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STRATEGIES TO ACHIEVE NET-ZERO CARBON GOALS IN CONSTRUCTION INDUSTRY

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ABSTRACT

The construction sector is a major contributor to global carbon emissions, highlighting the urgent need for effective strategies to achieve Net Zero Carbon Buildings (NZCBs). This study aims to investigate how to achieve Net Zero Carbon Goals in Construction. A comprehensive literature review was conducted to establish existing NZCB strategies, followed by a qualitative research approach using semi-structured expert interviews. The findings provide an integrated three-step framework for achieving NZCB including embodied carbon reduction, operational carbon reduction, and carbon offset, storage, and compensation as key steps. The study further identifies a range of applicable strategies under each step, including design efficiency, life cycle assessment, and carbon trading mechanisms. The results highlight that effective implementation of NZCB requires early-stage decision-making, lifecycle-based approaches, and the integration of advanced technologies. This study recommends industry stakeholders to prioritise integrated carbon reduction approaches, enhance professional awareness and training, and adopt digital tools for monitoring and decision-making. Policymakers are encouraged to introduce clear regulations and incentives to accelerate NZCB adoption. This study contributes to both theory and practice by refining NZCB strategy classification and providing an industry-relevant framework. Its implications extend to society by improving environmental performance and promoting sustainable development.

Keywords: *Embodied Carbon; Net Zero Carbon Buildings (NZCB); NZCB Strategies.*

1. INTRODUCTION

The construction industry is highly resource-demanding and plays a major role in environmental degradation due to its substantial energy use, material waste, and carbon emissions (Passer et al., 2020). The construction industry significantly contributes to global carbon emissions, responsible for around 38% of energy-related CO_2 emissions globally (Falana et al., 2024). Buildings generate carbon emissions at every stage of their lifecycle, encompassing construction, utilisation, demolition, and disposal (Myint & Shafique, 2024). By 2050, all new buildings must meet net-zero whole-life and embodied carbon targets, while existing buildings will be required to undergo renovation, repair,

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refurbishment, or retrofitting to achieve net-zero operational carbon emissions (Falana et al., 2024). Achieving Net Zero Carbon Buildings (NZCBs) for both new and existing structures is widely regarded as one of the most internationally recognised and innovative strategies for decarbonising the building sector (Ohene et al., 2022). NZCB is a building that achieves zero carbon status when the greenhouse gas (GHG) emissions linked to its operational and embodied footprint throughout its entire lifecycle, including disposal, are zero or negative (Myint et al., 2025). NZCB construction is achieved by offsetting emissions produced during the building's production and construction stages, while net zero carbon in operational energy is reached by reducing yearly operational emissions to zero or below through energy-efficient practices and the use of both on-site and off-site renewable energy sources (Abdullah et al., 2024). NZCB achieve a balance of zero emissions during their life cycle, promoting both reduction and compensation by adopting many strategies (Tirelli & Besana, 2023).

To achieve the NZCB goal, it is possible to adopt many strategies, both in the case of new construction and in the case of retrofitting or refurbishment (Tirelli & Besana, 2023). Embodied carbon can be reduced by minimising emissions from the building's materials, type, function, location, orientation, structure, transport, demolition, and reuse/recycling processes. In contrast, operational carbon reduction focuses on decreasing emissions through efficient façade design, improved insulation, advanced ventilation systems, the integration of renewable energy, as well as optimised building location, orientation, height, structural configuration, and occupant behaviour (Myint et al., 2025). Furthermore, multi-objective optimisation methods, such as facade design optimisation, building form selection, and component specification, have been identified as effective approaches for reducing embodied carbon in the built environment (Torabi & Evins, 2024).

The main contributor of CO2 emissions is the construction sector, accounting for 38% of CO_2 emissions in 2019, equivalent to 10 billion tons, with 28% from buildings and 10% from construction materials (Tirelli & Besana, 2023). The building sector alone is responsible for more than one-third of total global GHG emissions (Besana & Tirelli, 2022). In addition, the infrastructure and buildings developed by the construction industry require a substantial amount of non-renewable energy, which results in high levels of CO2 emissions (Abdullah et al., 2024). Consequently, achieving a substantial reduction in GHG emissions is critical in the coming decades to mitigate the severe impacts of climate change, including extreme droughts, heatwaves, and floods. In this context, Falana et al. (2024) highlighted that achieving net-zero carbon emissions is the most effective solution to address or mitigate global warming.

From a theoretical perspective, a growing body of literature has examined various aspects of NZCB, including NZCB concepts (Myint & Shafique, 2024; Tirelli & Besana, 2023), NZCB strategies (Lou & Hsieh, 2024), barriers and mitigation measures (Ohene et al., 2022), stakeholder roles across the building life cycle (Falana et al., 2024), indicators, challenges, and strategies in implementing Net-Zero Carbon construction projects (Abdullah et al., 2024), and sustainability considerations (Passer et al., 2020). However, despite these contributions, there remains a lack of studies that comprehensively explore the key steps required to achieve NZCB and the most critical strategies associated with each step. Therefore, addressing both the practical need and the existing theoretical gap, this study aims to investigate how to achieve net-zero carbon goals in construction.

Accordingly, the study objectives are to identify the key steps of achieving NZCB and to investigate the important strategies for each NZCB key step.

2. LITERATURE REVIEW

2.1 SUSTAINABILITY IN THE CONSTRUCTION INDUSTRY

Sustainability in the construction sector supports the fulfilment of present and future generations' needs by conserving energy, water, and natural resources through reuse, recycling, innovative design, and by minimising waste and pollution (Passer et al., 2020). The built environment significantly influences long-term quality of life, economic prosperity, health, well-being, and overall happiness through the planning, design, management, and maintenance of built assets (Besana & Tirelli, 2022). A building is considered sustainable only when all three dimensions which are environmental, economic, and social are adequately addressed throughout its life cycle (Falana et al., 2024). Therefore, the development of sustainable buildings and infrastructure not only enhances human health and well-being but also contributes to reducing social inequalities and promoting inclusive development (Torabi & Evins, 2024).

2.2 CONCEPT OF NET ZERO CARBON

The concept of net-zero carbon originates from climate science and is central to global efforts to mitigate climate change (Lou & Hsieh, 2024). Carbon dioxide (CO_2), while essential for regulating Earth's temperature and supporting plant life, becomes harmful when present in excessive concentrations, as it intensifies the greenhouse effect and drives global warming (Abdullah et al., 2024). In response, countries under the Paris Agreement have committed to limiting global temperature rise to well below 2 °C, with efforts to cap it at 1.5 °C (UK Green Building Council, 2019). Achieving this target requires a significant reduction in emissions to reach near-zero carbon emissions by mid-century (Lou & Hsieh, 2024). According to Besana and Tirelli (2022), net-zero carbon is achieved when anthropogenic CO_2 emissions are balanced by equivalent removals through natural or technological processes over a defined period. This balance necessitates not only substantial emission reductions but also the careful implementation of carbon removal and offset mechanisms (Tirelli & Besana, 2023). Hence, the concept of NZCB has emerged as a key strategy for reducing emissions in the construction sector and contributing to broader decarbonisation goals (Ohene et al., 2022).

2.3 KEY STEPS OF NZCB

To date, the building sector accounts for approximately 38% of global carbon emissions (Besana & Tirelli, 2022). Thus, it is crucial to develop building strategies that support the transition toward carbon-neutral buildings (Tirelli & Besana, 2023). NZCB is "When the amount of carbon emissions associated with a building's embodied and operational impacts over the life of the building, including its disposal, is zero or negative" (UK Green Building Council, 2019, p.22). Accordingly, NZCBs are designed to be energy efficient and powered by a combination of on-site and off-site renewable energy sources, with any remaining emissions being offset (Falana et al., 2024). Importantly, controlling and reducing carbon emissions must begin at the design stage and continue through the manufacturing of construction materials, construction processes, technology implementation, and operational phases of the building (Abdullah et al., 2024). According to Besana and Tirelli (2022), the decarbonization process of a building can be summarised in four phases: reduction of embodied carbon, reduction of operational carbon, increase of renewable energy supply, and compensation of residual embodied emissions (Tirelli & Besana, 2023; UK Green Building Council, 2019). These phases provide a structured framework for systematically addressing carbon emissions throughout the building life cycle. Building on these phases, a range of targeted strategies can be adopted at each stage to facilitate the effective achievement of NZCB objectives, ensuring a comprehensive and integrated approach to carbon neutrality in the built environment.

2.4 STRATEGIES OF ACHIEVING NZCB

To attain net-zero carbon construction, it is crucial to develop and apply effective strategies that balance carbon emissions with carbon removal. These approaches focus on minimising or compensating for the emissions generated by construction activities (Abdullah et al., 2024). According to the four-step framework of NZCB by Tirelli and Besana (2023), strategies to achieve NZCBs can be categorised into each step. To reduce embodied carbon emissions, a wide range of strategies has been identified, with particular emphasis on material selection, building design, and construction approaches. The adoption of circular economy principles, including the use of recycled and reused materials, is recognised as a strategy to minimise resource consumption and reduce embodied carbon emissions (Tirelli & Besana, 2023). In addition, the use of biobased materials such as wood, hemp, mycelium, straw, bamboo, cork, cellulose, and wool has gained increasing attention due to their carbon storage potential and lower environmental impact compared to conventional materials (Kamel et al., 2024; Besana & Tirelli, 2022). Furthermore, the selection of low-carbon materials plays a crucial role in reducing embodied emissions. Materials such as timber and cross-laminated timber, cold-formed steel, and interlocking compressed earth bricks (Asman et al., 2020) have also been identified as viable low-carbon options. Moreover, other established strategies include the adaptive reuse of existing buildings, which can achieve up to a 50% reduction in embodied carbon emissions (Hill et al., 2020). Dematerialisation through minimising material use and optimising resource efficiency has been highlighted as a critical approach, as buildings with higher material intensity tend to exhibit greater embodied carbon footprints (Langston & Langston, 2008).

With regard to operational carbon reduction, strategies primarily focus on improving energy efficiency and optimising building performance during the use phase. The utilisation of photosynthetic materials has been explored for their potential to absorb CO_2, although their application remains emerging (Lou & Hsieh, 2024). More established approaches include the adoption of energy-efficient HVAC systems and passive design strategies, such as passive solar design, high-performance façades, improved air tightness, and optimised window design to enhance natural ventilation and daylighting (Besana & Tirelli, 2022; Ng et al., 2016). In terms of zero-carbon energy sources, the integration of on-site renewable energy systems, such as photovoltaic panels, is essential to meet operational energy requirements with minimal emissions (Tirelli & Besana, 2023). Additionally, surplus energy generation enables buildings to export electricity to the grid, contributing to broader decarbonisation efforts (Torabi & Evins, 2024). Finally, carbon offset, storage, and compensation strategies address residual emissions that cannot be eliminated through reduction measures. Carbon offsetting, including the use of carbon credits, supports investments in renewable energy and afforestation projects (Tirelli & Besana, 2023). Meanwhile, carbon storage strategies, particularly through the use of biobased materials, enable the absorption and long-term storage of CO_2 within building elements (Kamel et al., 2024). These approaches are typically implemented after maximising emission reductions, highlighting the need for a comprehensive and sequential strategy to achieve NZCB.

3. METHODOLOGY

This study adopts a comprehensive literature review to examine existing knowledge on NZCB practices and strategies in the construction sector, followed by a qualitative research approach. The qualitative approach is particularly suitable for analysing original, text-based data using interpretive methods, especially in contexts where existing knowledge is limited (Taherdoost, 2022). It enables the exploration of emerging concepts and the development of new insights through in-depth data collection, rather than testing predetermined hypotheses. As this study investigates the achievement of net-zero carbon goals in construction through NZCB strategies, an area that relies heavily on expert perspectives and practical experiences, a qualitative approach is considered most appropriate. In qualitative data collection, data can be gathered through various methods, including interviews, observations, and document analysis (Rosenthal, 2016). Among these, interviews are the most widely used technique and can be conducted in structured, semi-structured, or unstructured formats. According to Rosenthal (2016), the relatively low level of structure in semi-structured interviews highlights the inherent flexibility of this qualitative data collection approach. Thus, this study employs semi-structured expert interviews to explore the implementation of NZCB strategies in construction. Purposive sampling involves selecting participants with relevant expertise who are able and willing to provide informed insights (Etikan et al., 2016). As this study relies on data collected from industry experts, purposive sampling is considered the most appropriate method. Considering time constraints and the point of data saturation, a total of 15 interviews were conducted. The profiles of the selected experts are presented in Table 1. When selecting the experts, a combination of academic researchers and industry practitioners was chosen to ensure a balanced perspective. Academic experts contributed insights on emerging research developments in the NZCB area, while industry practitioners provided practical, experience-based knowledge related to the implementation of net-zero carbon strategies.

Table 1: Profiles of experts

Respondent Code	Designation	Mandatory qualifications		Additional qualifications (Satisfy at least two)			
		Industry/research experience > 5 years	Experience in net-zero carbon > 3 years	Bachelor's degree in built environment	Postgraduate qualification in built environment	Professional qualifications > 3 years	Index publications in related areas
R01	PhD candidate/ Academic researcher	✓	✓	✓	✓	-	✓
R02	Quantity Surveyor/ Academic Researcher	✓	✓	✓	-	-	✓

Respondent Code	Designation	Mandatory qualifications		Additional qualifications (Satisfy at least two)			
		Industry/research experience > 5 years	Experience in net-zero carbon > 3 years	Bachelor’ s degree in built environment	Postgraduate qualification in built environment	Professional qualifications > 3 years	Index publications in related areas
R03	Project Manager	✓	✓	✓	✓	✓	
R04	Senior Cost Manager	✓	✓	✓	✓	✓	-
R05	Professor in Civil Engineering/ Academic researcher	✓	✓	✓	✓	-	✓
R06	Facilities Manager/ Academic researcher	✓	✓	✓	✓	-	✓
R07	Managing Director	✓	✓	✓	✓	✓	✓
R08	Senior Quantity Surveyor	✓	✓	✓	✓	✓	-
R09	PhD candidate/ Academic researcher	✓	✓	✓	✓	-	✓
R10	Senior executive in environmental sustainability	✓	✓	✓	✓	✓	-
R11	Chartered Quantity Surveyor	✓	✓	✓	✓	✓	-
R12	Senior lecturer/ Academic researcher	✓	✓	✓	✓	✓	✓
R13	Cost consultant/ Arbitrator/ PhD researcher	✓	✓	✓	✓	✓	-
R14	Senior Professor/Chartered Civil Engineer	✓	✓	✓	✓	✓	-
R15	Contract Administrator/ PhD researcher	✓	✓	✓	✓	✓	✓

Data were analysed using manual content analysis, a well-established qualitative technique for interpreting interview data, particularly in situations where quantitative analysis is not applicable (Bengtsson, 2016). This method involves the systematic coding and categorisation of textual data to uncover recurring patterns, themes, and underlying meanings. Accordingly, manual content analysis was deemed appropriate for this study, as it enables an in-depth exploration of participants’ perspectives and facilitates the extraction of meaningful insights.

4. FINDINGS AND ANALYSIS

4.1 KEY STEPS OF ACHIEVING NZCB

In literature findings, 4 key steps for achieving NZCB were identified as embodied carbon reduction, operational carbon reduction, zero carbon energy sources and carbon offset, storage and compensation. However, findings from the expert interviews led to a refinement of these categories into three primary steps: embodied carbon reduction, operational carbon reduction, and carbon offset, storage, and compensation, which collectively align with the core strategies for achieving NZCB. R01 and R03 emphasised that *"strategies related to 'zero-carbon energy sources' contribute to both embodied and operational carbon reduction and therefore should not be treated as a separate category"*. It was highlighted that the adoption of renewable energy systems contributes simultaneously to reducing operational emissions and influencing embodied carbon through material and system choices. Therefore, treating zero-carbon energy sources as a distinct category was considered conceptually redundant. Hence, strategies related to zero-carbon energy were integrated into the embodied and operational carbon reduction categories. Consequently, the framework for achieving NZCB was consolidated into three key steps, providing a more streamlined and practically relevant structure for understanding and implementing NZCB strategies within the construction sector.

4.2 IMPORTANT STRATEGIES FOR EACH NZCB KEY STEP

In literature findings, five NZCB strategies were identified under Embodied Carbon Reduction, three NZCB strategies were identified under Operational Carbon Reduction, and two NZCB strategies were identified under carbon offset, storage and compensation. These are presented as the literature-based strategies. Among those strategies, some were excluded due to less affirmation from experts, which are shown in strikethrough (Ex: ~~Modular Integrated construction~~). In addition, respondents suggested strategies are displayed in bold letters (Ex: **Industrial symbiosis**), whereas the modified strategies are shown in italicised (Ex: *Trading carbon credits)*. Overall, the strategies without strikethrough are the validated strategies after expert interviews. The finalised NZCB strategies corresponding to each key step are summarised in Table 2.

Table 2: Categorisation of important NZCB Strategies based on key steps

Key Steps	Important NZCB strategy	In lit	Respondents
Embodied Carbon Reduction	Adopt circular economy practices	✓	R02, R08
	Use biobased (Carbon storing) materials	✓	R09, R12
	Use of other low-carbon materials	✓	R04, R05
	Industrial symbiosis	-	R02, R06, R15
	Design efficiency	-	R13, R05, R11
	Conduct Life Cycle Assessment (LCA)	-	R03, R07
	Use of construction automation techniques (ex: AR, VR, 3D printing)	-	R14, R03
	Creating awareness among professionals	-	R05, R08
	Use digital carbon tracking tools	-	R03, R12

Key Steps	Important NZCB strategy	In lit	Respondents
	Reduce process emissions	-	R10
	Develop building design based on Green Building certification (LEED, BREEAM and GreenSL)	-	R10
	Use local materials	-	R01
	Use highly durable materials	-	R05
	~~Modular Integrated construction~~	✓	-
	~~Use of prefabricated materials~~	✓	-
Operational Carbon Reduction	Passive designs and Architecture	✓	R08, R12
	Decarbonised Grid	✓	R07
	Onsite renewables	✓	R10
	Alignment of GHG emission reduction plan with SBTi (Science Based Targets initiative)	-	R01, R04, R09
	Operational management	-	R03, R05, R13
	Smart Building Management Systems (BMS)	-	R07
	Use digital carbon tracking tools	-	R03
	Energy storage systems		R02
	~~Energy-efficient HVAC~~	✓	-
	~~Utilise photosynthetic materials~~	✓	-
Carbon offset, Storage and Compensation	*Trading carbon credits*	✓	R06, R10
	Use biobased materials	✓	R02, R08
	Carbon sink- forestation, carbon capture and storage projects	-	R12
	Use of Harvested wood	-	R05

As per Table 2, with regard to embodied carbon reduction, the majority of the strategies identified in the literature were validated by the experts. However, some refinements were made based on their insights. For instance, prefabricated light timber, initially categorised under operational carbon reduction, was reconsidered. R01 stated "*prefabricated light clay timber is related to embodied carbon reduction and insert it as a separate strategy under embodied carbon reduction as 'use of prefabricated materials' without limiting the strategy to a single material type*". However, R02 mentioned that "*both modular integrated construction and prefabricated materials do not reduce embodied carbon, it depends with the material used to construct, if it constructed with a high carbon intensive material, there can be high carbon emission and it also consumes lot of energy*". R03 also agreed with that opinion. Consequently, due to limited consensus, 'modular integrated construction' and 'use of prefabricated materials' were not considered as strategies for embodied carbon reduction.

A significant strategy identified is industrial symbiosis, highlighted by R06 as the practice of connecting construction projects with nearby industries and utilising other industries' waste, by-products, and energy as inputs. R02 stated that *"industrial symbiosis reduces carbon emission by reducing waste and minimising the use of virgin material"*. Similarly, R15 stated that *"Material and energy exchange in various industries reduces embodied emissions and the applicability of industrial symbiosis depends on policy support",* emphasising the importance of regulatory frameworks for successful implementation. Design efficiency was another key strategy proposed by R13 to reduce embodied carbon emissions. R05 suggested that efficient design can be achieved through future-proofing buildings, designing for extended lifespan, design for disassembly, avoiding over-specification, and engineering optimised components. Furthermore, R11 stated that *"design resiliently also supports design efficiency, and it is the best option for climate adaptive buildings to remain resilient in a disaster situation, if not it will lead to demolitions and will cause carbon emission",* highlighting the role of resilience in minimising lifecycle carbon impacts. The importance of conducting LCA was also highlighted as a key strategy. According to R07, LCA supports informed decision-making, particularly during the design stage, by identifying high-carbon hotspots early in the project lifecycle. This enables designers and stakeholders to implement targeted interventions to minimise emissions. Furthermore, the strategy of reducing process emissions was identified, which involves optimising site planning, utilising energy-efficient or renewable-powered construction equipment and improving material transportation logistics. These measures collectively contribute to lowering emissions associated with construction activities. Technological advancements were also recognised as enablers of embodied carbon reduction. R14 stated that *"use of construction automation techniques such as AR/VR/3D printing technologies minimises rework and material waste contribute to reduce carbon emission"*. R03 also confirmed this strategy is applicable and noted that *"it requires a very skilled workforce and high initial investment"*.

In addition, adherence to green building certification systems, such as BREEAM, LEED, and GreenSL, was identified as a practical strategy for reducing embodied carbon. These certification frameworks promote energy efficiency, resource optimisation, and reduced GHG emissions throughout the building lifecycle. The use of locally sourced materials was also strongly supported by the experts, as it reduces transportation-related emissions and contributes to the local economy. However, R01 argued that *"material quality and availability should be carefully verified before adopting local materials"*. Creating awareness among professionals was another important strategy highlighted by R05, stating that *"educating and training professionals on net-zero carbon principles and emerging technologies can support the adoption of low-carbon design approaches, materials, and construction techniques"*. Supporting this perspective, R08 stated that *"continuous training and strong institutional support are necessary to make this strategy practical and effective"*. Moreover, the use of digital carbon tracking tools was proposed as an innovative approach to monitor and manage carbon emissions. R03 noted that real-time carbon accounting enables transparent decision-making across different project stages and is already widely adopted in countries such as Germany and Switzerland. R12 stated that *"using highly durable materials with long service life reduces the need for frequent replacements and maintenance, thereby minimising carbon emissions".* Collectively, these strategies were identified under the 'embodied carbon reduction' step to achieve NZCB in construction.

Following the omission of the step: 'zero-carbon energy sources', the strategies which were initially classified under that category were reclassified under 'operational carbon reduction strategy'. However, certain strategies, such as the use of photosynthetic materials, were excluded due to limited awareness and a lack of consensus among the respondents. R11 mentioned that *"there can be carbon emission from photosynthetic materials after the operation and cannot be considered as a strategy*". Further, R02 and R08 also agreed with that. In the literature, 'Energy-efficient HVAC systems' were identified as a strategy. R15 further suggested expanding this to include energy-efficient transport and electrical systems. Additionally, R07 proposed 'smart BMS systems' as a separate strategy, stating that all energy-efficient service systems could be integrated and managed under smart BMS systems. Therefore, the use of smart BMS systems was retained as a key strategy, replacing the narrower focus on HVAC systems. R03 proposed 'operational management' as an overarching strategy that encompasses proper maintenance of building elements and occupant behaviour management, which were also suggested by R05 and R13. R03 stated that *"it involves conducting regular maintenance and managing occupants' behaviour, and the above two strategies fall under this broader approach"*. Furthermore, aligning GHG emission reduction plans with the Science Based Targets initiative (SBTi) was identified as a strategic approach to achieving measurable and science-driven emission reductions. R09 noted that SBTi supports organisations in setting targets aligned with climate science and emissions through energy efficiency improvements, renewable energy adoption, and fuel switching. This strategy was strongly supported by the other experts. Furthermore, R03 proposed the 'use of digital carbon tracking tools' as a strategy to reduce operational carbon emissions, noting that *"operational-phase carbon accounting can be clearly monitored and demonstrated through digital tracking tools"*. Accordingly, this strategy was categorised under both embodied and operational carbon reduction steps, as digital tracking tools can monitor and manage carbon emissions throughout both construction and operational phases. Moreover, R02 explained that energy storage facilitates coordination with the national grid and allows excess renewable energy to be stored and utilised as needed, thereby improving energy efficiency and reducing reliance on fossil fuels. Overall, these strategies contribute to the effective reduction of operational carbon emissions.

In relation to carbon offset, storage, and compensation step, several modifications were made to the literature-based strategies. The concept of purchasing carbon credits was expanded to include both buying and selling, leading to the revised strategy of 'trading carbon credits'. Additionally, new strategies such as carbon sinks, carbon capture and storage, and the use of harvested wood were proposed by the experts. Further clarification revealed that forestation and carbon capture and storage are components of carbon sink strategies. R12 stated *that "forestation involves planting trees, restoring forests to absorb CO2 from the atmosphere"*. R05 pointed out that *"harvested wood stores carbon absorbed during tree growth"*. In addition, the use of bio-based materials was identified as a strategy contributing to both embodied carbon reduction and carbon offset, storage, and compensation. The experts highlighted that bio-based materials reduce embodied carbon through lower carbon-intensive production processes while also acting as carbon storage mechanisms by storing absorbed atmospheric carbon during their lifecycle. Therefore, this strategy was categorised under both steps due to its dual contribution towards NZCB achievement. These strategies were widely supported by the respondents as effective mechanisms for compensating residual emissions. However, the experts acknowledged that carbon offsetting practices are still relatively underdeveloped in many developing countries, although they are more widely implemented in developed contexts. Despite this limitation, there was a general consensus that carbon offset, storage, and compensation strategies are applicable and hold significant potential for supporting the achievement of NZCB targets within the construction industry.

5. DISCUSSION

To achieve net-zero carbon construction, it is essential to develop and implement effective strategies that balance carbon emissions with carbon removal (Abdullah et al., 2024). This study examined NZCB strategies across key steps to identify those most applicable to the construction industry. While existing literature classifies NZCB strategies into four key steps: embodied carbon reduction, operational carbon reduction, zero-carbon energy sources, and carbon storage (Besana & Tirelli, 2022), the empirical findings support a more integrated three-step framework. The exclusion of zero-carbon energy sources as a standalone category reflects expert consensus that such strategies inherently contribute to both embodied and operational carbon reduction, thereby supporting a more holistic and practice-oriented classification. Furthermore, the evaluation of literature-derived strategies through expert interviews revealed a high level of alignment, with most strategies being confirmed as applicable. In particular, the strong emphasis on embodied carbon reduction strategies supports existing studies that highlight the significance of early design decisions, material selection, and lifecycle thinking in reducing emissions (Hill et al., 2020; Kamel et al., 2024). Apart from the strategies identified in the literature, including adopting circular economy practices (Tirelli & Besana, 2023) and using bio-based materials (Besana & Tirelli, 2022), the empirical findings emphasise the importance of novel, under-explored strategies such as industrial symbiosis and the use of digital carbon tracking tools. Similarly, the findings on operational carbon reduction are largely consistent with existing literature, particularly in relation to passive design and energy-efficient systems (Ng et al., 2016). The incorporation of smart BMS and alignment with the SBTi highlights a shift towards more integrated, measurable, and performance-based approaches. Considering carbon offset, storage, and compensation, the findings align with previous studies that emphasise the role of carbon credits and offset mechanisms as a final step after maximising emission reductions (Tirelli & Besana, 2023). The expansion of this category to include carbon sinks, carbon capture and storage, and harvested wood reflects a broader and more practical interpretation of offset strategies. Overall, this study contributes to the body of knowledge by bridging theoretical frameworks with practical insights, offering a more streamlined and context-sensitive approach to achieving NZCBs.

6. CONCLUSIONS AND RECOMMENDATIONS

The building sector contributes significantly to global carbon emissions through both operational activities and the manufacturing of construction materials. In response, NZCBs have emerged as an important approach for reducing carbon emissions across the building life cycle. This study aims to investigate how to achieve net-zero carbon goals in construction. The findings identified embodied carbon reduction, operational carbon reduction, and carbon offset, storage, and compensation as the key strategic areas for NZCB implementation. The study further revealed that embodied carbon reduction strategies received strong emphasis, particularly through lifecycle thinking, the use of bio-based and low-carbon materials, and industrial symbiosis. Operational carbon reduction strategies such as passive design, smart BMS, and performance-based approaches were also identified as critical to improving building carbon performance. In addition, the study highlighted the growing importance of carbon offset, storage, and compensation mechanisms, including carbon sinks, harvested wood products, and carbon credits, despite their relatively limited implementation in developing countries. Overall, it suggests a strong potential for future adoption, provided that appropriate regulatory and institutional support is established. The successful delivery of NZCBs requires strong collaboration among all stakeholders, including policymakers, developers, investors, urban planners, architects, and construction companies. This study recommends that construction stakeholders adopt an integrated approach to NZCB implementation by prioritising embodied and operational carbon reduction strategies from the early design stage. Greater emphasis should be placed on lifecycle thinking and digital carbon tracking tools to support informed decision-making. Continuous training and awareness programmes are essential to enhance understanding of NZCB principles and emerging technologies. Additionally, policymakers should establish clear regulatory frameworks and incentives to encourage the adoption of low-carbon materials, renewable energy systems, and carbon offset mechanisms.

Considering the impact of this study to the industry, it provides a structured framework of NZCB strategies that can guide decision-making and improve carbon performance across building life cycles. For literature, the study contributes to existing knowledge by refining NZCB strategy classification and highlighting the importance of integrating theoretical and empirical perspectives. From a societal perspective, the adoption of NZCB strategies can contribute to climate change mitigation, improved environmental quality, and enhanced human well-being. Nevertheless, this study is subject to several limitations. The findings are primarily based on a qualitative approach with a relatively small sample size of experts, which may limit the generalisability of the results. Further, the study relies on expert opinions, which may be influenced by individual experiences and contextual factors. Despite these limitations, the study provides valuable insights into NZCB strategies and offers a foundation for future research. Future research could explore the economic feasibility and cost implications of implementing these strategies in different contexts. Investigating policy frameworks, regulatory barriers, and incentives in developing countries would also provide valuable insights for enhancing NZCB adoption. Moreover, case studies examining the performance of NZCB projects over time would contribute to a deeper understanding of their long-term benefits and challenges.

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