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TOPICAL REVIEW

Net zero emission buildings: a review of academic literature and national roadmaps

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Abstract

Addressing the growing issue of climate change demands active measures. With its significant carbon footprint, the building industry needs to make immediate efforts contributing to achieving the Paris Agreement's objective of restricting global warming to 1.5 °C. This review focuses on net zero emission buildings (NZEBs) which are claimed to offer a viable option to significantly reduce greenhouse gas emissions from the built environment. The review covers both the recent academic literature on NZEBs, and the NZEB roadmaps from the member organizations of the World Green Building Council, focusing on those Green Building Councils actively working to implement NZEBs in their local contexts. By synthesizing a broad range of viewpoints and practices derived from academic literature and roadmaps, this review provides a holistic overview of the different perspectives to the current state of NZEBs and to their future. The review shows that NZEBs have the potential to provide significant environmental, economic, and social advantages, improving the built environment's overall sustainability. The review also promotes a more thorough understanding over NZEBs that can facilitate collaborative policymaking and action amongst stakeholders.

1. Introduction

Climate change's increasing impacts seriously threaten our current social infrastructure, highlighting the urgency to research and implement effective strategies for reducing anthropogenic carbon emissions. The United Nations' Sustainable Development Goals (SDGs) underline the need for immediate action to address this pressing issue (United Nations n.d.), and the Paris Agreement's target of limiting global warming to 1.5 °C over pre-industrial levels presents a significant challenge (UNFCCC 2022).

With the construction industry accounting for a substantial component of the infrastructure sector, its role in reducing carbon emissions cannot be overstated (World Green Building Council 2019), making it vital to shift away from traditional construction methods with substantial environmental footprints (Marszal *et al* 2011). With 36% of total energy consumption and 39% of process-related GHG emissions attributable to the building industry, transforming the sector to prioritize net-zero energy and low embodied carbon structures is essential to attaining climate neutrality (Urge-Vorsatz *et al* 2020). Furthermore, transitioning the infrastructure sector and reducing its harmful effects on climate change can positively influence the economy (World Green Building Council 2019).

Existing international, regional, and national standards provide methods for assessing the environmental performance of buildings and related materials. However, while these guidelines specify calculation methods and system boundaries, they do not set clear performance targets, standards, or targets, leaving significant gaps in improving the environmental performance of buildings. Current standards such as ISO 21678 (ISO 2020) and ISO 21931-1 (ISO 2022) specify sustainability assessment protocols, but decision-making is still a challenge without clearly defined goals (Satola *et al* 2021).

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Buildings with net-zero carbon and energy emissions are becoming increasingly widespread everywhere, especially in North America and Europe. These regions' advanced research, technical developments, and economic prospects are most likely the reason for this trend (Ohene *et al* 2022a). Alongside these developments, the growing awareness of embodied energy and the urgency of reducing greenhouse gas (GHG) emissions are driving a move towards net-zero buildings. Due to considerable advances in building science and technology, this approach is viable and increasingly favored because of its potential to lower energy consumption and carbon emissions (Marszal *et al* 2011). GHG emissions are, therefore, an essential indicator of a building's environmental impact (Satola *et al* 2021). Meeting the Paris Agreement emission reduction targets requires reducing emissions during the operational phase of buildings and reducing GHG emissions associated with building materials production, use, and disposal (Monteiro *et al* 2016, Gao *et al* 2019, Shen *et al* 2019). Various stakeholders are pushing for net zero emission buildings (NZEB), but there is no consensus on the specific parameters and requirements to reach this goal.

Following the Paris Agreement's goals, the World Green Building Council (WorldGBC) aims for all new buildings to be carbon-neutral by 2030, and total carbon neutrality by 2050. The council underlines a holistic strategy for carbon reduction, focusing on reducing operational and embodied carbon emissions, and suggests using reliable carbon reduction methods for residual emissions. This strategy promises energy security, improved living conditions, and cost-effective, sustainable buildings (Ohene *et al* 2022a, WGBC n.d.).

In achieving NZEBs, it is necessary to understand the technologies and strategies required and the challenges that may arise and suggest potential solutions. NZEB has several definitions and is called by different names in academic literature and professional contexts, which is problematic. So far, no reviews exist combining the existing literature and analyzing the differences and knowledge gaps. Therefore, this review intends to offer a comprehensive overview of current NZEB knowledge. Given the distinct bifurcation in the sources of NZEB literature, the review will be split into two separate sections: academic literature on the topic and the Green Building Council's (GBC) roadmaps to NZEBs. The first entity will be utilized to answer the following two research questions (RQ):

1. 'What is the current knowledge regarding NZEBs, and what are the critical methods and technologies contributing to NZEB implementation?'
2. 'What main barriers and challenges hinder the development of NZEBs?'

In addition, strategies for addressing these obstacles will be discussed based on the findings from the literature. The GBC roadmaps collection is employed to study the third RQ:

3. 'How do the GBC's roadmaps for NZEBs compare regarding their approaches for attaining NZEBs?'

To pull the two collections together, the following fourth RQ was formed:

4. 'To what extent do the knowledge, the guidelines, and methods recommended by the literature review align with those outlined in the Green Building Councils' roadmaps for reaching NZEBs?'

This review can guide policymakers, building owners, and developers in informed decision-making by comprehending the necessary methods and technologies for net-zero carbon emissions in buildings. Next, we explain the review process in sections 2 and 3 covers RQs 1 and 2, and section 4 covers RQs 3 and 4. Section 5 discusses limitations and future research recommendations, and section 6 concludes the paper.

2. Materials and methods

2.1. Review scope and review material collection process

The studies covered by this review apply under the following categories and were selected using the listed criteria.

(1) Academic literature:
  1. Empirical academic articles that are peer-reviewed and published in 2016–2023,
  2. in Web of Science journals,
  3. in English language
  4. mention 'Net Zero Emission Buildings' or 'Net Zero Carbon Emission Buildings'

(2) GBC Roadmaps:
  1. Roadmaps from the World Green Building Council (WGBC) member organizations regarding NZEBs,
  2. accessible on public websites featuring English-written roadmaps

A systematic strategy was designed to collect articles using a search with selected keywords and complemented with the snowball method tracing additional papers through the citations in the search collection, then through the newly added papers, and so on until no new papers were found. The keywords used in the search string were: '*Net Zero Emission Buildings*', '*Net-Zero Carbon Emission Buildings*', '*Zero Emission Building*', '*Zero Carbon Building*', '*Zero Energy Building*', '*Whole life Carbon buildings*', *and* '*Climate-Neutral Buildings*'. Articles that did not mention Net Zero Emissions Buildings or Net Zero Carbon Emissions Buildings were determined to be outside the scope and hence excluded. The most often referenced building types in the collected literature were Net Zero Energy Buildings and Nearly Zero Buildings. It was noteworthy even though these terms were not explicitly included in the initial search terms, indicating their significance in the broader discourse on sustainable and low-emission building practices.

This study's scope is limited explicitly to literature published from 2016 onwards to ensure the inclusion of the most recent perspectives and discoveries on the subject. However, it is essential to note that the selected articles frequently reference and build upon earlier works, therefore indirectly broadening our analysis's extent and increasing its depth. The initial search phase resulted in an analysis of 184 articles, where most were eliminated due to a lack of pertinent focus, especially the absence of NZEB or NZCB. Finally, 28 articles were considered fitting for the research topic and selected for further analysis as the academic literature collection. Table 1 shows the academic literature collection.

In addition to the academic literature, roadmaps from the WGBC affiliates and national GBCs, were collected. WGBC is the leading international network advocating for sustainable building practices and comprises over 70 GBCs around the world. The GBCs are committed to implementing a net-zero emissions strategy to decarbonize the local built environment. These roadmaps are essential given the policy frameworks established in various countries and councils. In addition, WGBC and GBCs have incorporated the Whole Life Carbon (WLC) approach into national agreements to demonstrate their commitment to reducing the built environment's carbon footprint.

More than 70 countries under the WGBC were explored to identify countries with existing NZEBs roadmaps. Thirty-one countries had published a roadmap, but 19 were published only in a language other than English, leading to 12 roadmaps as the GBC final collection. Table 2 lists the countries having published the roadmap and shows the 12 with a version in English available in bold, highlighted with green, and referencing their roadmap.

3. Academic literature results and discussion

This section presents and discusses the key findings from the academic literature review, focusing on the RQs 1 and 2. The chapter starts with defining NZEBs, creating a foundational understanding for the following discussion. The progression covers the life cycle stages of buildings—Design, Construction, Operation, and Renovation—each punctuated by NZEB considerations. Following this, a focus on building materials and Life Cycle Assessment (LCA) methods sets the stage for evaluating energy efficiency measures and renewable energy technologies. The focus then turns to building management and the variety of obstacles that prevent the adoption of NZEB. Potential solutions to these barriers are then explored, covering diverse areas from regulations and financing to societal resistance and technology implementation challenges. The chapter then moves towards an exploration of carbon offsetting and measurement techniques. Lastly, it engages with an analysis of current policies and regulations worldwide. This chapter comprehensively reviews NZEBs by integrating the most recent research, prevailing barriers, and encouraging strategies.

3.1. Definition

NZEBs have been subjected to various interpretations and terms in academic and professional contexts. This diversity of terms and definitions can lead to misconceptions. To promote clarity and consistency throughout this paper, the term NZEB will be used, except when referenced articles employ a different acronym.

Due to the lack of harmonization of guidelines and definitions of NZEBs, it can be challenging to compare the environmental performance of different structures (Marszal *et al* 2011, Sartori *et al* 2012a, Wells *et al* 2018, Shirinbakhsh and Harvey 2021). As mitigating climate change is a top priority at several levels (e.g. country-, city-, individual building-) (Satola *et al* 2021), there is a need for harmonization to avoid the effect different calculation systems can have on the outcome (Bui *et al* 2021).

Table 1. Overview of Research Articles; year, author(s), article title, and journal.

Year	Authors	Title	Journal
2017	Rajeev Ruparathna, Kasun Hewage & Rehan Sadiq	Rethinking investment planning and optimizing net zero emission buildings	Clean Technologies and Environmental Policy
2018	Asaee, S. R., Sharafian, A., Herrera, O. E., Blomerus, P., & Mérida, W.	Housing stock in cold-climate countries: Conversion challenges for net zero emission buildings	Applied Energy
2018	Hossaini, N., Hewage, K., Sadiq, R.	Path toward net-zero buildings: a natural capital assessment framework	Clean Technologies and Environmental Policy
2020	Mata, Korpal, A. K., Cheng, S. H., Jiménez Navarro, J. P., Filippidou, F., Reyna, J., Wang, R.	A map of roadmaps for zero and low energy and carbon buildings worldwide.	Environmental Research Letters
2020	Röck, M., Saade, M. R. M., Balouktsi, M., Rasmussen, F. N., Birgisdottir, H., Frischknecht, R., Habert, G., Lützkendorf, T., & Passer, A.	Embodied GHG emissions of buildings—The hidden challenge for effective climate change mitigation	Applied Energy
2020	Urge-Vorsatz, D., Khosla, R., Bernhardt, R., Chan, Y. C., Verez, D., Hu, S., & Cabeza, L. F.	Advances Toward a Net-Zero Global Building Sector	Annual Review of Environment and Resources
2021	Bui, T. T. P., Wilkinson, S., Domingo, N., MacGregor, C.	Zero Carbon Building Practices in Aotearoa New Zealand	Energies
2021	Cohen, R., Desai, K., Elias, J., Twinn, R.	Net zero carbon: Energy performance targets for offices	Building Services Engineering Research and Technology
2021	Janda, K. B., Kenington, D., Ruyssevelt, P., Willan, C.	Pursuing a net-zero carbon future for all: Challenges for commercial real estate	One Earth
2021	Karlsson, I., Rootzén, J., Johnsson, F., Erlandsson, M.	Achieving net-zero carbon emissions in construction supply chains—A multidimensional analysis of residential building systems	Developments in the Built Environment
2021	Makvandia, G., Safiuddin, M., Reda, F., & Berardi, U.	Obstacles to Developing Net-Zero Energy (NZE) Homes in Greater Toronto Area	Buildings
2021	Pan, W., & Pan, M.	Drivers, barriers and strategies for zero carbon buildings in high-rise high-density cities	Energy and Buildings
2021	Panagiotidou, M., Aye, L., Rismanchi, B.	Optimisation of multi-residential building retrofit, cost-optimal and net-zero emission targets	Energy and Buildings
2021	Satola, D., Balouktsi, M., Lützkendorf, T., Wiberg, A. H., Gustavsen, A.	How to define (net) zero greenhouse gas emissions buildings: The results of an international survey as part of IEA EBC annex 72	Building and Environment
2021	Shirinbakhsh, M., & Harvey, L. D. D.	Net-zero energy buildings: The influence of definition on greenhouse gas emissions	Energy and Buildings
2022	Carcassi, O. B., Habert, G., Malighetti, L. E., Pittau, F.	Material Diets for Climate-Neutral Construction	Environmental Science and Technology
2022	Kilkis, B.	Net-zero buildings, what are they and what they should be?	Energy
2022	Maierhofer, D., Röck, M., Ruschi Mendes Saade, M., Hoxha, E., A. 109 476.	Critical life cycle assessment of the innovative passive nZEB building concept 'be 2226' in view of net-zero carbon targets	Building and Environment
2022	Ohene, E., Chan, A. P. C., & Darko, A.	Prioritizing barriers and developing mitigation strategies toward net-zero carbon building sector	Building and Environment

(Continued.)

Table 1. (Continued.)

2022	Ohene, E., Chan, A. P. C., & Darko, A.	Review of global research advances towards net-zero emissions buildings	Energy and Buildings
2022	Shen, K., Ding, L., & Wang, C. C.	Development of a Framework to Support Whole-Life-Cycle Net-Zero-Carbon Buildings through Integration of Building Information Modelling and Digital Twins	Buildings
2022	Too, J., Ejohwomu, O. A., Hui, F. K. P., Duffield, C., Bukoye, O. T., & Edwards, D. J.	Framework for standardising carbon neutrality in building projects	Journal of Cleaner Production
2023	Tirelli D, Besan, D	Moving toward Net Zero Carbon Buildings to Face Global Warming: A Narrative Review	Buildings
2023	Capelo, S., Soares, T., Azevedo, I., Fonseca, W., & Matos, M. A.	Design of an Energy Policy for the Decarbonisation of Residential and Service Buildings in Northern Portugal	Energies
2023	Greene, Jonah M., Hosanna, H. Robert, Willson, B., Quinn, Jason C.	Whole life embodied emissions and net-zero emissions potential for a mid-rise office building constructed with mass timber	Sustainable Materials and Technologies
2023	Roberts, M., Allen, s., Clarke, J., Searle, J., Coley, D.	Understanding the global warming potential of circular design strategies: Life cycle assessment of a design-for -disassembly building	Sustainable Production and Consumption

Contrary to 'absolute' zero emissions, 'net' zero allows for GHG emission removal or 'negative emission' solutions to counteract the emitted GHG emissions (Allwood *et al* 2019). This balancing system usually involves a specific time frame to be considered net-zero. Although used commonly in politics and academia, it is often unclear whether the terms 'zero energy,' 'zero carbon,' and 'zero emissions' refer to' absolute' zero or' net' zero. The varying definitions of NZEBs depend on the structure's system boundaries, both physical and temporal. These are all alternatives for advancing buildings' net-zero emission targets (Urge-Vorsatz *et al* 2020).

According to some literature, the aim of NZEB, similar to Net Zero Energy Buildings (NZE), is to minimize energy consumption while satisfying the remaining energy demand with affordable, accessible, and sustainable renewable energy sources (Steven Winter Associates 2016), either on- or offsite (Laski and Burrows 2017). Similarly, Shirinbakhsh *et al* (2021) define NZEBs as a building that produces emission-free renewable energy onsite and offsets annual operational emissions by exporting it offsite. NZEBs should, at a minimum, generate the same amount of emission-free energy as it consumes from elsewhere (Torcellini *et al* 2006), and therefore, NZEBs more easily achievable in countries with low-carbon electricity grids (Torcellini *et al* 2006), and even all buildings in a country with enough carbon capture, utilization, and storage (CCUS) can be regarded as using 'net zero' energy (Cohen *et al* 2021). Some definitions also require that the building employs energy efficiency strategies in addition to using emission-free renewable energy (Sartori *et al* 2012a).

Besides minimizing and offsetting the emissions from operational energy use, some definitions of NZEBs also include compensation for the energy used during the construction phase, e.g. by generating renewable energy during its lifetime, either on- or offsite. If onsite generation is not feasible, renewable energy certificates (RECs) can be used (Hossaini *et al* 2018).

Shirinbakhsh and Harvey (2021) describe an NZEB as a building producing and exporting emissions-free renewable energy to offset its yearly operational carbon emissions. Therefore, considering the emission parameters of various energy sources, which are impacted by short- and long-term variations in time and space, is necessary when designing for this purpose.

Achieving 'absolute zero' emissions during a building's life cycle is near unattainable. Therefore the phrases 'zero energy,' 'zero carbon,' and 'zero emissions', commonly employed in science and politics, typically mean 'net zero' and not 'absolute zero' even though it often is not explicitly said. It also often remains unclear whether the emissions referred to are CO_2 or GHG emissions (Satola *et al* 2021). According

Table 2. Overview of Green Building Council Roadmaps regarding NZEB. The 12 reports avaialble in English are marked with bold.

	Country	Roadmap
1	**Australia**	**Climate Positive Buildings and our New Zero Ambitions** (GBCA 2021)
2	Brazil	
3	**Canada**	**Zero Carbon Building—Performance Standard** (CAGBC 2022b) **and Zero Carbon Building—Design Standard** (CAGBC 2022a)
4	Chile	
5	Colombia	
6	Croatia	
7	**Finland**	**Method for the WLC assessment of buildings** (Kuittinen 2019)
8	**France**	**ROADMAP A pathway to decarbonization (2050)** (GBC France 2022)
9	**Germany**	**Climate positive now: How every building can make a contribution to climate action** (Braune *et al* 2020)
10	Guatemala	
11	Hong Kong	
12	Hungary	
13	**Ireland**	**Building a Zero Carbon Ireland—A roadmap to decarbonise Ireland's Built Environment across its Whole Life Cycle** (IGBC 2022)
14	Italy	
15	Jordan	
16	Kenya	
17	Korea	
18	Malaysia	
19	Netherlands	
20	**New Zealand**	**A Zero Carbon Road Map for Aotearoa's Buildings** (NZGBC 2019)
21	Norway	
22	Philippines	
23	**Poland**	**How to decarbonize the built environment by 2050, whole** (Kuczera and Płoszaj-Mazurek 2021)
24	Singapore	
25	**South Africa**	**Getting to zero a guide to developing net zero carbon buildings in South Africa** (Borman 2020)
26	**Spain**	**Whole Life Carbon Roadmap for a decarbonized built environment in Spain** (GBCe 2022)
27	Sweden	
28	Turkey	
29	**UK**	**Net Zero Whole Life Carbon Roadmap: A Pathway for the UK Built Environment** (UKGBC 2021a wang), **Net Zero Whole Life Carbon Roadmap: Stakeholder Action Plans** (UKGBC 2021b), **Net Zero Whole Life Carbon Roadmap: Technical Report** (UKGBC 2021c)
30	United Arab Emirates	
31	**United States**	**LEED Zero Program Guide** (USGBC 2020)

to Hossaini *et al* (2018), NZEBs are buildings constructed from sustainable materials, self-sufficient regarding energy and water. Satola *et al* (2021) have proposed a classification system, including energy, CO_2, and GHG emissions, in a balanced structure, recognizing different system boundaries and evaluation methods.

According to Kilkis *et al*'s study from 2022, existing interpretations of net-zero buildings are insufficient for long-term decarbonization unless they consider energy destruction a critical source of emission liabilities. The paper uses a case study to show how energy waste and potentially avoided CO_2 emissions are directly related. By substituting specific components, the study drastically cut the carbon emissions from the net-zero energy building by 96%. The study emphasizes the significance of only using solar energy to generate electricity to reduce exergy mismatches. It also demonstrates that even while a building is labeled as a net-zero energy construction, it may not achieve net-zero exergy or carbon neutrality because of exergy losses (Kilkis 2022).

The UK Green Building Council (UKGBC) offers a lucid definition of a net zero carbon building (NZCB), which is when the GHG emissions from both operational and embodied footprints across the building's life cycle, including disposal, are zero or negative (UKGBC 2019). While this whole life cycle definition is comprehensive, it is still under review. As a result, UKGBC suggests a tiered approach: net zero carbon in construction, which focuses on embodied emissions, net zero carbon for operational energy and operational emissions, and eventually, net zero carbon for the entire building life (Tirelli and Besana 2023).

Specifically, a building is net zero carbon in construction when GHG emissions from its creation to completion are zero or negative, made possible by offsetting emissions or using on-site renewable energy

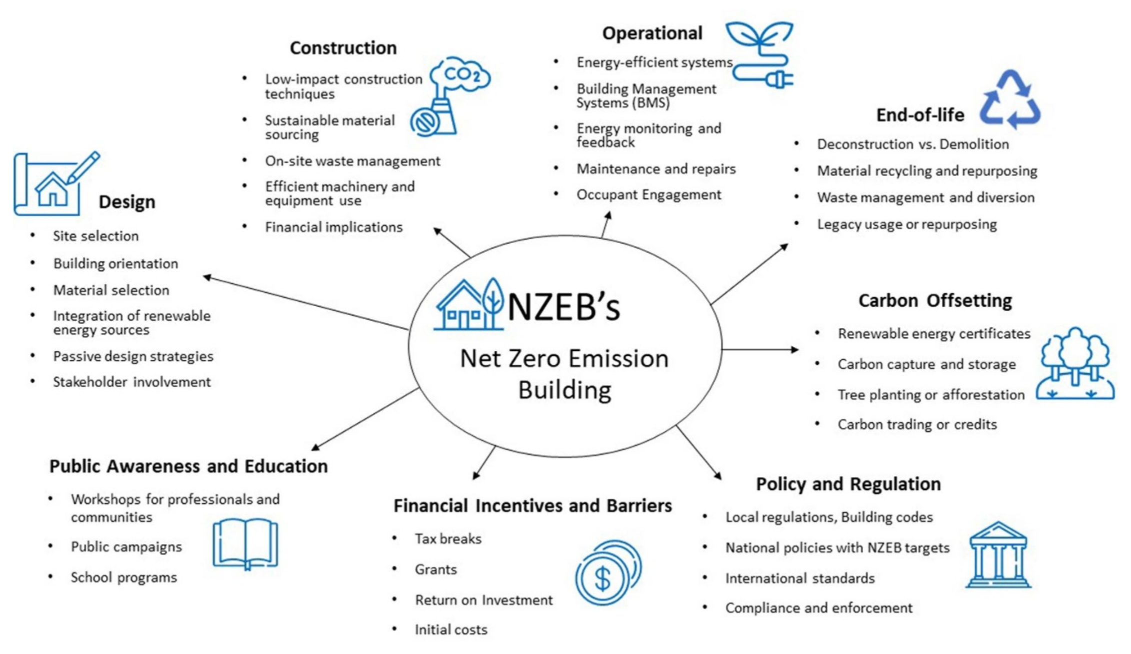

Figure 1. Graphical Representation of the NZEB Life cycle and Key Influencing Factors.

generation. On the other hand, a building is net zero carbon in operational energy when its yearly operational energy-related GHG emissions are zero or negative. Such a building would prioritize energy efficiency, rely on on-site and off-site renewables, and offset any remaining emissions (UK Green Building Council (UKGBC) 2019).

ARUP designers further clarify the concept, stating that net zero carbon necessitates cutting down energy and material demand to levels non-emitting sources can only satisfy. A projected 60% reduction in building energy use by 2050 is essential (Hill *et al* 2020). The findings clearly show that the terminology and definitions used to describe NZEBs are diverse and depend on several variables, including system boundaries and evaluation methods. There is an urgent need for a comprehensive, universally understood definition to promote more effective decarbonization strategies. These results show that harmonizing NZEB understanding among all stakeholders is necessary for effective decarbonization and true sustainability. We may more effectively evaluate and compare how well various structures affect the environment, improve effective communication, and encourage coordinated actions toward reducing climate change by advocating a clear, thorough definition.

3.1.1. NZEB graphical terminology

The NZEB graphical format visually outlines the life cycle phases of a building, from design to disposal, while its comprehensive terminology encapsulates the interplay of policy, financial factors, and public awareness in driving sustainable building practices.

The graphical representation of NZEB (figure 1) offers a holistic visualization of the NZEB approach. At the core of the diagram lies the NZEB, representing the ultimate goal of achieving zero emissions in the building sector. Radiating from this core are the main categories highlighting the key phases and considerations of NZEB: Design, Production, Operational, End-of-life, and Carbon offsetting. Under ‘Design,’ factors like energy-efficient planning, sustainable material selection, including considerations for materials with lower embodied carbon, responsibly sourced certifications, and potential for recycling or reuse, and stakeholder engagement come into play. ‘Construction’ emphasizes sustainable construction methods, local sourcing of materials assessed also for the carbon footprint of their production and transportation, and waste minimization. Efficient use of machinery and equipment during material extraction and processing is crucial to reduce the embodied impact. The ‘Operational’ phase underscores energy management, user engagement, and routine maintenance. ‘End-of-life’ delves into the considerations for building disposal, emphasizing recycling, repurposing of materials to account for their entire life cycle impacts, facilitating recycling and reducing the need for material repair or replacement, and waste reduction. Lastly, ‘Carbon offsetting’ touches upon strategies to counteract residual emissions through initiatives like afforestation or investing in renewable energy projects. NZEB practices are shaped by comprehensive factors, including ‘Policy and Regulation’ and ‘Financial Incentives and Barriers’. Local to international policies set construction criteria, while financial incentives and barriers, such as grants and initial costs, influence NZEB project feasibility. The success of NZEB also hinges on 'Public Awareness and Education', which promotes understanding through campaigns and educational programs, fostering a community-wide embrace of sustainable building practices.

3.2. Building life cycle stages

3.2.1. Design

To achieve an energy-efficient building, elements such as floor, roof, wall, and windows must be considered (Shen *et al* 2022), and the envelope of the structure is especially important in this regard (Hacker *et al* 2008, Sadineni *et al* 2011, Arnold *et al* 2016, Khan *et al* 2017). Passive design solutions, such as building orientation, can substantially decrease energy demand (Jaber and Ajib 2011, Wong and Fan 2013, Feng *et al* 2021), as well as the placement and size of interior areas, the window to wall ratio, thickness of glazing and shadings (Sadineni *et al* 2011, Rodrigues *et al* 2014, Anand *et al* 2017, Du *et al* 2020). The design of energy and service systems, such as building management systems, mechanical ventilation, energy systems, and warm water supply (Bajenaru *et al* 2016, Opher *et al* 2021a, Grgić *et al* 2022), can impact energy performance (Wei and Skye 2021, Greene *et al* 2023).

Embodied emissions are becoming crucial in life cycle emissions as buildings become more energy efficient. Often as energy efficiency increases, so do the additional embodied emissions stemming from more construction materials and technological systems (Röck *et al* 2020).

It has been suggested that the behavior of the occupants, energy consumption and generation, and carbon sequestration should be considered in the design of net zero carbon emission buildings (Li *et al* 2013, Pan *et al* 2014). These micro-level strategies can require the support of higher-level strategies, such as green energy technology development techniques (Chen *et al* 2014) encouraging renewable energy production on site, and e-feedback, social engagement, and gamification (Paone and Bacher 2018) encouraging altered user behavior. Meso-level initiatives can assist in applying micro-level controls (Pan and Pan 2021).

3.2.2. Construction

Constructing a net-zero-carbon building requires careful planning and execution throughout the construction phase. This includes setting performance specifications for materials and energy systems in contracts and subcontracts (Wang *et al* 2019, Papachristos 2020). It is essential to select experienced and knowledgeable contractors with the right resources, selecting the right providers with ecological and locally sourced products, and having a waste management plan that aims to reduce, reuse and recycle (Kamali and Hewage 2016, Kabirifar *et al* 2021, Yu *et al* 2021, Braulio-Gonzalo *et al* 2022). During the construction phase, the methods and machinery used can significantly contribute to minimizing emissions (Yan *et al* 2010, Mao *et al* 2013, Dong *et al* 2015, Dong and Ng 2015, Ding *et al* 2020). In addition, contractors can use energy-efficient appliances which run on renewable energy sources to reduce the water and energy used onsite (Lawania and Biswas 2018, Tian and Spatari 2022, Wu *et al* 2022).

3.2.3. Operation

The process of building operations encompasses the surveillance of energy systems, consistent maintenance, and modifying the structure to ensure it aligns with net-zero carbon emission goals. Previous research has pinpointed numerous energy-saving techniques, especially in the deployment of systems like solar photovoltaic, heating, ventilation, and air conditioning (Elnozahy *et al* 2015, Khan *et al* 2017, Vakalis *et al* 2021, Gibbons and Javed 2022). Timely maintenance and repairs are essential for extending service life and optimizing energy performance (Cellura *et al* 2014, Grigoropoulos *et al* 2016, Dong *et al* 2021, Jiang *et al* 2022). To reduce energy consumption while in operation, upgrading the structure's envelope remains vital (Evola *et al* 2014, Lizana *et al* 2016, Belussi *et al* 2019, Lin and Chen 2022).

3.2.4. Renovation

In NZEB research, the operation of existing buildings receives less attention than new construction, although the concept allows for retrofitting (Wells *et al* 2018). This may be because of financial risk and uncertainty (Miller and Buys 2008), and therefore it remains crucial to investigate the feasibility of utilizing current technologies to realize NZEBs (Ohene *et al* 2022b). As existing buildings make up most of the building stock, decarbonizing these structures is vital (Cornaro *et al* 2016), and can even be considered more crucial than focusing on newbuilds (Urge-Vorsatz *et al* 2020). In addition, retrofitting can offer better durability, affordability, functional quality, and social value than new construction (Poel *et al* 2007). The energy efficiency can become comparable to new construction, where the retrofitted buildings can even become energy-producing systems (Urge-Vorsatz *et al* 2020). According to McGrath *et al* (2015), they can outperform new buildings during the construction and operational phases but not the end-of-life phase (McGrath *et al* 2015).

In nations with cold climates, complete electrification of home heating systems has been termed less efficient than utilizing district heating systems which recycle low-temperature waste heat, as most of the energy demand in buildings is due to hot water use and space heating (Asaee *et al* 2018).

In commercial real estate, retrofitting to improve energy efficiency and energy source can become challenging due to the diversity of the buildings and the many actors involved; owners, tenants, and other stakeholders. Rethinking the terms of leases could facilitate the change to net zero (Janda *et al* 2021).

When analyzing the effectiveness of renovations, life cycle consequences are often ignored (Jafari and Valentin 2015). Economic, environmental, and historical factors should be considered in decisions on renovations (Kovacic *et al* 2015), but currently, no decision-support frameworks exist, which require precise information, motivation, knowledge, and funding availability (Hinnells 2008, Ruparathna *et al* 2017). The planning needs standardization to guarantee transparency and efficiency, and uncertainties stemming from the buildings' useful lifetime need to be considered (Ruparathna *et al* 2017).

3.3. Building materials

As building materials with low embodied emissions can reduce a building's carbon footprint (Hossaini *et al* 2018), several strategies have been researched (Urge-Vorsatz *et al* 2020). They include recycling, repurposing, reducing construction and demolition waste (Moncaster *et al* 2019), material efficiency (Allwood *et al* 2011), durability, bio-based alternatives or other material solutions with lower embodied emissions (D'Amico *et al* 2021), and carbon capture (Urge-Vorsatz *et al* 2020). Although these strategies can effectively reduce emissions, they do not eliminate them completely (Habert *et al* 2020a). Currently, cement is needed for most concrete foundations, which have high emissions due to the energy required for production and the calcination processes (Miller *et al* 2016, Monteiro *et al* 2017, Miller and Myers 2020). There have been some advancements in carbon-neutral concrete (Renforth 2019a, Shi *et al* 2019), but the supply needed for future urbanization (Hajer *et al* 2018) will be hard to meet at the rate needed to stay within planetary boundaries (Cao *et al* 2020).

To reduce emissions from concrete, the building structure can be slimmed down, the concrete mix can be optimized, and cement clinker levels can be lowered (Habert *et al* 2020a). In the production of cement, the switch from fossil fuels to biofuels or waste-based fuels can decrease emissions, as well as the use of carbon capture and storage (CCS) (Kajaste and Hurme 2016, Lechtenböhmer *et al* 2016).

Switching from primary steel to scrap steel in building steel can reduce embodied emissions and increase circularity and material efficiency (Energy Transitions Commission 2018, Allwood *et al* 2019, Material Economics 2019). In addition, using bio-based fuels, biocoke, or charcoal in steel plants can lower emissions (Suopajärvi *et al* 2018). For further emission reductions, technologies such as direct hydrogen reduction, top-gas recycling blast furnaces, electrowinning, and other melting methods are required (Wyns and Axelson 2016). Replacing fossil fuels with biomass in electricity production can reduce the carbon intensity of the electricity mix used for producing steel from scrap (Norgate *et al* 2012, Gunarathne *et al* 2016).

Using biobased materials in structures is a viable way to store carbon, thus reducing emissions from buildings and transforming them into carbon sinks. These materials extract CO_2 from the atmosphere during the growth phase, some of which is then stored in the plant after harvesting (Pittau *et al* 2018, Churkina *et al* 2020). There is a need for broader adoption of commercially available materials such as wood, straw, and hemp (Mouton *et al* 2023). Although wood is a promising alternative to concrete (Karlsson *et al* 2021), current resource availability is hindering large-scale adoption (Pomponi *et al* 2020), as well as the risk of diminishing forest carbon sinks (Ceccherini *et al* 2020).

As bamboo grows more quickly than trees, it has the potential to both be a more effective carbon storage than wood (Pittau *et al* 2018) and a better alternative to curtail tropical forest destruction in the Global South (Nath *et al* 2015, Churkina *et al* 2020). Recent research is optimistic that carbon-intensive building materials can rapidly be replaced by biobased materials such as bamboo and straw (Pittau *et al* 2018). Crop byproduct biomasses can minimize land use, shorter regrowth periods, and higher yields can be produced than the woody alternatives (Pittau *et al* 2018, Churkina *et al* 2020). However, no consensus exists on how the life cycle of biogenic carbon should be modeled in these biobased materials (Hoxha *et al* 2020).

A recent study by Carcassi *et al* (2022) demonstrates that herbaceous biobased insulating materials can be used to construct climate-neutral buildings which meet strict energy efficiency standards. However, the use of cross-laminated bamboo (CLB) as a structural material is currently mainly limited to low-rise buildings (less than four floors) (Sharma *et al* 2015). To mitigate the risks of excessive moisture, the study recommends employing waterproofing membranes and biobased basement insulation (Duque-Lazo *et al* 2018, Marques *et al* 2020). The research underscores the importance of utilizing low-carbon concrete solutions with optimized structural design to reduce the GHG emissions associated with concrete use (Renforth 2019a, Shi *et al* 2019). Optimizing structural concrete design can be facilitated by integrating Building Information Modeling (BIM) and automated construction methods (Röck *et al* 2018, Cavalliere *et al* 2019, Orr *et al* 2019). Additionally, multi-family houses (MFH) and terraced houses (TH) require less wall thickness compared to apartment blocks (AB) (Carcassi *et al* 2022).

3.3.1. Circular economy

Buildings are often constructed for a specific function and are subsequently demolished or renovated when they become obsolete, consistent with a linear economy (Huuhka and Lahdensivu 2016, Ellen MacArthur Foundation 2017). Such a practice leads to significant waste and inefficient material use (Ellen MacArthur Foundation 2017, López Ruiz *et al* 2020). Strategies have been provided to lessen environmental impacts throughout a building's life; nevertheless, it is critical that these do not just move impacts between life cycle stages (Pomponi and Moncaster 2016, Lavagna *et al* 2018).

By keeping resources in use and moving away from a 'take-use-dispose' mentality, the circular economy (CE) fosters sustainable growth (Ellen MacArthur Foundation 2013, Eberhardt *et al* 2019). According to the Ellen MacArthur Foundation (2017) and Joensuu *et al* (2020), implementing CE in the built environment can minimize waste, lessen the requirement for virgin materials, and provide a more sustainable approach. However, there is not a specific agreement on evaluating CE strategies in buildings, particularly when achieving carbon and energy targets (Eberhardt *et al* 2020, Van Gulck *et al* 2022).

By encouraging more reuse and recycling of building components at the end of their useful lives, design-for-disassembly (DfD) aims to disrupt the construction industry's 'take-use-dispose' cycle (Joensuu *et al* 2022). However, the DfD strategy primarily focuses on a building's end-of-life, and given that buildings often have extended lifespans, this phase can be unpredictable (Silvestre *et al* 2014, Resch *et al* 2021). Furthermore, there's limited empirical evidence showcasing the practical success of DfD methods (Akinade *et al* 2017).

While waste and reuse are addressed through circular design concepts like design for disassembly, their environmental impacts are not always measured. Current research, however, seems to place a higher priority on carbon and energy while ignoring the advantages of material reusing in circular methods. These goals need to be clarified to include other impact categories and material circularity (Roberts *et al* 2023).

3.4. LCA

Collecting and analyzing long-term emissions data for buildings is crucial due to their extended lifespan (Ibn-Mohammed *et al* 2013). However, this task becomes more challenging due to changes during maintenance, extensions, and replacements (Opher *et al* 2021a). Furthermore, the lack of standardization in building construction complicates data gathering (Seo *et al* 2022). To avoid unintended shifts in burden, decarbonization plans should consider and assess the potential impacts and trade-offs at different stages (Memarzadeh and Golparvar-Fard 2012, Peña *et al* 2021). Therefore, conducting a comprehensive life cycle evaluation is necessary to understand and prevent unintended consequences on carbon emissions (Rabani *et al* 2021).

LCA can assess a building's environmental impact throughout its lifespan, considering factors like material extraction, manufacturing, transportation, use, disposal, and recycling (Maierhofer *et al* 2022, Hossaini *et al* 2018, Ohene *et al* 2022a). Hossaini *et al* (2018) recommend employing LCA to achieve net-zero buildings. In the context of Net-Zero-Emission Buildings (NZEBs), LCA research often focuses on two main areas: Life Cycle Energy Assessment (LCEA) and Life Cycle Carbon Emissions Assessment (LCCEA). LCCEA examines carbon emissions to identify solutions for reducing global warming, while LCEA develops strategies for reducing primary energy consumption in buildings (Chau *et al* 2015). However, these assessment approaches have limitations that need to be addressed to enhance their applicability, and more research is needed to overcome these shortcomings and improve their relevance. Additionally, the practical implementation of these methodologies in the building industry remains challenging due to the lack of valid databases for construction processes and materials. Further efforts are necessary to enhance these databases and fully utilize these methodologies (Ohene *et al* 2022b).

It is crucial to acknowledge that the environmental impact assessment of a building can vary significantly depending on its design, sensitivity to local climate, and geological features (Too *et al* 2022). Considering the complexity of buildings, multiple factors and scenarios must be taken into account.

Retrofitting existing structures is essential since it reduces their energy usage and environmental impact. To achieve NZEBs, strategies such as energy retrofits, decarbonizing the electrical grid, and changing occupant behaviors can assist in transforming the residential and commercial real estate sectors. However, decision-support frameworks are required to help the industry make wise decisions on retrofit projects (Hinnells 2008, Ruparathna *et al* 2017). Cement, concrete, and steel manufacturing must be decarbonized to reduce emissions from building materials. Additionally, it is critical to promote sustainable construction materials and expand research into life cycle assessment techniques.

3.5. Technology systems

NZEBs employ cost-effective technologies to reduce emissions and offer financial benefits throughout their life cycle, utilizing low-carbon building materials, energy-saving strategies, and renewable energy sources. Consequently, several countries and organizations, including the US and EU, have established targets and implemented policies to achieve NZEBs (Ohene *et al* 2022b). Energy efficiency and electrification have been identified by The International Energy Agency (IEA) as the factors that could account for 70% of emission reductions in the building sector's transition to net-zero energy (NZE) by 2050, with the remaining reductions coming from bioenergy, solar thermal, and behavioral changes (International Energy Agency (IAE) 2021).

3.5.1. Energy efficiency measures

Energy efficiency measures and renewable energy technologies remain the primary focus of NZEB research (Ohene *et al* 2022b). To reduce energy utilization and, in turn, increase cost-effectiveness, several measures have been utilized, such as air-heat recovery systems, airtightness, improved insulation systems, and windows (Alirezaei *et al* 2016, Ohene *et al* 2022b), the optimization of building design through shape and orientation, as well as using natural ventilation and daylighting systems (Hughes *et al* 2011).

Incorporating phase change materials (PCMs) into NZEBs is an emerging field that can potentially reduce energy consumption for heating and cooling. By storing excess heat during the day, which is then released at night, PCMs can optimize the performance of NZEBs, and photovoltaic-PCM systems could further enhance efficiency (Ohene *et al* 2022b).

Photovoltaic (PV) energy systems are utilized to harness solar energy and convert it into electricity. These systems can be fixed or equipped with axial tracking mechanisms to follow the sun's movement. Typically installed on building rooftops, PV systems generate energy consistently throughout the year (Hossaini *et al* 2018).

3.5.2. Renewable energy technology

Sustainable renewable energy sources offer a viable alternative to conventional sources like coal and natural gas. Consequently, numerous studies have focused on utilizing renewable energy technologies to meet the energy demands of NZEBs. These technologies can be categorized into two main types: systems providing cooling, heating, and hot water (e.g. solar thermal systems, air-source heat pumps (ASHPs), ground-source heat pumps (GSHPs), and geothermal heat pumps) and technologies generating electricity (e.g. solar photovoltaic and wind power) (Ohene *et al* 2022b).

Heat pumps, specifically ASHPs and GSHPs have been identified as effective in reducing energy consumption and GHG emissions (D'Agostino *et al* 2020), although their adoption has been hindered by the lack of comprehensive studies on their feasibility and the absence of supportive policy strategies. Conversely, solar photovoltaic and wind energy technologies have gained significant attention, leading to widespread use and cost reduction (Jäger-Waldau 2018).

Solar systems, including PV, solar thermal, and PV/T panels, are the most prevalent renewable energy source systems deployed in urban areas and, considering market constraints, are the most feasible renewable energy source system (Panagiotidou *et al* 2021). However, their installation in multi-residential buildings is limited due to restricted available spaces caused by extensive site coverage and shaded areas.

For the utilization of wind power systems, the building's location and wind speed are the two most significant determinants of feasibility (Hossaini *et al* 2018).

Integrating Vehicle-to-Home (V2H) systems, which utilize electric vehicle batteries for grid storage and backup power, can potentially reduce emissions (Alirezaei *et al* 2016). Although the potential of V2H remains understudied, its relevance is growing due to the increasing popularity of electric vehicles, making it an intriguing subject for further NZEB research (Ohene *et al* 2022b).

3.5.3. Possibilities of a potential renewable energy source

Satola *et al* (2021) explored four options for renewable energy generation in buildings; (1) PV and solar thermal systems on rooftops or façades, (2) onsite renewable energy technologies such as ground-mounted or parking lot PV systems, solar hot water systems, and wind turbines, (3) transported renewable energy sources, mainly biomass, and (4) utilizing renewable sources accessed offsite to generate energy onsite. Options (1) and (2) offer the potential to export excess energy (Satola *et al* 2021).

Another approach to renewable energy is the purchase of offsite renewable energy. While it is often viewed as a cost-effective and straightforward method to reduce GHG emissions related to construction, concerns arise due to the lack of efforts in minimizing environmental impacts and energy consumption in buildings. Therefore, previous research suggests considering averaged primary energy and emission components for retained energy, considering the country's circumstances (Satola *et al* 2021).

According to the energy efficiency principle, energy demand should first decrease before introducing more advanced efficiency technologies (Filippidou and Jimenez Navarro 2019). Reda and Fatima (2019) found that implementing onsite solar technologies and adopting energy-efficient building design principles are viable approaches to realizing nZEBs in Northern European countries. In China, the leading technologies include heat recovery systems, building envelope insulation, and the utilization of renewable energy sources (Liu *et al* 2019). When designing technology solutions, it is crucial to consider climate scenarios and their influence on the adoption and utilization of technologies (Mata *et al* 2020a). Furthermore, advancements in the manufacturing of materials play a significant role in achieving effective climate change mitigation scenarios (Peñaloza *et al* 2018).

To achieve significant carbon reductions in the built environment, decarbonization measures must extend beyond the building industry and encompass other sectors, such as the power industry (Mata *et al* 2020a). Choosing electricity, heating, and cooling fuel combinations is crucial in decarbonizing the EU construction industry (Filippidou and Navarro 2019). Scandinavia commonly adopts district heating and GSHPs as standard practices (Reda and Fatima 2019). Flexible supply alternatives are needed to reduce strain on the power system (Seljom *et al* 2017, Mata *et al* 2020b). Urban energy networks and seasonal storage can enable positive energy buildings (Mata *et al* 2020a).

3.6. Building management

Strategies for achieving zero carbon emissions in buildings, such as smart technologies like Internet of Things (IoT) and artificial intelligence (AI), are vital in optimizing NZEBs (Blonsky *et al* 2019, Reda and Fatima 2019, Aliero *et al* 2021). AI utilizing methods like machine learning and artificial neural networks improve processes like renewable energy optimization and indoor environment control (Yang *et al* 2020, Lee *et al* 2022).

Building Information Modeling (BIM) and Digital Twins (DT) contribute to energy usage calculation, despite their limitations, and require the integration of DT with BIM information for a comprehensive analysis (Aljundi *et al* 2016, Shen *et al* 2022).

Furthermore, when integrated with IoT, AI, and BIM for intelligent building management, energy conservation techniques like Energy Efficiency Measures (EEMs) and Renewable Energy Technologies (RETs) can significantly reduce energy consumption (Ferrara *et al* 2021). Despite financial and legal challenges, these technical developments and the use of renewable energy sources highlight the significance of sustainable building design.

3.7. Barriers

3.7.1. Economic barriers

Achieving NZEBs involves overcoming various obstacles, including economic, legislative, technical, legal, and cultural barriers. Understanding these constraints is crucial to enhance the acceptance of NZEBs (Ohene *et al* 2022a). Economic viability has been identified as a key obstacle (Catto 2008, Persson and Grönkvist 2015), especially the high initial cost compared to conventional structures (Catto 2008, Pan and Pan 2021), and the investments needed for net-zero construction methods (Singh *et al* 2019, Mata *et al* 2021). Commercial viability is crucial for NZEB desirability but is particularly difficult in developing economies (Ohene *et al* 2022c). Therefore, a comprehensive economic analysis considering initial investment and future expenses is crucial (Sesana and Salvalai 2013). Still, there is a lack of accurate data on profitability and market demand (Ohene *et al* 2022a).

3.7.2. Legislative barriers

Policies and regulations are crucial in driving market demand for NZCBs as they can influence and encourage stakeholders towards low-carbon practices (Pan and Pan 2021). Government policies and building regulations have the potential to significantly reduce the environmental impact of building projects (Ozorhon 2013). Still, ineffective energy management, low energy efficiency requirements, and inadequate monitoring are common issues. The lack of support from key stakeholders, such as the government, can impede the widespread adoption of NZCBs (Ohene *et al* 2022a).

3.7.3. Professional/stakeholder barriers

The lack of professional and technical expertise in the construction industry challenges the adoption of NZCBs (Stevenson and Kwok 2020) and the lack of cooperation among stakeholders (Pan and Pan 2021). A robust project management framework can effectively manage stakeholders and foster internal and external participation (Ohene *et al* 2022b).

3.7.4. Technological barriers

Although the cost of various technologies to improve building envelopes, heating/cooling systems, and energy generation has reduced in recent years (Jäger-Waldau 2018), integrating them into NZCBs remains a challenge, especially at neighborhood or community-level (Makvandia *et al* 2021), and in high-rise and high-density settings (Pan and Pan 2019).

3.7.5. Sociocultural barriers

To drive the widespread adoption of NZCBs, stakeholders, particularly end users, should clearly understand the concept (Ohene *et al* 2022a). Lack of public awareness and comprehension has been identified as a significant hindrance to NZCB adoption (Heffernan *et al* 2015, Jones 2017, Godin *et al* 2021, Makvandia *et al* 2021, Pan and Pan 2021), as well as resistance to change (Heffernan *et al* 2015, Jones 2017).

3.7.6. Market barriers

The market heavily influences the adoption of NZCBs. Several market barriers have been identified which contribute to rising market prices (Ohene *et al* 2022a), including a lack of demand (Heffernan *et al* 2015) and ineffective marketing strategies (Persson and Grönkvist 2015, Zhang and Zhou 2015).

3.7.7. Geographic barriers

Constructing zero-carbon structures presents challenges due to geographical constraints, especially in densely populated, high-rise cities with limited available space (Pan and Pan 2019), and the feasibility can be influenced by location and climate. Retrofitting old buildings to achieve carbon neutrality has been proven to be a complex task (Attia *et al* 2017, Pan and Pan 2021, Liu *et al* 2020), and geographical obstacles include restrictions on the use of renewable energy (such as solar, geothermal, or wind energy), and barriers to domestic energy production (Ohene *et al* 2022a).

3.8. Approaches for overcoming obstacles

3.8.1. Regulations

Effective government policies, including building codes and appliance requirements, reduce emissions and promote NZCBs (Bui *et al* 2021, Ohene *et al* 2022a). Energy efficiency standards for both new and existing buildings should be updated (Heffernan *et al* 2015, Zhang and Zhou 2015, Pan and Pan 2021), clear building targets in nationally determined contributions should be pursued, standardization bodies and regulatory agencies should be strengthened to promote minimum energy performance standards, and buildings should be integrated into national climate policies (Ohene *et al* 2022b).

3.8.2. Economic returns

A lack of information on return on investment affects market demand, but providing specific cost guidelines aligned with Building Regulation standards could help address this issue, and governments can play a role in overseeing commercial real estate investors to ensure consistent and regulated costs. Furthermore, when calculating the cost of NZCBs, it is essential to include the quantification of environmental impacts to encourage end users to invest in NZCBs and actively reduce their carbon footprint (Ohene *et al* 2022a).

3.8.3. Government support and stakeholder involvement

Governments are crucial drivers for promoting sustainable housing through standards, guidelines, and policies (Bui *et al* 2021), but government support and collaboration with stakeholders are often lacking. Collaboration is essential (Laski and Burrows 2017), along with the swift implementation of an efficient plan throughout the supply chain to support sustainable building objectives (Osmani and O'Reilly 2009). Governments can motivate the industry by setting examples (Bui *et al* 2021) and promoting NZEBs with financial incentives, energy efficiency certificates, green leases, and green bond funding.

For the successful promotion of NZCB and widespread adoption, participation is necessary from all stakeholders, particularly during the design phase (Van Der Schoor and Scholtens 2015, Moore 2020). Industry and community collaboration and communication can address cultural, talent, and knowledge barriers (Pan and Pan 2021), and establishing a robust stakeholder structure is also crucial for promoting participation in net-zero projects (Karlsson *et al* 2021).

3.8.4. Financing

As obtaining financing and accessing information presents significant challenges in promoting and implementing NZCBs, governments and housing finance companies should develop innovative financing plans and make cost information accessible through websites, newsletters, and social media platforms (Ohene *et al* 2022a). Efficient allocation of funds towards low-emission buildings and the building industry requires scaling up investments (Likhacheva Sokolowski 2019), and supportive policy frameworks for investment and finance are crucial in addressing these challenges (Global Alliance for Buildings and Construction n.d.).

3.8.5. Definition clarification

Given the inconsistent and ambiguous understanding of NZCBs, it is essential to clarify and establish a knowledge base for this concept (Pan and Pan 2021). A standardized definition is necessary to encourage widespread adoption and enhance understanding NZCBs, facilitating effective education and training. Policymakers should adopt NZCB definitions that align with their needs and requirements (Ohene *et al* 2022a).

3.8.6. Resistance for changes

Resistance to change in the adoption of sustainable buildings stems from a lack of awareness regarding their benefits, which emphasizes the need for proactive efforts from the government to facilitate the transfer of information to professionals and policymakers. Organizational structures and processes should be adapted to support sustainable buildings, promote data transparency, and educate property owners and occupants about behavioral changes that can lead to energy conservation. Emphasizing sustainable buildings' energy-saving and health advantages is crucial in fostering societal acceptance.

3.8.7. Challenges in implementing technologies

To overcome obstacles related to geographic features, population density, and climate conditions, Ohene *et al* (2022b) propose enhancing specialized training for renewable energy technology and providing government-led funding for demonstration projects, which could also explore the use of CCS and heat pump technology.

3.8.8. Fiscal policy motivation

As the absence of fiscal policy incentives poses a significant challenge in promoting NZCBs, governments should offer fiscal incentives, tax breaks, and long-term economic reform roadmaps that incorporate sustainability and support feed-in tariff programs which promote the use of renewable energy sources (Ohene *et al* 2022a).

Although there are several widely-used green building certifications, such as LEED and BREEAM, experts argue that there is a need to develop a specialized, straightforward certification system for certifying net-zero buildings to help overcome the complexities of the certification process (Ohene *et al* 2022b). To further incentivize the implementation of NZCBs, cost rebates, incentives, and market-driven certification should be considered (Ohene *et al* 2022a).

3.9. Carbon offsetting and measurement

3.9.1. Carbon offset programs

Although carbon offset programs are often touted as an economical and environmentally sustainable way to achieve carbon neutrality (Shea *et al* 2020), they have become a subject of significant debate. Critics highlight several concerns: some view them as a mere mechanism for corporations to 'buy' their way out of true sustainability, leading to accusations of greenwashing. Others express concerns that these programs divert attention and resources from actual emission reductions in favor of more abstract and potentially less impactful strategies. Furthermore, the United Nations Environment Programme points to the potential misuse of carbon offsets as a justification for continued inactivity in making substantial changes to reduce emissions (UNEP 2019). In some cases, carbon offsets might only create the illusion of a solution, especially when real emission reductions are not genuinely achieved (Kumar *et al* 2020). Offshoring emissions, for instance, merely shifts the responsibility of fossil fuel reliance and does not genuinely tackle the root of the problem (Turner *et al* n.d.). Legal frameworks and decision-support systems are urgently needed to combat the escalating climate crisis to ensure genuine emissions reductions and adherence to the Paris Agreement targets (Too *et al* 2022).

3.9.2. Double counting and measuring carbon

While offsite renewable energy sources contribute to decarbonizing the electricity grid and reducing GHG emissions components (Satola *et al* 2021), accounting for the effects of onsite and offsite renewable energy production on emissions reduction presents challenges. Double counting can occur when exporting excess renewable energy or when it is generated and purchased from off-grid energy sources. Guidelines from the US Environmental Protection Agency (2018) recommend acquiring renewable energy certificates (RECs) and then retiring them instead of selling them to avoid double counting and ensure accurate environmental claims (Satola *et al* 2021).

Measuring operational carbon is relatively straightforward compared to measuring embodied carbon (Dixit 2017). Embodied carbon is often overlooked in carbon accounting due to the lack of legislation in many countries (Langston and Langston 2008). Barriers to calculating embodied carbon include the absence of nationally recognized databases for building materials (Giordano *et al* 2015) and the lack of a standardized method to accurately calculate embodied energy (Ibn-Mohammed *et al* 2013, Vukotic *et al* 2015).

3.9.3. Offset certificates

The Kyoto Protocol introduced a framework for assessing and evaluating carbon offset projects, which can be market-traded (CDM). Utilizing offset certificates and units plays a crucial role in global decarbonization by supporting mitigation efforts in developing countries. However, concerns have been raised regarding the effectiveness and reliability of offset units for compensation (Gillenwater *et al* 2007).

3.9.4. Technical measures

Offsetting, which involves techniques such as forestry, bioenergy with CCS, or direct air capture and carbon storage (Minx *et al* 2018), can contribute to the global goal of achieving net zero emissions and enables the achievement of zero GHG emission levels in buildings. However, concerns have been raised about the long-term sustainability of these methods (Satola *et al* 2021).

3.10. Current policy and regulation

Supportive policies, laws, and processes are crucial for achieving net-zero carbon buildings by 2050 (Ohene *et al* 2022a). Policymakers recognize buildings as a key leverage point for reducing GHG emissions (Carcassi *et al* 2022). However, there is a need for a comprehensive and global review of targets and roadmaps to identify effective strategies for decarbonizing the construction sector and implementing low-energy and carbon standards worldwide (Mata *et al* 2020a).

Ohene *et al* (2022a) identified the top 30 jurisdictions in the study of NZEBs and highlighted the importance of policy reform to promote partnership and collaboration. The study also emphasized the need for international information exchange and regional collaboration in NZEB research (Ohene *et al* 2022b).

Domestic NZEB policies have focused on residential buildings in North America and Europe (Ohene *et al* 2022a), which increases research interest and demonstrator projects (Berry and Davidson 2015). While NZEBs have gained interest in Asia, particularly in China (Besant *et al* 1979a), African nations have shown less interest despite the potential challenges of energy security and insufficient energy supply (Ohene *et al* 2022b).

3.10.1. Europe

The EU has emphasized the role of buildings in achieving climate neutrality by 2050 through the EU Green Deal and LTS 2050, which mandates that new construction should be nZEB from 2021 onwards (European Commission 2018a, 2021, European Union 2019). The Energy Performance of Buildings Directive (EPBD), the Energy Efficiency Directive (EED), and the Renewable Energy Directive (RED) are key legislative instruments promoting energy efficiency and renewable energy adoption in European buildings (European Commission 2012, 2018b, 2018c). These directives not only set targets but provide guidelines on the methods and metrics of measurement. However, there is variation in the implementation of rules and targets among Member States.

The EPBD, for instance, mandates Member States to set minimum energy performance standards and ensure that all new buildings are nearly zero-energy by 2021. The implementation among Member States varies due to national contexts and challenges. However, these Directives offer a supra-national standard for EU countries, ensuring a unified approach to achieving energy efficiency (European Commission 2018a, 2021, European Union 2019).

In recent years, the Energy Policies and Actions (EPA) has significantly enhanced building energy efficiency in Europe. Portugal, aiming for carbon neutrality by 2050, emphasizes improved energy efficiency, renewable electricity expansion, and broader electrification. The nation prioritizes reducing energy imports and maintaining affordable energy. Current EPAs empower consumers in energy communities, promoting energy efficiency and greater city self-sufficiency (Capelo *et al* 2023).

3.10.2. North America

In North America, roadmaps with clear objectives for achieving NZEB often utilize percentage reductions from baseline values rather than absolute metrics (Mata *et al* 2020a). Canada's roadmap includes the implementation of a zero-energy-ready building code by 2030 (Government of Canada n.d.), but how each province achieves it may differ. The advantage lies in allowing provinces like British Columbia to push for ambitious targets, like requiring zero-energy-ready buildings by 2032 (Mata *et al* 2020a).

Similarly, in the United States, the Department of Energy has set energy efficiency goals, and there is a move to make government buildings zero-energy (Presidential Documents 2015, Mata *et al* 2020a). There is not a single unified standard across North America, but rather a collection of individual national, state, or provincial targets that push the continent towards a net-zero future together.

California's comprehensive roadmap has short- and long-term objectives and milestones. Having its own building code gives California an advantage, aligning new construction with the existing code (Feng *et al* 2019).

The study by Mata *et al* (2020a) emphasizes that sustainability roadmaps are more prevalent at the city level in North America, where building regulations are often implemented, and cities have greater flexibility in pursuing ambitious sustainability goals. For example, the Los Angeles city government has introduced a Green New Deal program that aims for net carbon neutrality in all new and existing structures by 2050 (Mata *et al* 2020a).

3.10.3. China

The Chinese government established its first National Standard for Nearly Zero Energy Buildings in 2019, which requires Net Zero Energy Buildings to be certified by a government-appointed third party. It requires NZEBs to be approved by an appointed government entity, ensuring a level of oversight and standardization. The government also publishes five-year plans with targets, including goals for gross or net built area (MOST 2016). By 2020, new constructions must be 20% more energy-efficient than those built in 2015, and 600 million square meters of existing buildings must be rebuilt for improved energy efficiency. More than 10 million square meters of new Net Zero Energy Buildings demonstration projects are anticipated, and renewable energy sources are encouraged for new buildings (Mata *et al* 2020a).

Various provinces and towns have introduced Net Zero Energy Buildings into municipal plans (DHURDSP 2020, DIITHP 2020) and provide incentives such as direct funding for real estate investors (BMCHURD 2016) and permission to sell buildings at higher prices (SMPG 2018). Analysts predict that by 2030, 30% of buildings in China will be powered by renewable energy (Liu *et al* 2019).

3.10.4. Other countries

Mata *et al* (2020a) provide an overview of climate change roadmaps in countries beyond Europe and North America. Australia has set targets for increased energy efficiency by 2030, with Melbourne aiming for Zero Net Emissions by 2020 (Tozer and Klenk 2018, Feng *et al* 2019). In Asia and the Pacific, Malaysia aims to reduce its GDP's GHG emissions by 45% by 2030 (Feng *et al* 2019), while Singapore's Building and Construction Authority aims for a 40%–60% improvement in the Energy Efficiency Index by 2030. India has introduced the Energy Conservation Building Code for new structures, but a comprehensive official roadmap strategy is yet to be developed despite encouragement to do so since 2011 (Kapoor *et al* 2011). Chile has incorporated a zero-emissions building objective into its national energy strategy for South America and the Caribbean (Besser and Vogdt 2017). South Africa is the sole country in Africa and the Middle East, with a net-zero carbon performance target for new construction under the C40 South Africa Buildings Program (Feng *et al* 2019).

A consistent theme is the absence of a single unified international NZEB standard. Addressing international cooperation barriers, lack of research in underdeveloped countries, and enforcing building regulations calls for fostering collaborations and regional alliances, implementing forward-thinking strategies like NZEBs in emerging economies, and creating comprehensive action plans.

4. GBC roadmap review results and discussion

Through the global climate initiative Advancing Net Zero, the WGBC calls for all new buildings to achieve carbon neutrality by 2030 and all existing buildings to reach net-zero emissions by 2050. As members of WGBC, GBCs worldwide promote net zero strategies in their respective regions, advocate for legislative frameworks that support decarbonization, and align national tools, guidelines, and education programs with WLC principles (WGBC n.d.). Currently, 31 nations have developed roadmaps to achieve NZEB goals. To answer research question 3, 'How do the GBC's roadmaps for NZEBs compare regarding their approaches for attaining NZEBs?' an overview and comparative analysis are provided of the GBC roadmaps to net zero, which are available in English, presented in table 2.

4.1. Comparative analysis of the roadmaps: barriers, key technologies and methods

Key barriers, technologies, and methods found in the roadmaps are presented in table 3.

Table 3. The Key barriers, technologies, and methods identified in the Roadmaps.

Roadmap	Key barriers	Key technologies and methods
Australia	Refrigerants, fossil fuels, and emissions from materials	Energy-efficiency, renewable energy, building performance assessment, reduce emissions and offset, transportation electrification
Canada	Lack of awareness and technical expertise, cost constraints	Improving the building envelope, energy-efficiency, renewable energy, LCA
Finland	Cost constraints, limited availability of low-carbon materials, standardization lacking	WLC assessment, low-carbon materials, energy efficiency, circular economy
France	Cost constraints, lack of awareness, regulations and incentives	Renewable energy, energy-efficiency, circular economy, LCA
Germany	Cost constraints, lack of financing and public awareness	Renewable energy, energy-efficiency, WLC assessment
Ireland	Lack of financing, expertise and knowledge, need for behavioral change and policy	Energy-efficiency, renewable energy, building automation and controls, circular economy, LCA
New Zealand	Lack of financing, awareness and policy	Energy-efficiency, renewable energy, building automation and controls, LCA
Poland	Lack of public awareness, skills, financing, incentives and regulations, cost constraints	Energy-efficiency, renewable energy, building automation and controls, circular economy, LCA
South Africa	Lack of awareness, skills, financing and policy	Energy-efficiency, renewable energy, passive design
Spain	Cost constraints, lack of awareness, fragmented industry, need for behavioral change and policy	Renewable energy, energy efficiency, low-carbon materials, LCA
UK	Lack of awareness, knowledge, skills, policy and regulations, cost constraints	Energy-efficiency, renewable energy, low-carbon materials, WLC assessment
United States	Not explicitly discussed	Renewable energy, energy efficiency, water conservation, waste reduction, diversion practices, LCA

The roadmaps identify different barriers to achieving NZEBs, reflecting each country's unique challenges. The most common barriers include lack of knowledge, funding, financing, and skill, inadequate policies, high costs, and the need for behavioral change. Despite variations in priority, the recurrence of these barriers in multiple roadmaps underscores their significance in NZEB implementation. It emphasizes the need for tailored and collaborative strategies to advance global decarbonization efforts in the built environment.

Techniques and strategies to achieve emission reductions in the GBC roadmaps include energy-efficient building plans in Australia, South Africa, and the UK, as well as the widespread use of renewable energy systems in Germany, France, and South Africa. Other priorities include low-carbon heating and cooling systems in Ireland, New Zealand, and Poland and implementing circular economy principles in Finland and Spain. Improvements to the building envelope, including passive solar design, energy-efficient HVAC and lighting systems, and building automation and controls, are also emphasized in some roadmaps.

While certain techniques may be more prevalent in specific countries, such as France's use of solar, wind, and hydropower or Germany's focus on measurement and reporting, many of these methods, essential to decarbonization, are applicable globally.

Despite the challenges, nations have numerous opportunities for progress and development in implementing NZEBs. Embracing decarbonized built environments can lead to economic and environmental benefits, such as cost savings, job creation, and improved health for occupants. Additionally, countries can learn from each other, share best practices, and foster international cooperation to address the collective goal of decarbonization. Acknowledging barriers and opportunities can lead to developing tailored approaches based on nationally specific circumstances and resources.

4.1.1. Comparative analysis of the roadmaps: policy measures, focus, and certifications

Policy measures and regulations expedite the adoption of NZEBs, and certifications guide stakeholders and recognize their efforts in meeting decarbonization goals. The main policy measures, regulations, focus areas, and recommended certifications for each country are presented in table 4, with the aim of gaining insights into the diverse approaches taken by these countries in promoting energy efficiency, renewable energy, and sustainable building practices to achieve net zero emissions buildings.

Table 4. Main policy measures and regulations, focus, and certification recommendations in the roadmaps.

Roadmap	Main policy measures, regulations, and focus	Certification recommended
Australia	Updates to the Construction Code, voluntary NZEB commitments	Green Star—NABERS—Climate Active—Zero Carbon certification
Canada	Zero Carbon Building—Performance Standard and Zero Carbon Building—Design Standard	The Zero Carbon Building Standard—LEED
Finland	Method for WLC assessment	None
France	Decarbonization through energy efficiency and renewable energy	HQE—E + C-
Germany	Recommendations on energy-efficiency, renewable energy, and building materials	DGNB
Ireland	Strategies for WLC decarbonization	BER
New Zealand	Transition to NZEB through design, construction, operation, and end-of-life phases	Homestar, Green Star—NABERSNZ—Passive House
Poland	Recommendations on energy-efficiency, renewable energy, and sustainable materials	BIM—nZEB
South Africa	Guide to developing NZEBs through energy-efficiency, renewable energy, and sustainable building practices	Green Star S.A., Energy Water Performance and Net Zero/Net Positive
Spain	Decarbonization through a WLC approach	BIM
UK	WLC approach, stakeholder actions, and technical strategies for achieving NZEBs	CEEQUAL—BREEAM
United States	LEED Zero Program Guide, guide to developing NZEBs and net zero energy consumption	LEED

The approaches adopted by different countries in addressing building decarbonization are diverse, as some nations prioritize renewable energy and energy efficiency, while others focus on WLC reduction. The variations in suggested certifications reflect different methods for evaluating the performance of sustainable buildings. This analysis, by shedding light on the different strategies and certifications, allows policymakers and stakeholders to adapt and tailor best practices to their specific contexts. It also provides a foundation for future research on the effectiveness of these policies and certifications.

Clear and effective communication is essential to engage stakeholders and gain public support. The communication strategies outlined in the analyzed roadmaps demonstrate the interaction of key stakeholders and the utilization of various communication channels, mainly government websites, media outlets, public events, and stakeholder engagement initiatives. Collaborations with industry partners, non-governmental organizations, and other sustainable building organizations are also prevalent to raise awareness and promote the adoption of NZEBs. Stakeholder workshops, public consultations, industry and community engagement, and training and education programs are emphasized in some roadmaps to engage with stakeholders and the public, bridging knowledge gaps and driving behavioral change by equipping stakeholders with the necessary tools to pursue NZEBs. Although communication approaches vary between countries, there is a focus on engaging stakeholders and the public through diverse channels and ensuring widespread understanding of the objectives and strategies for achieving NZEBs.

4.1.2. Similarities among the roadmaps

The roadmaps show a shared commitment to built environment decarbonization, with a strong focus on retrofitting existing buildings. Despite varying priorities, these strategies share common themes and goals, most aiming for net-zero carbon emissions by 2050.

Although they all address both new construction and existing, addressing the need to increase energy efficiency and reduce emissions from the current building portfolio is a central aspect. Many roadmaps (including those from Finland, France, Ireland, New Zealand, Poland, Spain, and the U.K.) also emphasize a WLC, considering emissions throughout a building's lifetime, from materials and construction to usage and end-of-life.

Integration of renewable energy sources like solar, wind, and geothermal is a common feature, both through onsite generation and the purchase of offsite renewable energy credits. Legislation and policies are seen as important drivers for decarbonization, with building codes, incentives, and targets promoting low-carbon practices and technologies for both new construction and retrofit projects.

Education, training, and capacity building play a significant role in the successful implementation of decarbonization plans, collaboration, and stakeholder participation across government, industry, academia, and civil society.

4.1.3. Differences among the roadmaps

The roadmaps propose a variety of intermediate targets that align with each nation's specific context, priorities, and resources and vary in terms of timeframe and focus, providing a framework to monitor progress and adjust on the path to achieving net-zero emissions goals. For example, Australia aims to reduce embodied carbon in new buildings by 40% by 2030, while Spain targets a 50% decrease in building industry emissions compared to 2010 levels by 2050. France and Finland have set intermediate goals based on specific percentages of carbon reduction by 2030 or 2050. These varied targets highlight the importance of developing tailored strategies that consider local conditions while pursuing the shared goal of mitigating climate change.

The varying certification recommendations across roadmaps reflect each country's specific national context and priorities. These certifications or rating systems take into account energy efficiency, carbon emissions reduction, and WLC, serving as guidelines and standards. By adopting nationally appropriate rating systems, countries can address their unique barriers and opportunities while striving to reach climate goals.

4.1.4. Comparison of the GBC roadmaps and the recommendations from the literature review

Energy efficiency, renewable energy, and low-carbon technologies are essential NZEB components in literature reviews and GBC roadmaps. They emphasize stakeholder engagement, collaboration, and professional development within the construction industry while acknowledging the importance of policy, regulations, and certifications for promoting NZEB transitions.

While both addresses embodied energy and emissions, their emphases differ. While roadmaps see embodied carbon as a component of a larger strategy that includes operational carbon emissions, renovations, and total-life carbon strategies, literature generally explores embodied carbon and its reduction options in greater detail. Renovations are highlighted more in roadmaps than in the literature, presumably because they focus on short- to mid-term specific initiatives.

While roadmaps offer clear, practical guidelines for NZEB implementation, they may not cover all NZEB aspects as thoroughly as the literature. On the other hand, the literature provides a more thorough NZEB overview but may lack specific guidance for industry professionals and policymakers. Despite some differences and limitations, the alignment between the literature review and GBC roadmaps can provide valuable insights for a comprehensive net-zero emissions approach in the built environment.

5. Limitations and future research recommendations

The study focuses only on English literature published after 2016, and it may have missed relevant older or non-English sources on NZEBs. The scope of this study could have been expanded to include more comprehensive topics and a greater number of articles. The necessity for uniform terminology and guidelines in the NZEB sector also indicates future research directions. The analysis of GBCs' roadmaps was also restricted to English-language publications, suggesting that future studies should encompass a greater variety of languages and geographic areas.

Future NZEB research should focus on developing uniform frameworks for evaluating embodied energy and carbon, enhancing innovation and information sharing, and comprehending stakeholder interactions. Further study of innovative building materials, advanced energy efficiency measures, and innovative design approaches is also required.

NZEBs' social, economic, and environmental advantages should be further examined, as well as the efficacy of training for professionals and new methods and technology. Understanding the barriers stakeholders face when implementing NZEBs could lead to tailored strategies to overcome these challenges.

This study can be a helpful guide for sustainable construction focused on NZEBs. Additional research based on these limitations and recommendations could improve policymaking and industry procedures.

6. Conclusions

The construction sector plays a crucial role in reducing the built environment's carbon footprint and addressing the global challenge of climate change. NZEBs have therefore become an urgent priority given their ability to significantly reduce GHG emissions in the built environment. The increase in net-zero buildings results from growing concerns regarding climate change and the need for energy security globally. As a result, several nations have formulated policies and regulations to encourage the development of more environmentally and energy-efficient buildings. However, ambiguities in the literature regarding NZEBs can lead to misconceptions, indicating a need for a standardized definition and uniform understanding across the sector to promote wider adoption.

The implementation of NZEBs necessitates the application of energy-efficient design principles, innovative technologies, renewable energy sources, and sustainable materials to minimize GHG emissions. These procedures enable the replenishment of any residual energy consumption through renewable sources and compensate for any inescapable emissions. Life cycle assessments can be crucial in guiding this process by analyzing the environmental impact of a building over its life cycle, thereby revealing opportunities for enhancements and optimization.

The paper emphasizes how important it is to overcome challenges getting in the way of implementing NZEBs. The effective implementation of NZEBs depends on comprehensive government policies, strong stakeholder participation, innovative financial arrangements, and context-specific renewable energy solutions.

Roadmaps developed by the GBCs are helpful for industry stakeholders, outlining priority areas and providing decarbonization solutions. Despite some discrepancies, the goals and strategies suggested by these roadmaps and the literature share similarities. Therefore, policymakers and stakeholders may promote a collaborative environment for decarbonizing the built environment and lowering GHG emissions by acknowledging the views in literature and roadmaps. This cooperative strategy will encourage knowledge exchange, interpersonal learning, and adapting best practices to local conditions.

Through this mutual understanding and collaboration, stakeholders and policymakers can collaborate more efficiently to broaden and apply effective approaches for NZEBs. Advancing to NZEBs has a significant potential for societal, economic, and environmental gains. It will be crucial in the fight against climate change and in promoting sustainable development for our built environment.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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