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Challenges and Strategies for Achieving High Energy Efficiency in Building Districts

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Abstract: Achieving climate neutrality requires reducing energy consumption and CO_2 emissions in the building sector, which has prompted increasing attention towards nearly zero energy, zero energy, and positive energy communities of buildings; there is a need to determine how individual buildings up to communities of buildings can become more energy efficient. This study addresses the scientific problem of optimizing energy efficiency strategies in building areas and identifies gaps in existing theories related to passive design strategies, active energy systems, and renewable energy integration. This study delineates boundaries at the building and community scales to examine the challenges of attaining energy efficiency goals and to emphasize the intricate processes of selecting, integrating, and optimizing energy systems in buildings. The four boundaries describe: (B1) energy flows through the building envelope; (B2) energy flows through heating, ventilation, air conditioning and energy systems; (B3) energy flows through individual buildings; (B4) energy flows through a community of buildings. Current theories often treat these elements in isolation, and significant gaps exist in interdisciplinary integration, scalable frameworks, and the consideration of behavioral and socioeconomic factors. Achieving nearly zero energy, zero energy, and positive energy communities requires seamless integration of renewable energy sources, energy storage systems, and energy management systems. The proposed boundaries B1–B4 can help not only in analyzing the various challenges for achieving high energy efficiency in building communities but also in defining and evaluating these communities and establishing fair methods for energy distribution within them. The results demonstrate that these boundaries provide a comprehensive framework for energy-efficient designs, constructions, and operational practices across multiple buildings, ensuring equitable energy distribution and optimized performance. In addition, the definition of boundaries as B1-B4 contributes to providing an interface for energy-efficient designs, constructions and operational practices across multiple buildings.

Keywords: energy-efficient building types (NEB, nZEB, ZEB); building energy systems; sustainable building design; energy efficiency strategies; renewable energy integration; positive energy communities (PEC)

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1. Introduction

The building sectors, encompassing commercial, residential, and public buildings, represent a substantial percentage of global energy consumption, accounting for approximately 30% to 40% of the total [1]. Moreover, these sectors make a substantial contribution to greenhouse gas emissions, accounting for approximately 40% to 50% of the total emissions [2]. Given the crucial role that buildings play in the context of climate change and global warming [3], it is imperative that investigations are conducted to ensure that buildings are as environmentally friendly as possible throughout all stages of their lifecycle.

Among these stages, the operational stage, which encompasses the operation of building envelopes, energy systems, renewable energy (RE) technologies, and electric vehicles (EVs), among others, holds particular significance [4].

Building physics plays a significant role in determining the energy performance of a building during its operational phase [5]. For instance, the building envelope, which comprises external walls, roofs, base floors, windows, and doors [6], functions as a storage mechanism for energy, akin to a battery. Through the utilization of advanced materials and techniques, the building envelope effectively isolates indoor conditions from the transient outdoor conditions, thereby minimizing heat losses in colder months and heat gains during warmer seasons [7]. By optimizing the various components of building physics, it is possible to not only reduce the energy demands of a building but also to assist in maximizing energy storage within the building [6,8,9].

Beginning at least with the two energy crises of the 1970s, a significant focus of research in the field of building energy has been placed on improving energy efficiency [10,11]. One effective means of achieving this goal is through the optimization of building energy systems, such as heating, ventilation, air conditioning (HVAC) systems. This approach has been demonstrated to have a positive impact on reducing the environmental footprint of buildings. For example, Lee et al. [12] examined boiler control schemes in office buildings and found that a sequential control algorithm with a boiler grading ratio of 3:7 resulted in maximized efficiency and a reduction of approximately 7% in gas usage. Baldi et al. [13] evaluated a parametric cognitive adaptive optimization for building energy management systems (EMS) in office buildings, reporting substantial energy efficiency by managing the HVAC units. Wang et al. [14] investigated a school building equipped with a displacement ventilation unit and heat recovery facility, reporting that increasing the heat recovery efficiency reduces the energy demand for ventilation and cooling. Liu et al. [15] identified that higher coefficient of performance water-cooled chillers could reduce cooling system energy consumption compared to air-cooled chillers. These studies, among others, have underscored the critical role of building energy systems as a cornerstone in the pursuit of energy efficiency [10–16].

As the availability of fossil fuel energy diminishes, and awareness of the environmental harms associated with such resources increases, RE sources have become the fastest-growing energy sources for buildings and are expected to play a significant role in shaping the future of the world [17–19]. Viable RE systems for buildings typically include photovoltaic (PV) panels, wind turbines, solar thermal energy, combined heat and power systems (CHPs), and ground source heat pumps (GSHPs) [18]. These RE sources can be exploited for on-site or distributed energy supply to buildings [20,21] and can be utilized to provide electricity, heating, and cooling [22]. The utilization of RE sources is integral to the achievement of green buildings and green communities, as evidenced by various studies [19,23–25]. A specific examination conducted by Ordóñez et al. [19] evaluated the energy potential of PV systems in Andalusia, Spain, taking into account factors such as the building type, the available roof space, and the PV panel arrangement. The research found that if all residential buildings were equipped with PV systems, the solar PV production capacity could reach 9.73 GW/year, which would suffice to meet 78.89% of energy demand. Additionally, GSHPs have been acknowledged as a cost-effective solution to address environmental concerns within the building sector, with the potential to decrease heating and cooling requirements by 20%–40% and 30%–50%, respectively [26]. It is noteworthy that RE systems may allow for surplus electricity generation, which can be sold to the grid or other buildings, ultimately leading to the realization of zero energy or even positive energy buildings (PEBs) and communities.

It is more efficient, from an energy perspective, to utilize the surplus electricity locally within buildings as opposed to selling it to the grid. EVs can play a significant role in this. The global adoption of EVs is rapidly increasing, and EV charging can significantly contribute to the overall electricity demand of buildings [27,28]. Furthermore, the batteries of EVs have the potential to serve as distributed energy storage, mitigating fluctuations from RE sources [29] and offering peak load reductions [3]. There are various ways in which EVs can be employed, such as load shifting, vehicle-to-grid [30], and vehicle-to-building interactions [31]. Zhou et al. [32], for instance, developed an advanced battery-protected energy control strategy and mathematical model to describe real-time battery degradation for multi-directional energy interactions between vehicles, buildings, and the grid. Barone et al. [33] evaluated the potential of a building-to-vehicle-to-building scheme in Europe, which stores renewable electricity in the batteries of EVs and distributes it among multiple buildings, and found that this scheme could reduce electricity demand from the grid by up to 71%. Huda et al. [34] studied the potential use of EVs in the Indonesian power system and found that they could lead to a 2.8% (coal) and 8.8% (natural gas) reduction in peak hour supply. EVs offer a bridge between energy efficiency and RE [35].

In recent years, there has been a growing interest in the concept of zero-energy buildings (ZEBs) as a means of reducing energy consumption and improving energy efficiency in the built environment. The origins of this concept can be traced back to the early 2000s when the first proposals for zero-energy buildings were put forth [36]. In the following years, the concept of ZEBs gained traction, with a marked increase in research and development in this area beginning around 2006 [37,38]. ZEBs are designed to surpass traditional buildings in terms of building physics, efficiency of building energy systems, and integration of RE technologies. Since the inception of this concept [10], there has been a continued evolution in the development of ZEBs, leading to the emergence of related concepts such as nearly zero energy buildings (nZEBs) and net zero energy buildings [39]. Looking to the future, the next step in the evolution of ZEBs is the concept of PEBs [40], which holds the potential to not only meet their own energy needs but also to distribute surplus energy to the grid, EVs, and potentially neighboring buildings.

In recent years, there has been a growing body of literature that has begun to consider the potential benefits of utilizing RE resources for reducing primary energy consumption, energy sharing, and reducing reliance on the utility grid at the community, neighborhood, or district level, rather than at the individual building level [41,42]. This shift in focus is driven by the recognition that it is more efficient and impactful to achieve energy targets on a community scale, as opposed to an individual building scale. One of the first definitions of a zero energy community (ZEC) was published by the National RE Laboratory in 2009 [43]. In 2014, a research project presented a definition of a Nearly Zero Energy Neighborhood [44]. More recently, the term Zero Emission Neighborhood was coined by the Research Centre on Zero Emission Neighbourhoods and Smart Cities in 2018 [45].

In recent years, several European Union projects have been oriented towards the concept of a positive energy community (PEC) with the aim of efficiently and flexibly harnessing the RE generation and storage potential of communities and minimizing the impact on the centralized grid [46]. In 2018, the European Strategic Energy Technology (SET) Plan Action 3.2 Smart Cities and Communities Implementation defined the concept of positive energy district (PED) [47]. PECs and PEDs are regarded as effective solutions to facilitate energy transition and reduce CO_2 emissions in cities [48,49]. The goal of PECs and PEDs is to realize a balance between energy efficiency, energy flexibility, and energy production in order to achieve climate neutrality and energy surpluses [50]. These concepts encourage the adoption of RE and offer an enabling environment for sustainable lifestyles for residents [51,52].

In this study, a wide range of literature has been reviewed to provide a comprehensive understanding of the current state of research in energy efficiency strategies for buildings. This extensive review has identified significant scientific deficiencies and engineering challenges, particularly in integrating passive and active energy systems, renewable energy sources, and behavioral factors. The primary scientific problem addressed in this research is optimizing strategies for achieving high energy efficiency in building areas to meet sustainability goals and reduce carbon emissions. While existing theories provide valuable insights into passive design strategies (e.g., building orientation, natural ventilation, thermal mass), active energy systems (e.g., HVAC optimization, energy storage, smart grids), and renewable energy integration (e.g., solar panels, wind turbines), significant gaps remain. These gaps include the need for interdisciplinary integration that combines these elements effectively, the development of scalable and adaptable frameworks that can be applied from individual buildings to communities, and the inclusion of behavioral and socioeconomic factors that influence energy efficiency. Addressing these gaps highlights the need for more interdisciplinary approaches and scalable solutions. The current research aims to address these issues by proposing a comprehensive framework that integrates these elements effectively, thus advancing the field of energy-efficient building design and operation. This approach will enable the creation of comprehensive and effective strategies, ensuring practical application and maximum impact on energy efficiency and sustainability in building areas.

Despite these concepts being defined some years ago, it is well-recognized in the field that there is a lack of systematic frameworks to define the boundaries between negative energy, nearly zero energy, zero energy, and positive energy scenarios, both at the building and at the community scale. This study presents a comprehensive overview of two distinct scales of buildings and communities based on a historical research roadmap, to establish the boundaries of building scale and community scale, and to examine the role of buildings as modifiers of energy, climate, and cost. The motivation of this paper is to present the corresponding challenges and barriers through a deeper understanding of the current state of research on buildings and communities and to provide guidance for further research. For instance, the imperative pursuit of nearly zero energy communities (nZECs), ZECs, and PECs is paramount in curbing energy consumption and enhancing energy efficiency, while taking into account local climate conditions for optimal outcomes. As an approach, the seamless integration of energy efficiency into communities of building design and construction is pivotal in attaining nZECs, ZECs, and PECs. However, challenges persist in coordinating energy-efficient practices and establishing equitable methods for energy distribution within communities. Furthermore, cutting-edge technologies, such as real-time monitoring and data analytics, can bolster the efficacy of community-level energy efficiency strategies.

The structure of this manuscript is organized as follows: Section 2 outlines the methodology employed in the study. Section 3 provides a comprehensive analysis of the role of buildings as modifiers of energy, climate, and cost, supported by the examination of case studies. Section 4 discusses the challenges and future prospects associated with different boundary layers. Finally, Section 5 offers a discussion, and Section 6 presents a summary of the study.

2. Methodology

The examination of building performance has evolved from an initial focus on building envelope improvement to an emphasis on overall building energy performance. More recently, this focus has expanded to encompass the performance of communities of buildings. This examination encompasses various aspects such as the building envelope, the efficiency of energy systems and the integration of RE technologies. An important aspect of this examination is the alignment of different energy systems, including the relationship between energy systems and buildings, buildings and utility grids, and buildings within a community of buildings. In order to achieve higher or optimal performance, it is necessary to establish different boundary layers, identify the energy flows that cross these boundaries, and examine the research challenges associated with each layer of boundaries.

The process of establishing boundaries is executed in a two-fold approach. The initial step involves the conceptualization of three layers of boundaries for individual buildings. The second step involves the examination of the extension from the individual level to the community level and the establishment of boundaries for building communities.

For the purpose of inspecting an individual building, Figure 1 depicts the design in accordance with the first law of thermodynamics [53]. Supposing the building incorporates RE systems, three layers of boundaries encompass:

- The primary focus is directed towards the first layer boundary (B1), which encompasses the building envelope and internal heat gains, encompassing lighting, appliances, and occupants. This emphasis on optimizing the building envelope as a priority is driven by its pivotal role in effectively reducing the power rating of HVAC systems. The required energy to operate the building envelope (Q_1) can be supplied by the RE systems or purchased from the utility grid. In some cases, e.g., with some type of facades, the building envelope may interact with the HVAC. In addition to mitigating losses to the external environment, the building envelope plays a crucial role in fulfilling the occupants' visual and acoustic comfort criteria meaning that $C_1 \simeq P_1$.
- The second layer boundary (B2) is based on HVAC systems and EVs. The required energy to operate the HVAC systems and EVs (Q_2) can be supplied by the RE systems or purchased from the utility grid. Likewise, the HVAC systems and EVs allocate a portion of their energy consumption towards the building envelope, while the remaining portion is dedicated to fulfilling the occupants' thermal comfort and indoor air quality needs meaning $C_2 \simeq P_2$. It is presupposed that the building has been designed with the intent of meeting the occupants' comfort requirements.
- The third layer boundary (B3) is considered for the RE systems. This layer accounts for the generation of a surplus of energy within the building (*Sell*), which can be monetarily compensated through its sale to the utility grid.

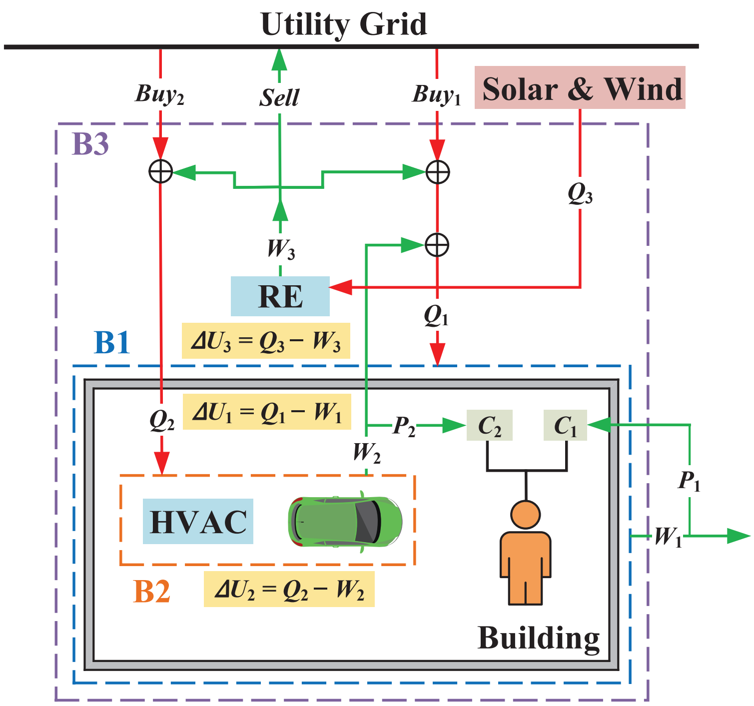

Figure 1. Boundaries of individual buildings. Q_1: Energy consumed by the building envelope; W_1: Energy to satisfy visual and acoustic comfort requirements (P_1), and losses of the building envelope; ΔU_1: Energy stored in B1. Q_2: Energy consumed by HVAC and EVs; W_2: Energy to satisfy thermal comfort and indoor air quality requirements (P_2) and to the building envelope; ΔU_2: Energy stored in B2. Q_3: Solar and wind energy to RE systems; W_3: Energy produced by RE; ΔU_3: Energy stored in B3. Buy_1: Energy bought from the grid for the building envelope; Buy_2: Energy bought from the grid for HVAC and EVs; *Sell*: Energy sold to the grid. C_1: Visual and acoustic comfort requirements of occupants; C_2: Thermal comfort and indoor air quality requirements of occupants.

According to the magnitude relationship between $Buy_{\text{sum}} = Buy_1 + Buy_2$ and $Sell_{\text{sum}} = Sell$, buildings can be classified into four categories. The classification of buildings as negative energy buildings (NEBs), nZEBs, ZEBs, and PEBs is predicated upon the level of yearly energy consumption in relation to energy generation. Table 1 quantitatively demonstrates this relationship by categorizing buildings based on their energy consumption levels relative to their energy generation capacity as follows: greater than, almost equal to, equal to, and less than.

Table 1. Categories of buildings/communities according to the magnitude relationship between of Buy_{sum} and $Sell_{\text{sum}}$ (yearly analysis).

Comparison	Term	Definition
$Sell_{\text{sum}} < Buy_{\text{sum}}$	NEBs / NECs	The level of energy consumption exceeds the energy generation
$Sell_{\text{sum}} \approx Buy_{\text{sum}}$	nZEBs / nZECs	The energy required from the grid is close to zero or very low, as most of the energy demand is supplied by RE sources
$Sell_{\text{sum}} = Buy_{\text{sum}}$	ZEBs / ZECs	RE balance the energy demand
$Sell_{\text{sum}} > Buy_{\text{sum}}$	PEBs / PECs	The energy generation exceeds the energy required for building's operation

For a community of buildings, the design is presented in Figure 2, taking two buildings as an example. In addition to the three-layer boundary of each building, a fourth-layer boundary (B4) is established through the inclusion of the energy flows between buildings. In addition, similar to the individual building scenario, depending on the magnitude relationship between $Buy_{\text{sum}} = Buy_{1a} + Buy_{2a} + Buy_{1b} + Buy_{2b}$ and $Sell_{\text{sum}} = Sell_a + Sell_b$, communities of buildings also can be classified into four categories: negative energy communities (NECs), nZECs, ZECs, and PECs, refer to Table 1. It is worth mentioning that communities/districts/neighborhoods are used as synonyms in this work.

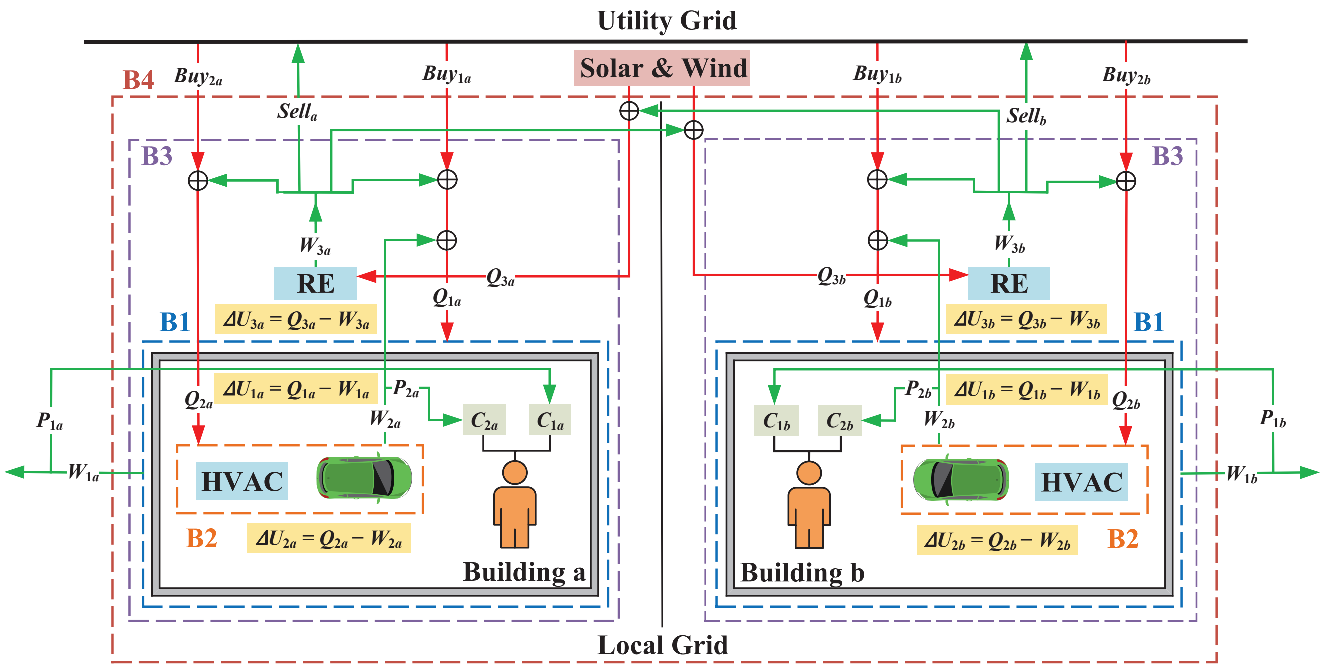

Figure 2. Boundaries of a community of buildings. Most of the energy flows have a similar meaning as in Figure 1. The new energy flows to be taken into account are the energy flows between buildings.

3. Buildings as a Modifier of Energy, Climate, and Cost

This section examines the impact of buildings on energy consumption, climate change, and economic costs. As depicted in Figure 3, the analysis is structured into two primary subsections: 3.1 focuses on individual buildings, including nZEBs, ZEBs, and PEBs, while 3.2 addresses communities of buildings, encompassing nearly nZECs, ZECs, and PECs. Critical components such as building envelopes (B1), energy systems (B2), renewable energy technologies (B3), and energy sharing mechanisms (B4) are also explored to elucidate their contributions to enhancing building performance and sustainability.

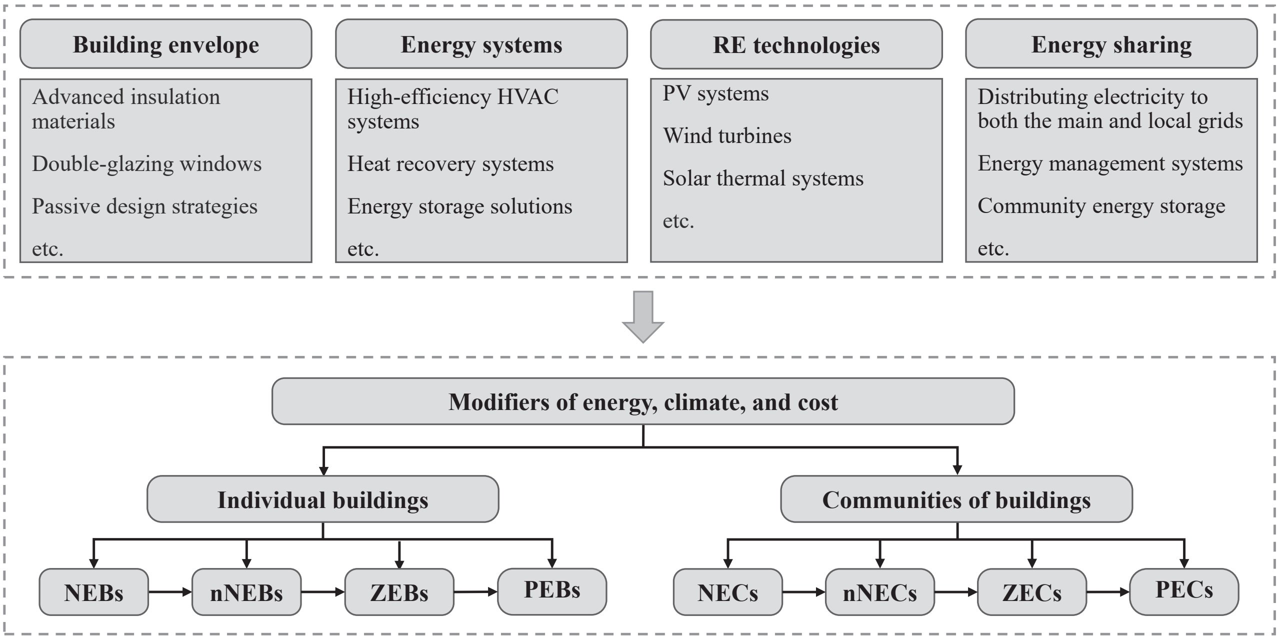

Figure 3. Conceptual framework for energy efficiency in buildings and communities.

3.1. Individual Buildings

The high energy demands and low energy performance of the vast majority of existing buildings, commonly referred to as NEBs, have been well-documented in literature [54,55]. A significant proportion of global energy consumption is attributed to these structures [56]. Consequently, the enhancement of energy efficiency in existing buildings has been identified as a crucial strategy for reducing energy consumption and carbon emissions on a global scale. In recent years, various countries have devoted substantial resources towards achieving this goal, with building retrofits specifically garnering widespread attention across the globe [57–59]. For example, Wang et al. [60] offered an HVAC system retrofit scheme for an existing office building in Tianjin, resulting in an overall energy efficiency improvement of 71.2%. In general, standard retrofit actions can reduce the total energy consumption, although the building will still remain an NEB in most cases. In case of major retrofit actions, it is possible to upgrade a NEB to a nZEB, as illustrated below.

3.1.1. Nearly Zero Energy Buildings (nZEBs)

The concept of nZEBs has gained significant global attention, as evidenced by its inclusion in the 2010 European Union Directive [61], which defines it as "a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby". Furthermore, the European Union Directive stipulates that all buildings occupied or owned by public authorities after 31 December 2018, should adhere to nZEB standards, and that all new buildings should conform to these standards by 31 December 2020 [61]. China, Japan, and the US are among the countries at the forefront of promoting nZEB goals. These nations have demonstrated a strong commitment to sustainable and energy-efficient building practices. For example, their initiatives include setting nZEB targets, implementing policies and regulations, and adopting strategies to drive nZEB adoption in the building sector. Their efforts encompass comprehensive analyses of China's nZEB policies, regulations, and strategies, as well as insights into Japan's policy frameworks, technological advancements, case studies, challenges, and lessons learned [62,63]. Given that energy conservation is often more feasible than its generation, it is widely recognized that reducing energy demand tends to be more cost-effective and efficient than generating energy on-site through RE sources [64]. This principle holds particularly true in the context of nZEBs.

The implementation of nZEBs has been extensively studied. Amani et al. [64] conducted a case study on a residential building in Tehran, Iran, which was retrofitted to nZEB standards through the addition of four layers of internal insulation, resulting in a 74% reduction in energy consumption. Ferrari et al. [65] retrofitted an office building on the campus of Politecnico di Milano, Italy with an improved thermal insulation envelope, replacement and upgrade of HVAC systems, renovation and installation of advanced lighting controls, and the incorporation of PV systems, ultimately reducing primary energy demand and green gas emissions by up to 40%. Hamdy et al. [66] presented a simulation optimization method and found that a single-family house equipped with PV and GSHP in a cold climate in Finland could achieve nZEB standards with a primary energy consumption of 70 kWh/m^{2}year. Zhao et al. [67] renovated the facade of a residential building in Dezhou, China, and optimized the angle of PV panels to achieve nZEB standards. This solution lowered the building's energy costs by 14.1%, increased PV power generation by 24.13%, and reduced CO_2 emissions by 4306.0 kg CO_2eq/year. Visa et al. [68] transformed a solar house in Romania, which was already a low-energy building with a geothermal system and solar energy converters, into a nZEB with less than 3% of the energy demand covered by the grid.

3.1.2. Zero Energy Buildings (ZEBs)

The concept of zero energy and emissions buildings emerged in the early 2000s, as a means of drastically reducing energy needs and carbon emissions in buildings through the realization of efficiency gains and the balance of energy needs being met through RE sources [69,70]. Significantly, the recast Energy Performance of Building Directive has introduced a notable shift in the standard for new buildings. Specifically, it mandates zero emissions buildings as the requirement from 2028 for all newly constructed buildings. Moreover, for new buildings occupied, operated, or owned by public authorities, the transition to zero emissions is expected even earlier, starting in 2026. This update marks a crucial milestone in the pursuit of sustainable building practices and signifies a concerted effort to align with environmental objectives [71]. It is expected that ZEBs play a further significant role in the advancement of smart cities by contributing to the achievement of goals related to energy efficiency, conservation, and RE generation [72].

In response to the growing concern for energy efficiency and sustainability, a number of countries have begun to investigate the potential of zero energy and emissions buildings. Kwan et al. [73] designed an affordable ZEB based on a typical house in Brisbane, Queensland by optimizing the building envelope, incorporating energy-efficient lighting and appliances, and adopting solar hot water collectors and a 5kW crystalline silicon PV panel system. Rey-Hernández et al. [74] studied the "LUCIA" building, a zero-energy building that reduced non-renewable resource depletion by 31% and significantly reduced the building's impact on climate change and soil fertility loss by using RE sources (biomass, geothermal and PV systems). Nord et al. [75] designed an integrated RE system consisting of flat plate solar thermal collectors (STCs) in combination with a GSHP and an exhaust air heat pump proposed for a single-family demo dwelling located in Larvik, Norway, as a demonstration zero-emission building. Lou et al. [76] studied a school building in Hong Kong, which achieved ZEB standard through the adoption of high-performance building envelopes, energy-efficient air-conditioning systems and lighting fixtures, and building-integrated PV (BIPV). Lindberg et al. [77] investigated cost-optimal solutions for the energy system design in a ZEB, using the case study of a German multi-family house equipped with GSHP, CHP, gas boiler, air source heat pump, STC and PV. The results indicated that a larger PV size was required to reach the zero energy balance.

3.1.3. Positive Energy Buildings (PEBs)

The advancement towards the enhancement of building efficiency has led to the emergence of the concept of PEBs. PEBs are characterized by their ability to generate energy in excess of that required for the operation of the building, for example through the utilization of RE systems to power EVs charging [39,78,79]. Cole et al. [80] emphasized that the aim of PEBs is not only to generate surplus energy but also to pay attention to the effective utilization and distribution of these excess resources. This surplus energy can be sold to the grid outside the building [39,81].

In recent years, PEBs have gained significant popularity across various nations. Ai et al. [82] conducted a study on a hybrid PV/wind system installed on Waglan Island, Hong Kong, and proposed a matching design approach that optimally determined the best configuration to fulfill the load demand at a minimal cost. Kolokotsa et al. [83] presented the design and energy technologies of a PEB school in Thessaloniki, Greece, and analyzed the energy performance which demonstrated a reduction of nearly 68% in energy demand, while significantly improving indoor thermal comfort. Bennani et al. [84] examined a high-rise office building in Morocco and applied energy efficiency measures to the baseline building, revealing a 56% reduction in energy consumption. Additionally, the integration of PV double glazing into the envelope reduced energy consumption by 15%, converting it to a PEB. Casini et al. [85] presented the results of the ReStart4Smart project, which achieved a PEB that was more than twice as energy efficient as Dubai's best practice through design choices of building form, building envelope, home systems, appliances, and EMSs in the geographical and cultural context of the Dubai region. Zomer et al. [86] presented the evolution of the energy balance and performance of all PV and BIPV systems at the Solar Energy Research Laboratory in Florianopolis, Brazil, and found that the PV system provides 148% of the building energy demand, thus it could be considered not only a ZEB but also a PEB.

3.1.4. nZEBs, ZEBs and PEBs: Case Studies

The classification of nZEBs, ZEBs and PEBs is presented in Table 2, which summarizes a variety of case studies from the literature. Each case study is examined in detail and analyzed in accordance with its unique characteristics. As countries around the world strive to meet low carbon and energy efficiency targets, nZEBs, ZEBs, and PEBs are being developed in a wide range of countries and regions. Given the variation in climatic, infrastructural, and other conditions among countries and regions, the building envelope methods (B1), building energy systems (B2) and RE technologies (B3) employed in the design of nZEBs, ZEBs, and PEBs are site-specific, resulting in variations in building performance.

The cases presented in Table 2 are drawn from various countries and regions, resulting in a diversity of weather conditions. The performance and level of achievement of each case are influenced by the specific building envelope design, building energy systems installed and RE technologies employed. As Table 2 illustrates, the effective coupling of the building envelope with RE technologies, and the appropriate selection of RE technologies, are critical factors in achieving zero energy targets, as previously noted in [87]. Additionally, the level of energy trading and energy demand are crucial considerations in the design and operation of nZEBs, ZEBs, and PEBs. These building types all exhibit lower levels of carbon emissions, thus contributing to the mitigation of the greenhouse effect and global warming, the reduction in environmental pollution, and the modulation of the climate. Hence, the level of carbon emissions is a key metric for evaluating the performance of these buildings. By fortifying the building envelope, increasing the efficiency of energy systems, and incorporating RE sources, energy demand can be reduced, allowing for the attainment of energy targets. As energy demand decreases, the associated costs also decrease.

Table 2. Summary of some case studies for individual buildings.

Country/ Region	Category	Building Envelope (B1)	HVAC and EV (B2)	RE Technologies (B3)	Key Performances	References
Iran	nZEB	A four-layer insulation system formed by 12 different thicknesses of typical insulation materials	HVAC	No	Reduced energy consumption by 74% and minimized CO_2 emissions.	[64]
Italy	nZEB	A thermally broken aluminum frame and double-pane glass, add polystyrene panels on walls and on the roof	HVAC	PV	Reduced primary energy consumption by 5% and greenhouse gas emissions by 40%.	[65]
Finland	nZEB	Good tightness and insulation level	AHU, GSHP	PV	Achieved lower primary energy consumption and lower CO_2 emissions.	[66]
Shandong Province	nZEB	Prefabricated concrete wall panels, glass curtain walls	HVAC	PV	Reduced energy cost by 14.1% and CO_2 emissions by 4306 kg CO_2eq/year, increased PV power generation by 24.13%.	[67]
Romania	nZEB	A light metallic structure covered with insulated panels outwards and plasterboard inwards, double-glazed windows, walls with 20 cm of cellular polystyrene thermal insulation	Ground source heat exchanger, heat pump	PV, STC	Reduced energy demand and CO_2 emissions, increased RE generation.	[68]
Queensland	ZEB	High insulation level for external walls and ceiling, white reflective roof, tinted reflective window glaze	HVAC	Solar hot water collectors, PV	Achieved energy savings by 66%.	[73]
Spain	ZEB	Thermal insulation of walls and apertures, double glazed argon-filled windows, materials of low environmental impact and life cycle, zigzag shaped facade, plastered internal insulated walls, green roofs	Ground heat exchanger, CHP, biomass boiler	PV	Reduced the depletion of non-RE by 31% and greenhouse gas emissions.	[74]
Norway	ZEB	N/A	GSHP, exhaust air heat pump	STCs, PV	Reduced electricity use noticeably.	[75]
Hong Kong	ZEB	High performance building envelope	HVAC	BIPV	PV installations can balance the energy use.	[76]
Germany	ZEB	U-values are setting according to the German passive building standard	GSHP, CHP, air source heat pump	STC, PV	Reduced energy demand and CO_2 emissions.	[77]
Hong Kong	PEB	N/A	HVAC	PV, wind generator, battery	Minimized the cost.	[82]
Greece	PEB	Extra insulation in the external walls and roofs as well as low U-values for windows, a solar chimney	HVAC	PV	Reduced energy demand by almost 68%.	[83]
Morocco	PEB	Double glazing, sun-shade	HVAC	BIPV	Reduced energy consumption by 71% and CO_2 emissions.	[84]
Dubai	PEB	Thermal envelope performances better than codes, ventilated roof, cool colors, automated windows, responsive solar shading, green wall	HVAC, EV	BIPV, STC, battery	Reduced contruction costs and energy needs.	[85]
Brazil	PEB	The asymmetrical lateral facades, the use of sustainable materials, the different mixed materials on the exterior (bricks, metal, and glass)	N/A	BIPV	Reduced CO_2 emissions and energy consumptions. PV sysems supplied 148% of energy demands.	[86]

Table 2 reveals that the use of insulation in the building envelope is the most commonly implemented solution, as it has been demonstrated to be cost-efficient and effective, as well as one of the simplest strategies for reducing building energy demand, as noted in [64,88]. Accordingly, energy goals are typically achieved by first reducing energy demand through the enhancement of the building envelope and the improvement of building energy systems, followed by the installation of RE technologies to meet any remaining energy demand. Furthermore, Table 2 illustrates that solar and wind energies are significant RE sources that can be employed to address climate change, as previously mentioned in [89]. However, wind power has relatively limited applications in individual building environments due to the constraints of urban space and the seasonal variability of wind, as discussed in [90]. In situations where space is not a constraint, such as in [82], the complementary nature of wind and solar energy can be fully exploited by selecting an appropriate combination of wind turbine and PV array capabilities, thereby significantly reducing power outage periods. Therefore, optimizing building performance requires matching technologies to each building's specific needs, from retrofitting to advanced designs like nZEB or ZEB. Customizing solutions ensures maximum efficiency and sustainability across diverse building types.

3.2. Communities of Buildings

There is a systematic history of building performance improvement, which can be traced back to the development of concepts such as nZEBs and ZEBs. However, for a significant number of buildings, it is not realistic to achieve these targets due to their high energy demand [87,91]. In recent years, there has been a growing emphasis on achieving zero energy goals at the community level, due to the advantages offered by load diversity, the ability to control, divert and store energy produced from various sources and regions, increased efficiency, reduced energy consumption, and enhanced energy resilience [87,92–94]. A community of buildings refers to a group of buildings, which may include residential, commercial, or other types of buildings, situated in close proximity and sharing some common areas [95,96].

3.2.1. Nearly Zero Energy Communities of Buildings (nZECs)

The low number of buildings that adhere to the new regulations, such as nZEBs, in comparison to those that do not, necessitates the implementation of innovative strategies in order to achieve decarbonized communities. One potential approach is to incorporate various RE technologies in these buildings, thereby enabling the sharing of surplus electricity within the community. This can aid in achieving the goal of nearly zero energy consumption at a community level, as evidenced by the work of Amaral et al. who have updated the definition of nZEBs to include the concept of nearly zero energy districts [97].

Currently, the trend towards reducing energy consumption and emissions from buildings is shifting towards a macro-level approach, specifically focusing on communities of buildings, such as nZECs. This orientation towards macro-level energy management is rapidly gaining momentum in the field. As exemplars of such research and initiatives, Synnefa et al. [98] presented an integrated and cost-effective system geared towards the implementation of nearly zero energy settlements. This system comprises solutions for the building envelope, building energy production, and energy management, and was implemented in four demonstration projects located in the European Union—in Cyprus, France, Italy, and the United Kingdom—with varying climates and building types. The results of the study indicate that the transition from a nZEB to a nZEC resulted in a significant reduction in energy consumption to less than 20 kWh/m^2 per year and a cost reduction of at least 16%. Ullah et al. [8] identified and analyzed 23 nZEBs as case studies. Through this analysis, they were able to discern various mitigation and control strategies employed by outdoor heat sources, building adaptation technologies, and RE technologies, with the aim of reducing energy consumption, mitigating greenhouse gas emissions and promoting RE generation and thermal energy production. In their study, Hachem-Vermette et al. [99] presented a case study of a mixed-use neighborhood in Calgary, Canada. The neighborhood comprised over 1000 residential units and approximately 8000 square meters of commercial, office, and educational buildings. The authors proposed the implementation of a PV system, which was designed to cover all south-facing roof areas to generate electricity for the district. Through energy simulations for different building types, it was determined that stand-alone and attached houses had the potential to be energy-positive for a given climate condition within the district, while other building types evaluated in the scenario, such as apartment buildings, offices, and supermarkets, were able to generate only a small fraction of their energy consumption. Sameti et al. [100] considered a net-zero energy district comprising seven residential and office buildings located in Switzerland and studied the impact of storage on the buildings' performance. The authors proposed the implementation of a CHP unit, a separate auxiliary boiler, and a thermal storage tank to satisfy the heat requirement of each building. Additionally, a PV array, a CHP unit, and a battery bank were proposed to meet the electrical load. The authors proposed that heat and power be exchanged among the buildings in the neighborhood through the heat and power transmission networks. The results of the study indicated that the adoption of an optimal district energy system with energy storage can deliver considerable economic and environmental benefits when compared to conventional energy systems, stand-alone energy systems, and net zero energy without storage. Wills et al. [101] presented a modeling approach for evaluating community-scale retrofit design alternatives aimed at converting an existing community to net-zero energy and applied it to a community comprising 50 single-detached dwellings located in Toronto, Canada. The case study demonstrated that the achievement of net-zero retrofitting can result in a significant reduction in annual energy imports by 80% and a reduction in associated greenhouse gas emissions by 95% for the community. The authors also illustrated that buildings that do not achieve net zero at the individual building scale can be balanced at the community level through the utilization of adjacent buildings with more usable roof areas and/or lower energy consumption intensity. Huang et al. [93] developed and validated an open-source nZEC virtual testbed based on a real-world nZEC located in Florida, US. The virtual testbed offers great flexibility in model selection and integrated simulation optimization, enabling a more comprehensive assessment of integrated control from the building to the grid level. The transition towards nZECs emphasizes a holistic approach to energy management that efficiently merges the upgrading of existing buildings with the integration of advanced management and technologies. This strategy is particularly effective in leveraging the collective potential of both new and older buildings, significantly enhancing sustainability and energy savings across the community. By focusing on comprehensive community-level transformations rather than isolated updates, nZEC initiatives profoundly impact energy efficiency, cost reduction, and environmental sustainability, demonstrating the substantial benefits of coordinated energy management.

3.2.2. Zero Energy Communities of Buildings (ZECs)

In 2009, the US Department of Energy established the definition of a ZEC as "an energy-efficient community in which the actual annual delivered energy on a source energy basis is less than or equal to the on-site renewable exported energy" [44]. This concept was further explored by Katipamula et al. [102] in 2010, who conducted a comparison of ZEC and individual ZEB and found that the economies of scale inherent in the community approach can help achieve equivalent overall energy performance at a lower cost. However, it should be noted that the implementation of ZECs also presents certain limitations, such as the complexity of planning, design, and monitoring, as well as the challenges of engaging stakeholders [44].

In the context of this research, numerous countries have been focusing on the design strategies employed in the creation of ZECs. Mavrigiannaki et al. [103] conducted an analysis of real data obtained from the first year of monitoring a zero-energy pilot community. The results of the performance analysis indicated that the community successfully achieved its targets for net regulated consumption, RE production, and cost. Furthermore, a positive balance was attained when considering the total energy consumption and PV production of the community for the first five months of monitoring, beginning with the start of summer. Overall, the community was able to achieve a positive energy balance for each year of energy demand. Fouad et al. [104] proposed an innovative sustainable ZEC comprising eight distinct building designs and 52 buildings, in order to simulate a realistic community. The ZEC featured well-insulated walls and roofs, as well as the incorporation of a green roof. The results demonstrated that all buildings within the ZEC met the criteria of the zero energy concept and fully satisfied the energy demand while generating excess energy through the utilization of RE sources. Shnapp et al. [105] presented a case study of a ZEC in Denmark, which was able to reduce energy consumption by 50% through the implementation of the following three steps: (1) optimization of district heating systems with new radiators, ventilation systems, solar storage, and heat pumps, (2) insulation of building envelopes, improved windows, use of smart meters and reduction in district heating temperature set points, and (3) the remaining energy demand was met through the use of thermal solar, PV, and BIPV. González et al. [106] investigated a zero-energy neighborhood of 400 houses in the Netherlands. They proposed passive design measures and distributed power generation to achieve the zero energy target and demonstrated that passive design is a fundamental prerequisite for reducing building energy demand. De León et al. [107] provided a solution for achieving zero energy targets in a residential district under a tropical climate in Panama. They reduced energy consumption through the optimization of bioclimatic and energy strategies, achieving savings of 31%, with the remaining demand met through the generation of solar electricity. It can be noted that the progression from nZECs to ZECs represents the next phase in sustainable urban development, demanding enhanced technical solutions and improved building qualities. This transition involves a deeper integration of advanced energy technologies and updated standards for building performance, enabling communities to not only reduce but potentially negate net energy usage and emissions on a broader scale. This shift to ZECs requires technical upgrades and a holistic approach to community planning and management to achieve the ultimate goal of zero net energy.

3.2.3. Positive Energy Communities of Buildings (PECs)

Given the complexity of the calculation procedure necessary to achieve the goal of a ZEC and the difficulties inherent in attaining an exact zero, a positive target is often easier to calculate and implement, which in turn accelerates the realization of carbon neutrality [105]. As a result, research related to PECs has been proposed and developed in recent years, and the concept is gaining increasing attention due to the pressing energy and environmental crisis and the critical role of the building sector in emissions reduction [108–110]. Derkenbaeva et al. [108] provide a definition of PECs as "an energy-efficient and energy-flexible urban area or a group of connected buildings, which produces net zero greenhouse gas emissions and actively manages an annual local or regional surplus production of renewable energy". This definition highlights that PECs are primarily concerned with energy conservation, emission reduction, and sustainability, which are conducive to the development of smart cities [111]. However, it should be noted that PECs typically consist of a mix of existing buildings and new constructions.

The concept of PECs has been widely adopted globally since 2018 [3]. Barone et al. [112] developed an EMS that facilitates the transfer of energy from a RE building to two traditional buildings using three EVs as energy vectors. The EVs were charged and discharged based on a scheduled trip and the state of charge of the battery, resulting in the system achieving an energy positive of 8.6 MWh/year. Rehman et al. [89] proposed a centralized solar district heating network that is integrated with a renewable-based electricity network to meet the heating and electricity needs of 100 houses. This RE system was comprised of PV panels, wind turbines, and a stationary power storage system. The results of the study indicated that the system was able to reduce imported electricity by 2 kWh/m^2/year when the storage system was taken into account. Brennenstuhl et al. [113] presented a Plus-Energy settlement consisting of 23 residential buildings that were equipped with decentralized heat pumps and PV systems in Germany. The study found that under ideal conditions, cost savings of up to 50% can be achieved at the building level by optimizing the self-consumption of PV electricity. Bambara et al. [114] examined the potential of replacing one stand-alone house with two houses of equal living space on the same parcel, with the new house being designed to be energy efficient in terms of HVAC, envelope and fitted with BIPV. The results revealed that the retrofitted scheme was 30% more energy efficient and that residential densification could significantly contribute to the transformation of existing communities into resilient PEDs. Gouveia et al. [115] conducted a study on the historic district of Alfama in Lisbon, Portugal, through building retrofits. The study found that the potential energy demand for heating and cooling was reduced by 84% and 19%, respectively. Additionally, integrating building PV technology on roofs and windows potentially generated energy of 60 GWh/year. The results of the study demonstrated the potential for energy retrofit measures and solar PV products in households. It can be summarized that the transition to PECs offers a more practical route to achieving substantial carbon neutrality, proving to be more cost-effective for property owners compared to nZECs and ZECs. PECs, which focus on net-zero greenhouse gas emissions and renewable energy surplus, are evolving as a sustainable urban development strategy that combines energy conservation with advanced EMSs to enhance the energy efficiency of both new and existing buildings.

3.2.4. nZECs, ZECs and PECs: Case Studies

The classification of nZECs, ZECs, and PECs is based on factors such as country/region, categorization, building envelope, building energy systems, renewable energy technologies, the scale of the community (number of buildings and total floor area), and key performances, as detailed in Table 3. This is similar to the evaluation of individual buildings in Table 2, but in contrast to the individual building scenario, the consideration of scale is crucial as existing cases of communities of buildings vary in scope and magnitude.

The cases examined in this study originate from various regions characterized by distinct meteorological conditions, as well as varying building envelope designs, building energy systems, RE technologies and scales of communities. As a result, their performance exhibits significant variation. It is crucial to recognize that each factor contributing to differences in community performance represents a significant challenge that must be addressed in order to achieve greater efficiency. For example, in the context of PECs developed under the auspices of European Union funding from H2020, a minimum floor space of 15,000 m^2 and the inclusion of at least three large buildings (new construction, renovation, or a combination of both) [116] are mandatory requirements. Consequently, the scale of the community is of paramount importance and must be considered when determining the optimal location for B4 of the community.

The results of the case studies presented in this research demonstrate that targets for nZECs, ZECs and PECs can be attained through the reduction in energy consumption, CO_2 emissions, investment costs, and/or the enhancement of RE production. Furthermore, it has been established that a more optimal interface between the building envelope and RE technologies, as well as a more seamless interaction amongst RE technologies, leads to a reduction in investment costs. Thus, the compatibility of the building envelope and RE technologies, as well as the compatibility of RE technologies, is of critical importance. Additionally, energy trading between buildings, which allows for buildings that are not ZEBs to obtain energy from PEBs within a community of buildings, is also essential.

The primary sources of RE currently remain solar and wind; however, they are inherently intermittent and uncontrollable, resulting in temporary mismatches between energy supply and demand [117]. Seasonal mismatches [118] are particularly prevalent, such as in regions with harsh climates, where a mismatch exists between the large-scale heating demands in winter and the abundance of solar resources in summer [119]. In certain countries, such as Spain, non-RE flows are only required to be compensated by energy exports within the same month [120], indicating that this variability will lead to strain on the grid and ultimately compromise grid stability [3], which has direct implications for the realization of nZECs, ZECs and PECs. Similar to seasonal mismatches, there are also hourly mismatches, where grid challenges such as overvoltage may emerge in the summer due to the large size of building-based PV installations and the concentration of buildings in a small area [121]. These mismatches can only be addressed through the incorporation of short or long-term energy storage in a community of buildings [101]. Additionally, a more advanced type of energy storage, such as using EV batteries as mobile energy storage devices to serve as power sources for buildings, can improve the resilience and flexibility of buildings, enabling peak shaving and load shifting, and reducing the power consumption of buildings during peak hours [112].

Table 3. Summary of some case studies for community of buildings.

Country/Region	Category	Building Envelope (B1)	HVAC and EV (B2)	RE Technologies (B3)	Scale (B4)	Key Performances	References
Cyprus, France, Italy, UK	nZEC	Advanced insulating material based on the new generation of extruded polystyrene	CHP, solar air conditioning	Combined solar and wind system, PV	123 buildings, 323608 m^2; 48 dwellings, 1400 m^2; 4 villas, 30,000 m^2; 500 family homes, area N/A	France, Italy and the UK reduced investment cost by 16%, while Cyprus reduced 12.4%. Energy use $\leq$ 20 kWh/m^2. RE production $\geq$ 50 kWh/m^2.	[98]
Calgary, Canada	nZEC	Wall and roof insulation of 7 m^2K/W and 10 m^2K/W, respectively, triple glaze, low-e argon fill windows, airtight construction	HVAC	BIPV	1003 residential units including 180 houses and 27 apartment buildings, area N/A	Schools and houses reduced annual primary energy consumption and CO_2 emissions, and increased RE production to offset the negative energy balance of most of the remaining buildings.	[99]
Switzerland	nZEC	N/A	CHP, thermal storage tank	PV, battery	7 buildings, area N/A; heat and electricity exchange	Reduced CO_2 emissions by 60%. Lower cost.	[100]
Toronto, Canada	nZEC	Exterior wall insulation, ceiling insulation, foundation wall insulation, triple-glazed low-e argon filled windows	GSHP, heat pump	PV	50 single-detached dwellings, area N/A	Reduced energy demand by 69%. Reduced CO_2 emissions by 95%.	[101]
Florida	nZEC	Cool roofs, low-E glass and extra insulation	PV	2 retail stores, one commercial office, and two residences, 2776 m^2	GSHP	After operating for a half years, the annual electricity generation was very close but slightly less than production.	[93]
Italy	ZEC	Extruded polystyrene insulation	HVAC	PV, battery	2 single-family houses, 2760 m^2	Reduced investment cost by 24%. Energy conservation was 75.7% compared to a standard community. Achieved RE production of 50.03 kWh/m^2/year.	[103]
Egypt	ZEC	Insulated walls and roofs, green roof, single glazing windows	HVAC	PV, wind turbines	52 buildings, area N/A	Reduced energy consumption by 57.6%. Reduced CO_2 emissions by 390 tons.	[104]
Denmark	ZEC	Insulation of building envelopes, improved windows	HVAC	STC, PV, BIPV	Avedøre Green City, area N/A	Reduced energy consumption by 50%.	[105]
The Netherlands	ZEC	High-transmission and low emissivity glazing, user-controllable window shades, insulation walls, floors and roofs, 30mm-thick plaster layer to the walls	CHP, EVs	PV, battery, STC collectors	400 houses, area N/A	Reduced the primary energy demand for heating by 50%. In terms of electricity it can be positive.	[106]

Table 3. *Cont.*

Country/Region	Category	Building envelope (B1)	HVAC and EV (B2)	RE technologies (B3)	Scale (B4)	Key performances	References
Panama	ZEC	The inclusion of local shading, double glass, and insulation roofs	HVAC	BIPV	34 houses, 1870 m^2	Reduced energy consumption by 31%. PVs could cover 100% of the demand.	[107]
Italy	PEC	N/A	HVAC, EV battery	BIPV	3 buildings and 3 EVs, area N/A	Electricity saving of about 11.4% and economic saving of 8.1%.	[112]
Finland	PEC	N/A	Heat pumps, borehole thermal energy storage, EVs	Wind turbines, PV, STCs, battery	100 houses, area N/A	Maximized the onsite-energy fraction and onsite-energy matching.	[89]
Germany	PEC	N/A	Heat pumps	PV, battery	23 residential buildings, area N/A	Achieved cost savings up to 50%.	[113]
Québec, Canada	PEC	High insulation, double glazed argon low-e windows, airtight construction	HVAC	BIPV	2 houses, 220.176 m^2	Reduced energy consumption by 30%. Generated nearly 3 times more electricity than they consumed.	[114]
Portugal	PEC	Roof (thermal insulation with mineral wool), PVC window frames with standard double glass, walls through internal insulation	HVAC	BIPV	6004 dwellings, area N/A	Reduced energy demand by 84% and 19% for space heating and cooling.	[115]

4. Challenges, Future Outlooks and Recommendations

The energy performance of various building communities has been evaluated through measurement or simulation, revealing that a multitude of factors significantly impact performance. These effective factors present challenges from various perspectives and necessitate a thorough examination of each. This research endeavors to focus on individual boundaries in order to identify and address the challenges associated with increasing the energy performance of individual buildings or building communities, as well as the intended distribution of energy and costs within the community, including energy storage systems. The challenges primarily center around the following aspects, such as macro-level target identification; planning evaluation; calculation of energy demand and supply; enhancement of the building envelope and its interaction with energy systems; mapping and synchronization of building energy systems (e.g., RE); identification of mismatches between energy supply and demand due to RE sources; degradation of EV batteries; adjustments to EMSs. These challenges are classified and grouped according to the boundaries specified in Section 3, with an overview provided in Figure 4, as detailed below.

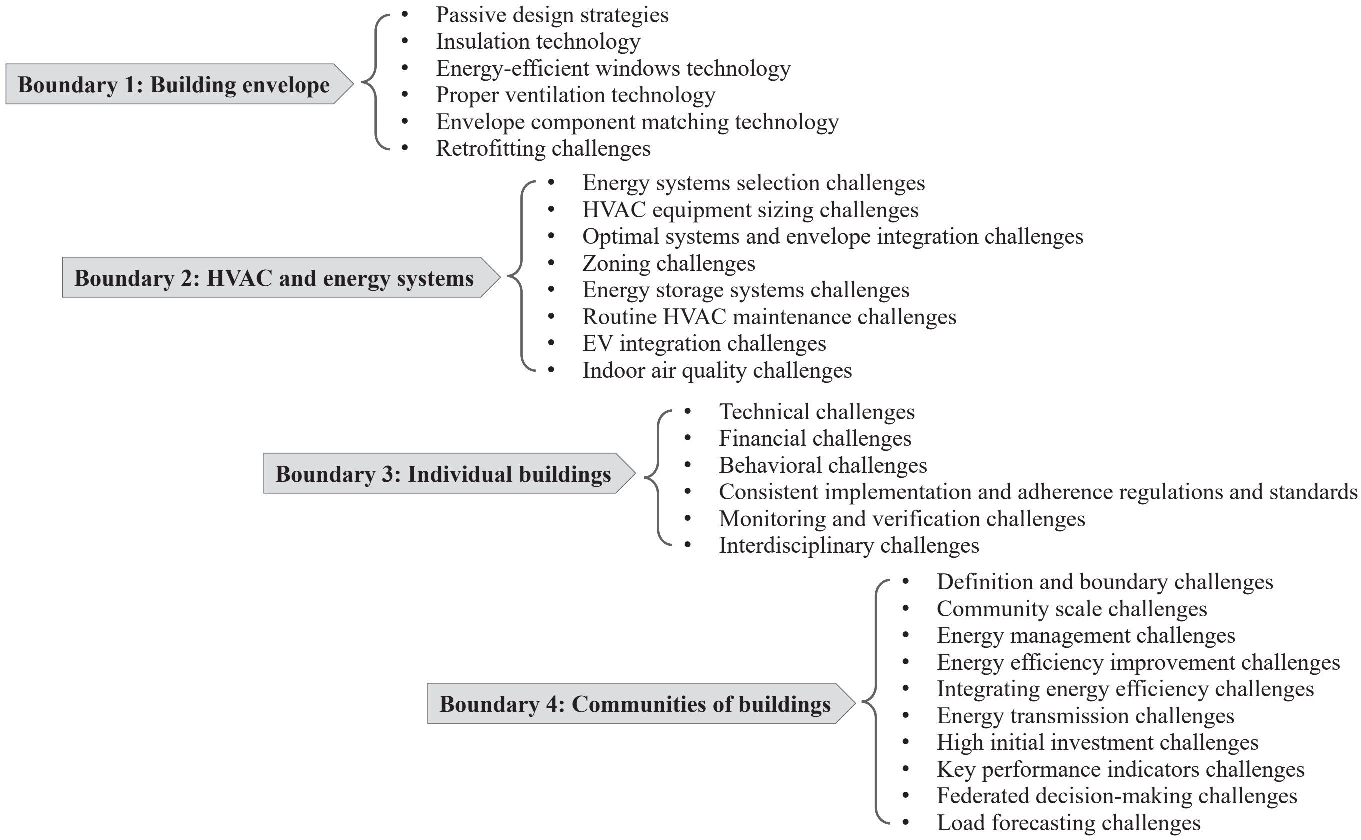

Figure 4. Framework illustrating the boundaries and key components for enhancing energy efficiency in buildings and communities.

4.1. Boundary 1: Building Envelope

The literature review and subsequent analysis have delineated the primary technical and practical challenges as follows:

Passive Design Strategies: Building design can be optimized to reduce energy consumption, for example by using natural light, optimizing the orientation of the building, and using passive design strategies such as thermal mass. Using high-reflectance roofing materials such as cool roofing can reduce heat gain in the summer and lower cooling costs. Green roofs, walls, and facades can help to reduce energy consumption by providing insulation, shading, and cooling effects.

Insulation Technology: Proper insulation of the building envelope can help to reduce heat loss and gain. Increasing the insulation levels in the walls, roof, and floors can help to reduce heat loss in the winter and heat gain in the summer, which can lower the amount of energy needed to heat and cool the building. The reduction in heat loss in the winter can be achieved through the manipulation of infiltration levels using sealing gaps and cracks in the building envelope. Specifically, the sealing of openings around doors and windows, as well as in the walls, floors, and ceilings, can effectively prevent drafts and thus lower the overall heat loss in the winter.

Energy-efficient Windows Technology: Installing energy-efficient windows can help to reduce heat loss and gain. For example, replacing old, single-paned windows with energy-efficient, double-paned windows equipped with shading devices can significantly reduce heat loss in the winter and heat gain in the summer. Installing shading devices such as overhangs, awnings, or shading screens on the south- and west-facing windows can reduce heat gain in the summer and increase energy efficiency. Incorporating passive solar design elements such as south-facing windows and thermal mass can reduce the need for heating and cooling.

Proper Ventilation Technology: Proper ventilation systems that bring in fresh air and remove stale air can help to keep the building comfortable, which can reduce the need for heating and cooling.

Envelope Component Matching Technology: Optimization of energy demand within a building can be achieved through the strategic alignment of building envelope elements with the annual energy consumption patterns. This process referred to as "envelope component matching", involves the selection and configuration of building envelope systems and elements that correspond to the specific energy demands of the building throughout the year.

Retrofitting Challenges: The building envelope assumes paramount importance in shaping the energy demand of buildings. Consequently, it becomes evident that focusing on the physical attributes of buildings represents the primary means to achieve substantial reductions in energy demand. This involves establishing novel guidelines for new constructions and undertaking comprehensive retrofitting measures for existing buildings. Despite the growing prevalence of building retrofits, the unique physical characteristics and preservation principles associated with historic buildings, for example, present significant limitations, warranting further consensus on the criteria to be considered. Consequently, the domain of retrofitting necessitates further refinement and advancement.

4.2. Boundary 2: HVAC and Energy Systems

Energy Systems Selection Challenges: The selection of appropriate energy systems for buildings is a complex process that is influenced by a variety of factors, including climatic conditions and geographical location. Despite the acknowledged importance of energy systems in building design, the methodologies for determining the most suitable energy systems for a specific building are not well-established. It is common for buildings to incorporate a variety of different energy systems; however, the interactions between these systems, and how they can be optimized for improved energy efficiency performance, remains poorly understood. The lack of a cohesive approach to energy systems integration in building design is a significant obstacle to achieving higher levels of energy efficiency in buildings. Therefore, it is crucial to develop a systematic methodology for the selection, integration, and optimization of energy systems in buildings to improve overall energy performance. Furthermore, the interconnections between different energy systems in a building should be well-defined, and the ways in which they can interact to achieve higher efficiency performance should be thoroughly investigated.

HVAC Equipment Sizing Challenges: The critical role of proper HVAC equipment sizing in promoting energy efficiency and reducing waste in buildings cannot be overstated. An HVAC system must be able to provide adequate heating and cooling to maintain comfortable indoor temperatures while avoiding oversizing, which can cause energy waste and negatively impact indoor air quality and equipment reliability. Conversely, undersized systems struggle to maintain desired temperatures, leading to increased energy consumption and decreased comfort. The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) recommends sizing HVAC systems based on building loads and occupancy patterns, considering factors such as insulation, airtightness, solar gains, and ventilation needs [122]. This can be achieved through energy simulation models, manual calculation methods, and design guidelines provided by organizations like ASHRAE. In conclusion, proper HVAC equipment sizing is crucial for reducing energy waste and improving efficiency in buildings. It enables optimization of energy performance, lower operating costs, and enhanced indoor comfort.

Optimal Systems and Envelope Integration Challenges: The optimal combination of building energy systems and building envelope has been shown to significantly reduce energy consumption, CO_2 emissions, and energy costs. Consequently, it is essential to carefully consider the unique characteristics of each building in order to effectively match the appropriate energy systems and achieve superior building energy performance.

Zoning Challenges: Zoning a building into temperature control areas provides targeted and efficient heating and cooling, leading to improved energy performance. The installation of separate heating and cooling systems for zones with higher internal heat loads or lower heating and cooling requirements allows for individually controlled heating and cooling, resulting in energy savings and improved thermal comfort. The US Department of Energy reports that zoning can save 30–40% of heating and cooling energy consumption [123]. This is supported by the ASHRAE Handbook of Fundamentals, which states that zoning improves thermal comfort, reduces energy consumption, and increases control flexibility [122]. Zoning is, therefore, a critical aspect of building design and operation for enhancing heating and cooling efficiency and reducing energy consumption.

Energy Storage Systems Challenges: The challenge of balancing energy supply and demand is a complex issue, particularly in light of the diverse infrastructure and environmental conditions present in different regions. In this context, energy storage systems have been identified as a crucial element in achieving a balance. While energy storage has the potential to mitigate seasonal mismatches, this necessitates the implementation of large-scale storage capacity. The current state of the industry necessitates the development of standard, cost-effective seasonal and long-term energy storage systems for heating and cooling, as well as electricity [124]. Furthermore, the rational design of energy storage systems is crucial for the achievement of optimal performance.

Routine HVAC Maintenance Challenges: Routine HVAC maintenance, sealing and insulating ductwork, and upgrading equipment are crucial to building performance and energy management. Neglect of maintenance leads to decreased performance, increased energy consumption, and poor air quality. Routine inspections, cleaning, and addressing wear and tear improve longevity, reduce breakdown risk, and ensure compliance with regulations, safety, and health standards. Sealing ductwork stops leaks, improves air circulation, and reduces energy loss. Insulating ductwork regulates air temperature, reduces heat transfer, and improves efficiency, potentially reducing energy use by up to 20%. Upgrades, such as high-efficiency air filters, programmable thermostats, and variable-speed fans, can result in energy savings, improved indoor air quality, and reduced carbon footprint. Regular inspections and maintenance of the ductwork and HVAC system are essential to enhance overall building performance and prevent energy loss.

EV Integration Challenges: The integration of EVs into buildings or communities has been gaining increasing attention due to the potential for utilizing surplus electricity generated from RE sources, thus reducing emissions [125]. However, the high frequency of charging and discharging associated with EVs has been identified as a major challenge, as it can lead to accelerated battery degradation and impede the integration of EVs into the grid. This constitutes a significant barrier to the wider adoption of EVs in this context.

Indoor Air Quality Challenges: In the context of designing new buildings or retrofitting existing ones, it is imperative to acknowledge and address the indoor air quality [126] needs of building occupants, encompassing aspects such as thermal comfort, indoor air quality, and visual and acoustic comfort. To ensure precise pre-analysis, the utilization of energy performance simulation tools becomes indispensable, as they facilitate accurate energy calculations and enable comprehensive assessments of thermal comfort [127–129].

4.3. Boundary 3: Individual Buildings

The pursuit of nZEBs, ZEBs, and PEBs is a complex and multi-faceted endeavor, requiring the resolution of a multitude of technical, financial, behavioral challenges, consistent implementation, monitoring and verification, and interdisciplinary challenges as presented, for example, in [64,89,130–132]. The realization of nZEBs, ZEBs, and PEBs necessitate a comprehensive understanding of these challenges and the development of effective strategies to overcome them. The following represents a list of the various challenges.

Technical Challenges: The main technical challenges associated with the pursuit of nZEBs, ZEBs, and PEBs encompass (1) the design and construction of energy-efficient building systems; (2) the integration of RE sources; (3) the optimization of building performance, specifically in terms of energy demand, cost reduction, and emissions mitigation; (4) the technical standards and regulations. Overcoming these technical challenges requires a comprehensive and interdisciplinary approach, encompassing expertise from various fields such as architecture, engineering, and RE.

Financial Challenges: The pursuit of nZEBs, ZEBs, and PEBs presents substantial financial obstacles that must be overcome to achieve these highly energy-efficient buildings. These challenges encompass a variety of factors, including elevated initial construction expenses, restricted access to financing and investment capital, a lack of knowledge regarding the long-term cost savings and benefits of nZEBs, ZEBs, and PEBs, and a scarcity of incentives or subsidies for sustainable building practices. Additionally, the integration of EMSs focusing on the operational period is crucial to cover all financial aspects and enhance the economic feasibility of these buildings. Addressing these financial barriers requires concerted collaboration between governments, building owners, contractors, and financial institutions, aimed at advancing sustainable building practices and promoting their economic viability.

Behavioral Challenges: The pursuit of nZEBs, ZEBs, and PEBs requires the resolution of various behavioral challenges, which pertain to human attitudes and behaviors that must be addressed to achieve these highly energy-efficient buildings. These challenges may encompass resistance to change, lack of understanding or awareness of the benefits of energy-efficient building practices, as well as an absence of incentives or motivations for individuals and organizations to embrace sustainable building practices. Moreover, issues pertaining to building operations and maintenance such as insufficient training for building occupants and staff, and lack of accountability for energy usage may also pose a significant challenge. Overcoming these behavioral barriers necessitates a collaborative effort from governments, building owners, contractors, and educational institutions to promote sustainable building practices and educate building occupants and staff about the importance of energy efficiency.

Consistent Implementation and Adherence Regulations and Standards: The consistent implementation and adherence to regulations and standards in the pursuit of nZEBs, ZEBs, and PEBs poses significant challenges that must be overcome to achieve these highly energy-efficient buildings. These challenges encompass a lack of clarity and uniformity in standards, difficulties in ensuring compliance, and an absence of transparency and accountability in the building design, construction, and operations process. Furthermore, the compatibility of new technologies with existing standards and the absence of adequate technical expertise can hinder effective implementation. Addressing these challenges requires a collaborative effort from governments, industry professionals, and educational institutions to establish clear, consistent regulations and standards, promote transparency and accountability, and provide technical expertise and training to support their successful implementation.

Monitoring and Verification Challenges: The challenges of monitoring and verification in the pursuit of nZEBs, ZEBs, and PEBs represent a formidable impediment to the achievement of highly energy-efficient buildings. These challenges may encompass a dearth of accurate and trustworthy monitoring systems, obstacles in attaining comparable and uniform data, and the complexity of verifying the energy efficiency of buildings. Furthermore, there may be difficulties in integrating monitoring systems with existing infrastructure and a shortage of technical knowledge to effectively operate and analyze the collected data. Addressing these challenges necessitates collaboration between governments, building industry professionals, and educational institutions, in order to establish accurate monitoring systems, implement consistent and comparable data-gathering techniques and equipment (e.g., IoT devices), and provide technical proficiency to ensure effective monitoring and verification of energy performance in these buildings.

Interdisciplinary Challenges: The main challenges related to interdisciplinary cooperation in the endeavor to attain nZEBs, ZEBs, and PEBs encompass concerns that must be resolved to ensure the accomplishment of these energy-efficient buildings. These challenges may involve the absence of synchronization and collaboration between various specialists and stakeholders, including architects, engineers, building proprietors, and contractors. Additionally, there may exist a lack of correspondence between the aims and objectives of diverse groups, resulting in conflicting design and construction decisions. With the aim of overcoming these interdisciplinary challenges, a robust dedication to collaboration, effective communication and mutual comprehension of respective roles and goals, and a common objective of creating highly energy-efficient buildings are crucial.

Addressing these challenges requires a concerted effort from multiple sectors, including governments, building industry professionals, and educational institutions. A key factor in overcoming these challenges is clear and effective communication, which promotes a shared understanding of the goals and objectives involved in the creation of energy-efficient buildings. Additionally, there must be a strong commitment to sustainable building practices and a willingness to collaborate and work together towards the common goal of creating buildings that are not only energy-efficient but also environmentally responsible and sustainable in the long term.

4.4. Boundary 4: Communities of Buildings

The scholarly inquiry and subsequent practical innovations within the domain of building communities are characterized by their technological sophistication and the exigent nature of contemporary challenges, as evidenced by the comprehensive body of work accumulated up to the completion of this study. The pursuit of nZECs, ZECs, and PECs poses a complex set of challenges that must be addressed to achieve their highly energy-efficient objectives. Some of these challenges include coordination of energy-efficient design, construction, and operational practices across multiple buildings, a lack of established and universally accepted standards and guidelines, difficulties in ensuring compliance with regulations, and insufficient transparency and accountability in the design, construction, and operational processes. The integration of new and advanced technologies with existing standards and regulations, as well as the availability of specialized technical expertise and knowledge for effective implementation, are also significant challenges in this pursuit. The integration of RE sources, energy storage systems, and EMSs [133] into the community-wide energy system presents additional difficulties. In order to overcome these obstacles, a collaborative effort is needed from government agencies, building industry professionals, and educational institutions to establish clear and consistent regulations and standards, enhance transparency and accountability, and provide the necessary technical training and expertise to support successful implementation.

Definition and Boundary Challenges: The definition and boundaries of nZECs, ZECs, and PECs remain a topic of research and debate. Uncertainty surrounds the inclusion of infrastructure energy demand and the classification of energy loads as controllable or uncontrollable. The geographical boundary of these communities is also debated, with proposals ranging from virtual neighborhood boundaries to physical city or regional boundaries. It is important to establish a clear definition and methodology for evaluating communities, taking into account the complexities of different energy systems and communities. Advanced technologies, such as real-time monitoring and advanced data analytics, may aid in overcoming current evaluation limitations. Therefore, it is needed to establish a consistent framework for these communities' analysis.

Community Scale Challenges: The scale of a community of buildings, including the number and physical dimensions of each building, is crucial for determining energy performance. Energy demand is influenced by the quantity of buildings and their scale, as larger buildings require more energy for heating, cooling, and lighting. The feasibility of incorporating RE sources, energy storage systems, and EMS is impacted by the community scale. Larger communities may face greater challenges in implementing RE sources and require more sophisticated EMSs. Conversely, smaller communities may be able to adopt simpler EMSs and integrate RE sources more easily. Overall, community-scale plays a significant role in energy performance.

Energy Management Challenges: As previously discussed, the EMS plays a pivotal role in enhancing energy efficiency and curbing consumption by facilitating synchronized interactions between buildings and the electrical grid. The efficacy of EMS is significantly influenced by the scale and complexity of the building community it serves. In compact communities with a limited number of buildings, EMS deployment tends to be more straightforward, allowing for seamless integration at either the individual building or community-wide level. This smaller scale permits a direct correlation between the EMS control strategies and the underlying mathematical models governing the energy systems. Conversely, in expansive communities encompassing a multitude of structures, the deployment of EMS becomes inherently more complex. The necessity for distinct simulation and programming tools to manage energy systems introduces potential discrepancies and elongates operational processes, complicating the alignment between control strategies and their mathematical representations. To address these challenges in larger communities, the adoption of cutting-edge EMS technologies becomes imperative.

Energy Efficiency Improvement Challenges: Improving energy efficiency at the community level is crucial for reducing energy consumption and addressing climate change. Strategies should be designed with consideration of local climate conditions, such as temperature, humidity, and wind patterns, to optimize results. Evidence supports the importance of local climate consideration in energy efficiency strategies. For instance, in warm regions with high solar radiation, reducing cooling demands through shading and ventilation is more effective, while in colder regions, reducing heating demands with insulation and efficient heating systems is key. It can be noted that a one-size-fits-all approach is ineffective and that strategies must be tailored to local conditions to achieve optimal results. Moreover, the significant role of local climate in determining energy consumption patterns and that strategies that take these conditions into account are more likely to be effective. In conclusion, the design and implementation of energy efficiency strategies at a community level must take into account local climate conditions to achieve optimal results. To effectively enhance energy efficiency at the community level, it is crucial to figure out the relationship between local climate variables and energy usage, forming strategies that are conventional to each area's unique conditions. Furthermore, integrating cutting-edge technologies such as real-time monitoring systems, sophisticated data analysis, and robust communication networks will amplify the formulation and execution of more successful and sustainable energy efficiency measures for communities.

Integrating Energy Efficiency Challenges: Integrating energy efficiency into community building design and construction is crucial for achieving nZECs, ZECs, and PECs. The density of the community and available roof and facade area for RE generation must be considered. Integrating city and building design into energy planning ensures effective energy solutions. However, the method of sharing remaining grid imports among community buildings can impact energy performance [134]. Currently, there is no universally accepted and equitable method for distributing energy within communities and to the grid. In conclusion, nZECs, ZECs, and PECs can be achieved when communities of buildings are designed and constructed with high levels of energy efficiency and sufficient spaces, for example, roof and facade area for RE generation, provided the density of the community is not too high. An integrated planning process, incorporating city and building design into energy planning, is critical for the success of these initiatives. Additionally, further research is needed to establish a fair and widely accepted method for energy distribution within communities of buildings.

Energy Transmission Challenges: Energy transmission between buildings in a community requires an internal network. Financial and technical challenges, as well as main grid impact, may arise. Mitigating these challenges requires careful design and implementation, considering technical and economic feasibility. Adopting advanced technologies, such as smart grid systems and distributed energy resources, can improve efficiency and reliability [135]. Integrating energy storage systems and using RE sources, such as solar and wind power, can enhance stability, resilience and overall energy performance, reducing reliance on the main grid and sharing within the community. In conclusion, the development of an effective internal energy network for communities of buildings requires a comprehensive approach that takes into account both the technical and economic feasibility, as well as the protection and reliability of sharing electricity in both the local and main grid. The use of advanced technologies, energy storage systems, and RE sources can help overcome some of the challenges associated with the development of an internal energy network, and ensure its success.

High Initial Investment Challenges: It is essential to consider long-term benefits; therefore, the design of sustainable buildings and communities faces a major challenge in the high initial investment required. A comprehensive and integrated approach is needed, taking into account the local climate, future climate trends, building type, energy costs, system operation, and techno-economics, to balance economic viability, environmental sustainability, and energy efficiency while ensuring comfort. Conflicting objectives may require multi-objective optimization models to identify trade-offs and find the optimal solution. High-efficiency building technologies and materials, such as insulation and air-tightness systems, and the integration of RE sources like solar and wind power can help reduce energy consumption and reliance on conventional energy sources, mitigating the challenge of the high initial investment. In conclusion, successful sustainable building practices hinge on effectively integrating and balancing multiple design goals, including cost-effectiveness, environmental impact, and energy efficiency. Considering multi-objective optimization and leveraging state-of-the-art technologies like RE sources and EMSs are key to addressing the challenges of high initial costs and achieving these objectives.

Key Performance Indicators Challenges: Evaluating the effectiveness of zero energy projects requires using key performance indicators to measure progress. Environmental and energy key performance indicators, such as RE produced, CO_2 reduction, and RE share increase, provide a neutral assessment. However, a lack of standard key performance indicators, calculation methods, and tools results in difficulty in quantifying energy use, emissions, and efficiency. The local resource potential and inherent characteristics of regions can affect project feasibility and success. A uniform assessment methodology referencing model assumptions and choices is needed to ensure comparability and transparency across projects and case studies. In order to overcome the lack of standard key performance indicators and assessment tools, there is a need for more research and collaboration between stakeholders to develop a consistent and comprehensive methodology for evaluating the performance of ZECs. Additionally, the use of advanced technologies, such as smart grid systems and distributed energy resources, can help to improve the accuracy and reliability of energy use and emissions data and provide a more comprehensive picture of the community's energy performance.

Federated Decision-making Challenges: Effective energy project planning demands a federated, iterative, and transparent approach to accommodate changes in technology, policies, and processes within political, economic, cultural, and social contexts. A federated decision-making method integrates multiple stakeholder perspectives, leading to a comprehensive understanding of challenges and opportunities. Continuously monitoring and evaluating progress and adapting strategies accordingly is crucial for success. Accurate, real-time information is necessary for informed decision-making, achieved through robust monitoring and evaluation systems. It can be concluded that this approach enables decision-makers to effectively respond to evolving technologies, policies, and processes in different contexts and support the achievement of project goals.

Load Forecasting Challenges: Accurate forecasting of building energy demand and load is critical for optimized energy management in integrated systems. This precise load prediction is key to effectively managing and distributing energy resources. Current methods include building simulation software and data-driven technologies. However, simulation software may have low accuracy and data-driven methods lack in considering interrelationships between loads. Hence, advanced forecasting methods are needed to provide a comprehensive picture of future energy demand. This can be achieved by considering coupling relationships between loads and integrating real-time data from various sources with machine learning algorithms and big data analytics. The unique characteristics of the energy system and its loads must also be considered to improve forecasting accuracy. It can be noted that to ensure optimal scheduling of integrated energy systems, accurate and comprehensive energy demand forecasting is a necessity. Advanced energy demand forecasting methods need to be developed that take into account the complex relationships between multiple loads, and that use real-time data and machine learning algorithms to provide a more accurate and comprehensive picture of future energy demand. By doing so, energy systems can be managed more efficiently, leading to reduced energy costs, reduced greenhouse gas emissions, and improved energy security.

5. Discussion

The building sector is responsible for a significant portion of global energy consumption and CO_2 emissions. Key measures to achieve green buildings and communities include optimizing building physics, building energy systems such as HVAC, and utilizing RE systems like PV panels and wind turbines. The surplus electricity generated by RE systems can be used for EV charging and as distributed energy storage, contributing to peak load reductions. Additionally, EVs offer multidirectional energy interactions between vehicles, buildings, and the grid, reducing electricity demand from the grid.

Building performance evaluation has evolved to encompass the energy efficiency of communities of buildings. Establishing different boundary layers is crucial for identifying energy flows that cross them and examining associated challenges. The three boundary layers for individual buildings are based on the building envelope, energy systems, EVs, and surplus energy. Buildings can be classified as negative energy, nearly zero energy, zero energy, or positive energy based on energy consumption and generation. For communities of buildings, a fourth-layer boundary is established to include energy flow exchange between buildings, and they can also be classified based on energy consumption and generation.

Efficient energy use in buildings is pivotal for reducing global energy consumption and curbing carbon emissions. NEBs exhibit high energy demands and poor performance, but standard retrofit measures can significantly lower their total energy consumption. nZEBs are increasingly prevalent, as reducing energy demand proves more cost-effective than on-site energy generation. ZEBs achieve self-sufficiency by integrating RE sources and advanced energy-efficient technologies. PEBs not only meet their own energy needs but also produce surplus energy, substantially contributing to enhanced energy efficiency and sustainability.

The trend towards reducing energy consumption and emissions from buildings is shifting towards a macro-level approach, specifically focusing on communities of buildings. A community of buildings consists of a group of buildings sharing common areas in proximity and can lead to advantages such as load diversity, the ability to control, store, and divert energy produced from various sources and regions, increased efficiency, reduced energy consumption, and enhanced energy resilience. nZECs integrate various RE technologies in the buildings, enabling the sharing of surplus electricity within the district, leading to a significant reduction in energy consumption and costs. ZECs are energy-efficient communities where the actual annual delivered energy on a source energy basis is less than or equal to the on-site renewable exported energy. The latest approach is to develop PECs, where the community produces more energy than it consumes, leading to enhanced energy resilience, cost savings, and a reduction in greenhouse gas emissions.

This study thoroughly examines the energy efficiency of both individual buildings and communities, pinpointing key challenges and offering strategic solutions. The primary challenges include setting macro-level targets, accurately calculating energy demand and supply, enhancing the building envelope, and aligning various energy systems. These issues are systematically organized into four essential categories: building physics, HVAC and energy systems, the performance of individual buildings, and energy dynamics within communities. Additionally, we have presented a detailed comparison of our results with existing literature to highlight the advancements and unique contributions of our research. This comparison underscores the effectiveness of our proposed boundaries and frameworks in enhancing energy efficiency and sustainability in building areas.

Boundary 1: Building Envelope: Optimizing building design to reduce energy consumption involves several building physics strategies. These include natural light utilization, passive design techniques, proper insulation, energy-efficient windows, and ventilation systems. Additionally, using high-reflectance roofing materials, shading devices, and incorporating passive solar design elements can increase energy efficiency. Envelope component matching, where building envelope systems are configured based on annual energy consumption patterns, is essential for optimizing energy demand within a building.

Boundary 2: HVAC and Energy Systems: The selection, integration, and optimization of energy systems in buildings are complex processes influenced by various factors. Proper HVAC equipment sizing, zoning, and routine maintenance are crucial for reducing energy waste, improving efficiency, and enhancing thermal comfort. Energy storage systems are vital for balancing energy supply and demand. However, developing standard, cost-effective, and rational energy storage systems for heating, cooling, and electricity is necessary to achieve optimal performance. While integrating EVs into buildings holds potential, the high frequency of charging and discharging remains a significant barrier to their widespread adoption.

Boundary 3: Individual Buildings: The pursuit of nZEBs, ZEBs, and PEBs involves overcoming several challenges, including technical, financial, behavioral, regulatory, monitoring, and interdisciplinary issues. Technical challenges encompass designing and constructing energy-efficient building systems, integrating RE sources, optimizing building performance, and adhering to technical standards and regulations. Addressing these challenges necessitates an interdisciplinary approach. Financial challenges include elevated construction expenses, lack of financing, and a scarcity of incentives for sustainable building practices. Behavioral challenges relate to human attitudes and operations and maintenance practices. Consistent implementation and adherence to regulations and standards pose additional challenges, as do monitoring and verification processes. Overcoming these challenges requires collaboration among governments, building industry professionals, and educational institutions to establish regulations, promote transparency and accountability, and provide technical expertise for effective monitoring and verification of energy performance. Interdisciplinary challenges require effective communication, collaboration, and mutual understanding of roles and goals to create highly energy-efficient and sustainable buildings.

Boundary 4: Communities of Buildings: The pursuit of nZECs, ZECs, and PECs is increasingly important for reducing energy consumption and improving energy efficiency. The scale of a community of buildings significantly influences overall energy performance, necessitating the design of energy efficiency strategies that consider local climate conditions for optimal results. Integrating energy efficiency into community building design and construction is critical for achieving nZECs, ZECs, and PECs. Advanced technologies, such as real-time monitoring and advanced data analytics, support the development of more effective and efficient community-level energy efficiency strategies. The method of allocating remaining grid imports among community buildings critically impacts energy performance, emphasizing the need to establish a fair and widely accepted approach for energy distribution within building communities. However, the lack of a clear definition and methodology for evaluating these communities and the challenges of coordinating energy-efficient design, construction, and operational practices across multiple buildings pose significant obstacles to their realization.

This research builds on and expands the existing body of knowledge by providing a comprehensive framework that integrates RE sources, energy storage systems, and real-time monitoring technologies. This holistic approach ensures optimal energy flow and equitable distribution within building communities. The proposed framework has demonstrated greater effectiveness in achieving energy efficiency compared to previously documented isolated strategies. Furthermore, our findings underscore the importance of considering local climate conditions and the specific energy needs of the community, aspects often overlooked in earlier studies. This comprehensive comparison highlights the practical application and significant impact of our proposed boundaries and strategies in enhancing energy resilience and sustainability in building communities.

6. Conclusions

This research provides an in-depth analysis of energy efficiency in both individual buildings and communities. It identifies key obstacles and proposes strategic solutions to address them. The main challenges involve establishing overarching targets, precisely determining energy demand and supply, improving building envelopes, and coordinating various energy systems. These challenges are categorized into four main areas: building physics, HVAC and energy systems, performance optimization of individual buildings, and energy interactions within communities. By addressing these areas, this study offers a comprehensive approach to enhancing energy efficiency, emphasizing the importance of integrated strategies and collaborative efforts among stakeholders. The insights gained from this research contribute significantly to the development of sustainable and resilient building practices, paving the way for future advancements in the field.

Effective collaboration among government agencies, industry professionals, and academic institutions is imperative to establish robust and consistent regulations and standards. Such cooperation will enhance transparency and accountability, ensuring the successful implementation of energy-efficient initiatives. Additionally, providing comprehensive technical training and expertise is essential to support these efforts. Integrating city planning with building design into a cohesive energy planning process is vital for achieving the ambitious goals of sustainable and resilient communities.

In summary, this research contributes to the existing body of knowledge by presenting a comprehensive framework that addresses the integration of RE sources, energy storage systems, and advanced monitoring technologies. The framework's effectiveness in optimizing energy flow and ensuring equitable energy distribution within building communities is a significant advancement over previous strategies. By considering local climate conditions and specific community energy needs, our approach offers a practical and impactful solution for enhancing energy efficiency and sustainability in the built environment.

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Abbreviations

The following abbreviations are used in this manuscript:

BIPV	Building-integrated Photovoltaic
CHP	Combined Heat and Power
EMS	Energy Management System
EV	Electric Vehicle
GSHP	Ground Source Heat Pump
HVAC	Heating, Ventilation and Air Conditioning
NEB	Negative Energy Building
NEC	Negative Energy Community
nZEB	Nearly Zero Energy Building
nZEC	Nearly Zero Energy Community
PEB	Positive Energy Building
PEC	Positive Energy Community
PED	Positive Energy District
PV	Photovoltaic
RE	Renewable Energy
STC	Solar Thermal Collector
ZEB	Zero Energy Building
ZEC	Zero Energy Community

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