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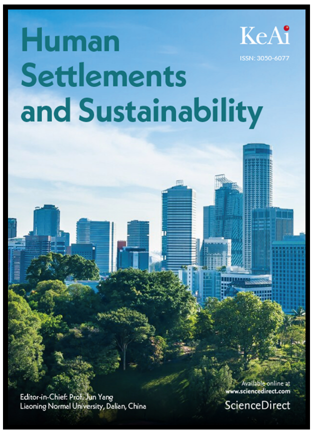

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Carbon Technologies and Decarbonisation Strategies in Buildings: A Scoping Review and Conceptual Framework

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Abstract:

Global pressure on the built environment is rising to reach zero carbon emissions by 2050. Many new technologies and strategies aim to cut building emissions, but fast growth has fragmented knowledge and reduced clarity. This study aims to map current carbon tools and approaches in the building sector. It uses a PRISMA-based scoping review of studies between 2023 and early 2025. As a result, 66 studies were identified from the Web of Science database and examined in detail. Using bibliometric analysis, this study identified three key research topics and emerging themes within the field: (i) energy optimisation and renewable technologies in buildings, (ii) advanced modelling and AI in building performance, and (iii) sustainable building design and life cycle assessment. Studies within each group were then analysed to generate in-depth insights into each category. This study introduces a novel theoretical decarbonisation framework to assess the intricacy of decarbonisation in the building industry. The framework comprises four stages and seven steps that can help identify practical approaches to delivering zero-carbon buildings. The outcomes of this research contribute to understanding the development of decarbonisation strategies and demonstrate their future advancements in this field.

Keywords: Carbon; Net Zero; Technologies; Decarbonisation; Buildings; Framework.

1. Introduction

Climate change is accelerating, prompting increased global efforts to reduce carbon emissions. The built environment is a critical sector for action. The building sector alone accounts for nearly 37% of global energy-related CO_2 emissions [1,2], positioning it at the centre of efforts to reverse current warming trends. In response, national and international initiatives have set ambitious targets to cut embodied carbon by 40–50% by 2030 and to reach net-zero emissions by 2050 [3]. To meet these goals, research and practice now use many tools and design strategies [4]. These include low-carbon materials, efficient systems, renewable energy, and digital tools. However, their rapid spread has fragmented knowledge across the sector, making net-zero pathways harder to understand and apply.

One sign of this fragmentation is found in the inconsistent decarbonisation terms used in the building sector. Studies have shown that several concepts have been introduced and are often used interchangeably by professionals, such as carbon neutrality [5], carbon-neutral buildings [6], net-zero carbon buildings [7], zero carbon building (ZCB) [8], net-zero emission building [9], net-zero energy buildings (NZEBs) [10], and nearly zero energy building (nZEB) [11]. In fact, clear and usable definitions and scope shape the industry's understanding of decarbonisation and influence how goals are set, measured, and applied in practice. For example, net-zero frameworks focus on reducing total GHG emissions. This approach aligns with the 1.5 °C target and broader carbon-neutral goals [12]. Yet carbon neutrality lacks a universal definition; it is commonly described as achieving a balance between emitted and absorbed CO_2, or as reaching a state in which emissions from human activity are effectively zero, often accounting for all GHGs [13]. The UK Green Building Council (UKGBC) defined Net Zero Carbon Buildings (NZCB) as "*when the quantities of greenhouse gas emissions associated with the operational and embodied footprint of the building throughout the life cycle, including its disposal, are zero or negative*" [14]. Further distinctions arise in the scope and time frame of assessment. For instance, 'zero annual operational emissions' that account for buildings with no yearly operating emissions [15]. And 'life-cycle zero operational emissions', which account for emissions throughout a building's lifespan [5]. Kristjansdottir et al. [16] noted an overlap between the concepts of zero energy and zero emissions and found that Zero Energy Buildings are often described as achieving both. In general, gaps in metrics and terminologies reveal a deeper issue in the building sector. As a result, further attention is required to overcome the lack of a shared framework for defining, assessing, and guiding decarbonisation.

The conceptual ambiguities surrounding decarbonisation are also mirrored in the development of carbon-neutral building technologies (CNBTs). These technologies limit emissions and energy use through passive design, efficient operation, and renewable energy systems [17,18]. Many CNBTs still struggle to deliver consistent carbon-neutral results due to the varied interpretation of carbon-neutral goals and metrics across studies and countries [19,20]. Some studies assess CNBTs using embodied carbon or embodied energy alone [21]. Others use different life-cycle boundaries, which produce partial or uneven findings. Craft et al. [22] indicated that many LCA studies lacked the inclusion of secondary systems and material interactions. These inconsistencies hinder a clear understanding of CNBT performance. Furthermore, these inconsistencies also weaken the link between these technologies and wider decarbonisation goals.

The increased recognition of these deficiencies has led to the establishment of initiatives with clear pathways to implement carbon-neutral buildings. Wang et al. [23] observed that current research tends to prioritise green building rating systems over the evaluation of the actual emission reductions achieved through green building technologies. For example, in the UK, buildings account for approximately 17% of national GHG emissions and 59% of total electricity consumption [24]. To consider these challenges, several frameworks have been introduced to target both operational carbon and embodied carbon emissions [14, 25]. The UK Net Zero Carbon Buildings Standard was launched in September 2024. As one of the first national examples of an evidence-based decarbonisation framework, it provides a science-based framework to reduce emissions by 78% by 2035 and achieve net zero by 2050 [26]. The standard applies to both new and existing buildings. It offers technical specifications and phased requirements for fossil-fuel-free operation, embodied carbon, and renewable energy generation. The pilot phase integrates reporting mechanisms for design, construction, and operational stages. During the pilot phase, the standard requires further information to support improvements, including Design, Construction, at or near Practical Completion, Recently Occupied (less than 1 year), and In Occupation (min 75%) for more than 1 year. The initiative demonstrates a structured method that could inspire comparable actions in other regions seeking to align their pathways towards net-zero building transitions.

1.1 Motivation for this Study

The increasing attention to building decarbonisation has led to numerous review studies aimed at consolidating the fragmented body of knowledge [27–32]. For instance, Leal Filho et al. [28] examined institutional decarbonisation strategies in the higher education sector, emphasising the role of universities in climate action. Their outcomes indicated structural barriers, weak institutions, and financial constraints that limit the large-scale adoption of low-carbon practices. Building on this work, Gillett et al. [29] offered science-based views on decarbonising existing European buildings, with a focus on renovation depth, carbon metrics, and policy. Although their work indicated the potential of deep-renovation frameworks, it remained region-specific and policy-centred. Also, it offered limited insight into the technological and analytical mechanisms driving emissions reduction.

Santos et al. [30] proposed structured methods for embodied carbon assessment using LCA during the design stage. Their study improved carbon quantification accuracy. However, it treated LCA as a stand-alone process, separate from operation and digital modelling. Ibn-Mohammed et al. [31] addressed methodological fragmentation and promoted the adoption of mixed-mode research paradigms in decarbonisation research. In another study, Awuzie et al. [32] reviewed how artificial intelligence may support circularity and decarbonisation; however, its use in buildings remains limited. Together, these studies show a shift from policy to methods and digital tools; however, the work remains conceptually scattered and methodologically disconnected. Although there has been significant progress, approaches remain incomplete. There is no common framework for integrating technological advances, analytical tools, and design strategies into a coherent roadmap for achieving net-zero carbon buildings.

Overall, this study presents an overview of recent developments in building decarbonisation. This scoping review draws on work published between 2023 and early 2025. The timeframe encompasses a period of rapid innovation and method improvement. The review implements a two-stage method (bibliometric mapping and detailed content analysis to support the identification of emerging research trends and key themes. It also links technologies, design strategies, and modelling methods. The research presents a decarbonisation framework with four stages and seven steps. The process spans the entire building life cycle and integrates technologies, methods, and strategies to support carbon reduction. Finally, it illustrates specific steps to guide researchers, policymakers, and industry professionals in pathways towards net-zero outcomes.

2. Research Methodology

This study adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines (Figure 1). PRISMA 2020 is a robust framework for systematic reviews and has been widely accepted across disciplines due to its clarity and rigour [33]. In this research, the PRISMA 2020 structure was adapted to identify, screen, and synthesise recent studies on building decarbonisation. The review followed three main stages. These are (1) database development, (2) bibliometric analysis, and (3) content analysis. Each stage is explained in the sections that follow.

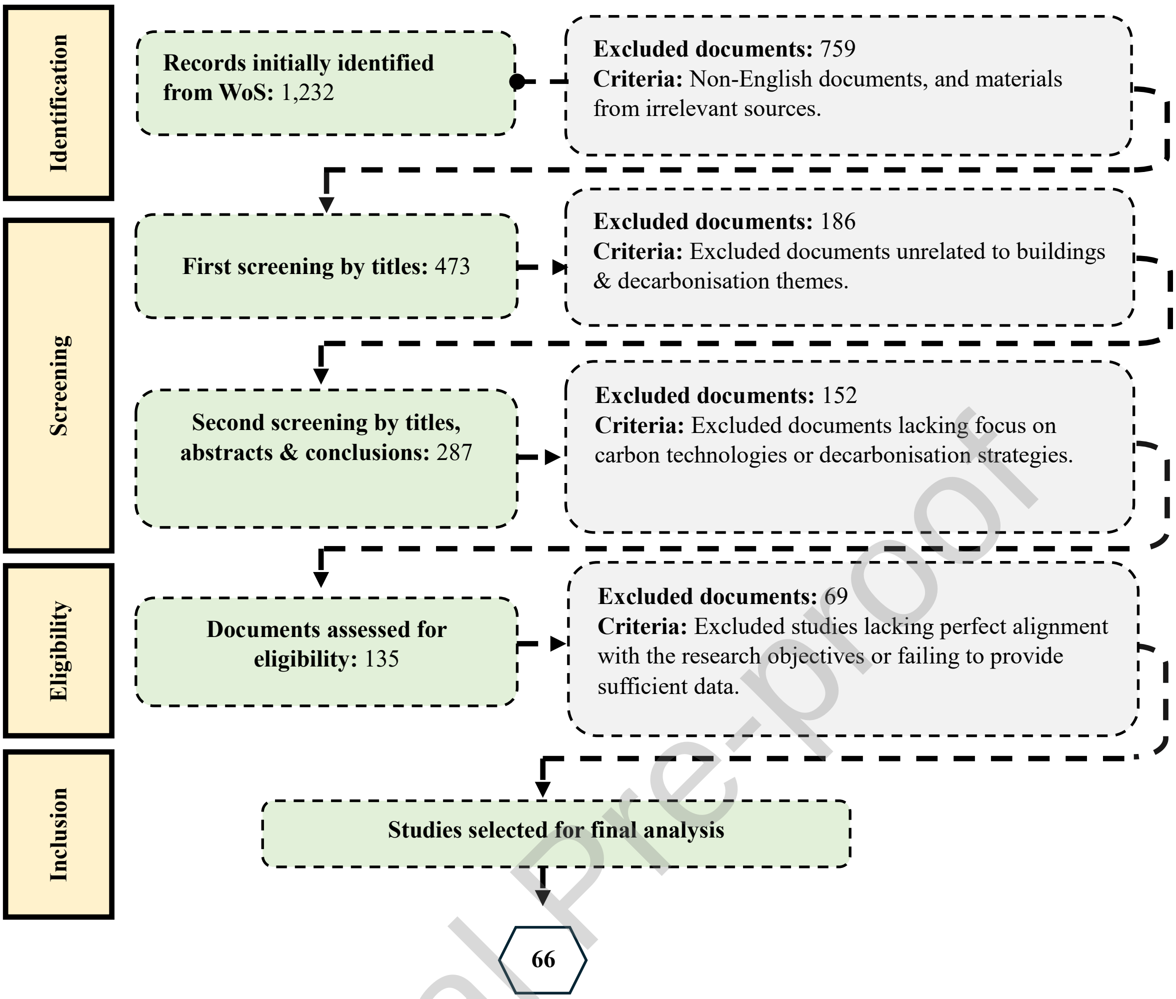

Figure 1. Methodological approach of the study based on PRISMA protocols.

2.1 Database Development

The initial step was to establish a comprehensive search syntax to identify papers relevant to the research topic. The Web of Science (WoS) platform was chosen to carry out the search. WoS offers access to an extensive database of over 171 million records from 34,000 journals and more than 2.5 billion cited references spanning a wide range of disciplines. It is noteworthy to mention that WoS served as the sole information source for this review, and thus, no additional registers, websites, organisational sources, or grey-literature repositories were consulted. The study adhered to the PRISMA

2020 guidelines for transparency and consistency. The review addressed several items in the PRISMA 2020 checklist, including title, abstract, introduction, methods, results, and discussion; however, it did not cover all 27 items. As this study is a scoping review that maps existing evidence rather than testing effects, the study identified that bias checks and effect measures were not required under scoping review guidance. This action was taken to examine the current evidence rather than to evaluate the intervention's effects, in accordance with the scoping review approach described in several studies [34,35]. As shown in Figure 1, the study reports all screening steps, eligibility rules, and data extraction methods. Therefore, the following syntax was constructed and applied in WoS search engine to identify the relevant materials: (“carbon” OR “decarbonisation”) AND (“net” OR “zero” OR “neutrality”) AND (“buildings” OR “construction”) AND (“technologies” OR “design”) AND (“emissions”). The initial search was conducted on October 26, 2024, using WoS and retrieved 1,232 documents, including papers assigned to the 2025 publication year.

The authors implemented several steps to maintain the quality of the selected papers: (1) non-English sources and documents from unrelated disciplines, such as medical sciences and marine biology, were excluded. This helped the researchers to narrow the dataset to 473 records. (2) The remaining studies were screened in two stages that covered: (a) titles were reviewed to remove clearly irrelevant papers, (b) abstracts and conclusions were then examined to confirm a focus on buildings and decarbonisation. Studies with only limited relevance to net-zero goals were excluded, leaving 135 papers. (3) A further qualitative review assessed the extent to which each study aligned with the research scope. To maintain the research focus, the study excluded papers that lacked technical depth or were based solely on policy, interviews, or single product development. However, it only included studies that offered clear design strategies or actionable solutions. As a result, the final dataset consisted of 66 studies suitable for consistent and focused analysis.

2.2 Bibliometric Analysis

The second stage involved a bibliometric analysis to map the intellectual and collaborative landscape of research on building decarbonisation. VOSviewer was used to conduct a keyword co-occurrence analysis. The software is a well-established method for identifying conceptual linkages and major research themes within a body of literature [27]. This assessment delivers a visual and quantitative representation of how topics are interrelated. Furthermore, it provides insights into the field’s structure and evolution. To improve accuracy, a customised thesaurus file was developed to merge variations of similar terms, for example, “life-cycle analysis,” “life-cycle assessment,” and “LCA” were standardised under “life-cycle assessment.” This ensured dataset consistency and minimised analytical noise.

In addition, an organisational collaboration analysis was conducted to examine research partnerships and institutional linkages in the field. Using the co-authorship function in VOSviewer with organisations as the unit of analysis, this step visualised the network of institutional cooperation driving building decarbonisation research. The resulting map revealed key research hubs and cross-institutional collaborations. The map provides an overview of how knowledge and expertise are shared across geographical and disciplinary boundaries. The findings from these analyses revealed key thematic patterns and collaboration networks, which then guided the content analysis examining the technological, methodological, and strategic dimensions of each theme in greater depth.

2.3 Content Analysis

Following the bibliometric step, the authors conducted a qualitative content analysis to identify themes emerging from the keyword co-occurrence outputs. The mapped clusters generated through co-occurrence guided the research in identifying key literature themes. As a result, the corresponding papers within each cluster were downloaded and examined in detail to examine their main focus, methodological approach, and technological contributions.

To support systematic theme identification, keywords with high co-occurrence and strong links were grouped. Grouping was based on their conceptual proximity, as shown in the co-occurrence network (See Figure 3). By comparing keyword clusters with paper content, the study identified 20 distinct themes. These themes emerged within each category through an inductive process. They reflect frequent, conceptually strong research foci. Together, they show the field’s main methodological and technological directions. These themes were determined by the frequency and conceptual prominence of recurring research foci. They indicate the field's most dominant methodological and technological directions. The final categorisation comprised: (i) energy optimisation and renewable technologies in buildings (six themes), (ii) advanced modelling and AI in building performance (six themes), and (iii) sustainable building design and LCA (eight themes). This triangulated process helped in strengthening the reliability of theme identification. Also, each category provides a coherent, evidence-based synthesis of current decarbonisation research. The outputs are presented and discussed in Section 3.1, including the network of keyword co-occurrence and the identified thematic clusters.

3. Results and Discussion

This section delves into detail to reveal the outcomes of both the bibliometric and content analyses. It begins with an overview of collaboration and keyword co-occurrence findings, which help reveal emerging patterns and thematic links across the field. Later subsections examine studies within each theme in detail. As a result, this section offers deeper insight into current decarbonisation trends and methods.

3.1 Findings of Bibliometric Analysis

Using VOSviewer software, this section provides an overview of the most influential organisations in decarbonisation research employing the co-authorship function with organisations as the unit of analysis. Figure 2 and Table 1 offer an overview of the collaboration network and the top ten contributing organisations. Examining the dense network of collaborating institutions (see Figure 2) demonstrates specific regions that are advancing research on decarbonisation, such as East Asia, Europe, and Australia. Interestingly, the results show a strong link to institutions, including the Hong Kong University of Science and Technology (HKUST), Southeast University, and the China Academy of Building Research. Based on a descriptive assessment using link analysis, the interpretation of nodes indicates sustained research productivity and influential regional partnerships. The findings provide a map for examining future collaborations.

Table 1 presents the ranks of the top 10 institutions by publication count, citations, and link strength, which collectively indicate the scholarly influence of their publications and the total link strength. This displays the extent of collaborative engagement across institutions within the network. These metrics indicate that HKUST is the most influential contributor, with 10 publications, 79 citations, and the highest total link strength of 21. The assessment shows that research is increasingly organised into regional clusters of expertise, particularly in Asia. It indicates that joint research frameworks are becoming more established and are promoting interregional linkages and cross-institutional information exchange.

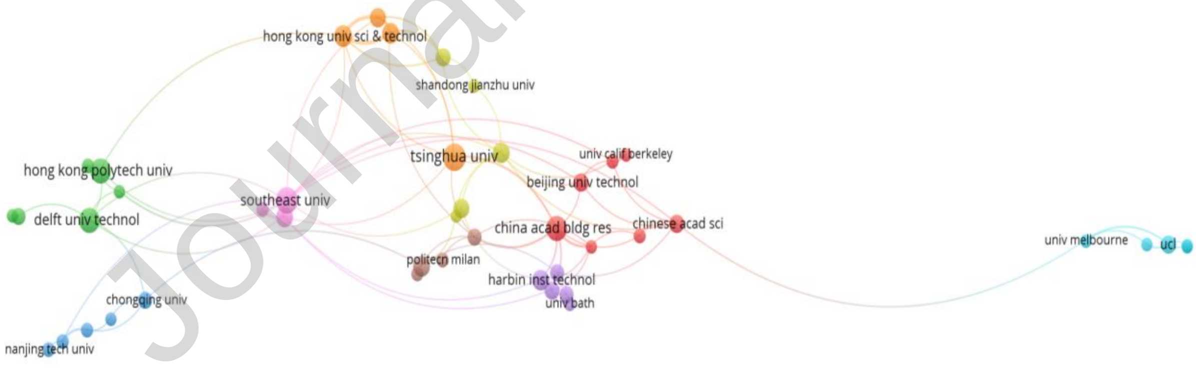

Figure 2. Collaboration network of research organisations.

Table 1. Top ten organisations contributing to building decarbonisation research.

Top Ten Contributing Organisations	Documents	Citations	Total link strength
Hong Kong University of Science and Technology (HKUST)	10	79	21
Southeast University	15	66	20
HKUST Guangzhou	9	68	19
HKUST Shenzhen–Hong Kong Collaborative Innovation Research Institute	8	60	19

China Academy of Buildings Research	14	29	16
The Harbin Institute of Technology	9	32	14
City University of Hong Kong	7	25	13
National University of Singapore	9	65	12
Tsinghua University	16	50	9
Tongji University	9	29	9

Figure 3 displays the results of the co-occurrence analysis by incorporating all keywords, including those provided by authors and keywords catalogued by journals (keywords plus). The analysis employed a minimum threshold of 10 occurrences per keyword, identifying 45 keywords that met it. This threshold was selected to balance analytical clarity and network density, allowing dominant thematic structures to emerge without introducing excessive noise into the co-occurrence network.

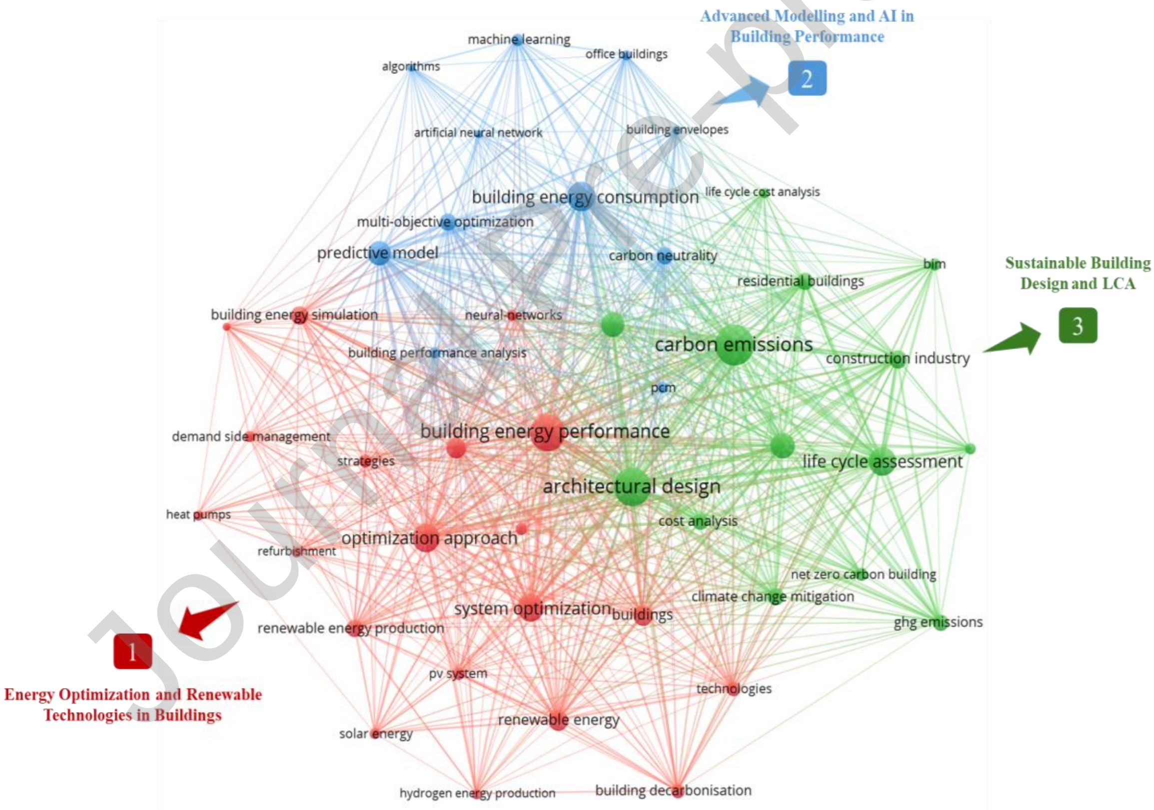

Figure 3. An illustration of the co-occurrence network of selected studies.

The results of the keyword co-occurrence analysis revealed three main clusters, each containing a series of keywords that suggest popular research topics and emerging themes within the field. Table 2 presents the 10 keywords with the highest occurrence counts for each cluster. These clusters include:

Table 2. Ten keywords in each category with the highest co-occurrence values.

Cluster	Keyword	Occurrences	Total link strength
Energy Optimisation and Renewable Technologies in Buildings	Building energy performance	90	323
	Optimisation approach	62	237
	System Optimisation	57	220
	Buildings	37	141
	Renewable energy	37	142
	Net-zero energy building	37	138
	Building energy simulation	31	106
	Renewable energy production	28	89
	Building decarbonisation	23	67
	Technologies	22	90
Advanced Modelling and AI in Building Performance	Building energy consumption	65	240
	Predictive model	48	179
	Carbon neutrality	29	81
	Multi-objective Optimisation	28	108
	Machine learning	18	55
	Building performance analysis	16	47
	PCM	15	42
	Office buildings	14	51
	Building envelopes	12	37
	Algorithms	10	35
Sustainable Building Design and LCA	Carbon emissions	106	352
	Architectural design	98	382
	Life cycle assessment	61	217
	Environmental impacts	52	219
	Building energy efficiency	48	166
	Construction industry	33	147
	Climate change mitigation	30	102
	Residential buildings	28	123
	Cost analysis	26	96
	GHG emissions	26	91

- Cluster 1, titled 'energy optimisation and renewable technologies in buildings', demonstrates a group of keywords that have a strong focus on improving performance in buildings via renewable energy integration and energy optimisation techniques. The study found that most keywords emphasise the enhancement of energy efficiency and implementing strategies to optimise energy use within buildings. Also, some keywords align with the growing adoption of carbon technologies as a central component of sustainable construction practices. This also implies integrating advanced decarbonisation strategies to evaluate and improve building systems, which is critical for renewable energy systems.

- Cluster 2, titled 'advanced modelling and AI in building performance', exhibits a group of keywords that have a strong focus on using advanced computational tools and artificial intelligence (AI) to enhance building performance. The study noticed that most keywords emphasise specific meanings that highlight the use of data-driven techniques to monitor and predict energy usage. Additionally, it covers keywords related to supporting decision-making in building design and operations. Furthermore, it was found that topics in this cluster discuss the integration of algorithms and AI technologies and areas to deal with complex challenges in zero carbon buildings, such as balancing occupant comfort, energy efficiency and cost-effectiveness. Finally, several keywords underline the increasing momentum of analytical methods employed by advanced modelling tools to refine and predict energy performance.

- Cluster 3, titled ‘sustainable building design and LCA,’ represents a research stream that integrates environmentally driven strategies and life cycle approaches in the industry. Several keywords demonstrate efforts to reduce environmental footprints and to promote innovative decarbonisation solutions. Also, highlight the growing attention to evaluating construction materials and practices from a cradle-to-grave perspective and indicate a strong drive to reduce energy consumption and align with global sustainability goals. Collectively, this cluster highlights the industry's evolving commitment to embedding decarbonisation into every phase of building design and operation.

The following sections will further delve into these categories to develop a deeper understanding of their relevance to carbon technology practices and decarbonisation strategies in buildings.

3.2 Energy Optimisation and Renewable Technologies in Buildings

This section synthesises findings from 25 selected studies on decarbonising buildings through energy optimisation and renewable technologies. Table 3 presents a detailed summary of each study’s contributions. The reviewed studies were grouped under six main themes: ‘Technologies’, ‘Decarbonisation and Net Zero’, ‘Performance’, ‘Optimisation’, ‘Simulation’, and ‘Heating’.

Table 3. Key findings from 25 studies on energy optimisation and renewable technologies for building decarbonisation.

Key themes	Reference	Carbon Focus	Implementation Context	Enabling Technologies Used	Key Findings
Techno logies	Zhou and Herr [36]	Operational	Theoretical analysis: high-rise buildings in Hong Kong’s	BIPV, double-skin façades, shading systems, vertical greenery.	• BIPV and double-skin façades were identified as most effective for lowering operational emissions in

			subtropical climate.		subtropical high-rise buildings.
	Wei et al. [37]	Operational and embodied.	Global bibliometric analysis (2000–2021); urban-scale decarbonisation.	CiteSpace (for bibliometric mapping), simulation and Optimisation tools (e.g., TRNSYS, GenOpt), PV systems, and hybrid energy systems.	• Identified unclear definitions, regional gaps, and limited technical integration as key barriers to ZEB adoption. • Highlighted the need for consistent life cycle definitions and multi-objective optimisation methods.
	Salem and Elwakil [38]	Operational	Simulation study using BIPV for two buildings (hot and cold climates: KSA and USA)	BIPV (roof-integrated), GIS-based solar feasibility analysis, tilt/azimuth optimisation.	• Found Building-Integrated Photovoltaics (BIPV) systems most effective in hot climates, achieving about 80% of that yield in cold regions. • Recommended roof-integrated PV for its high energy output and efficient use of unoccupied space.
	Lee et al. [20]	Operational	Reviewed 65 papers and 75 cases; categorised by climate group and building type.	Thirteen CNBTs were classified into four categories: (I) renewable energy sources, (II) building design features, III) system improvements, and IV) energy storage.	• CNBTs show greater energy-saving potential in non-residential buildings, with RES integration improving economic viability. • Optimal strategies depend on climate and building type. • Combining multiple CNBTs shortens payback periods.
	Wang et al. [39]	Operational	Urban environments with high-density building typologies.	Integration of BIPV with green roofs and green facades.	• Integrating BIPV and greening enhances PV efficiency (1–3% gains), mitigates UHI, and improves building sustainability. • Efficiency depends on PV height, plant species, climate, and distance between elements.
	Senyonyi et al. [40]	Operational and embodied.	Global review, with Scientometric mapping	Assessed passive and active systems, along with hybrid configurations, using simulation and experimental methods.	• Identified passive and active solar techniques for ZEBs, stressing the need for climate-specific design, stronger passive–active integration, skilled labour, and broader industry adoption.
	Watari et al. [41]	Embodied	Modelled Japan's national decarbonisation scenarios using dynamic material flow and CO_2 flux analysis across building materials and forests.	Analysed decarbonised electricity, low-carbon steel and concrete, increased timber use, optimised design, and extended building lifespan.	• Net-zero embodied carbon in Japanese buildings is achievable by 2050 using existing technologies. • Timber use offers the most considerable savings by reducing emissions and enhancing carbon storage.
Decarbonisation and net zero	Tirelli and Besana [42]	Operational and embodied	Narrative review of academic and policy literature on NZCB strategies, classifications, barriers, and drivers.	Passive design strategies include renewable energy systems, bio-based materials, and digital tools.	• NZCBs are achievable with current technologies, but uptake is limited by economic, legislative, and technical barriers.

	Kalmár et al. [43]	Operational	Empirical assessment of 236 detached houses in Debrecen, Hungary; energy modelling and CO_2 emission analysis were conducted.	Thermal retrofitting; Air–water and geothermal heat pumps; PV systems; Solar collectors; Low-temperature radiant heating; Smart control systems.	• Newer homes showed lower energy demand and CO_2 emissions due to improved insulation and compact design. • NZEB-level decarbonisation is achievable with heat pumps and PV, though cost remains a constraint.
	Arowolo and Perez [44]	Operational	Techno-economic simulation of rooftop solar PV + EV in Paris, Lyon, and Marseille using SAM model.	Rooftop solar PV; EVs with bidirectional V2H charging; System Advisor Model (SAM); Smart charging strategies.	• Coupling rooftop PV + EV can cut CO_2 emissions by 43–48% and supply up to 43% of urban electricity. • Achieves 2–3-year payback.
	Weerasinghe et al [45]	Operational and embodied	Mixed-methods review of 125 studies using bibliometric and qualitative analysis on NZC retrofitting of existing buildings.	Envelope upgrades (insulation, glazing); Energy system upgrades (efficient HVAC, lighting, controls); On/off-site renewables (PV, solar thermal, wind).	• NZC retrofitting requires combining passive and active strategies, lifecycle carbon accounting, and user-focused benefits. • Barriers include high costs, lack of data, fragmented policies, and limited stakeholder collaboration.
	Yan et al. [46]	Operational and embodied	Case study of NZE house in China using life-cycle carbon assessment approach.	Whole biomass material envelope (straw, wood, bamboo); Prefab box girder walls; OSB panels; EnergyPlus-based thermal simulation.	• Biomass envelope reduced embodied emissions, ranking well among NZE cases. • Operational emissions were average due to heat loss from the roof and infiltration. • Low-cost system suits rural or developing areas.
Performance	Noh et al. [47]	Operational	Narrative review of NZEB concepts, RE synergies, performance evaluations, policies, climate impacts, and challenges.	Solar (PV, thermal); Wind turbines; Geothermal; Biomass systems; Smart grids; Energy storage; Passive design strategies.	• NZEBs can reduce building-related emissions by integrating diverse RE technologies and passive strategies. • Climate change affects energy balance and RE reliability. • NZEBs need tailored policy, tech integration, and multi-stakeholder strategies for large-scale uptake.
	Lizana et al. [48]	Operational	Case study of a university building in Oxford using a post-occupancy evaluation and intervention (POEI) protocol.	Employed data-driven energy management using smart controls, PV panels, efficient lighting, and calibrated energy modelling.	• A stepwise POEI approach cut emissions by 77% and energy use by 50%. • Coordinated interventions reduce life-cycle cost by 23% and achieve near-zero carbon.
	Ampatzidis et al. [49]	Operational	Analysis of 44,300 UK dwellings to evaluate retrofit impact and policy strategies.	Used insulation, glazing, boiler upgrades, renewables (PV, heat pumps), and a fabric-first retrofit approach.	• Upgrading homes may lead to higher carbon savings.
Optimisation	Ohene et al. [50]	Operational	Optimisation study using BEopt simulation for NZEB design in Ghana's four climate zones	Passive design (shading, airtightness, ventilation); Efficient HVAC and lighting; Rooftop PV; BEopt +	• Cost-optimal designs save 34–35% energy. Passive strategies and efficient cooling are key in hot climates.

			based on LCC analysis.	EnergyPlus simulation.	• NZE is technically feasible but costlier than the baseline.
	Guo et al. [51]	Operational	Simulated ventilated floor heating in NZEBs in Changchun, China.	Analysed ventilated floor heating in a mixed grid–wind system with thermal mass utilisation.	• Multi-objective optimisation (cost, wind use, emissions) improves heating performance and comfort. • Best outcomes achieved when cost, emissions, and wind power are co-optimised.
	Xu et al. [52]	Operational and embodied	Retrofit study of a Nanjing school using multi-objective optimisation to reduce energy use and life-cycle carbon.	Used insulation, double glazing, LED lighting, VRV HVAC, fresh air system, and rooftop PV; optimisation done with DesignBuilder.	• Energy-saving retrofit achieved NZEB status with 102,786 kWh/year excess renewable energy. • Life-cycle decarbonisation cut carbon emissions by 1.92 million kg.
	Ma et al. [53]	Operational and embodied	Macro-scale optimisation of 9 residential building archetypes in Ningbo, China, using energy and economic simulation.	Thermal insulation (walls, roof, floor, windows); Airtightness; Shading; Natural ventilation; LED lighting; HVAC with heat recovery; Rooftop PV; IES-VE software.	• 512 design schemes were tested per archetype. • Optimal NZEB schemes achieved 84–88% energy savings with ~3-year payback. • PV system covers most ULEB/NZEB loads for low-rise buildings.
	Makhloufi and Louafi [54]	Operational and embodied	Simulation-based optimisation of a residential building in Algeria using RCP climate scenarios and a multi-stage framework.	Passive strategies (orientation, insulation, ventilation); High-efficiency HVAC; LED lighting; 24 kW PV system; multi-objective optimisation; RCP climate models.	• Integrated passive, active, and renewable strategies achieved 100%+ energy savings and up to 126% CO_2e reductions. • Multi-stage framework reduced simulation load and identified cost-effective pathways.
Simulation	Ke et al. [55]	Operational	Scenario-based SD modelling of nZEBs in China using VENSIM and real-world case data from Wuhan (2010–2035).	System dynamics modelling; Building-integrated PV; Passive envelope design; Energy-saving behaviour; Carbon sink modelling.	• OBS reduced energy and carbon by 36–44%; IMS achieved 54% emissions cut. • Energy-saving awareness and PV area were most impactful. • Integrated approaches outperformed single-factor strategies.
	Amoruso and Schuetze [56]	Operational	Simulation-based analysis of three retrofitted Korean buildings using PHPP and a parametric CAD-to-PHPP data transfer system.	Modular timber renovation systems; Balanced ventilation with heat recovery; Hybrid HPs for DHW/heating/cooling; Parametric PHPP integration (Grasshopper, Ladybug, Rhinoceros).	• Only apartment blocks met PH-classic standard. User behaviour (ventilation, shading, DHW, lighting) greatly influenced energy outcomes. • Mixed-use/multi-unit cases fell short without BIPV or behavioural change. • Parametric system streamlined PH-compliant retrofits.
	Zhou and Zheng [57]	Operational	Cross-scale platform development linking materials, components, buildings, and districts via AI-integrated simulation and digital twins.	Nanoporous materials (PCM, MOF, aerogel); Smart coatings; BIPV; Solar thermal; Wind turbines; AI-driven simulation; Digital twin modelling.	• Platform achieved up to 17.4% energy savings via PCM walls, BIPVs, and coatings. • AI and digital twins improved prediction accuracy and long-term performance tracking. • Embodied carbon is discussed conceptually but not quantified.

Heat	Lu et al. [58]	Operational	Simulation-based comparison of two heat recovery schemes for data centre waste heat reuse in building space heating (Finland).	Evaluated direct-to-chip liquid cooling with heat exchangers, district heating integration, and smart flow control using TRNSYS modelling.	• Waste-heat recovery systems reused data centre heat without pumps, saving up to 155 MWh and 292 tCO_2 with payback under one year.
	Zhang et al. [59]	Operational	Tested five heating modes in a Shenyang NZEB.	Used PVT systems, multi-source heat pumps, and smart control with DeST software and AHP/FCE evaluation.	• PVT-DSHP mode improved COP by ~8% and showed the best energy, cost, and carbon performance. CDER reached 3424 kg CO_2/year. • PVT integration enhances efficiency and mitigates soil temperature drop.

The outcomes demonstrate a broad range of solutions across operational and embodied carbon. These solutions are presented in the form of passive design strategies, renewable energy integration, and digital simulation tools. Technologies such as BIPV, advanced façades, and integrated PV systems were used for their potential to reduce operational emissions, particularly in high-rise and climate-responsive designs [36,38]. On the other hand, several studies have proposed comprehensive frameworks for NZEB retrofits [45,48]. They demonstrated the benefits of integrating envelope upgrades, energy systems, and renewable energy sources. Other studies examined optimisation methods to find cost-effective solutions across different climates and building types [50,53]. Despite the breadth of research presented to date, many studies focus on single actions and rarely address policy, cost, or social limitations. Assessing the content from a critical perspective, the study found that technical solutions are improving; however, their wider adoption requires consideration of context.

The review also identified a range of technologies and optimisation strategies proposed to support decarbonisation, particularly through the application of CNBTs. These typically combine building design features, system upgrades, renewable energy integration, and storage solutions [20,40]. For instance, Lee et al. [20] showed that combining several CNBTs shortens payback times and improves viability across buildings and climates. In another study, Senyonyi et al. [40] reviewed solar design techniques and emphasised the importance of passive strategies like orientation, Trombe walls, and shading devices. The review found that some active systems, such as PV and PVT collectors, are effective. However, their integration with passive approaches was often treated as an afterthought rather than a coordinated strategy. These findings reveal a gap between theory and practice of decabonsation. It was found that optimisation across technical components is rarely contextualised or operationalised.

Weerasinghe et al. [45] examined retrofit pathways for existing buildings with the goal of achieving net zero-carbon. The study found fragmented research with a limited focus on climate and building types. Additionally, the study emphasised the need to integrate retrofit methods with climate-responsive design and new tools. It also showed the value of assessing occupant comfort and measured retrofit benefits. Weerasinghe et al. [45] further reported limited empirical validation and weak links between retrofit measures and measurable performance outcomes. Lizana et al. [48] introduced a systematic study to assess building performance and zero carbon upgrading through post occupancy evaluation and intervention (POEI). The study showed that by implementing renewables, reducing demand, optimising control and increasing efficiency, the building achieves its aim towards the nearly zero-carbon building with a 23% lower life-cycle cost and payback period of 13 years compared with the standard case. Together, these studies show the growing emphasis on practical, data-driven retrofit strategies, yet reveal that current approaches remain limited in empirical grounding and contextual adaptability across different climates and building types.

Ohene et al. [50] provided design guidelines using optimisation for net zero energy residential buildings in cooling climates. The research found that the most cost-effective strategies are natural ventilation, minimal façade air leakage, highly efficient fans, air conditioning, dehumidification, adequate window-to-wall ratio, north orientation, and PV systems. Ma et al. [53] introduced an optimisation of zero-energy design approaches for residential buildings at a macro scale, from economic and energy perspectives, in China. The study used optimisation steps targeting building shape coefficients, window-to-wall ratios, average floor areas and the number of floors as categorisation variables. However, to fully realise their impact, future work could consider tailoring these strategies to local regulations, construction practices, and occupant behaviours across different regions.

Ke et al. [55] used a system dynamic simulation to investigate decarbonisation pathways of nearly zero-energy buildings. The study used VENSIM simulation software to model subsystems including buildings, occupants, the energy environment, and the socio-economy. The study employed various scenarios, including changes to the heat-transfer coefficient, energy-use patterns, household size, grid carbon-emission factor, area of solar photovoltaic panels, energy-awareness level, electricity price, and temperature. The findings demonstrated that raising knowledge of energy conservation had a significant impact. Zhang et al. [59] conducted research on providing a comprehensive evaluation and analysis of nZEB heating system. The study targeted a severe cold region to assess a multi-source heat pump. Several systems were selected, including air-source heat pump (ASHP), ground-source heat pump (GSHP), photovoltaic/thermal dual-source heat pump (PVT-DSHP), photovoltaic/thermal air-source heat pump mode (PVT-ASHP), and dual-source heat pump (DSHP). The study concluded that a successful strategy for achieving net-zero energy (nZEB) is the combined use of multi-source coupled systems and photovoltaic/thermal (PVT) systems. Both studies highlight the importance of system-level thinking linking technical, behavioural, and environmental factors to support climate-specific nZEB design strategies.

Examining the listed technical solutions, ranging from basic to advanced systems, has shown considerable promise. However, their effectiveness depends on climatic conditions, economic feasibility, and occupant behaviour. As a result, optimisation and simulation methods are expected to continue strengthening early-stage decision-making. It has been found that such an advancement can be achieved through adequate consideration and its wider adoption, which depend on alignment with regional construction practices and regulatory frameworks. This section indicates that achieving Zero-Carbon Buildings (ZCBs) requires an integrated approach that prioritises context-responsiveness.

3.3 Advanced Modelling and AI in Building Performance

This section synthesises findings from 20 selected studies by examining the use of advanced modelling tools and AI techniques to support building decarbonisation. The section presents a detailed summary of each study's contributions in Table 4. The studies were categorised under six key themes: 'Algorithm', 'Energy Consumption', 'Machine Learning', 'Prediction', 'Uncertainty', and 'Multi-Objective Optimisation'.

Table 4. Key findings from 20 studies on advanced modelling and AI for building performance in decarbonisation.

Key themes	Reference	Carbon Focus	Implementation Context	Enabling Technologies Used	Key Findings
Algorithm	Wang et al. [68]	Operational and embodied	Lifecycle analysis of a commercial complex in Hangzhou using emergy theory, LCA, and neural network prediction.	LCA; Emergy accounting; Neural networks for sustainability prediction; Green design (rainwater reuse, sponge city); Carbon sink via concrete.	• Operational and material stages account for 90%+ of carbon/emergy load. • Cross-feedback system improves data correction (15.8% for CO_2, 11.3% for emergy).
	Li et al. [69]	Operational and embodied	Systematic review and science mapping of 154 articles on AI applications in NZCs.	AI techniques (ANN, ML, DL, genetic algorithms); LCA; BIM; IoT; DSS; Smart energy modelling; EnergyPlus; Carbon capture and storage.	• AI supports lifecycle decarbonisation via prediction, optimisation, and control. • Embodied carbon addressed via AI-LCA integration; gaps remain in real-world adoption and policy support.
	Saad et al. [70]	Operational and embodied	Development of surrogate models for retrofitting a historic commercial building in Montreal; physics-based model validated with empirical data.	DesignBuilder simulations integrated with LCA and LCCA.	• Surrogate models predicted energy, carbon, and cost with high accuracy (MAPE 0.29–2.77%). • Feature selection reduced overfitting and improved model interpretability.
Energy Consumption	Li et al. [71]	Operational	Review and case analysis of six BIPV projects in China.	BIPV systems; thin-film and monocrystalline PV modules; Open-frame curtain wall PV integration.	• BIPV projects achieved near 100% net-zero operation with up to 254 tCO_2 annual savings. • Adoption driven by green building standards and carbon-neutral goals; barriers remain in cost, regulation, and civil uptake.
	Ke et al. [72]	Operational	Simulation and orthogonal experiment on an nZEB in Wuhan to analyse multi-factor effects on	Passive envelope design; PV and solar hot water systems; Ground-source heat pump; DOE2 simulation.	• Baseline design achieved 71% renewable share with 19.18 $kWh/m^2/year$ energy use and 10.08 $kgCO_2/m^2/year$. • Optimal scenario reduced emissions and energy by >80%.

			energy use and emissions.		Occupant behaviour and ventilation rate had the greatest impact.
	Xu et al. [73]	Operational	Comparison of three RL-based battery–PV scheduling strategies was performed.	Q-learning, DQN, DDPG; PV-battery system; Smart RL-based control; Real-time electricity prices; Python-based simulation.	• DDPG achieved 49.4% PV self-consumption and 36.7% self-sufficiency, cutting energy cost by 7.2%. RL outperformed rule-based control. • DDPG showed the best load shifting and revenue in summer; Q-learning was most flexible to price.
Machine Learning	Zhou et al. [74]	Operational	LightGBM–SHAP model for analysing 24 energy parameters affecting carbon, PV offset, and net emissions in Hangzhou offices.	Passive envelope design; High-performance glazing; Efficient lighting systems; Rooftop PV systems.	• WWR, LDP, and EPD most affect operational carbon; PVArea and PVEff dominate offset. • Synergistic effects among variables (e.g., depth × WWR) are critical.
	Wang et al. [65]	Embodied	Analysis was done on 35 case studies of public buildings in Xi'an, China.	BIM (for modelling and material tracking); Process-based LCA (for emission quantification); Foundation optimisation (to reduce material-related carbon).	• Materialisation-stage emissions ranged 100–2000 $kgCO_2e/m^2$; materials (esp. concrete, steel) contributed 78–97% of total.
	Zhang et al. [64]	Embodied	Machine learning-based prediction of embodied carbon intensities using 850 residential buildings in China across planning and preliminary design phases.	Process-based LCA; Embodied carbon intensity standardisation; Predictive ML models; Feature combination scenarios for early design stages.	• ET model using building features predicted planning-phase carbon with R^2=0.821. An XGB model using features and materials achieved an R^2 of 0.917 in the preliminary design. • Material cost, steel, and concrete were the top predictors. • Models help early-phase low-carbon design.
	Wang et al. [75]	Operational	Real-world data-driven study using hybrid machine learning and NSGA-II to optimise thermal comfort and carbon emissions in a large public aquatic building.	Thermal comfort management system (KB, GB, GCHS, AHU); Hybrid ML model (MLPNN + NSGA-II); Building system control optimisation.	• Hybrid ML model improved thermal comfort by up to 29% and reduced carbon emissions by 386.9 $kgCO_2$ (11.06%) vs human-based management. • Optimal trade-offs identified via Pareto fronts. • Model supports low carbon retrofit and operational planning.
Prediction	Jiang et al. [60]	Operational	Development and evaluation of a deep learning-based generalisation model to predict hourly energy consumption in multiple office buildings in Dalian, China.	Multi-source generalisation model (TDC–CNN–AttLSTM); Deep learning (CNN, LSTM, Attention); Transfer learning; Energy monitoring systems.	• Generalisation model predicted energy consumption trends 1 hour ahead with R^2 > 0.93 on unseen buildings.

	Zhang and Chen [61]	Operational	Short-term heat load prediction in hotel buildings using an ensemble deep learning model (ST-LSTM-RR) combining seasonal-trend decomposition and ridge regression.	Smart building sensors (indoor/outdoor factors); STL decomposition; LSTM networks; Ridge regression ensemble.	• Proposed model reduced RMSE and MAE across eight hotel groups. Incorporating trend and seasonal components improved LSTM prediction stability. • Effective for managing short-term heating demand and improving energy efficiency.
	Li et al. [76]	Operational	Systematic review of 222 studies on occupancy detection and prediction methods, sensors, and algorithms to enhance building energy efficiency.	Occupancy detection sensors (PIR, CO_2, cameras); Indirect methods (Wi-Fi, BLE, plug load meters); Hybrid ML algorithms (HMM, SVM, ANN); Smart building control systems.	• Accurate occupancy prediction improves HVAC efficiency and reduces emissions. • Hybrid detection and prediction methods offer the highest accuracy. • Integration of real-time data and predictive control systems enhances decarbonisation outcomes in intelligent buildings.
	Jiang [77]	Operational	Development of a BAS-LSTM model to predict carbon emissions in intelligent buildings using time-series decomposition and deep learning.	Smart energy monitoring systems; BAS-optimised LSTM network; Secondary decomposition (VMD + EEMD); Sliding window data control.	• Model achieved high accuracy ($R^2 > 0.94$) across low-carbon, energy-saving, and baseline scenarios. • Outperformed PCA, Qlattice, and standard LSTM in stability and predictive performance. • Effective for carbon planning in intelligent buildings.
Uncertainty	Hu et al. [66]	Operational	Simulation and optimisation of energy systems in a Hong Kong ZEB integrating grid-friendly metrics and uncertainty quantification using NSGA-II and Monte Carlo.	Passive design (wind catchers, high-performance glazing); PV panels; Wind turbines; Biodiesel generators; Battery storage; EnergyPlus simulation; Grid-friendly interaction optimisation.	• Uncertainty-based optimisation reduced lifecycle cost by 9%, carbon emissions by 6.8%, and improved grid friendliness by 10.8% versus deterministic design. • Uncertainty analysis supports reliability-adjusted energy system sizing in ZEBs.
	Zhuang et al. [67]	Operational	Probabilistic retrofit study of hybrid ASHP–gas boiler systems in three university buildings (UK), incorporating climate scenarios and energy flexibility.	Air-source heat pumps; Hybrid heating systems (ASHP + gas boilers); Passive envelope insulation; Smart grid interaction; TRNSYS simulation.	• Hybrid systems achieved 88% carbon emission reduction, 54% cost savings, and ~3-year payback. ASHPs met 80% of demand; GBs served peak load. • Retrofit feasible without radiator/fabric upgrades.
	Wang et al. [78]	Operational	Stochastic optimisation of hybrid CCHP system design under multiple uncertainties (solar radiation, loads, and market prices) using a two-layer model.	PV systems; Solar thermal collectors; Gas turbines; Ground-source heat pumps; Absorption chillers; Thermal energy storage (TES).	• Two-layer optimisation improved cost, energy, and emissions by up to 13.54%, 12.38%, and 21.73% vs single-strategy baselines. • Grid reliance was minimal with well-sized renewables.

Multi-objective Optimisation	Kang et al. [62]	Operational	Simulation and optimisation of passive design in a Beijing ZCB office using PSO-SVM-NSGA-III for CE, cost, and comfort trade-offs.	Passive design strategies (thermal insulation, airtightness, glazing, shading); EnergyPlus and jEPlus simulation; PSO-SVM prediction; NSGA-III optimisation.	• NSGA-III reduced CE by up to 28.6%, improved thermal comfort by 12%, and achieved balanced trade-offs among objectives. • PSO-SVM achieved an R^2 of 0.977 for CE prediction. • Passive parameter optimisation outperformed baseline and traditional designs.
	Luo et al. [79]	Operational and embodied	Systematic review of 64 studies on nZEBs and nZCBs was performed.	LCA; Passive design strategies; BIPV; Bio-based materials; Envelope insulation; Parametric modelling.	• Strategies for achieving nZEB/nZCB span design, materials, systems, and governance. • Embodied carbon is crucial for full decarbonisation. • Case-based retrofitting and early design tools support lifecycle decarbonisation.
	Wu et al. [63]	Operational and embodied	Simulation and multi-objective optimisation of NZEB office buildings across four Chinese climate zones using BIM-DB and PSO-RF-NSGA-III framework.	Passive envelope design (glazing, airtightness, insulation); Air conditioning temperature optimisation; LCA (for material production emissions).	• Optimisation reduced operational carbon by up to 39.7% and embodied carbon by up to 35.6%. • Passive envelope parameters and AC temperature settings were most impactful. • Region-specific NZEB designs were proposed for enhanced thermal comfort and low-carbon operation.

The reviewed studies demonstrated a wider use of data-driven methods to improve energy efficiency and minimise carbon emissions. From examining the survey studies, the review identified specific solutions, including simulation tools, machine learning models, and hybrid optimisation approaches. Additionally, several studies have implemented predictive algorithms to support building design and operation [60,61], while other studies have used multi-objective optimisation tools to balance cost, comfort, and carbon emissions [62,63]. Several investigations have examined the integration of machine learning with LCA to estimate embodied carbon in early design stages [64,65]. Other studies investigated how low-carbon energy systems can be improved by using uncertainty modelling and AI-based control systems to improve reliability and grid responsiveness [66, 67]. The outcomes indicate that advanced modelling and AI tools present considerable promise. However, their wider impact depends on multiple factors, including integration into practical design processes, the availability of robust datasets, and cross-disciplinary collaboration.

As data-driven approaches become central to building decarbonisation, recent studies have demonstrated the value of combining simulation techniques with predictive modelling to guide performance-based design and retrofit decisions. For instance, Saad et al. [70] introduced multiple criteria building retrofitting analysis using surrogate models, supporting decision-making for building decarbonisation was researched and produced. The study proposed a modelling framework to develop, optimise, and enhance surrogate prediction models for carbon emissions, energy consumption, and the associated costs of building energy retrofit procedures. To achieve consistent prediction stability, the study included several techniques, including feature selection techniques with interpretable models such as multiple adaptive regression splines (MARS) and multi-variate linear regression (MVLR). In another study, Ke et al. [72] used simulation to investigate carbon emissions and energy usage of Nearly Zero-Energy Buildings. The research utilised simulation and suggested a hybrid strategy that blends orthogonal tests and building energy simulation. The results showed that a basic model with specific design details, such as envelope, occupant behaviour (OB), number of ventilation times (VT), household structure (HS) and building orientation (BO), the application of renewable energy technologies, including ground-source heat pumps, solar photovoltaic power generation and solar hot water, can lead to a 71% renewable energy utilisation rate and a 61.76% energy savings.

Increasing data availability and demand for rapid, accurate results are driving the use of machine learning in carbon research. The review identified that current machine learning models inform low-carbon design and building-use decisions. In a study, Zhang et al. [64] evaluated the use of machine learning techniques to forecast the types of embodied carbon emissions throughout the design stages. The study used twelve algorithms, including Ridge regression, Linear regression, Elastic net regression, Bayesian ridge regression, K-nearest neighbours, Back-propagation artificial neural network, Gradient boosting, Random Forest, Support vector regression, extreme gradient boosting, Histogram-based gradient boosting, and Extremely randomised trees. The findings indicated that the relevant analysis and optimal models are considered helpful in facilitating low-carbon designs by efficiently predicting embodied carbon emissions. Jiang [77] presented an approach for intelligent buildings to predict carbon emissions. The study used both comprehensive empirical and variational mode decomposition to decompose historical carbon emissions data using a long short-term memory (LSTM) network. The BAS algorithm was developed to optimise the LSTM model's weights. The findings demonstrated that, in addition to exhibiting a strong decomposition effect and the capacity to capture all components of the data, this method also displays stable performance and an effective global search mechanism. These studies demonstrate how machine learning can strengthen data-driven carbon assessments, enabling early-stage design optimisation and intelligent building management.

This review also found that researchers are turning to intelligent design methods that incorporate uncertainty and address competing performance objectives in response to increasingly ambitious decarbonisation goals. For instance, Hu et al. [66] suggested methods for uncertainty-adaptive design in zero-energy buildings by presenting the grid-friendly interaction index to evaluate the grid compatibility of ZEB energy exchanges. Using 26 years of historical meteorological data, the findings showed that, compared with deterministic design schemes, the proposed approach can reduce costs by up to 9%, grid-friendliness by 10.8%, and carbon dioxide emissions by 6.8%. Wu et al. [63] proposed an intelligent Multiobjective optimisation design that uses NZEBs in four Chinese climate areas. The BIM-DB and PSO-RF-NSGA-III methodologies were integrated into an intelligent optimisation method. The study indicated that the use of these methodologies, employing optimised building design parameters, satisfied the NZEB requirements. As a result, these examinations underscore the practical relevance of uncertainty-adaptive design for supporting climate-responsive and performance-driven building design.

The reviewed studies show that intelligent models are now central to building decarbonisation research. Several examples were identified across design and operation, including surrogate models, machine learning, and optimisation frameworks. In addition, the review found that many tools link energy use, emissions, and occupant behaviour within connected modelling systems to improve building performance. However, key limitations remain, including poor data quality, low model clarity, weak system links, and scaling issues.

3.4 Sustainable Building Design and LCA

This section synthesises findings from 21 selected studies that examine the roles of sustainable building design and life-cycle assessment (LCA) in decarbonisation efforts. This section provides an exhaustive summary of each study's contributions as listed in Table 5. The studies were classified under eight key themes: 'BIM', 'Embodied Carbon', 'Carbon Reduction', 'Circular Economy', 'Design', 'Framework', 'LCA', and 'Cost'.

Table 5. Key findings from 21 studies in sustainable building design and LCA towards decarbonisation.

Key themes	Reference	Carbon Focus	Implementation Context	Enabling Technologies Used	Key Findings
BIM	Ullah et al. [80]	Operational and embodied	BIM-based LCA of the C-House green prefabricated building at Southeast University, Nanjing, China.	BIM (Rhino, Grasshopper); LCA; Prefabricated PV panels; Passive design; Reversible prefab construction.	• LCA across three reuse cycles showed cumulative carbon reduction of 70.57%. • Disassembly and reuse led to negative net emissions.
	Alzara et al. [81]	Embodied	Design-phase integration of embodied carbon assessment using a Dynamo script linked to BIM, validated through a real case study in Cairo.	BIM (Revit); Dynamo (for automated EC calculations); BIM360 (for collaboration and data sharing); SE2050-compliant EC database.	• The tool enables real-time LCA analysis during early design; reinforced concrete contributed the most emissions. • Workflow reduced reliance on third-party software, validated results using online LCA estimator with <5% variance.
	Klumbyte et al. [82]	Embodied	Development and validation of a 6D BIM API for whole-building LCA, tested on a Dutch residential case study.	BIM (IFC, Revit); 6D BIM API (Python, ifcOpenShell, PyPDF2); LCA (OneClickLCA validation); Environmental Product Declarations (EPDs).	• 6D BIM API accurately computed embodied carbon from cradle-to-gate (A1–A5); results aligned with OneClick LCA. • Method enabled integration of LCA into early design workflows with high precision.

Embodied Carbon	Fang et al. [83]	Embodied	Systematic review and meta-analysis of 288 studies on early-stage structural design strategies for reducing embodied carbon.	LCA (for structural materials); Parametric design frameworks; Bio-based and recycled materials; Design for reuse and disassembly.	• Identifies 11 design strategies classified into baseline, holistic, material-specific, cradle-to-grave, and emerging categories. • Emphasises early-stage decision-making, with structural systems representing major EC contributors.
	Craft et al. [22]	Embodied	LCA-based comparative analysis of typical, best-practice, and stretch scenarios for an office building to assess the feasibility of net-zero embodied carbon.	LCA (using EPDs and EPiC); Biogenic carbon accounting; Timber structures; Hybrid timber–aluminium façades; Straw insulation; Recycled and reused materials.	• Upfront embodied carbon reduced by up to 45%. • Net-zero embodied carbon is temporarily achievable when biogenic storage is included.
Carbon Reduction	Elsarrag [84]	Operational and embodied	Whole life cycle carbon analysis of seven DHW system designs in a typical office building.	Air source heat pumps (ASHPs); Low-GWP refrigerants (R32); Low-temperature DHW systems; Point-of-use design; IES-VE ApacheHVAC; CIBSE TM65 + EPDs.	• ASHP at 45°C had the lowest whole life cycle carbon (7.7 $kgCO_2e/m^2$), a 38% reduction compared with point-of-use systems.
	Elsarrag [85]	Operational and embodied	Whole life carbon analysis of seven HVAC systems for a UK office building.	ASHPs; Radiator systems; Displacement ventilation; Active and passive chilled beams; Low-GWP refrigerants (R32); CIBSE TM65; IES-VE ApacheHVAC.	• ASHP + radiator + displacement ventilation system had the lowest whole life cycle carbon (112 $kgCO_2/m^2$). • VRF systems had high refrigerant-related emissions despite using R32.
Circular Economy (CE)	van Oorschot et al. [86]	Embodied	Scenario-based spatial MFA of Dutch building stock (2018–2050) assessing material flows, circularity, and GHGs across conventional, biobased, and circular design strategies.	LCA (with Ecoinvent data); Biobased construction (CLT, wood fibre insulation); Design for disassembly; Recycled/reused materials; GIS-based material flow analysis.	• Biobased and circular strategies reduce GHGs by ~45% vs conventional. • Circular design lowers land demand and boosts long-term reuse.
	Sevindik and Spataru [87]	Operational and embodied	Integrated modelling of Orkney housing stock using LCA, energy system optimisation, and cost modelling for ASHP-based heating under circular economy scenarios.	ASHPs; TES tanks; LCA (SimaPro, ReCiPe Midpoint); SAP-based energy modelling; Circular design (eco-design, reuse, secondary materials); EEI retrofits.	• CE scenario reduced emissions by 98%, energy supply by 82%, and heating costs by 84%. • EEI measures significantly reduce demand but require large upfront support (£130M for full stock).
Design	Lou and Hsieh [88]	Operational and embodied	Systematic literature review and bibliometric analysis of 64 articles on nearly-zero energy buildings and net-zero energy	LCA (cradle-to-grave); PV systems; Bio-based and recycled materials; Passive design; Parametric design tools; Insulation systems; Energy simulation platforms	• Research highlights 13 subfields across three domains: design strategies, energy systems, and governance. • Transition from nearly-zero energy buildings to net-zero energy buildings requires

			buildings (2013–2024).	(e.g., IES-VE, EnergyPlus).	lifecycle-based decision-making. • Embodied carbon is often under-addressed but critical for achieving true net-zero.
	Kamel et al. [89]	Operational and embodied	Parametric optimisation of a residential prototype, evaluating 300 scenarios with biobased and conventional insulation under future climates.	Biobased insulation (hemp shives); PV panels; Parametric LCA (Bombyx); Honeybee + EnergyPlus (for OC); GWPbio method (for dynamic carbon accounting); Galapagos optimisation tool.	• Bio alternatives achieved LC-ZCB target with negative GWP (−0.64 to −0.54 $kgCO_2e/m^2/year$). • Biobased materials reduce embodied carbon significantly and are resilient under future climate scenarios.
	Liang et al. [90]	Operational and embodied	Systematic literature review and bibliometric analysis of 280 papers using CiteSpace.	Passive design strategies; Renewable energy systems (PV, wind, geothermal); BIM; LCA; Smart building technologies; High-performance insulation and HVAC.	• Emphasises integration of carbon-neutral design with urban planning and SDGs. • Advocates for early-stage strategy optimisation using digital and passive technologies.
Framework	Bilardo and Fabrizio [91]	Operational	Development and testing of a Zero Power Building (ZPB) framework using dynamic power balance analysis on a Minnesota office.	PV panels; Battery Energy Storage System (BESS); EnergyPlus; Dynamic CO_2 weighting system; Hourly CO_2 intensity data (EIA-based).	• ZPB framework enables detailed assessment of grid interaction and hourly CO_2 emissions. • BESS improved zero-carbon operation hours from 29.84% to 55.58%.
	Wu and Zhong [92]	Operational	Integrated BIM-BEM framework with uncertainty and energy optimisation to assess hydrogen-based storage in NZEBs across 20 Canadian cities.	PV systems; Hydrogen-based energy storage (LOHC + PEM electrolyzer and PEMFC); EnergyPlus; MATLAB-based optimisation; BIM for building modelling.	• SESH2ES reduced grid dependency and carbon emissions across all cities. • Hydrogen storage enabled seasonal balancing, though cost and efficiency varied by region. • Provides city-level planning insights for hydrogen adoption.
LCA	Shi et al. [93]	Operational and embodied	Comparative LCA of residential and public buildings in China, Finland, and the U.S., exploring energy source, material, and structure substitution scenarios.	LCA (ONE-CLICK LCA); Engineered wood products (CLT, GLT, LVL); District heating; Biobased insulation; Scenario-based energy mix substitution.	• Chinese buildings showed 2–4× higher emissions than U.S. and Finnish references. • Replacing materials and energy sources reduced lifecycle GHG by 50–60%. • Wood structures outperformed concrete and steel except for long-span applications, where steel was more efficient.
	Kayaçetin and Hozatli [94]	Operational and embodied	Whole life carbon assessment of three representative building typologies (SFH, apartments, office) across four Turkish climate zones under baseline.	LCA (EN 15978; RICS); BEP-TR energy simulation tool; Envelope upgrades; Solar PV (on-site, 8 kW max); Heat pumps (air and ground source); VRV systems; High-efficiency glazing.	• NZEB reduced OC by 30–80% but raised EC by 15–20%. NZEB plus further reduces whole-life-cycle carbon by 25%. • Study proposes benchmarks for Turkish NZEBs by climate and typology.
	Umdu et al. [95]	Operational and embodied	LCA and LCC analysis of building envelope materials and HVAC systems across 225	LCA (EPDs + EN 15978); Ground source heat pumps (GSHP); TES; Air-source heat pumps; Ceramic fibre	• Optimised envelope + GSHP reduced GWP by 67% and LCC by 90%. Low-emission design is achievable with only a 6.7% increase in capital.

			configurations for a public office building in İzmir, Turkey.	insulation; Double low-E glazing.	• LCA integration into contracts enables 50% GHG cut without exceeding current cost limits.
Cost	Kim and Lim [96]	Operational	Techno-economic analysis of solar-based NZEBs in the U.S. non-residential sector using a 5-parameter logistic function to project PV efficiency and costs through 2050.	PV panels; ASHP; Energy storage systems (ESS); TRNSYS; Five-parameter logistic function (5PL); Discounted payback analysis.	• PV-integrated systems reduce operation cost up to 26.8% depending on the solar region. • Recommends gradually reducing solar tax credit post-2033.
	Elaouzy and El Fadar [17]	Operational and embodied	Simulation-based assessment of seven bioclimatic strategies in a typical residential building across six global locations with varying climates, GDP, and electricity prices.	Thermal insulation; Green roofs; Triple glazing; Venetian blinds; Window opening control; EnergyPlus; OpenStudio; Meteonorm climate data.	• Thermal insulation achieved the highest energy and CO_2 savings in hot/cold climates. Window Opening was most effective in moderate zones.
	Vecchi et al. [97]	Operational	Mixed integer linear programming-based optimisation of energy supply for detached houses and apartments in temperate and sub-tropical Australia under different emissions, tariff, and fuel price scenarios.	ASHP; Gas and hydrogen boilers; the use of PV; Battery energy storage; Solar thermal collectors; Split systems; TES.	• Progressive electrification was the least-cost pathway. • PV + ASHP + TES achieved deep abatement at low cost. • Hydrogen is only viable if <40% of electricity price. • Distributed Energy Resources and tariff structure critically shape outcomes. • Net-zero is not always feasible without grid decarbonisation.

The reviewed literature presents diverse and practical actions within this cluster, including those related to early design-phase decision-making. The study demonstrated the integration of digital tools and the use of biobased and recycled materials to support whole-life carbon analysis [80,82,89]. Besides, studies have investigated the influence of equipment selection and refrigerants on embodied and operational emissions associated with heating, cooling, and domestic hot water (DHW) systems [84, 94]. Others introduced region-specific frameworks and optimisation methods to address carbon reduction under varying climatic, economic, and policy contexts [22,87]. On the other hand, the research outputs demonstrate improvements in life-cycle methods; however, limitations remain widespread in specific areas, including standards, data access, and real-world scalability [22,82,90]. Examining these outcomes, future action should focus on improving tool interoperability and expanding local carbon data and lifecycle modelling. This approach should be taken beyond a single building to support decarbonisation planning at larger scales.

This review also identified a rising amount of research supporting embodied carbon reduction by integrating building design and LCA. This is echoed in a study by Klumbyte et al. [82], which investigated the use of building information modelling to enhance whole-building life-cycle assessment by exploring principles and best practices. Utilising information from Building Information Modelling (BIM) files, the study made use of an Application Programming Interface (API) created to make Life Cycle Assessment (LCA) for complete structures effortless. The study notes that developing a standardised database platform for BIM-LCA poses difficulties and that region-specific databases are required to enable automated material classification for assessing potential environmental impacts. In another study, Craft et al. [22] explored net-zero embodied carbon by examining approaches to reduce embodied carbon in a multi-story office building using a life-cycle assessment (LCA). Consistent with the findings, material and design improvements, such as a full timber structure, reduced column grids, straw insulation, and a hybrid timber-aluminium façade, can yield 17–45% reductions in upfront embodied carbon. However, the technique and relevant data sources significantly affect the magnitude of the reductions. Taking into account biogenic emissions stored in wood and other biomaterials for up to 19 years, net-zero embodied carbon was achieved. These studies reinforce the importance of embedding LCA early in design decisions and highlight gaps in data consistency and in the clarity of carbon practices to guide low-carbon decision-making in real-world projects.

This study also pointed out the importance of system-level assessments in minimising lifecycle carbon impacts by adopting low-carbon technologies and circular strategies. Such assessments consider the combined effects of equipment, operational practices, and energy sources across the whole building lifecycle, making them essential for identifying effective decarbonisation pathways. Elsarrag [84] investigated the whole life carbon of various Domestic Hot Water (DHW) systems and designs in net-zero projects. The work included the development of a toolkit that encompasses the carbon footprint associated with DHW equipment, refrigerants, pumps, pipework, insulation, and storage, as well as operational energy-related carbon emissions. The results showed that analysis of several DHW designs for an office building revealed that low-temperature systems consistently exhibited the lowest whole-life carbon (WLC), underscoring the impact of grid decarbonisation and low-GWP refrigerants. In a wider circular economy context, Sevindik and Spataru [87] suggested an extensive approach to implementing low-carbon technologies towards a circular economy. The study developed a comprehensive method to assess the environmental, energy, and economic impacts of air-source heat pump deployment scenarios. The findings showed that implementing aggressive energy-efficiency improvement initiatives within the context of a circular economy could result in an 82% reduction in energy demand. Emissions associated with the utilisation phase may be reduced by 98% when the sole heating method used is the air-source heat pump. As a result, these studies demonstrate a wide range of techniques that provide forward-looking assessments by balancing early and whole-system reviews that track long-term performance and carbon results of integrated building systems.

Emerging scholarship is also placing greater emphasis on strategic frameworks and conceptual models to direct the progression of net-zero carbon buildings. For instance, Lou and Hsieh [88] reviewed methods for constructing net-zero energy and carbon buildings. Three principal components were identified by the study, including guidance, energy systems, and multidisciplinary methods. The study critically analysed the concept of NZEBs. It indicated several factors that should be considered including (1) Selection of data for the evaluation of buildings' GHG emissions, (2) Achieving an equilibrium between environmental sustainability and energy efficiency, (3) Decisions about building design, (4) Climate-dependent behavioural variations, (5) Evaluation and certification for buildings, (6) Difference between developed and developing countries in the creation of NZEBs and (7) Stakeholder attitudes, since social acceptability is essential for the long-term objective. Complementing this perspective, Wang et al. [98] proposed a technological framework grounded in control theory, system theory, and synergy theory for tropical island Zero-Carbon Buildings (TIZCB), with an emphasis on energy production, conservation, and utilisation, as well as intelligent technologies. The report offered a methodical framework and useful recommendations to promote China's dual-carbon plan and Hainan's clean energy growth. The study indicated that TIZCB only produces zero carbon emissions when the building is in operation. The reviewed studies showed that current frameworks are conceptually effective but operationally distant from practice. Therefore, decarbonisation pathways should reflect policy settings, climate conditions, and stakeholder expectations to support the achievement of net-zero progress.

This review also captured the evolving understanding of carbon trade-offs and cost-effective pathways in response to tightening net-zero energy requirements. This is reflected in a study by Kayaçetin and Hozatli [94], which examined the environmental impact of improving building envelopes and technological systems resulting from nZEB requirements. Using a complete life-cycle carbon assessment (wLCA), the operational and embedded carbon emissions were computed for several technological system scenarios and building envelope configurations. Across four distinct climates, the results showed that the current nZEB approaches reduce operational carbon by 30% and increase embodied carbon by 15% on average. Vecchi et al. [97] presented least-cost solutions to decarbonise household energy supplies in temperate and subtropical regions. The primary findings of this study indicated that in both temperate and subtropical climates, complete building electrification is the most affordable net-zero solution for all types of residential buildings. These studies imply the need to balance carbon savings across life cycle phases and to account for local economic and energy contexts when defining realistic, scalable decarbonisation targets.

This section has outlined diverse strategies for advancing decarbonisation through sustainable building design and LCA. The studies identified specific strategies for embodied carbon and operational emissions. First, material selection, bio-based options, and design for disassembly are common strategies for reducing embodied carbon. Second, efficient systems, full electrification, and renewable energy use are common among strategies for operational emissions. Third, integrating digital tools with dynamic LCA methods can enhance the precision of environmental impact evaluation. Ultimately, key barriers to development in this field include methodological inconsistencies, limited regional data, and trade-offs between embodied and operational carbon.

4. Conceptual Framework

The review demonstrated that research on building decarbonisation is progressing across a wide range of technologies, modelling techniques, and LCA-based evaluations. Furthermore, reviewing existing frameworks such as the UKGBC Net Zero Carbon Buildings Framework [99], which consists of five generic stages that cover (Net Zero Carbon Scope, Reduce Construction Impacts, Reduce Operational Energy Use, Increase Renewable Energy Supply and Offset Any Remaining Carbon), and the zero carbon trajectory using the elements of net zero carbon by LETI that include (Operational Energy, Embodied Carbon, Future Of Heat, Demand Response and Data Disclosure) [100]. The review identified that strategies to achieve zero carbon are fragmented and remain isolated across different life-cycle stages. The assessment of the three clusters indicates significant technical advances. However, addressing them within a holistic framework is limited, especially when approaches link material selection, design decisions, construction methods, and operational optimisation within a unified model. This fragmentation hindered the development of effective models for translating decarbonisation strategies into integrated pathways across the whole building lifecycle. Therefore, the review outcomes indicated the need for a conceptual framework to address gaps and provide a structured approach to action. The outcomes indicated a need for a balanced approach that links embodied and operational carbon and aligns with decarbonisation strategies. In response to this gap, the present study proposes a conceptual decarbonisation framework that organises these insights into an integrated and actionable sequence.

Examining findings from the bibliometric clusters and the 20 synthesised themes provided us with a perspective on how to shape an understandable structure. Although the review outcomes showed that studies approached decarbonisation from different views, the studies reported a typical sequence for achieving life-cycle decision-making. The sequences are presented in four practical stages: inputs on materials and energy, design choices, construction practices, and operational optimisation. These orders provided a coherent basis for organising the framework into four stages. Delving into each stage independently helped define the steps required to enrich the framework. Reflecting on the reviewed studies, supported by the authors' expertise in lifecycle analysis and decarbonisation, helps interpret how these dispersed contributions fit into a coherent process.

Figure 4 provides an overview of the framework's structure, which aligns with the building lifecycle. Elaborating further on the framework's flow, the research developed seven sequential steps. In the **Resource Stage**, two steps were covered to emphasise the foundational role of material selection and renewable energy inputs. These steps were supported by the examined literature, which covers reductions in cradle-to-gate emissions, including bio-based materials, high-performance composites, and optimised material substitutions [83,86,89,93]. On the other hand, evidence from technology-focused studies indicates that the early integration of renewable energy sources affects operational profiles, load balancing, and carbon content [20,38,39,44]. Reflecting on the two steps mentioned, the insights indicate that the resource stage provides a critical entry point for decarbonisation.

At the **Design Stage**, the framework focuses on two actionable steps developed from the reviewed studies. The review outputs indicate evidence of two distinct steps: building design and building systems. Also, it is critical to mention that Stage 2 encompasses the interior and exterior environments that influence embodied and operational outcomes. In Step 3, key factors forming long-term carbon trajectories have been identified. For example, envelope performance, system configuration, and thermal strategies. Interestingly, these factors have been explored using optimisation and simulation techniques. The application of these techniques affects design variables, including glazing ratios, shading geometry, façade systems, insulation levels, and others, as listed in Figure 4. As a result, managing these variables showed a substantial impact on heating and cooling demand. Step 4 demonstrates the development of active systems and their integration with renewable technologies, such as heat pumps [43], hybrid CCHP systems [78], solar thermal collectors [97], BIPV installations [38], and dynamic facades [18], which alter load profiles and reduce emissions. It is worth drawing attention to these technologies and to the impact of modelling and machine learning tools [63,64,74,78], which have been recognised as the most influential predictors of energy use and carbon intensity. The findings of this stage indicate that informing the design stage is the key factor underpinning the framework process.

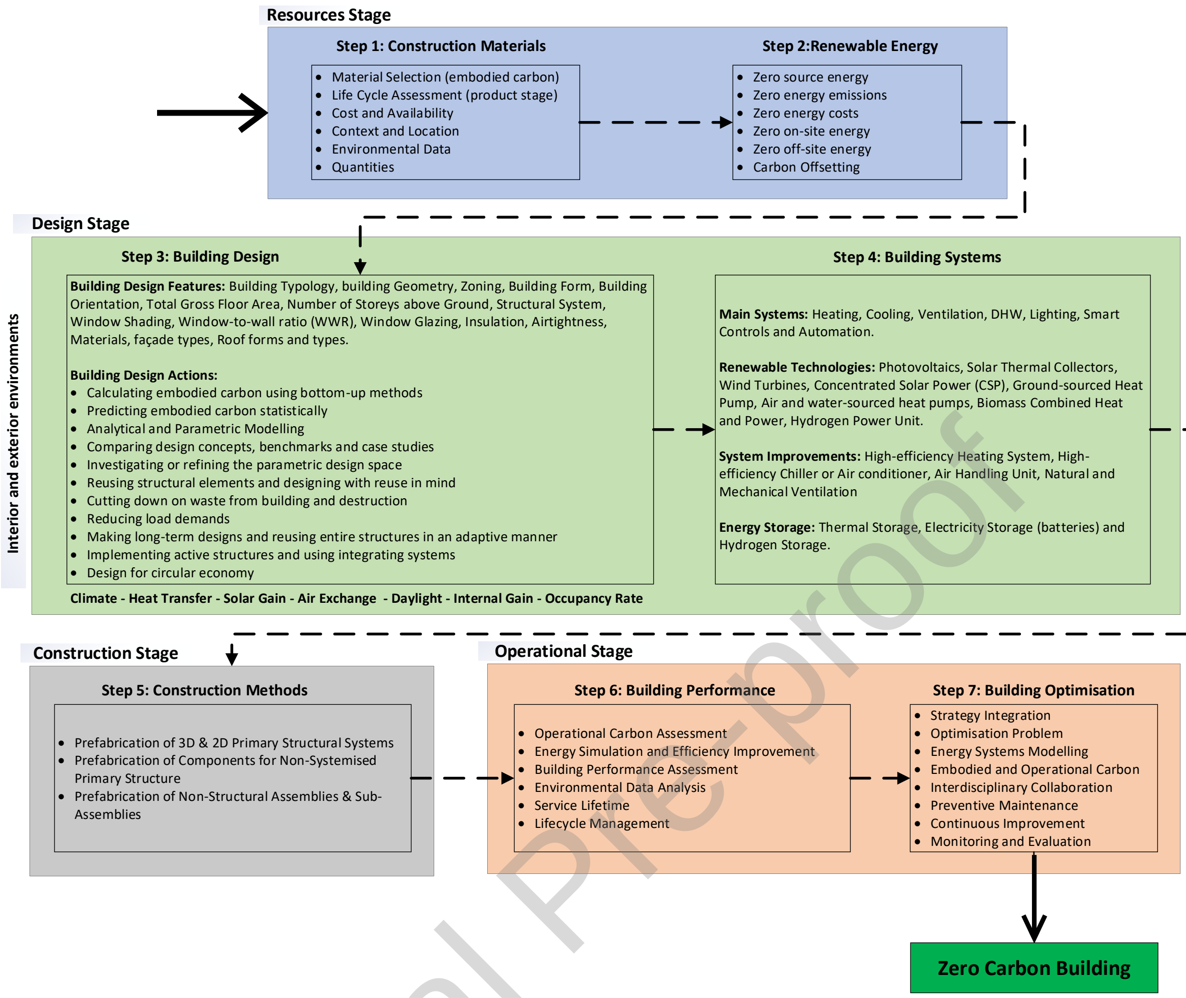

Figure 4. Proposed conceptual framework for decarbonisation in buildings (author's own work).

The **Construction Stage** is captured through a single step that focuses on methods to minimise waste and reduce embodied emissions. This stage encompasses various techniques, including modern methods of construction. The review indicates that off-site and prefabricated approaches offer measurable benefits in controlling manufacturing conditions to minimise carbon emissions [46,80]. These benefits extend to improved material utilisation and reduced on-site disturbances. Furthermore, the benefits of modular assemblies have shown to streamline construction logistics, shorten project timelines, and reduce transport demand, collectively lowering embodied impacts [46,80]. The identified pattern at this stage underscores the importance of adopting construction methodologies to reduce carbon emissions. Still, it emphasises that the selected approach is tied to earlier design decisions and material choices.

The final phase focuses on the **Operational Stage** and has been developed through the lens of performance and optimisation. The core process of this stage aims to sustain low-carbon outcomes through continuous monitoring, predictive control, and adaptive system management in dealing with changing internal and external conditions. Step 6 involves managing and accessing real-time data through analytical performance across diverse modern applications [101], including carbon, energy, environmental factors, service life, and life-cycle management. The reviewed modelling and AI-based studies supported the directions in Step 6, particularly the capability of new technologies to enable automation and optimisation routines that adjust system operation. In Step 7, building optimisation focuses on implementing state-of-the-art techniques that employ reinforcement learning [67,73], hybrid optimisation models [62,75], and data-driven control [60,78]. These advanced optimisation tools support adaptive management and can improve HVAC efficiency, renewable energy utilisation, and thermal storage performance. A critical examination of both steps indicates that building performance and operational optimisation should not be treated as isolated activities. The proposed framework facilitated their integration, as evidenced by the research and supported by previous literature. Therefore, interpreting this approach through the proposed framework would reinforce decarbonisation strategies and coordinated actions distributed across the entire lifecycle.

The insights gained from this review and the proposed framework show that effective decarbonisation relies on decisions distributed across all stages of a building's lifecycle. It provides evidence that isolated technological interventions can support decarbonisation goals but have limitations in achieving effective carbon control and reduction. The framework summarises diverse contributions identified in the literature while presenting a coherent process that clarifies all steps in the formation of carbon outcomes. Its significance lies in offering a structured perspective that can assist researchers in examining emerging technologies, aid practitioners in making early decisions with long-term performance effects, and guide policymakers in recognising where regulatory emphasis may be most effective.

5. Conclusion and Future Research Directions

This review identified the complexity and breadth of research on decarbonisation in buildings, particularly with respect to technologies and strategies. The review indicates that research and development on decarbonisation knowledge are expanding rapidly; however, insights are frequently distributed across individual technologies and isolated lifecycle stages. In addition, it limits their applicability for coordinated decision-making. The findings indicated that achieving decarbonisation is not limited to a single method; it is a holistic action encompassing reducing energy consumption, improving building comfort, lowering building operation and maintenance costs, securing the energy supply, and improving efficiency. It is a joint endeavour that needs proper coordination and management. The review proposed a technical solution based on a conceptual framework that presents a structured workflow to support carbon management throughout the building lifecycle.

The framework offers a new decarbonisation process comprising four stages and seven steps to identify areas for Zero Carbon Buildings. The structured process provides a solution to clarify vagueness and inconsistency across various literature on decarbonisation. Regardless of context or climate, this process provides a framework for specialists to identify needs and potential actions required to implement Zero Carbon initiatives. Furthermore, the framework offers insights to highlight measures and challenges for supporting academics, practitioners, governments, and policymakers in understanding decarbonisation and potential areas for knowledge generation towards net-zero targets by 2050. Key findings of the study can be summarised as follows:

- Managing and inspecting resources, including materials and renewable energy, is considered essential for establishing early carbon trajectories.
- Building design and systems pathways demonstrate the drive for both embodied and operational outcomes, and the core mechanism to achieve a critical intervention point in carbon reduction.
- Construction methods aligning with modern techniques play a crucial role in limiting waste and reducing embodied emissions. They influence early resource types and design models.
- Delivering performance and optimisation at the operational phase are effective keys to achieving long-term emission reductions. They demonstrate an interconnect stage that informs and controls carbon outcomes.
- The study shares substantial insights into decarbonization techniques that will help shape thinking on coherent carbon pathways.

Pointing out the review's limitations, the study acknowledges shortcomings in research development. Firstly, the research did not encompass the entire literature on zero carbon; it only included publications from 2023 to early 2025. This action was taken to examine contemporary publications rather than historical tracks, which might exclude relevant studies published in databases outside the selected scope. Furthermore, the extracted content was drawn from a single bibliographic database, the Web of Science, using pragmatically predefined keywords. Secondly, this study is a scoping review that aims to provide an overview of the evidence. The review addressed several items in the PRISMA 2020 checklist, including title, abstract, introduction, methods, results, and discussion; however, it did not cover all 27 items. Furthermore, a formal assessment of risk of bias and reporting measures was not conducted. This action was taken to examine the current evidence rather than to evaluate the intervention's effects, in accordance with the scoping review approach mentioned by several studies. Thirdly, the proposed conceptual framework is interpretive rather than empirically validated. The framework should be viewed as an integrated overview of current evidence rather than a prescriptive model.

Building on these limitations, several avenues for future research can be pursued to extend the insights generated in this review:

- In resources, the study identified limitations in current materials research, which focuses mainly on emissions and carbon intensity from the supply chain, manufacturing methods, and initiatives for regional energy decarbonisation. Future research should consider wider applications from a contextual perspective, including strategic sourcing and processing technologies.

- In building design and systems, the study exhibits limitations in using hypothetical building models that utilise simplification modelling in examining static environmental conditions, climate uncertainty, and microclimate effects. Future research should explore the interconnections among lifecycle carbon profiles, dynamic environmental conditions, and the optimised carbon technologies required for future climate projections.
- In construction, the review demonstrated initiatives and actions in assessing carbon measures using logistics, sequencing, and process-level emissions. Future research should examine how the efficiency of construction machinery, weather-driven delays, and site management influence embodied carbon in real projects.
- In building performance and optimisation, these areas have been supported by state-of-the-art solutions and technologies. However, future research should prioritise validated datasets that link design intentions to in-use carbon outcomes. Future research should overcome the limitations of AI-based optimisation in simulation-based scenarios. Exploration in real-world building deployments would constitute a substantial advancement in the field.
- Finally, the proposed conceptual framework invites further research on carbon measures across lifecycle stages. Future research could explore its applicability in practice, test it, and identify where misalignments between design, construction, and operation lead to unintended carbon outcomes. As a result, integrating the proposed framework into physical and digital environments via digital twins would offer a new paradigm for future developments.

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Declaration of Interest Statement

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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