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Case Report

Energy Positive Futures: A Critical Overview of Energy Plus Buildings

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Abstract: Energy Plus Buildings (EPBs) represent a transformative leap in sustainable architecture by producing more energy than they consume annually. As nations commit to net-zero targets and climate resilience, EPBs serve as living laboratories for integrating renewable energy, energy-efficient systems, and smart technologies. This editorial synthesises current advancements, policy frameworks, and technological integrations enabling EPBs. It also critically examines the barriers, economic, regulatory, and technological, that must be addressed to scale this paradigm. A longitudinal analysis of energy generation versus consumption highlights the growing viability of EPBs in achieving positive energy balance. Strategic pathways forward include harmonised policy incentives, urban-scale energy planning, and lifecycle carbon accounting. With interdisciplinary collaboration, EPBs can play a pivotal role in reshaping energy ecosystems.

Keywords: Energy Plus Buildings, Sustainable Architecture, Low Carbon Economy, Energy Efficiency

Introduction

Buildings account for roughly 40% of worldwide energy use and carbon dioxide emissions (Anac *et al.*, 2024). This reflects the construction industry's enduring dependence on traditional materials and methods, notwithstanding the significant technological advancements and enhanced comfort levels that have been achieved (Alhassan *et al.*, 2024). With the global population on the rise, building energy consumption is expected to increase, making it critical to develop and implement sustainable building practices (Kontoleon *et al.*, 2023). EPBs, also known as energy-positive or plus-energy buildings, represent a visionary shift in which buildings are not passive consumers but active contributors to energy systems (Nešović *et al.*, 2024). This editorial study provides a critical overview of the EPB concept, assesses current advancements, and outlines strategic priorities for research, policy, and practice.

An EPB is a building that, over the course of a year, generates more primary energy, often from renewable sources like solar photovoltaics (PVs) (Sreenath *et al.*, 2020), than it requires for its operational needs, including heating, cooling, lighting, appliances, and occupant usage (Lou and Hsieh, 2024). This net-positive energy balance is typically calculated based on site or source energy metrics, accounting for energy exports to and imports from the grid. These buildings have evolved from net-Zero Energy Buildings (nZEBs), which aim to produce as much energy as they consume annually, thus reducing the usage of non-renewable energy (Alvur *et al.*, 2024). In the design of EPBs, not only the source of energy generation but also the design, retrofit and reinforcement of the buildings play a key role. In this regard, EPBs are directly linked to novel materials (Cuce, 2014) and various solutions of sustainable built environment design (Cuce *et al.*, 2019).

At the global policy level, the urgency of adopting EPBs is reinforced by leading international roadmaps and scientific assessments. The International Energy Agency (2021) underscores that achieving climate neutrality by mid-century requires that all new buildings be zero-carbon in operation by 2030, alongside a deep retrofit rate of 2.5-3% annually for the existing building stock to achieve full decarbonisation by 2050. Similarly, the Intergovernmental Panel on Climate Change (2022)

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identifies the buildings sector as having the highest cost-effective mitigation potential across all major sectors, capable of delivering substantial greenhouse gas reductions through integrated design, renewable energy deployment, and EPB concepts. These strategic documents emphasise that EPBs, with their surplus renewable generation and advanced demand management, directly contribute to achieving the 1.5°C target by bridging local-scale innovation with global decarbonisation trajectories. By embedding EPBs within such internationally endorsed pathways, technical solutions at the building scale are positioned as integral components of systemic, multi-level climate action.

In comparison to previous studies on EPBs, which often remain confined to descriptive overviews of technologies and policy frameworks, this study offers an integrated, multi-scalar perspective that directly connects building-level innovations with broader urban energy ecosystems. The paper uniquely combines recent advances in high-performance envelope design, renewable integration, and intelligent energy management with emerging concepts such as Positive Energy Districts and decentralised peer-to-peer energy trading, which remain underrepresented in existing literature. Unlike earlier works, the analysis is explicitly structured to bridge technical solutions, regulatory mechanisms, and socio-behavioural factors, presenting EPBs not merely as isolated architectural exemplars but as pivotal components of systemic decarbonisation strategies. This approach not only synthesises technological and policy developments but also positions EPBs within the evolving discourse on resilient, low-carbon urban transitions, thereby advancing the field beyond the scope of prior studies. It should also be noted that this paper is conducted as a comprehensive editorial review and therefore does not involve new experimental data collection or primary quantitative analysis but rather synthesises and critically evaluates existing knowledge to provide a consolidated overview and future research roadmap.

Current Developments and Case Studies

EPBs represent a significant advancement in the pursuit of sustainable and energy-autonomous built environments. These buildings are designed not only to meet their own operational energy demands but to produce a net surplus of energy over the course of a year, typically through the integration of renewable energy technologies (Atiba and Chwieduk, 2024). Notable examples of EPBs can be found across Europe, North America, and Asia, driven by forward-thinking policy instruments, technological innovation, and performance-based building codes (Carlucci *et al.*, 2024). EPBs employ a technologically integrated suite of systems, including high-performance envelopes, on-site renewables, storage systems, smart controls, and grid-interactive capabilities (Calotă *et al.*, 2024). The development and proliferation of EPBs are increasingly being driven by global policy frameworks aimed at mitigating climate change, improving energy efficiency, and reducing greenhouse gas emissions. One such policy instrument is the European Union's Energy Performance of Buildings Directive (EPBD), which mandates that all new buildings must meet the nZEB standard. EPBs go a step further by exporting surplus energy back to the grid, contributing to a more decentralised and resilient energy infrastructure (Cai and Gou, 2024).

Technological innovation plays a pivotal role in the realisation of EPBs. Contemporary design approaches emphasise a holistic integration of active and passive energy strategies, including high-performance building envelopes (Cuce *et al.*, 2016), advanced thermal insulation (Cuce and Riffat, 2015), airtight construction (Cuce, 2017), and passive solar design principles (Sarir and Sharifzahed, 2024). Renewable energy systems, particularly Building-Integrated PV (BIPV), solar thermal collectors, and geothermal heat pumps, are central to achieving a positive energy balance. In parallel, the deployment of intelligent building systems, such as Internet of Things (IoT) devices (Shu *et al.*, 2025), smart meters, and Artificial Intelligence (AI)-driven energy management platforms, enables real-time monitoring, predictive control, and optimisation of building performance (Mohanty *et al.*, 2025). Additionally, the use of Phase Change Materials (PCMs) for thermal energy storage, daylighting systems, and energy recovery ventilation further enhances energy efficiency and occupant comfort. To ensure a smoother transition from high-level policy frameworks to technical design recommendations, it is essential to contextualise advanced solutions like PCMs and Artificial Intelligence (AI)-driven systems within broader sustainability objectives. Recent empirical and review studies demonstrate tangible performance gains from integrating PCMs and AI in buildings. For instance, PCMs can reduce peak cooling and heating loads by up to ~30-38%, stabilise indoor temperature fluctuations by ~46%, and decrease overall heating/cooling demand by ~31% depending on placement and climate zone (Alassaad *et al.*, 2025; Kamel *et al.*, 2024). Similarly, AI-based Heating, Ventilation, and Air Conditioning (HVAC) and energy management systems have achieved reductions in operational energy use ranging from ~8 to ~37 % in various building types, office buildings seeing up to 37 %, residential up to ~23 %, and educational buildings up to ~21 % (Ali *et al.*, 2024). A case study of an AI-enabled system (BrainBox AI) in a Manhattan office building showed a ~15.8 % HVAC energy reduction,

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saving 37 tCO_2 annually (Ding *et al.*, 2024). These metrics support how material innovations and digital intelligence can directly further global policy targets, including the EU EPBD, reducing operational carbon emissions, improving energy resilience, and aligning technical pathways with climate goals. Incorporating them provides a logical bridge between policy imperatives and specific technical recommendations, ensuring design guidance is grounded in validated performance evidence. Architects and engineers are increasingly combining innovative design, advanced engineering, and digital technologies, creating buildings that are both energy-productive and environmentally responsive (Brozovsky *et al.*, 2024).

Empirical case studies from across the globe illustrate the practical implementation and performance outcomes of EPBs in both residential and commercial contexts. One of the earliest and most influential examples is the PlusEnergy House developed by architect Rolf Disch in Freiburg, Germany. This project, completed in 2000, embodies the principles of energy surplus architecture by combining passive solar design, triple-glazed windows, and rooftop PVs (Freytag *et al.*, 2014). The house not only satisfies its energy needs but also generates excess electricity that is fed back into the public grid, exemplifying the economic and environmental feasibility of the EPB model. In a commercial setting, the Powerhouse Brattørkaia in Trondheim, Norway, stands out as a landmark project. Completed in 2019, it is considered the world's northernmost EPB. The building's design incorporates a comprehensive suite of energy-efficient technologies, including solar tracking panels, highly efficient mechanical systems, and an innovative building orientation that maximizes solar gain in a subarctic climate. Its performance demonstrates the adaptability of EPB strategies to challenging environmental conditions (Oross, 2022).

Moreover, large-scale initiatives such as the EU-funded "Energy-Positive Neighbourhoods" and pilot projects in North America and Asia are expanding the EPB concept from individual buildings to integrated urban systems. These developments suggest that the future of urban sustainability may lie in the proliferation of energy-positive districts and smart energy networks (Clerici Maestosi, 2024). In this context, EPBs serve not only as isolated technical achievements but as critical components in broader efforts to decarbonise the built environment, enhance energy security, and promote long-term ecological resilience. The growing body of evidence from both practice and research underscores the transformative potential of EPBs and points to the need for continued interdisciplinary collaboration in their design, implementation, and regulation.

In contemporary residential buildings, HVAC systems account for over 80% of the total energy consumption (Simpeh *et al.*, 2022). While improving insulation effectively reduces thermal losses and enhances indoor comfort, it remains an insufficient measure to fully mitigate the building sector's environmental impact. Insulation strategies primarily decrease the operational energy demand; however, they do not eliminate the dependence on external, often fossil-fuel-based, energy sources, thus sustaining a significant carbon footprint. Consequently, transitioning towards EPBs has become imperative. EPBs are not only designed to minimise energy consumption through advanced building envelopes but also integrate renewable energy systems such as PV panels and micro-wind turbines to generate more energy than they consume over an annual cycle. This dual strategy directly addresses the core of carbon emissions, promoting a substantial decrease in the building's lifecycle carbon footprint, potentially achieving near-zero or even negative emission levels. Unlike conventional buildings, where energy flows are predominantly inward (high consumption, low production), EPBs invert this paradigm by significantly lowering energy imports while increasing on-site energy generation. This shift not only supports global decarbonization goals but also enhances building resilience against energy supply fluctuations. Furthermore, the adoption of EPBs is expected to escalate as regulatory frameworks tighten and market awareness grows regarding sustainable living solutions. Although initial investments may be perceived as high, the long-term benefits, including extended building lifespan, operational cost reductions, and climate impact mitigation, strongly outweigh the upfront costs. Figure 1 clearly illustrates this critical transition: Moving from typical high-consumption, low-generation structures towards future-ready, EPBs capable of self-sufficiency and environmental stewardship.

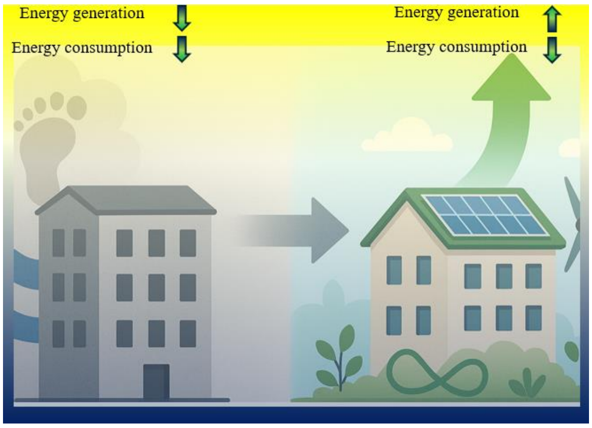

Fig. 1: Energy transition trajectory from traditional buildings to energy-positive models

Table 1: Key Features of EPBs Compared to Traditional Buildings

Feature	Traditional Building	Net-Zero Building	Energy Plus Building	Key Strategies for Transition
Energy Consumption	High	Reduced	Minimised	Passive design measures, high-performance insulation, airtight envelopes, optimised orientation, and advanced glazing (Cuce *et al.*, 2016; Cuce and Riffat, 2015; Sarir and Sharifzahed, 2024)
Energy Production	None or Minimal	Equal to consumption	Exceeds consumption	Deployment of BIPV, solar thermal, micro-wind, thermal/electrical storage, and seasonal storage (Ma *et al.*, 2024)
Grid Interaction	Passive consumption	Net metering	Active exporting	Smart inverters, bidirectional metering, demand-response mechanisms (Uzum *et al.*, 2020; Ahmad *et al.*, 2023)
Technology Integration	Basic HVAC, lighting	Efficient systems	Smart, adaptive systems	IoT-enabled monitoring, AI-driven predictive control, integrated energy management systems (Ali *et al.*, 2024; Ding *et al.*, 2024)
Environmental Impact	High emissions	Neutral operational impact	Negative operational impact	Low-embodied-carbon materials, modular prefabrication, recycling strategies (Pomponi and Moncaster, 2016; Röck *et al.*, 2020)
Lifecycle Assessment	Often ignored	Sometimes considered	Increasingly integrated	Mandatory lifecycle carbon assessments and certification schemes (Pomponi and Moncaster, 2016; Röck *et al.*, 2020)

The progression from traditional buildings to net-zero and ultimately to energy plus performance is underpinned by a combination of passive and active design strategies, renewable integration, smart technologies, and supportive policy measures. Energy consumption reduction begins with passive measures such as high-performance insulation, airtight construction, optimised orientation, and advanced glazing systems, which can decrease heating and cooling demands by 50-70% before active systems are considered (Cuce *et al.*, 2016; Cuce and Riffat, 2015; Sarir and Sharifzahed, 2024). Energy production advances from negligible generation to on-site renewable deployment, most notably BIPV, solar thermal collectors, and micro-wind turbines, paired with thermal or electrical storage to align supply with demand (Ma *et al.*, 2024). Seasonal energy storage further enables the transition from net-zero to surplus generation. Grid interaction evolves through the adoption of smart inverters, bidirectional metering, and demand-response mechanisms, allowing buildings to export excess power and support grid stability (Uzum *et al.*, 2020; Ahmad *et al.*, 2023). Technology integration shifts from conventional HVAC and lighting to IoT-enabled monitoring, AI-driven predictive control, and integrated energy management systems, which have been shown to cut operational energy use by up to 37% in certain building typologies (Ali *et al.*, 2024; Ding *et al.*, 2024). Reducing environmental impact requires not only minimising operational energy but also addressing embodied carbon through low-impact materials, modular prefabrication, and end-of-life recycling strategies (Pomponi and Moncaster, 2016; Röck *et al.*, 2020). Embedding lifecycle assessment as a routine practice ensures that operational gains are not offset by material-related emissions, safeguarding the net-positive status of EPBs over their entire lifespan. These strategies illustrate how targeted interventions at each stage can enable the transition from one performance column in Table 1 to the next, underscoring the necessity of technological innovation, behavioural adaptation, and systemic policy alignment to mainstream EPBs.

Challenges and Barriers

Despite their proven technical feasibility and increasing recognition in global sustainability agendas, the widespread implementation of EPBs continues to face a range of complex and interconnected barriers. These challenges span across economic, regulatory, technological, behavioural, and infrastructural dimensions, all of which must be addressed in tandem for EPBs to transition from isolated success stories to mainstream building practice.

One of the foremost barriers is the economic burden associated with constructing and maintaining EPBs. The integration of advanced building materials, on-site renewable generation, storage systems, and intelligent controls significantly increases the upfront cost of construction (Ajirotutu *et al.*, 2024), by as much as 20-30% compared to conventional buildings. Although operational savings and energy payback may be realised over time, the long-term financial benefits are often overshadowed by short-term budget constraints. Furthermore, the lack of consistent and long-term financial incentives, such as feed-in tariffs, tax credits, or green mortgages, exacerbates the problem, particularly in developing markets (Onabowale, 2024). These economic and market-related challenges are amplified by pronounced regional disparities between developed and developing economies. In high-income regions such as the EU, North America, and advanced economies in East Asia, mature renewable energy infrastructure, stable policy frameworks, and access to sophisticated financing mechanisms, including green bonds and energy performance contracts, enable faster and more widespread EPB adoption (Carlucci *et al.*, 2024; Dulian, 2024). Conversely, many developing economies face additional structural constraints, like underdeveloped supply chains for advanced building technologies, limited institutional capacity for enforcing energy performance standards, and reduced availability of affordable capital (Atiba and Chwieduk, 2024). In sub-Saharan Africa, South Asia, and parts of Latin America, volatile energy prices, lower grid reliability, and competing socio-economic priorities further limit investment potential (Lazaroiu *et al.*, 2025). Climatic variations compound these disparities: in tropical and arid regions, high cooling loads and water energy nexus issues demand costly and technically advanced solutions, whereas in cold climates of emerging economies, high-performance heating systems remain financially prohibitive without targeted subsidies. Addressing these disparities requires region-specific pathways that integrate technology transfer, capacity-building programmes, and tailored policy instruments to ensure EPB adoption becomes a truly global transition rather than a feature of economically advanced markets alone.

Regulatory frameworks also lag behind technological innovation. While policies like the EU EPBD have pushed for nZEBs, there is a lack of standardised definitions and performance metrics for EPBs, which exceed nZEB benchmarks. This ambiguity leads to fragmented implementation and hinders cross-border policy alignment and benchmarking. In many jurisdictions, planning regulations, zoning restrictions, and grid interconnection protocols were established decades ago and are ill-equipped to accommodate decentralised, prosumer-based energy systems (Lazaroiu *et al.*, 2025).

Technological complexity presents another formidable challenge. EPBs require seamless integration of PV systems, building-integrated renewables, thermal energy storage, passive solar strategies, AI-driven energy management, and IoT-based smart sensors. Ensuring interoperability between these diverse components demands high levels of technical expertise and robust commissioning protocols, which are not standard practice in many construction sectors (Liu *et al.*, 2023). As a result, performance gaps often emerge between design expectations and real-world operation.

Grid compatibility remains a critical constraint. Most national grids were not designed to accommodate large numbers of decentralised energy producers feeding back into the system. In this context, EPBs can inadvertently cause voltage fluctuations, reverse power flow, or frequency instability, especially during peak production periods (Uzum *et al.*, 2020). A recent report by the International Energy Agency (IEA) notes that without smart grid infrastructure and dynamic demand-response mechanisms, the scalability of EPBs may strain national energy systems rather than support them (Ahmad *et al.*, 2023).

Lifecycle carbon assessment is another underdeveloped area. Whilst EPBs are praised for their operational energy surplus, embodied carbon, the emissions generated during the production of building materials and construction processes, is often neglected. A study by Röck *et al.* reveals that embodied emissions can account for more than 50% of total life cycle emissions in highly efficient buildings (Röck *et al.*, 2020). Without rigorous lifecycle accounting frameworks, the environmental credentials of EPBs may be overstated, especially when carbon-intensive materials like reinforced concrete or aluminium are heavily used.

On the social front, occupant behaviour plays a pivotal role in EPB performance. Studies have shown that user interaction with smart systems, ventilation patterns, and appliance use significantly influence net energy balance (Salerno *et al.*, 2021). However, many EPB designs fail to adequately consider behavioural dynamics or provide occupants with the necessary training and feedback mechanisms to make informed energy decisions. Digital literacy and technological acceptance remain uneven, particularly among older or economically disadvantaged populations.

Maintenance and operational reliability also pose serious concerns. EPBs rely heavily on intelligent control systems and sensor-based data analytics. In the absence of skilled technicians, malfunctioning systems can go undetected, undermining performance and user comfort. Additionally, cybersecurity risks are emerging as a new frontier, with smart energy

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systems becoming potential targets for malicious attacks (Diaba *et al.*, 2024).

From an urban planning perspective, spatial and contextual constraints limit EPB deployment. In dense urban settings, optimal solar access and façade design may be compromised due to shading from adjacent buildings. Furthermore, retrofitting existing building stock to EPB standards remains both technically and economically challenging. A study by Fülöp and Harmathy (2024) reports that less than 3% of existing buildings in Europe are undergoing deep renovation annually, far below the required rate to meet climate targets.

Skills and workforce gaps represent another barrier. The successful realisation of EPBs requires a multidisciplinary workforce trained in green construction methods, energy modelling, digital systems, and building commissioning. However, educational curricula and vocational training programmes have not evolved quickly enough to meet this demand. Without adequate capacity building, the industry risks facing a bottleneck in talent and expertise. Furthermore, policy uncertainty undermines investor confidence. Political changes often lead to abrupt modifications or cancellations of incentive programmes. The reduction of solar feed-in tariffs in several European countries during the past decade is a cautionary example that illustrates how inconsistent policy frameworks can destabilise emerging markets for sustainable technologies (Padilla, 2021). In terms of knowledge dissemination, best practices and lessons learned from successful EPB projects are not systematically shared. This lack of institutional learning and replication results in repeated mistakes, inefficient resource use, and missed opportunities for performance optimisation across regions. To overcome these barriers, a systemic approach is essential, one that aligns policy instruments with technical standards, market incentives, and public engagement. Strategies should include the establishment of binding EPB performance definitions, robust lifecycle carbon accounting, and investment in smart grid infrastructure. Moreover, upskilling the construction workforce, promoting occupant education, and ensuring open-source dissemination of EPB data can accelerate the transition. In conclusion, whilst EPBs represent a visionary shift toward carbon-neutral living environments, their full potential will only be realised through coordinated action across all sectors. The barriers are significant but not insurmountable. With strategic intervention and interdisciplinary cooperation, EPBs can evolve from niche innovations to mainstream solutions, playing a critical role in achieving global climate goals and sustainable urban development.

Overall, Figure 2 illustrates the direct relationship between key barriers to EPB adoption and their targeted solutions. High upfront costs are addressed through green financing options, while inconsistent financial incentives can be overcome by long-term funding mechanisms. Fragmented regulations are resolved via harmonised building codes, and technical knowledge gaps are reduced by promoting open-source platforms for knowledge exchange. Finally, poor occupant engagement is mitigated through participatory design approaches. This mapping offers a concise visual framework to support policymakers, practitioners, and researchers in aligning strategies with specific challenges.

The Way Forward: Research, Policy, and Collaboration

Achieving the full potential of EPBs requires a paradigm shift driven by research innovation, proactive policymaking, and multi-stakeholder collaboration. Addressing the systemic barriers identified earlier demands comprehensive and integrated strategies across all sectors of the built environment.

Research must prioritise developing holistic models that consider both operational and embodied carbon emissions across the building life cycle (Pomponi and Moncaster, 2016). Advanced simulation tools, including digital twin technologies and AI-driven predictive analytics, are essential for optimising energy flows, occupant behaviour, and maintenance schedules in real time (Boje *et al.*, 2020). Moreover, interdisciplinary studies linking architecture, material science, energy systems, and user psychology are necessary to design buildings that are technically efficient, socially acceptable, and adaptable.

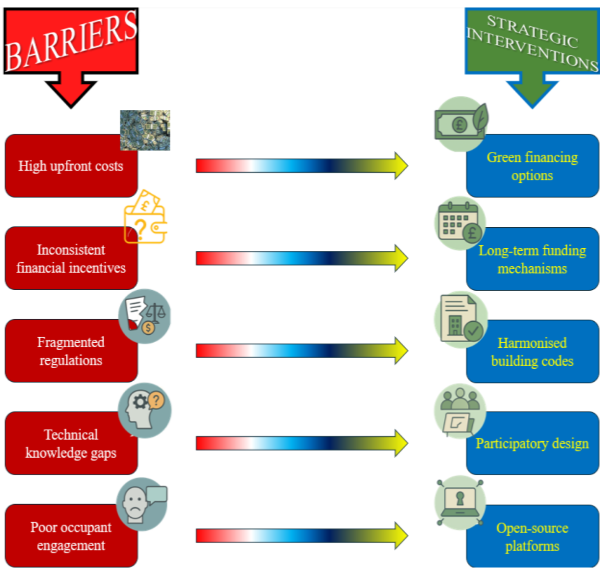

Fig. 2: Barriers to EPBs and corresponding strategic interventions

Emerging fields such as BIPV, thermal storage materials, and decentralised energy networks offer promising research directions (Ma *et al.*, 2024). Furthermore, investigating the scalability of urban microgrids and peer-to-peer energy trading platforms can facilitate the integration of EPBs into existing urban energy infrastructures (Parag and Sovacool, 2016). On the policy side, a robust and harmonised regulatory environment is critical. Standardised definitions for EPBs, surpassing current nZEB benchmarks, must be established to align national and international sustainability goals (Dulian, 2024). Mandatory lifecycle carbon assessments, performance-based certification schemes, and dynamic building codes should become integral parts of legislative frameworks (Carlucci *et al.*, 2024).

Incentivising EPBs requires innovative financial instruments, including green bonds, carbon credits, energy performance contracts, and flexible tariff structures (MacRae and Tozer, 2024). Policymakers must also ensure that funding programmes target deep retrofitting of the existing building stock, which represents a significant share of future emissions. Additionally, integrating EPBs into urban planning guidelines, through solar access zoning, decentralised storage mandates, and smart mobility infrastructure, would accelerate systemic transformation.

Collaboration among academia, industry, government, and civil society remains a cornerstone for scaling up EPBs. Interdisciplinary partnerships can accelerate technology transfer, facilitate knowledge dissemination, and enhance workforce capacity. Establishing open-source platforms for sharing EPB performance data, best practices, and post-occupancy evaluations would foster institutional learning and iterative improvement (Mahdavi and Tahmasebi, 2017). Occupant engagement strategies, including participatory design, digital literacy programmes, and personalised energy feedback, are equally important for maximising performance outcomes (Ahmed *et al.*, 2021). Upskilling the construction and facility management workforce through specialised curricula and vocational training in energy-positive practices can be essential for bridging the skills gap. To consolidate the strategic recommendations and ensure clarity, Table 2 maps each of the key barriers to a proposed actionable solution, aligned with the broader goals of scaling EPB.

In conclusion, transitioning towards energy-positive built environments requires more than technical innovation; it demands systemic realignment across research priorities, regulatory frameworks, market incentives, and social practices. By fostering interdisciplinary collaboration, enacting visionary policies, and driving forward-looking research, EPBs can evolve from experimental showcases into foundational elements of a resilient, carbon-neutral urban future.

Table 2: Mapping for each key barrier across a proposed actionable solution

Challenge	Proposed solution
High upfront costs for EPB implementation	Introduce green bonds, energy performance contracts, and carbon credit schemes to improve investment appeal (MacRae and Tozer, 2024)
Lack of consistent financial incentives	Design long-term funding mechanisms for deep retrofitting and support flexible tariff structures (MacRae and Tozer, 2024)
Fragmented regulatory frameworks and unclear EPB definitions	Harmonise building codes and define EPBs beyond nZEB standards at national/international levels (Dulian, 2024)
Limited focus on lifecycle emissions	Mandate lifecycle carbon assessments and performance-based certification schemes (Carlucci *et al.*, 2024)
Insufficient integration with urban infrastructure	Encourage EPB integration through zoning reforms, decentralised storage policies, and smart mobility planning
Technological isolation and slow knowledge transfer	Foster open-source platforms and multi-stakeholder collaborations for data sharing and best practices (Mahdavi and Tahmasebi, 2017)
Limited interdisciplinary research and systems thinking	Support studies that connect architecture, material science, energy systems, and social sciences (Pomponi and Moncaster, 2016; Ma *et al.*, 2024)
Poor real-time energy management and optimisation	Adopt AI-driven predictive tools and digital twin technologies for dynamic energy control (Boje *et al.*, 2020)
Inadequate occupant engagement	Implement participatory design, digital literacy, and personalised energy feedback systems (Ahmed *et al.*, 2021)
Skills gap in the construction and facility management sectors	Develop vocational training and new curricula focused on EPB design, installation, and operation

Conclusion

EPBs represent not merely an architectural innovation but a fundamental rethinking of the relationship between the built environment and energy systems. By consistently generating more renewable energy than they consume, EPBs serve as crucial instruments in the global pursuit of decarbonisation, energy security, and urban resilience. Recent technological advancements, such as the integration of BIPV, AI-driven energy management, and thermal storage materials, have rendered the EPB model increasingly feasible across diverse climatic conditions and building typologies. Nonetheless, the large-scale adoption of EPBs necessitates overcoming persistent economic, regulatory, technological, and behavioural barriers. Upfront investment costs, fragmented policy landscapes, grid integration challenges, and occupant behaviour remain significant hurdles. Moreover, the need for rigorous lifecycle carbon assessments is paramount to ensure that operational energy gains are not undermined by embodied emissions. Interdisciplinary collaboration across architecture, engineering, material science, and behavioural studies will be essential to bridge the gap between ambition and implementation. By promoting holistic design approaches, harmonised policy frameworks, and public engagement strategies, EPBs can transition from isolated flagship projects to foundational elements of mainstream urban development. In shaping a truly energy-positive future, the built environment must evolve beyond energy efficiency alone, embracing regenerative design principles and dynamic interaction with smart energy networks.

- EPBs significantly contribute to net-zero carbon goals by producing surplus renewable energy and reducing operational energy demands
- High-performance building envelopes, renewable integration, and intelligent control systems are central to EPB success
- Lifecycle carbon assessment must be systematically integrated to avoid the hidden burden of embodied emissions
- Economic viability remains constrained by higher upfront costs and the absence of consistent financial incentives, particularly in emerging markets
- Technological interoperability and commissioning standards are critical to bridging the performance gap between design and real-world operation
- Grid compatibility challenges highlight the urgent need for smart grids and dynamic demand-response mechanisms
- Occupant behaviour and digital literacy play pivotal roles in achieving the projected performance of EPBs
- Skills shortages in the construction and facility management sectors necessitate urgent investment in education and vocational training

Future Research Directions

- Evaluation of cybersecurity risks and resilience measures for intelligent, grid-interactive building systems (Diaba *et al.*, 2024)
- Comprehensive lifecycle carbon modelling of EPBs, considering embodied, operational, and end-of-life phases (Pomponi and Moncaster, 2016)
- Development of dynamic simulation models leveraging AI and digital twins for real-time energy flow optimisation (Boje *et al.*, 2020)
- Investigation of BIPV combined with thermal energy storage to enhance seasonal energy balancing (Ma *et al.*, 2024)
- Exploration of peer-to-peer energy trading models at district and neighbourhood scales, particularly within Positive Energy Districts (Parag and Sovacool, 2016)
- Policy analysis on the standardisation of EPB definitions and metrics beyond current nZEB frameworks (Dulian, 2024).
- Quantitative studies on occupant engagement strategies to maximise the benefits of smart energy systems (Mahdavi and Tahmasebi, 2017)
- Assessment of retrofitting strategies to transform existing building stock into energy-positive assets

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