consumers of global energy resources, accounting for approximately 36% of worldwide energy consumption and nearly 40% of total direct and indirect CO_2 emissions (IEA, 2022). As environmental concerns intensify, especially in light of climate change, energy efficiency in buildings has become a critical focal point for achieving sustainability goals. In response, Net-Zero Energy Buildings (NZEBs) have emerged as a transformative concept in sustainable construction. NZEBs are designed to minimize energy use and operate autonomously by producing as much energy as they consume on an annual basis (Li et al., 2021). Achieving net-zero status relies on the seamless integration of energy harvesting and storage systems, which together enable NZEBs to harness renewable energy and efficiently store surplus power for future use.

At the core, NZEBs aim to balance energy consumption with renewable energy generation within the same building, achieving a "net-zero" energy balance by the end of each year (Marszal et al., 2011). The increasing prominence of NZEBs reflects a broader trend toward creating sustainable urban environments with minimal dependence on fossil fuels and a reduced carbon footprint. Global policies like the European Union’s Energy Performance of Buildings Directive (EPBD) mandate that all new buildings in the EU should aim for near-zero energy standards by 2030 (European Commission, 2019). This regulatory momentum has led many governments to invest in renewable technologies for buildings, thereby accelerating the deployment of NZEBs across residential, commercial, and public sectors (Pan et al., 2022).

The design of NZEBs is inherently dependent on both energy-efficient building materials and active renewable energy systems, which can include solar, wind, and thermal energy technologies. However, the intermittency of renewable energy sources poses a significant challenge in meeting the constant energy demands of buildings. For instance, solar panels cannot generate electricity at night, and wind turbines depend on wind availability. Therefore, robust energy storage systems are essential in NZEBs, allowing them to capture surplus energy when available and utilize it when generation falls short (Stinner et al., 2016; Olabi et al., 2021). Together, energy harvesting and storage technologies provide a foundation for NZEBs to achieve reliable, self-sustaining energy performance.

According to Gao et al. (2020) energy harvesting technologies capture renewable energy from the environment and convert it into electrical or thermal power for building use. The most widely adopted technology in NZEBs is solar photovoltaic (PV) systems, which directly convert sunlight into electricity (Pérez-Lombard, Ortiz, & Pout, 2008). Recent advancements in PV materials, such as perovskite and organic solar cells, have demonstrated significant potential to enhance energy conversion efficiency while reducing production costs. Building-integrated photovoltaics (BIPV), where PV panels are embedded into building materials like windows or facades, represent an innovative approach to optimize solar energy capture without occupying additional space (Wang et al., 2021). Additionally, wind energy systems, although less commonly used in urban settings, are increasingly designed to suit urban microclimates, with vertical-axis wind turbines offering enhanced performance and flexibility for NZEBs in wind-rich areas (Mekhilef et al., 2012).

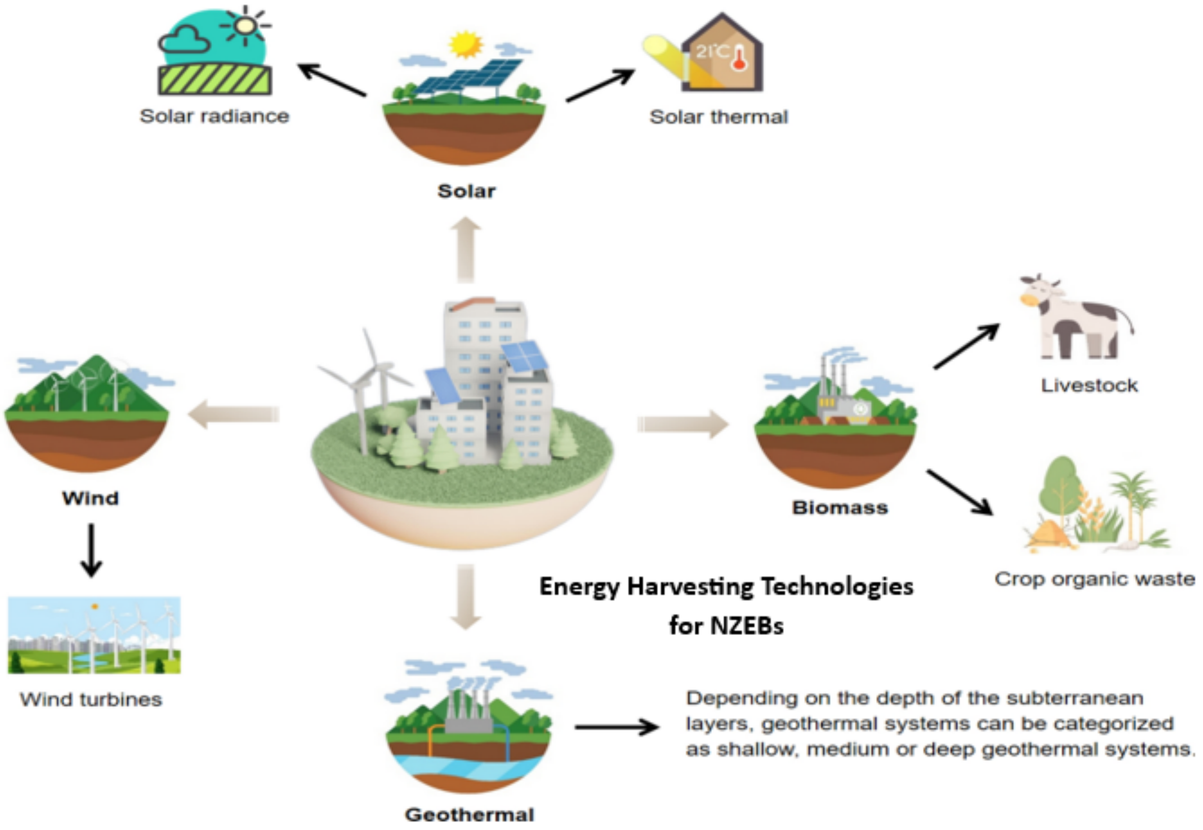
Thermal energy harvesting, which captures heat from solar thermal systems or ambient temperature differences, is another promising technology for NZEBs. Solar thermal collectors, for instance, are efficient for space heating and hot water production, directly offsetting the building’s energy load (Tian & Zhao, 2013). Emerging technologies, such as thermoelectric generators, convert temperature differentials within buildings into electricity and offer an alternative means of energy capture (Rowe, 2018). Piezoelectric and triboelectric systems are also gaining attention for harvesting small amounts of kinetic energy, such as from foot traffic, to power low-energy devices (Zhu et al., 2020).

While energy harvesting is essential, NZEBs would not be viable without efficient energy storage solutions that maintain the energy balance throughout the day. Battery storage is the most common form, with lithium-ion batteries being widely used for their high energy density and reliability (Luo et al., 2015). Recent developments in solid-state batteries and flow batteries offer enhanced safety, durability, and scalability, making them attractive for future NZEB applications (Chen et al., 2020). Thermal energy storage (TES) is also a critical component, particularly in colder climates, where excess heat can be stored for later use in space heating. Phase change materials (PCMs) are highly effective in TES systems, as they absorb and release heat at specific temperatures, thus stabilizing indoor temperatures and reducing heating and cooling loads (Zalba et al., 2003). Additionally, hydrogen and fuel cells present a promising avenue for long-term energy storage in NZEBs, enabling the storage of renewable energy in the form of green hydrogen, which can be used to generate electricity on demand (Foss et al., 2021). While still nascent, hydrogen storage and fuel cell technology are increasingly viewed as a viable solution for enhancing the resilience of NZEBs, especially in grid-independent or remote applications.

Given the critical role of energy harvesting and storage systems in advancing NZEBs, this review aims to provide a comprehensive analysis of recent technological developments and identify potential directions for future research and application. The focus will be on major energy harvesting technologies, such as solar and wind power, and emerging methods like thermoelectric and kinetic energy harvesting. Furthermore, the review will examine advancements in energy storage systems, including batteries, thermal storage, and hydrogen-based solutions, which are pivotal for energy resilience and independence in NZEBs. By examining these advances, the review would highlight the integration of energy harvesting and storage systems within NZEBs and discuss how innovative solutions can address current limitations. It would also consider the economic, regulatory, and environmental challenges that must be overcome to realize widespread NZEB adoption. Ultimately, this review envisions a future where NZEBs become the norm in sustainable urban development, contributing to climate change mitigation and fostering resilient energy infrastructures for buildings worldwide.

2. ENERGY HARVESTING TECHNOLOGIES FOR NZEBs

Energy harvesting technologies is crucial in achieving the goals of Net-Zero Energy Buildings (NZEBs) by providing renewable energy sources that can be seamlessly integrated into building structures. As NZEBs aim to produce as much energy as they consume, harnessing energy from natural and environmental sources such as solar, wind, thermal, biomass, and mechanical movements ensures these buildings remain self-sustaining and environmentally friendly. Recent technological advancements have enhanced the efficiency and versatility of these energy harvesting systems, making them more viable and scalable for various building types and urban settings.



2.1 Solar Energy Harvesting

Solar energy harvesting technologies in NZEBs such as Photovoltaic (PV) systems are directly converting sunlight into electricity through the photovoltaic effect. Standard PV panels are often installed on rooftops or facades, taking advantage of available solar radiation to offset building energy needs. Their efficiency and decreasing costs have made them popular, even as standalone energy systems in residential and commercial buildings (Li et al., 2021; Wang et al., 2021). Building-Integrated Photovoltaics (BIPVs) are a recent innovation, allowing PV technology to be seamlessly incorporated into the building's structure, such as windows, facades, and roofing materials. This integration offers both aesthetic and functional benefits, maximizing the available surface area for energy generation while maintaining architectural integrity (Gao et al., 2020). Advancements in PV materials have brought about new possibilities for energy efficiency and cost reduction in NZEBs. Among the most promising developments are perovskite solar cells, which offer high efficiency, flexibility, and cost-effectiveness. These cells use a unique crystal structure that allows for better light absorption and potentially higher efficiencies than traditional silicon cells (Kojima et al., 2021). In addition, perovskite materials are lightweight and can be manufactured using less energy-intensive processes, contributing to the sustainability goals of NZEBs (Green et al., 2022).

2.2 Wind Energy Harvesting

Small-scale wind turbines are increasingly used in NZEBs, particularly in areas with moderate to high wind availability. Unlike large, industrial turbines, these smaller systems are designed to operate in low-wind-speed environments typical of urban areas, allowing buildings to capture local wind energy to supplement other renewable sources (Simões et al., 2021). Urban wind energy systems are generally installed on rooftops or integrated into the building structure to minimize space usage while leveraging airflow patterns around buildings. Studies show that rooftop wind turbines can contribute significantly to reducing the grid reliance of NZEBs, especially in mixed-use or high-rise buildings with increased exposure to wind (Lee & Lee, 2022). However, challenges related to noise, vibration, and integration remain, making urban-specific wind turbine designs crucial. Recent advancements have focused on developing quieter, more compact, and efficient wind turbine designs tailored to urban applications. Vertical-axis wind turbines (VAWTs), for example, are increasingly favored in city settings because they can capture wind from all directions and operate effectively in turbulent, low-speed conditions typical of urban areas (Dabiri, 2021). Additionally, bladeless wind turbines, which rely on oscillations instead of traditional rotor blades, have shown promise for urban use due to their low noise output and reduced maintenance needs (Yoon et al., 2021). Some of these innovative designs also include hybrid systems that integrate solar panels or energy storage to maximize energy harvesting efficiency and provide steady power output even when wind conditions are less favorable (Harris & Kim, 2022).

2.3 Thermal Energy Harvesting

Thermal energy harvesting technologies, including thermoelectric generators (TEGs) and solar thermal collectors, enable NZEBs to capture and utilize heat energy. TEGs operate by converting temperature differences into electricity, allowing them to harvest waste heat generated within buildings or from the environment (Luo et al., 2020). Solar thermal collectors, on the other hand, capture solar radiation to provide heating for water and indoor spaces. These collectors are often used alongside storage systems to ensure a continuous supply of thermal energy, which is essential for managing energy demand in NZEBs during colder periods (Tian & Zhao, 2021). The integration of these systems not only supports electricity generation but also enhances building thermal comfort while reducing dependency on external heating sources. Advances in thermoelectric materials have led to significant improvements in the efficiency of TEGs, making them more suitable for building applications. Materials such as bismuth telluride and recent innovations in nanostructured thermoelectrics have increased the efficiency and power output of TEGs (Rowe, 2018; Chen et al., 2021). Moreover, flexible thermoelectric modules are now available, enabling seamless integration into building surfaces or HVAC systems. These improvements allow TEGs to capture energy from ambient temperature variations more effectively, which is particularly beneficial for NZEBs where small-scale, distributed power generation is advantageous (Zhang et al., 2022).

2.4 Biomass Energy Systems

Biomass energy systems play an important role in providing renewable heat and electricity for NZEBs by converting organic material, such as wood chips, agricultural waste, or other biomass sources, into energy through combustion or gasification (McKendry, 2002). For NZEBs, biomass boilers and combined heat and power (CHP) systems are common applications, particularly in colder climates or rural areas with access to local biomass resources (Foss et al., 2021). By generating energy on-site, these systems support NZEBs in achieving energy self-sufficiency, especially during low solar or wind availability periods.Recent advances in biomass energy technology have focused on improving the efficiency of conversion processes and reducing emissions, which makes them more compatible with NZEB standards. Gasification technologies have been optimized to achieve higher energy yields from smaller quantities of biomass, thereby reducing the environmental impact and enhancing system efficiency (Kratzeisen et al., 2020). Additionally, integration with advanced filtration systems has enabled biomass systems to meet stringent environmental regulations for indoor and outdoor emissions. These advancements make biomass energy a viable and sustainable choice for heating and power in NZEBs (Wang et al., 2022; González et al., 2021).

2.5 Piezoelectric and Triboelectric Energy Harvesting

Piezoelectric and triboelectric energy harvesting technologies capture energy from mechanical movements, vibrations, and pressure changes, making them particularly suitable for indoor applications in NZEBs. These systems can convert ambient kinetic energy from activities like foot traffic, elevators, or door movements into electrical energy (Zhu et al., 2020). They are commonly used in small-scale applications within buildings, such as powering sensor networks and low-energy devices, which can contribute to the energy autonomy of NZEBs. Due to their compact size and ability to operate in low-light or confined spaces, piezoelectric and triboelectric generators offer a decentralized energy source that complements primary energy systems (Wang et al., 2021). Recent advancements in piezoelectric and triboelectric materials have led to improved energy conversion efficiencies and durability, making them more practical for building applications. Nanostructured materials and composites, for instance, have enhanced the energy output of these systems, allowing them to harvest more energy from subtle mechanical movements (Shi et al., 2021). Additionally, researchers have developed flexible and stretchable piezoelectric materials that can be integrated into floors, walls, and furniture, creating interactive and energy-generating surfaces within NZEBs (Yang & Lee, 2022). These innovations offer an efficient way to supplement the energy needs of NZEBs, particularly in densely populated spaces where frequent movement can generate substantial kinetic energy (Chen et al., 2020).

3. ENERGY STORAGE SYSTEMS FOR NZEBs

Energy storage systems are essential for achieving the energy independence and resilience of Net-Zero Energy Buildings (NZEBs), allowing these buildings to balance energy supply and demand effectively. By storing excess energy generated from renewable sources, such as solar and wind, storage systems provide a reliable backup for periods when energy generation is low or demand peaks. This capacity to store and regulate energy not only reduces NZEBs' dependency on the grid but also optimizes energy use, enhances efficiency, and supports sustainability goals. The main types of storage technologies used in NZEBs such as battery storage, thermal storage, compressed air, hydrogen fuel cells, and flywheels each offer unique benefits and applications, from short-term load leveling to long-term energy security.

3.1 Battery Storage Systems

Battery storage systems are among the most prevalent energy storage solutions for Net-Zero Energy Buildings (NZEBs), offering reliable and flexible storage capacity that can align with the intermittent nature of renewable energy sources. Lithium-ion batteries, in particular, are widely adopted due to their high energy density, relatively low self-discharge rate, and long cycle life. These batteries provide an efficient solution for capturing and storing excess energy generated from renewable sources like solar and wind, making it readily available during periods of peak demand or low generation. Solid-state batteries, an emerging technology, promise to improve upon lithium-ion batteries by offering higher energy density and enhanced safety. These batteries replace the liquid electrolyte in lithium-ion cells with a solid electrolyte, which reduces the risk of thermal runaway and increases battery stability, although they are still in developmental phases and face cost and scalability challenges (Zakeri & Syri, 2015; Manthiram, 2020; Chen et al., 2020; Zhang et al., 2021).

Flow batteries, specifically vanadium redox flow batteries, offer a scalable option for NZEBs, especially for larger buildings that require higher energy capacity. Unlike lithium-ion batteries, flow batteries store energy in external tanks containing electrolytes, making it easier to adjust storage capacity by simply increasing tank size. This flexibility, along with a long cycle life and minimal degradation, makes flow batteries particularly suitable for long-term storage applications in NZEBs. However, flow batteries generally have lower energy density than lithium-ion batteries and require more space, which can limit their application in compact urban environments (Weber et al., 2011; Alotto et al., 2014; Wang et al., 2019; Dunn et al., 2011).

3.2 Thermal Energy Storage

Thermal energy storage (TES) is a key technology for NZEBs that supports heating and cooling systems by capturing and storing thermal energy. TES systems generally fall into three categories: sensible heat storage, latent heat storage, and thermochemical storage. Sensible heat storage systems store energy by heating or cooling a material, such as water or concrete, which can then release the energy as needed to regulate building temperatures. This method is widely used in NZEBs due to its simplicity and cost-effectiveness, though it has limitations in terms of storage density (Cabeza et al., 2011; Zhou et al., 2012; Dincer & Rosen, 2010). Latent heat storage systems utilize phase change materials (PCMs) to store energy during phase transitions, such as melting or freezing, which allows for higher energy storage density than sensible heat storage. PCMs are integrated into building structures, enabling effective temperature regulation and reducing reliance on HVAC systems (Mehling & Cabeza, 2008; Kenisarin & Mahkamov, 2007; Farid et al., 2004).

Thermochemical storage systems, though less commonly used, provide significant energy storage potential by utilizing chemical reactions to store and release energy. These systems offer high energy density and minimal thermal losses over long periods, making them suitable for long-term storage in NZEBs. However, thermochemical storage is still in the research and development stages, with challenges related to reaction reversibility and system cost hindering widespread adoption (Bélayachi et al., 2017; Pinel et al., 2011; Tian & Zhao, 2013; Abhat, 1983).

3.3 Compressed Air Energy Storage (CAES)

The research of Luo et al. (2015) opined that compressed air energy storage (CAES) systems are a viable energy storage option for NZEBs, particularly where long-term energy storage and load shifting are required. CAES systems work by using surplus electricity to compress and store air in high-pressure containers or underground caverns, which can later be released to generate electricity when needed. This technology can support NZEBs in meeting energy demands during times of low renewable energy generation, although its implementation typically depends on the availability of suitable storage sites for large-scale systems (Budt et al., 2016; Ibrahim et al., 2008). CAES has the advantage of a long lifespan and a relatively low self-discharge rate, making it a stable and cost-effective option for NZEBs. Advances in CAES technology, such as adiabatic CAES, are helping to improve system efficiency and reduce environmental impacts by retaining heat generated during the compression process, which can later be reused. These advancements make CAES systems more compatible with NZEBs, although they remain more practical for larger-scale buildings or community energy storage setups due to the spatial requirements of compressed air tanks (Amiryar & Pullen, 2017; Chen et al., 2013; Al-Badi & Bourdoucen, 2018; Künne et al., 2017). CAES remains a promising storage technology for net-zero energy solutions, particularly in areas where underground storage facilities are available.

3.4 Hydrogen and Fuel Cells

The study of Andrews & Shabani (2012) asserted that hydrogen storage and fuel cell technologies offer a versatile solution for NZEBs, particularly as hydrogen can be produced using surplus renewable energy and stored for later use. Hydrogen storage systems, when combined with fuel cells, provide a way to convert renewable energy into hydrogen via electrolysis, then reconvert it into electricity through fuel cells when needed. This approach enables long-term, high-capacity energy storage, making it especially useful for NZEBs with fluctuating energy demands. Furthermore, hydrogen has the potential to contribute to grid stability and provides a zero-emission solution when paired with green energy sources (Dunn et al., 2011; Holladay et al., 2009; Yao & Wang, 2020). The development of hydrogen storage systems for NZEBs has advanced through innovations in materials, such as metal hydrides and carbon-based compounds, which offer safer and more compact storage options. Fuel cell technology, particularly proton-exchange membrane (PEM) fuel cells, has also progressed, with improved efficiency and durability. Despite challenges, including infrastructure and cost barriers, hydrogen storage is increasingly viewed as a cornerstone for future NZEBs, due to its scalability and potential for large-scale energy storage (Bourgeois et al., 2019; Conte et al., 2004; Carriveau & Ting, 2013; Ni et al., 2006).

3.5 Flywheel Energy Storage

In the work of Sangroya & Nayak (2017), flywheel energy storage systems, which store energy in the form of rotational kinetic energy, are advantageous for NZEBs requiring rapid response energy storage with high cycle life. Flywheels operate by accelerating a rotor to high speeds and maintaining rotational energy in the system until electricity is needed. This type of energy storage is especially valuable for short-term energy balancing and power smoothing applications, as flywheels can discharge energy quickly and are less affected by temperature variations than batteries (Gyuk et al., 2005; Johnson et al., 2010; Shah & Bansal, 2017; Bleijs et al., 2004). Flywheels are highly durable, with the capability to handle frequent charging and discharging without significant wear, which enhances their reliability in NZEB applications. Recent advancements in magnetic bearings and composite materials have improved flywheel performance, enabling higher rotational speeds and greater energy storage density. These improvements have expanded the potential for flywheel storage in NZEBs, although space and cost considerations can limit their widespread adoption. In urban NZEB settings, flywheels are often deployed in conjunction with other storage technologies to optimize energy management and reduce grid dependency (Van de Ven et al., 2011; Ritchie et al., 2004; Sander et al., 2018)

4. INTEGRATIVE SYSTEMS FOR ENERGY HARVESTING AND STORAGE

Integrative systems for energy harvesting and storage in Net-Zero Energy Buildings (NZEBs) are critical for creating a cohesive, efficient, and resilient energy framework. These systems work by combining various renewable energy sources, like solar, wind, thermal, and mechanical, with advanced storage technologies to ensure a continuous and reliable energy supply that aligns with the building's energy demands. The integration of multiple energy harvesting and storage technologies allows NZEBs to maximize the use of available resources, optimize energy generation and consumption, and reduce dependency on external power grids. This approach is particularly advantageous for handling the intermittency associated with renewable energy sources by providing a balance between supply and demand through seamless energy storage solutions.

4.1 Smart Energy Management Systems

Smart Energy Management Systems (SEMS) leverage intelligent control algorithms and data analytics to manage energy flows efficiently, ensuring that energy demand and supply are balanced throughout the day. By integrating various renewable energy sources and storage technologies, these systems minimize energy waste, reduce costs, and maximize the use of locally generated energy. SEMS monitor and predict energy usage patterns, adapting to changing demand while also factoring in weather forecasts, occupancy levels, and energy prices to make real-time adjustments. This level of automation enables NZEBs to enhance energy efficiency, achieving net-zero or even net-positive energy performance (Mengelkamp et al., 2018; Siano, 2014; Soshinskaya et al., 2014; Han et al., 2016).

Recent advances in Artificial Intelligence (AI) and the Internet of Things (IoT) have significantly enhanced SEMS capabilities in building energy management. IoT sensors monitor a range of variables, from temperature to lighting levels, providing real-time data that AI algorithms can process to optimize energy distribution across building systems. AI-driven predictive maintenance also helps reduce downtime by identifying and addressing potential system failures before they escalate. Additionally, machine learning techniques allow SEMS to continuously learn and refine energy optimization strategies based on historical data and changing building requirements. As a result, SEMS not only reduce the environmental impact of NZEBs but also contribute to cost savings and improved operational efficiency (Amasyali & El-Gohary, 2018; Li et al., 2020; Ahmad et al., 2016; Bui et al., 2019).

4.2 Energy System Integration and Synergy

Chatzivasileiadi et al. (2013) stated that integrating various energy harvesting and storage systems within a single NZEB is essential to achieving high levels of energy efficiency and operational synergy. By combining multiple energy sources such as solar PV, wind, and biomass with diverse storage technologies like batteries and thermal storage, these integrative systems can mitigate the intermittency of renewable sources. This approach ensures a more consistent and reliable energy supply, reducing dependence on external power grids and enhancing building resilience. Integrated systems operate through advanced controls that prioritize the use of available resources in a dynamic manner, shifting energy between sources and storage units based on current needs and resource availability (Díaz et al., 2018; Li & Li, 2021; Fischer & Madani, 2017)

Case studies of successful NZEB implementations underscore the benefits of energy system integration. For instance, the Energy Hub system in Zurich, Switzerland, integrates solar, wind, and geothermal energy with battery and thermal storage, allowing it to meet nearly all its energy demands locally. Similarly, the Freiburg Solar Settlement in Germany combines solar PV and battery storage within a community of NZEBs, achieving net-positive energy production. These examples demonstrate how integrative approaches enable buildings to achieve self-sufficiency, reduce environmental impact, and contribute to grid stability. With continuous advancements in integration strategies and storage solutions, the effectiveness of NZEBs in supporting sustainable energy objectives is expected to increase even further (Kolokotsa et al., 2011; Stevanović et al., 2018; Barbieri et al., 2017; Fosas et al., 2018).

4.3 Vehicle-to-Building (V2B) Systems

Ioakimidis et al. (2018) opined that Vehicle-to-Building (V2B) systems offer a novel approach to energy flexibility within NZEBs by utilizing electric vehicles (EVs) as mobile energy storage units. Through bidirectional charging technology, V2B systems allow EVs to transfer stored energy back to the building when required, such as during peak energy demand or in cases of shortfalls in renewable generation. This capability transforms EVs into backup energy sources, helping NZEBs to balance supply and demand while reducing grid dependency. V2B systems also contribute to energy savings by charging EVs during off-peak hours, when electricity is cheaper, and discharging them during peak periods, which benefits both building energy management and the overall electricity grid (Cecere et al., 2020; Tan et al., 2016; Yilmaz & Krein, 2013)

Recent advancements in V2B technology include improved battery management systems, enabling EV batteries to withstand frequent charging and discharging cycles without compromising longevity. Additionally, smart charging infrastructure supports real-time communication between the building and EVs, facilitating efficient energy transfers and allowing NZEBs to better integrate renewable energy sources. As cities adopt more EVs, V2B systems are expected to become increasingly valuable, helping NZEBs enhance their energy independence and support the broader shift toward a sustainable energy future (García-Villalobos et al., 2014; Khan et al., 2019; Lopes et al., 2011; Tomic & Kempton, 2007).

5. CHALLENGES AND LIMITATIONS

Despite the growing momentum towards Net-Zero Energy Buildings (NZEBs) as a sustainable solution for reducing carbon emissions and enhancing energy efficiency, several challenges and limitations impede their widespread implementation. These challenges stem from a combination of technological, economic, regulatory, and social factors that can hinder the transition to NZEBs.

5.1 Technological Challenges

Technological challenges are a significant barrier to the widespread adoption of energy harvesting and storage systems in Net-Zero Energy Buildings (NZEBs). Issues related to efficiency, durability, and scalability of existing technologies often hinder the seamless integration of renewable energy sources and storage solutions. For instance, photovoltaic (PV) systems, though widely used in NZEBs, face limitations in energy conversion efficiency, which impacts the overall energy yield, especially under varying light conditions. Research on advanced PV materials, such as perovskite solar cells, shows promise in improving efficiency; however, these materials currently suffer from stability issues that affect long-term durability (Green et al., 2014; NREL, 2021). Similarly, while lithium-ion batteries are popular due to their high energy density, their durability and lifespan can be impacted by frequent cycling and temperature variations, raising concerns about their long-term viability in NZEB applications

(Manthiram, 2020; Goodenough & Park, 2013). Furthermore, emerging technologies, such as solid-state batteries and advanced thermal storage materials, remain in the early stages of development and face barriers to mass production and affordability (Luo et al., 2015; Zakeri & Syri, 2015).

5.2 Economic and Financial Barriers

Economic and financial barriers are among the primary obstacles to implementing advanced energy harvesting and storage systems in NZEBs. The high upfront costs associated with purchasing, installing, and maintaining these systems can be prohibitive for both developers and homeowners. For instance, installing a complete PV system along with a battery storage solution can represent a significant investment, often making NZEBs more expensive than traditional buildings (IRENA, 2020). This high cost is compounded by the maintenance expenses of advanced technologies like lithium-ion batteries, which require periodic replacement, adding to the total lifecycle cost (Zubi et al., 2018; IEA, 2019). Funding and incentives are also critical issues, as limited access to subsidies, grants, or low-interest financing can discourage investment in NZEBs. While some countries offer tax credits or rebates for renewable energy installations, these programs are not always sufficient or widely accessible, leaving developers with limited options to offset costs (IEA, 2021).

5.3 Regulatory and Policy Issues

Regulatory and policy challenges are a significant hurdle in the development and implementation of NZEBs. In many regions, existing building codes and standards are not designed to accommodate the specific requirements of energy-efficient or net-zero buildings, which can limit the types of technologies or designs that can be implemented. Additionally, permitting processes and zoning regulations may add complexity and delay to NZEB projects, as developers navigate different standards and regulations across jurisdictions (IEA, 2020; Janda & Parag, 2013). For example, some local codes restrict the installation of rooftop PV systems or wind turbines, which are essential for energy harvesting in NZEBs (IEA, 2019). Furthermore, the lack of uniform NZEB standards across regions creates uncertainty for developers and complicates the implementation of consistent energy efficiency measures. Policies that provide clear definitions, certifications, and incentives specific to NZEBs could greatly support adoption by establishing regulatory certainty and simplifying compliance (Levine et al., 2007; Zhang et al., 2018).

5.4 Environmental and Sustainability Concerns

Environmental and sustainability concerns are also critical issues associated with energy harvesting and storage systems for NZEBs, particularly regarding the extraction and disposal of materials. For example, lithium-ion batteries, commonly used for energy storage, require significant amounts of lithium and cobalt materials that are often sourced through environmentally harmful mining practices. These mining processes can lead to land degradation, water pollution, and biodiversity loss, raising ethical and environmental concerns around the sustainability of battery storage systems in NZEBs (Vikström et al., 2013; Manthiram, 2020). Similarly, the extraction of rare earth metals required for some advanced PV and wind turbine technologies also has substantial environmental costs (Ali et al., 2017). Large-scale storage solutions, such as flow batteries or hydrogen storage systems, may also have environmental impacts due to their infrastructure requirements and chemical compositions. Flow batteries, for instance, use vanadium, a metal that can be harmful to ecosystems if not handled properly (Zhang et al., 2019).

6. FUTURE DIRECTIONS IN ENERGY HARVESTING AND STORAGE FOR NZEBs

6.1 Technological Innovations

The future of energy harvesting and storage for Net-Zero Energy Buildings (NZEBs) is heavily tied to ongoing technological innovations that promise to enhance efficiency, reduce costs, and expand the range of applications for renewable energy systems. One promising area of advancement is the development of next-generation solar cells, particularly those using materials like perovskite, which have shown the potential to significantly improve efficiency while lowering production costs compared to traditional silicon-based solar cells. Furthermore, research is focusing on creating tandem solar cells that combine multiple materials to capture a broader spectrum of sunlight, thus increasing overall energy conversion efficiency. Coupled with advancements in battery technologies, such as solid-state batteries and lithium-sulfur batteries, the energy storage landscape is expected to transform, offering higher capacities and faster charging times (Green et al., 2020; Park et al., 2019; Zhao et al., 2021; NREL, 2021).

6.2 Policy and Regulatory Support

Emerging policies and regulatory frameworks are critical for promoting the adoption of NZEBs and encouraging innovation in energy harvesting and storage technologies. Governments worldwide are increasingly recognizing the importance of sustainable building practices and are implementing policies that incentivize energy-efficient designs and renewable energy integration. For instance, various countries are establishing strict energy performance standards for new buildings, mandating that they meet net-zero energy criteria. Additionally, financial incentives, such as tax credits, grants, and rebates for installing renewable energy systems or energy-efficient technologies, are becoming more common, facilitating the transition to NZEBs (International Energy Agency, 2020; U.S. Department of Energy, 2020; European Commission, 2019; World Green Building Council, 2021).

6.3 Sustainability and Circular Economy Approaches

The integration of sustainability and circular economy approaches is crucial for the future development of energy harvesting and storage technologies in NZEBs. Innovations in sustainable materials for construction and energy systems can significantly reduce the environmental impact of building processes. For example, the use of recycled materials in solar panels and batteries can minimize resource extraction and waste generation. Furthermore, advancements in bio-based materials and the use of life cycle assessment (LCA) tools can help identify opportunities for enhancing the sustainability of building materials and energy systems throughout their life cycle (Zhang et al., 2020; Geng et al., 2019; Ellen MacArthur Foundation, 2019; Wastl et al., 2021).

6.4 Towards Autonomous and Resilient NZEBs

The concept of autonomous and resilient Net-Zero Energy Buildings is gaining traction as advancements in technology and design converge to create buildings that can operate independently while adapting to external conditions. Future NZEBs are envisioned to incorporate smart technologies that enable them to autonomously manage energy production, storage, and consumption. This includes the integration of smart sensors and IoT devices that monitor real-time energy usage, environmental conditions, and occupancy patterns, allowing buildings to optimize energy efficiency without manual intervention. Such systems can dynamically adjust heating, cooling, and lighting based on actual needs, thereby minimizing energy waste and enhancing occupant comfort (Ghaffarianhoseini et al., 2019; Alavi et al., 2020; Kofler et al., 2021; Mavrogianni et al., 2020).

7.0 Conclusion and Recommendations

Conclusion

Energy harvesting and storage systems are essential components in achieving net-zero energy buildings (NZEBs), which aim to balance energy consumption with renewable energy generation. Recent advances in these technologies have demonstrated significant improvements in efficiency, integration, and sustainability. Energy harvesting methods, such as photovoltaic systems, thermoelectric generators, piezoelectric devices, and ambient energy harvesters, have matured, offering promising solutions to capture and convert waste or ambient energy into usable forms. Similarly, developments in energy storage technologies, including batteries, supercapacitors, and emerging solutions like solid-state and flow batteries, are addressing the challenge of balancing intermittent renewable energy generation with continuous demand.

While these advancements are encouraging, several challenges remain, including high costs, limited energy density, integration complexities, and material sustainability concerns. Additionally, the lack of standardized frameworks for evaluating and comparing different energy harvesting and storage solutions for NZEBs remains a barrier to widespread adoption. Overcoming these challenges will require continued innovation, cross-disciplinary research, and supportive policy frameworks that promote sustainable building designs and energy-efficient technologies.

Recommendations

1. To maximize the potential of energy harvesting, it is crucial to develop hybrid systems that combine different energy sources (solar, thermal, mechanical, etc.) to ensure consistent energy generation in various environmental conditions. Additionally, research into smart and adaptive energy harvesting systems that respond to changes in energy demand and supply can further improve efficiency.
2. Reducing the cost of energy harvesting technologies and storage systems is critical for their widespread adoption in NZEBs. This can be achieved through economies of scale, material innovations, and production process improvements. Incentives and subsidies for integrating renewable energy systems in building projects could also lower upfront investment costs.
3. To support the intermittent nature of renewable energy, energy storage systems need to offer higher efficiency, longer lifespan, and greater storage capacity. Research into advanced materials, such as solid-state batteries and redox flow batteries, should be prioritized, along with efforts to increase their scalability for use in residential and commercial buildings.
4. Governments and industry stakeholders should work together to create policies that incentivize the development and adoption of energy harvesting and storage technologies in NZEBs. These may include tax credits, building code mandates, and research funding that prioritize sustainability, energy efficiency, and the reduction of carbon emissions.

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