

# From global evidence to local action plan: a novel building decarbonization maturity scale and roadmap for nZEB office buildings in developing contexts – case of Türkiye<sup>☆</sup>

Başak Yüncü Karanfil<sup>a</sup>, Nuri Cihan Kayaçetin<sup>b,\*</sup>, Ayşegül Tereci<sup>c</sup>, Neslihan Bıyıklı<sup>d</sup>, Merve Kılınc Gilisiralıoğlu<sup>c</sup>, Diğdem Karaer<sup>b</sup>

<sup>a</sup> Middle East Technical University, Üniversiteler Mahallesi, Dumlupınar Bulvarı No:1, 06800, Çankaya, Ankara, Türkiye

<sup>b</sup> İhsan Doğramacı Bilkent University, Üniversiteler Mahallesi, 06800, Bilkent, Çankaya, Ankara, Türkiye

<sup>c</sup> Necmettin Erbakan University, Köyceğiz, Demeç Sk. 39/2, 42040, Meram, Konya, Türkiye

<sup>d</sup> Fenerbahçe University, Atatürk Mah. Ataşehir Bulvarı, Metropol İstanbul, 34758, Ataşehir, İstanbul, Türkiye

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## ABSTRACT

To effectively combat climate change, various policies and strategies are being developed to reduce emissions by 2050. The construction sector assumes a pivotal role in achieving decarbonization targets. It is imperative to acknowledge the potential of practices in developing countries, which can provide the critical part of carbon reduction on a global scale. In this context, Nearly Zero Energy Buildings (nZEB) are attracting global attention as a key component of sustainable construction and urban regeneration. Despite high level of energy efficiency and potential to utilize renewable energy, nZEBs have not found widespread application in developing countries. This study benefits from a systematic review of the whole-life decarbonization process of nZEB office buildings. The study evaluated policy frameworks, implementation, and potential emission reduction strategies through energy efficiency measures, material selection, and the integration of renewable energy. In response, the study proposes a structured, context-sensitive decarbonization maturity scale and roadmap to guide policy and practice in developing countries and utilized Türkiye as a case study example. The findings reveal that Türkiye's current nZEB definition positions it at Level 2 (Emerging) on the decarbonization maturity scale. The country's high carbon intensity signals the urgency of prioritizing demand reduction and efficiency. Despite enhancements, nZEB offices in Türkiye exhibit high carbon emissions, with operational emissions ranging from 7.5 to 35 kgCO<sub>2</sub>-eq/m<sup>2</sup>/year and embodied carbon from 182 to 201 kgCO<sub>2</sub>-eq/m<sup>2</sup>. As a result, the maturity scale identifies leverage points offering a mechanism to benchmark progress and accelerate climate action in line with international examples approaching Level 5.

## 1. Introduction

As stated in the 2024 report of United Nations Environment Program, the construction sector is responsible for 37 % of the world's total energy-related CO<sub>2</sub> emissions [1]. More than 70 % of these emissions originate from the operation and utilization of existing buildings, highlighting the requirement for immediate and extensive decarbonization initiatives. The construction sector plays a critical role in climate change; on the other hand, it represents an important target for mitigation efforts. Hence, adopting sustainable construction methods,

increasing energy efficiency and using renewable energy sources are key to reducing the environmental impact of buildings [2–12].

While efforts to lower operational energy demand have been widely adopted [13], focusing only on operational energy or carbon overlooks major life cycle impacts [14]. A more comprehensive approach should also target embodied energy and carbon, with an inclusive building system scope including all relevant systems such as HVAC [15] and be evaluated within a whole life carbon (WLC) framework to guide early design decisions [16]. Recent research has focused on the identification and management of WLC, a pivotal approach particularly noticeable in

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\* Corresponding author at: İhsan Doğramacı Bilkent University, Üniversiteler Mahallesi, 06800, Bilkent, Çankaya, Ankara, Türkiye.

E-mail addresses: [basakyuncukaranfil@gmail.com](mailto:basakyuncukaranfil@gmail.com) (B.Y. Karanfil), [cihan.kayacetin@bilkent.edu.tr](mailto:cihan.kayacetin@bilkent.edu.tr) (N.C. Kayaçetin), [atereci@erbakan.edu.tr](mailto:atereci@erbakan.edu.tr) (A. Tereci), [neslihanbiyikli.phd@gmail.com](mailto:neslihanbiyikli.phd@gmail.com) (N. Bıyıklı), [merveeklnc96@gmail.com](mailto:merveeklnc96@gmail.com) (M. Kılınc Gilisiralıoğlu), [digdem.karaer@bilkent.edu.tr](mailto:digdem.karaer@bilkent.edu.tr) (D. Karaer).

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the context of the global climate change initiative [2]. Whole life carbon assessments (WLCA) provide a broader perspective by incorporating emissions from material production, construction, and end-of-life (EoL) scenarios. Standardizing WLC benchmarks can help set clear GHG emission limits for buildings, ensuring sustainability is integrated into the entire building lifecycle [17–19].

One widely adopted strategy for reducing building emissions is the nearly zero-energy building (nZEB) concept. Although there is a definition that varies according to countries due to differences in climate, economic conditions, and regulatory environments [20], nZEB refers to buildings that use low primary energy and can make their annual energy balance zero by exporting part of the energy produced on site, so that this approach by decreasing dependence on fossil fuels contributes to reducing the carbon footprint in the construction sector. In the EU, the Energy Performance of Buildings Directive (EPBD) requires that all new buildings meet nZEB standards to ensure high energy efficiency and increased reliance on renewable energy sources [21]. Although this policy has driven progress, challenges remain in its uniform implementation. The nZEB concept endeavors to address the energy demands of buildings through the utilization of renewable sources. However, the absence of replicable, whole-life-cycle-based models for the design and construction of such buildings, particularly in developing countries, continues to delay the capacity of local governments and investors to recognize and act on their potential [22,23]. Especially, it is necessary to facilitate knowledge exchange on nZEB applications in developing countries so they can evaluate the feasibility and challenges of applying. Research shows that while renewable energy integration can significantly lower operational emissions [24], high initial investment costs remain a barrier to widespread adoption [25]. Government incentives and policy support can help address this challenge [16,17,20] and accelerate the transition to net-zero energy buildings by supporting optimization efforts regarding building envelopes and technical systems [26]. While recent research has highlighted the growing importance of WLCA in the built environment, it is clear that both operational and embodied carbon need to be addressed to achieve decarbonization and that standardized frameworks, metrics and assessment methods are still evolving.

Another gap in literature is the lack of case studies on nearly zero-energy office buildings, particularly in developing countries [26]. While residential and public buildings have been the focus of most research, office buildings present unique challenges due to their higher energy demands and complex systems. They also possess an opportunity as there is a higher capacity to adopt developed solutions due to available financial and technical resources. Examining how different regions integrate energy efficiency and carbon reduction strategies in office buildings can provide valuable insights into future policies and design approaches. The objective of this research is to carefully evaluate the most recent practices concerning the construction of building envelopes and technical systems for the advance of zero-carbon office buildings for developing countries. Thus, office buildings were chosen as the primary focus of this study for many reasons listed below:

- Higher energy demand when compared to other building typologies
- Higher saving potential due to the investment capacity of the building owners
- Higher management capacity for easier decision-making on building design,

In this process, an analysis of current regulations and standards that guide practitioners is intended to contribute to implementing sustainable construction practices. Additionally, by analyzing current research trends, this study seeks to anticipate future developments in the definition of nearly zero-energy buildings and their role in decarbonizing the built environment.

To achieve these goals, this research addresses three key questions:

- i. How comprehensively do existing studies on nZEB office buildings address WLC, particularly in terms of embodied carbon, EoL strategies, and regional policy integration?
- ii. What thematic patterns, methodological trends, and regional disparities can be observed across high-quality studies on nZEB office buildings, and how do these inform decarbonization progression?
- iii. How can a progression roadmap and maturity scale be developed to guide the decarbonization of office buildings in developing countries?

By addressing these aspects, this study aims to contribute to the ongoing discourse on sustainable building design and carbon reduction strategies, offering insights that can inform future practices and policies on nZEB office buildings towards decarbonization in developing countries.

The remainder of this paper is organized as follows: [Section 2](#) presents the methodology, including the systematic review protocol, data collection and evaluation strategy, the development of the proposed decarbonization maturity scale, and the case study [Section 3](#) provides the results of the review, including thematic analysis, carbon and energy metric trends, identified research gaps, and findings from grey literature. [Section 4](#) offers a detailed discussion of the review findings, need for and development of the maturity scale, supported by a comparative synthesis of whole life carbon data and its relevance to Türkiye's decarbonization context. Finally, [Section 5](#) outlines the key conclusions, policy implications, and recommendations for future research.

## 2. Methodology

To explore nZEB office building applications in developing and developed countries in terms of carbon reduction strategies and to develop a path that can be followed by developing countries to keep up with the latest trends, the research is handled in three parts: a systematic literature review, evaluation and presentation of the review results, and the development of a decarbonization maturity scale and a roadmap for buildings. The methodology of each part is explained in detail in the following subheadings.

### 2.1. Database search and screening

In the first stage, the literature was methodically reviewed in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. This approach was adopted to ensure transparency, replicability, and adherence to stringent scientific standards [27,28]. Given its effectiveness in ensuring transparency and methodological rigor, PRISMA is applied to systematically review WLC literature on office buildings. This approach allows for a structured synthesis of existing research, assisting a clearer understanding of key trends, challenges, and best practices in reducing carbon emissions throughout a building's life cycle and literature gaps. A visual summary of the PRISMA-based protocol stages is presented in [Fig. 1](#).

The search strategy of this phase of the study that follows the PRISMA-based protocol stages is based on three main stages: identification, screening and deciding. In the first stage, Web of Science (WOS), Scopus and TR-Dizin (The Turkish Database) databases are used for identification of the relevant journal articles. Aiming to cover the full spectrum of existing studies on the whole life carbon approach in nZEB office buildings, three main keywords are used in literature search on January 31, 2025:

1. "whole life carbon" with its equivalents: "wlc", "whole life cycle" and "cradle to grave"
2. "nZEB" with its equivalents: "zero energy building", "zero carbon building", "low energy buildings", "net zero energy building", "zero emission building" and "low emission buildings".

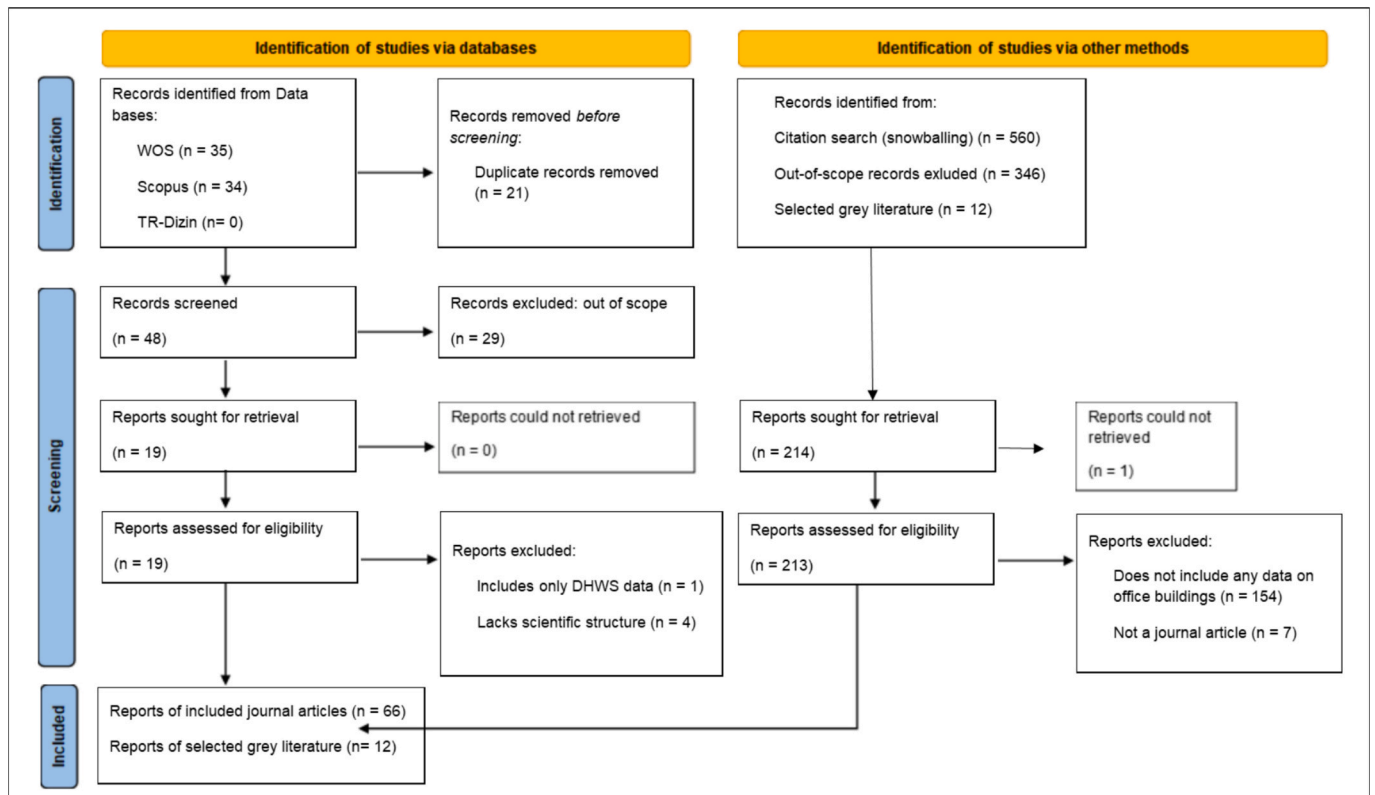


Fig. 1. PRISMA 2020 flow diagram of this study [27].

### 3. “office buildings” with its equivalents: “office building”, “offices” and “administrative building”.

The search is restricted to the following publication type: peer-reviewed journal articles, encompassing original research and reviews, which are required to have been published from the year 2010 onwards, in accordance with the adoption of the EU’s EPBD nZEB policy [21], and must be written in the English language. The queries searched in the databases are presented in Appendix-1. Accordingly, the following queries are searched in,

The second stage, screening, includes the following steps:

- Screening of the Records: The records are evaluated if they are relevant to this study based on the titles and the abstracts of the records identified from the databases.
- Screening of the Retrieved Reports: The full texts of the chosen records are screened by two reviewers in terms of methodology, discourse themes, metrics, exclusion criteria and relevance to the discussion topics of this study. A third reviewer was consulted in cases of discrepancies regarding the inclusion of a report in this study.
- Citation Search: The references cited in the reports decided to include in the study are screened based on their titles and abstracts in the same manner as the first screening of the records.
- Second Screening of the Retrieved Reports: The full-text reports of the records chosen after citation search are retrieved and added to the retrieved reports inventory for the second phase of report screening.

To ensure the validity and quality of findings synthesized from the 66 selected articles, a structured methodological quality evaluation was conducted during the full-text screening phase. This evaluation focused on both the scientific quality of the source and its relevance to the research objectives. The following quality assessment process was

applied:

- Indexing and Journal Ranking Check: Only peer-reviewed journal articles published in SCIE-indexed journals were considered eligible. Journal quartile rankings (Q1–Q4) were also documented to assess the scientific credibility of the source.
- Eligibility Decision by Reviewers: Each retrieved report was independently reviewed by at least two researchers based on a predefined list of inclusion/exclusion criteria (Table 1).
- Thematic Relevance Tagging: For each study, thematic tags were assigned (e.g., “Trade-off between operational and embodied carbon”, “Importance of end-of-life strategies”, “Content of nZEB definition”, etc.). This helped ensure topic relevance and facilitated structured analysis in subsequent stages.
- Automatic Filtering and Final Selection: An automated formula was used to flag eligible articles. Only those that passed both reviewer validation and thematic relevance assessment were retained for final synthesis ( $n = 66$ ).

The detailed scoring sheet that illustrates the structured data fields, reviewer decisions, and thematic tagging applied during this full-text screening phase is available on request. This approach ensured that all included studies met a minimum threshold of scientific rigor, while also being directly relevant to the study’s decarbonization roadmap and nZEB-focused objectives.

In the second phase of the study, the authors include relevant [2–12] grey literature to the study. Through a comprehensive evaluation of the legal frameworks established by both developed and developing countries in this domain, a framework has been devised to guide the establishment of appropriate practices for developing countries.

## 2.2. Data collection, evaluation and presentation

Following PRISMA guidelines, a comprehensive literature search

**Table 1**  
The list of eligibility criteria.

Inclusion:	Exclusion:
<ul style="list-style-type: none"> <li>• WLCA approach: building scale LCA</li> <li>• Refurbishment and retrofit scenarios for energy efficiency or decarbonization</li> <li>• Review articles focusing on nZEB offices</li> <li>• Includes office buildings.</li> <li>• Building system scope (one or more): “structural system”, “renewable energy”, “building envelope”, “heating, cooling and air conditioning (HVAC)”, lighting, “interior finishes and components”</li> <li>• Energy and carbon-based metrics.</li> <li>• High scientific quality: SCIE-indexed</li> <li>• Up to date: published in 2010 and later</li> <li>• Relevant to the discussion topics of this study:                             <ul style="list-style-type: none"> <li>• decarbonization,</li> <li>• embodied and operational carbon trade-offs,</li> <li>• importance of EoL scenarios,</li> <li>• content of nZEB definition.</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• Building typology: healthcare, industrial, residential.</li> <li>• Renovation or historical building restoration cases</li> <li>• Irrelevant metrics: solely cost based etc.</li> <li>• Too narrow or too broad LCA scale: Material, product, room, urban, infrastructure, industrial power production.</li> <li>• No reference to office buildings</li> <li>• Building system scope focused on only domestic hot water system (DHWS) or natural ventilation system.</li> <li>• Low scientific quality: not in SCIE</li> <li>• Irrelevant to the discussion topics of this study.</li> </ul>

focusing on nearly zero-energy office buildings was conducted across multiple databases, yielding 608 records. After duplicate removal and two screening stages (an initial title and abstract scan followed by full-text eligibility review), 66 studies met the inclusion criteria and were retained for detailed analysis. Throughout this process, key information from each record was compiled in a structured Excel spreadsheet to facilitate comparison across studies. Each entry captured attributes such as the study’s methodology, primary thematic focus, reported performance energy and/or carbon metrics, the considered building systems, geographical context, and building typology. To ensure rigor and consistency in selection, screening and data extraction were performed independently by two reviewers, with any discrepancies in study inclusion resolved through consultation with a third reviewer. All included studies underwent a detailed thematic analysis guided by the 4 defined themes: “decarbonization”, “embodied & operational carbon tradeoffs”, “end-of-life strategies” and “the content of nZEB”. Miro, a digital collaboration platform [29], was used for the visualization of the data presented in Fig. 2, which presents a general overview of the

included articles. Additionally, for the subset of 44 original research studies that reported quantitative energy and/or carbon performance metrics, a comparative analysis of these metrics was conducted. Finally, the synthesized results were organized into summary tables grouping studies by the scope of building systems addressed, and by contextual factors like geographic region and building typology, thereby highlighting patterns and contrasts across different contexts.

2.3. Development of a decarbonization maturity scale

In order to map the decarbonization approaches and standpoints in this research area, a “building decarbonization maturity scale” is developed, by means of translating Hudson’s (2001) cultural maturity model into the decarbonization context. Hudson categorizes and describes different types of safety cultures and presents them within a health, safety and environment (HSE) ladder, where maturity level increases by each of the five different levels: (i) pathological, (ii) reactive, (iii) calculative, (iv) proactive and (v) generative [30,31]. This model

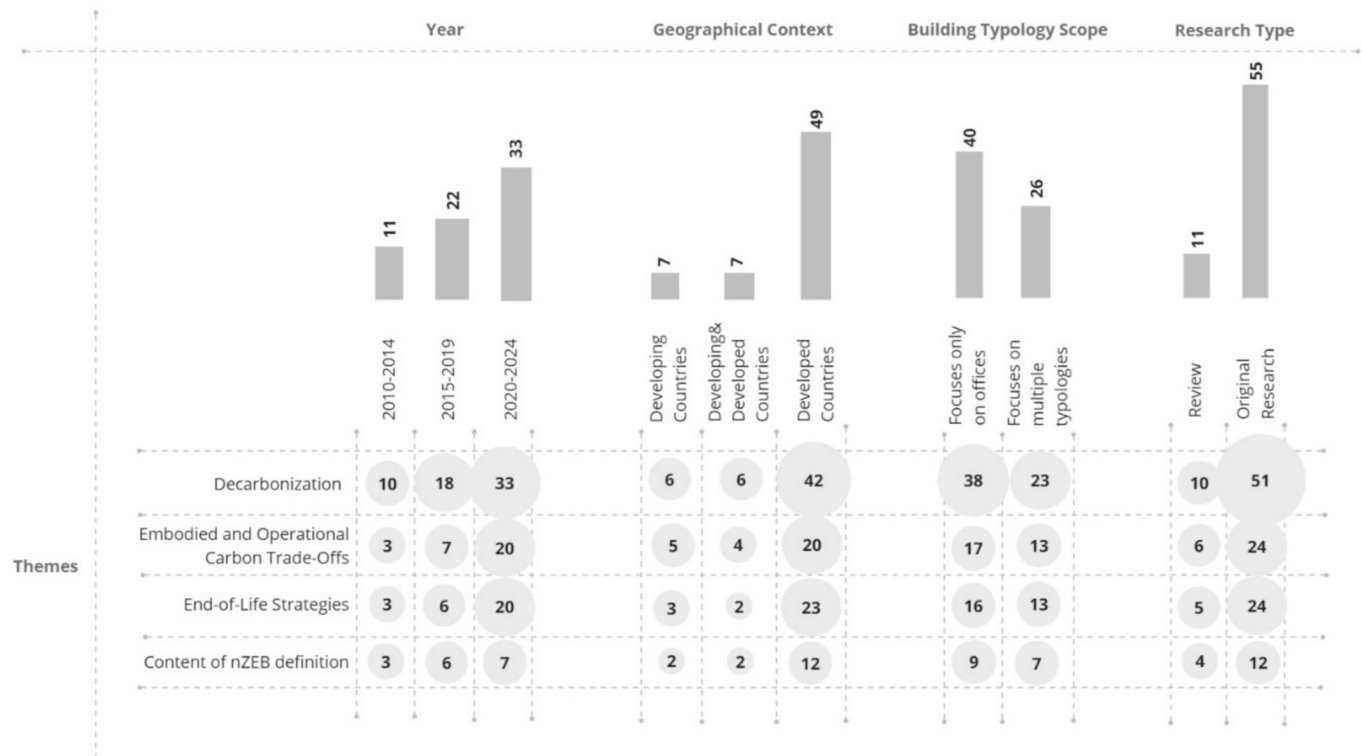


Fig. 2. The general overview of the included journal articles in the systematic review.

has been modified, applied and brought success in several various sectors. A recent example from computer sciences introduces a “decarbonization maturity level” of five levels: (i) beginner, (ii) adaptor, (iii) integrator, (iv) innovator and (v) transformer [32]. These models from the literature inspired the authors to develop a decarbonization maturity scale tailored to the built environment context. Such an interpretation of the accumulated managerial experience in other sectors is predicted to support accelerating decarbonization efforts in the built environment. The developed maturity scale and its justification are further explained in relation to the systematic review results under the discussion section.

#### 2.4. Case study

A case study approach was adopted to reflect on the development of maturity scale and to display how a progression roadmap can be implemented in a developing country, such as Türkiye. The country has recently implemented an nZEB definition in 2020 for all new buildings constructed after 2023 with an initial total area above 5,000 m<sup>2</sup> and revised to 2,000 m<sup>2</sup> in 2025. Currently, an nZEB must achieve an energy performance class B or better (which implies least 20 % lower total primary energy demand than the BEP-TR baseline version of the building), and at least 10 % of its total primary energy need must be met from renewable energy sources [3]. Due to the large building stock and relatively high construction rate, it also possesses high potential for carbon savings. Since 2002, more than 2 million buildings have been constructed, among which 7 % are composed of office buildings [33]. An additional 96,000 buildings with a total construction area of 120 million m<sup>2</sup> are annually added to the stock [33]. As the ratio of new buildings is higher than that of the EU, the definition of nZEB for new buildings is significantly important.

The Turkish building industry is dominated by (i) reinforced concrete, (ii) polystyrene thermal insulation and (iii) ceramic tiles and plaster & paint for exterior finish and (iv) single or double-glazed windows with plastic or aluminum frame [34]. As of January 2025, there are more than 20,000 nZEBs in the country [35] across six climate zones ranging from BSh to Dfb in the Köppen-Geiger scale, with a heating degree day range between 993 and 4444, as per the recent revision on the thermal insulation requirements [36]. The average operational energy consumption and carbon emissions of nZEBs are respectively ranging between 29–148 kWh/m<sup>2</sup>/year and 7.5–35 kgCO<sub>2</sub>-eq/m<sup>2</sup>/year [35]. In a recent study [16], the ratio between embodied and operational carbon emissions was displayed around 25 %. The variety of geographical climate zones enables comparison with several nearby regions such as Middle East and North Africa (MENA) and Eastern Balkans.

The electricity mix is one of the most significant aspects that affects WLC emissions. Türkiye is one of the countries which does not have nuclear energy in the mix, hence the carbon intensity is higher than nearby countries in the EU [37]. The carbon conversion factor in 2024 is 0.697 kgCO<sub>2</sub>-eq/kWh [38], which is expected to drop to 0.325 by 2050 [16]. Hence, it is important to decrease the energy demand, which will have a significant impact on carbon emissions.

### 3. Results

In this study, 608 journal articles (records) were reviewed and judged by their titles and abstracts, initially. 232 of them were selected as appropriate for full text (report) screening. Among the screened reports, 66 articles have been decided to be included in this review according to the criteria presented in Table 1. A general overview of the included articles is summarized in Fig. 2 in terms of main themes categorized by publication year, geographical context, building typology scope, and research type. The categorized articles in Fig. 2 present significant trends in the research on nZEBs across various themes, years, geographical contexts, building typologies, and research types.

Among the key themes, decarbonization emerges as the most

frequently addressed topic, followed by policy and net-zero regulations, EoL strategies, embodied and operational carbon trade-offs, and finally, the content of nZEB definitions. Decarbonization, in particular, is discussed in 61 studies and is notably prominent from 2020 to 2024, reflecting a growing interest in the scientific community. Other themes, such as EoL strategies and carbon trade-offs, have also gained attention in recent years, suggesting a trend towards a whole building LCA approach and a holistic sustainability perspective in the research area. While policy frameworks and definitions are covered more evenly over time, they are still a gradually growing research interest for both developing and developed countries.

In terms of chronological development, the volume of research has steadily increased from 11 studies in the 2010–2014 period to 33 studies between 2020 and 2024. This upward trend signals a growing academic and practical interest in decarbonization in the built environment. Particularly, the attention to themes like EoL strategies and embodied carbon trade-offs has intensified in the most recent years, indicating a shift toward a broader LCA scope and accounting for embodied carbon. Geographically, the research is concentrated in developed countries: 3 studies do not specify any country, 7 studies consider only developing, 7 studies consider both developing and developed countries, while 49 consider developed countries, mostly mainland Europe and North America. This imbalance suggests a lack of context-specific studies addressing the unique challenges and opportunities in developing regions. With respect to building typologies, more than half of the studies focus solely on office buildings. Decarbonization and policy themes are especially common in office-focused studies, presenting that offices are considered a strategic typology for carbon mitigation. Finally, original research dominates the field, with 55 studies compared to only 11 review articles.

The results of this study are given under five subheadings in this section: “Thematic Analysis”, “Carbon / Energy Metrics Analysis”, “Literature Gaps Identified and Addressed in the Review Articles” and “Analysis of the Selected Grey Literature” and they are summarized altogether in the “Highlights” subheading at the end of this section. 11 of the 55 original research articles included in this study either report their performance improvement findings in percentages only or do not include any energy or carbon related data in common metric units such as kg CO<sub>2</sub>-eq or kWh that can serve as a benchmark. Therefore, those 11 articles are only covered by means of thematic analysis [39–49]. The remaining 44 original research articles are categorized in terms of building system scope(s) and reported separately under the second subheading under this results section. Among the included original research articles, 30 articles focus exclusively on office buildings, whereas 14 of them include office buildings as part of a broader analysis covering multiple building typologies. Moreover, the 11 review articles included in this study and one original research article that includes a systematic literature survey [50] are analyzed and compared in terms of the literature gaps they point out and their proposals that address those gaps on Table 2 in the third subheading. Finally, the selected grey literature is presented chronologically in terms of geographical context, building system scope, considered LCA modules and the carbon/energy benchmarking policies on Table 3 in the fourth subheading. The overall results of the study are summarized as highlights at the end of this section.

#### 3.1. Thematic analysis

The main discourses and discussion themes related to the research area were analyzed towards decarbonization and nZEB. According to the studies, it is found that there is a tendency towards 4 main themes: “decarbonization”, “embodied & operational carbon tradeoffs”, “end-of-life strategies” and “the content of nZEB”. Each of these themes are evaluated qualitatively below.

**Table 2**

The comparison of the review articles included in this study, in terms of identified and addressed literature gaps.

Reference	Year	Geographical Context		Identified Literature Gaps	Proposed Framework
		Country	Climate Zone		
[51]	2010	New Zealand, Canada, Australia, Thailand, EU, India	A, B, C, D	<b>Sparse data</b> on environmental impacts of construction and demolition phases. <b>Low standardization in LCA data.</b> Insufficient daylight integration strategies. <b>Few studies</b> on dynamic lighting systems in <b>cold climates.</b>	N/A
[52]	2011	Sweden	D		<ul style="list-style-type: none"> <li>• 10 kWh/m<sup>2</sup>-year target for lighting electricity in low-energy office buildings</li> <li>• strategies to reach it</li> </ul>
[53]	2012	Belgium, Sweden, USA, UK, and Japan	B, C, D	<b>Limited studies</b> following new CEN/ISO LCA standards. <b>Lack of data</b> on material/construction/end-of-life phases. Weak comparability across LCA case studies.	N/A
[54]	2013	UK, US, Australia, China, Canada, EU, Switzerland, South Korea, Japan	B, C, D		Marginal Abatement Carbon Cost Curve for EC/OC balance
[55]	2018	UK	C	Insufficient data on whole-life CO <sub>2</sub> equivalent for various technologies. <b>Inconsistency in LCA methods</b> used for <b>embodied energy.</b>	N/A
[25]	2018	North America, EU, MENA	B, C, D	<b>Lack of nZEB studies</b> on existing buildings and maintenance. Vague <b>definitions of nZEB</b> across standards.	<ul style="list-style-type: none"> <li>• a systematic approach combining design and optimization to meet net-zero energy goals</li> <li>• nZEB definitions</li> <li>• “Zero” vs “plus” energy building</li> <li>• primary energy factor</li> <li>• surplus energy index</li> <li>• policy incentives</li> </ul>
[20]	2019	EU (27 Member States)	B, C, D		
[56]	2019	United States Singapore France (Réunion Island) China (Hong Kong SAR) Israel	A, B,C	Limited cost and carbon metrics in nZEB case studies. Lack of standardization of reporting methods. Limited data from developing countries and warm-humid regions. Future work should integrate life cycle carbon more systematically.	N/A
[57]	2020	China, USA, Europe, Australia	B, C, D	Policy <b>neglect of embodied emissions.</b> Lack of incentives for mass timber.	N/A
[50]*	2020	Europe, Asia, Oceania, North America, South America	A, B, C, D	New studies with large datasets are needed. <b>Limited transparency and comparability in LCA data.</b>	A methodological foundation and a policy direction: <ul style="list-style-type: none"> <li>• Policy-relevant recommendations</li> <li>• A call for carbon-effective investment and decarbonization strategies</li> <li>• A structured research agenda</li> </ul>
[58]	2023	China, Japan, US, South Korea, Iran, Sweden, Spain, UK, Finland, Singapore, France, Hong Kong	A, B, C, D	Limited attention to material stage in LCA. Insufficient policies addressing <b>embodied carbon.</b>	N/A
[19]	2024	EU (27 Member States)	B, C, D	Lack of <b>harmonized whole-life building strategies</b> across life cycle stages and countries. Insufficient contextual applicability assessment.	Taxonomy of 11 Carbon Reduction and Removal Strategies (CRRS) covering all life-cycle stages

\* Not a review article but original research that also includes a comprehensive systematic literature survey.

**Table 3**

The comparison of the selected grey literature in terms of geographical context (location and Köppen climate zone), building system scope (S: structural system, B: Building envelope, H: HVAC, D: DHWS, L: lighting, R: renewable energy), included LCA modules, and whole life cycle carbon/energy metrics.

Ref.	Year	Geographical Context		Building System Scope					Considered LCA Modules				Carbon/Energy Benchmarking Policy			
		Location	Climate Zone	S	B	H	D	L	R	A	B	C	D	Embodied	Operational	Whole life
[3]	2020	TR	B, C, D	-	+	+	+	+	+	-	-	-	-	N/A		
[5]	2021	TR	B, C, D	+	+	+	+	+	+	+	-	-	-	+	N/A	N/A
[6]	2021	DK	C, D	+	+	+	-	-	+	+	+	+	+	N/A	N/A	+
[59]	2021	EU	B, C, D	+	+	+	-	+	+	+	+	+	-	+		
[7]	2022	EU	B, C, D	+	+	+	-	-	+	+	+	+	+	N/A		
[2]	2022	EU	B, C, D	+	+	+	+	+	+	+	+	+	+	N/A		
[8]	2023	UK	C	+	+	+	-	-	+	+	+	+	+	N/A		
[9]	2023	EU	B, C, D	+	+	+	+	+	+	+	+	+	+	+	N/A	N/A
[11]	2024	Nordic & EE	C, D	+	+	+	+	+	+	+	+	+	+	+		
[12]	2024	Global	All	+	+	+	+	+	+	+	+	+	+	+		
[60]	2025	EU	B, C, D	+	+	+	-	-	+	+	+	+	+	+		

3.1.1. Decarbonization

Only five of the included articles, published between 2010 and 2021, center primarily on optimizing building energy performance without engaging in carbon emissions or environmental impact discourse [51,61,62]. Among the studies, some key actions about decarbonization are optimizing building energy performance, minimizing operational

energy and analysis energy demands. Solid findings from the studies to decrease carbon emissions show that:

- B6 (operational stage) and building envelope system scope express the focus to minimizing energy needs and energy efficiency. Due to

insulation materials at facade, operational carbon emissions can be reduced up to 87–88 kWh/m<sup>2</sup>/year (see Appendix 2B) [63].

- Climate zone is another factor for operational carbon stating at the study that northern climatic zone has 64 kWh/m<sup>2</sup>/year operational energy while southern climatic zone 92 kWh/m<sup>2</sup>/year. The results suggest that there is a need for more empirical research for warm climate zones to decrease carbon emissions [63] (see Appendix 2B).

These studies provide valuable technical insights but remain within a strictly energy-efficiency framework, excluding decarbonization themes. On the other hand, the majority of the journal articles included in the systematic literature review mention and discuss decarbonization through at least one of these subthemes; national and international emission reduction priorities, balance between embodied and operational carbon, whole-life and whole-building LCA approaches, net zero carbon targets or carbon sequestration. These results reflect the increasing and inevitable importance of decarbonization in recent years.

### 3.1.2. Trade-offs between embodied and operational carbon

In this study, 24 articles discuss the reduction of whole-life carbon emissions through embodied and operational carbon trade-offs. Many studies emphasize the importance of embodied carbon in terms of environmental impact due to new regulations, anticipations about future greenhouse gas emissions, reducing the reliance on fossil-based energy resources, building materials, national energy strategies [40,50,64–66]. The type of building being assessed, how the building use, the types of building materials used, construction methods employed, and geographic differences can also affect the proportion of embodied versus operational emissions [16,63,54,67]. Regarding building lifecycle, almost all embodied emissions are incurred once, in the initial construction stage of a building [54] and embodied carbon emissions emerge mainly in first years whereas operational carbon emissions happen mainly over time [16]. Thus, the operation (use) and construction stage of a building has also a significant influence on total environmental impact [47,64,58,53]. In specific building projects; The demolition phase is critical for rebuilding project whereas it has smaller impact on retrofit projects [40], and the type of retrofit measure is important for carbon emissions [68].

Key aspects from the studies about trade-off embodied and operational carbon have shown that:

- Material production (production phase A1-A3) stage at LCA plays a great role in contributing to embodied emissions, stating that A1-A3 phase has more than %70 of embodied carbon in related study [63].
- Regarding building system scope; among construction systems, the light steel construction system has the lowest embodied emissions (2 GJ/m<sup>2</sup>) compared to reinforced concrete construction system (3 GJ/m<sup>2</sup>) while express structural steel is the largest contributor (3999 tCO<sub>2</sub>-eq) compared to mass timber buildings with 50–795 tCO<sub>2</sub>-eq embodied carbon emissions [67] (see Appendix 2D).
- Regarding building re-construction types; operational energy emissions have an important effect on the greenhouse gas emissions of renovation projects expressing that 7 kgCO<sub>2</sub>-eq/m<sup>2</sup>/year out of 14 kgCO<sub>2</sub>-eq/m<sup>2</sup>/year whole life carbon emissions are operational based (see Appendix 2D). Renovation instead of constructing a new building has more emission savings in contrast with retaining existing old building that has higher operational carbon emissions [19].
- Material choice is a factor that contributes to operational emissions, regarding that the operational energy with subsequent years of use of the building exceeds embodied energy related to construction materials [69]. Replacement conventional building materials with mass timber, use of sustainable materials considering the construction stage provide decrease carbon emissions [58,57] and smart HVAC control system considering operational stage [47].
- Fossil-based energy sources have a great impact upon embodied carbon stating that renewable-based structural frames have less than

half the WLC emissions of fossil-based frames [65]. At this point, renewable technologies are a great alternative even though they have a significant embodied carbon footprint. Energy savings from these technologies, especially at use stage, overshadow its embodied impact [55]. Moreover, applied renewable energy sources such as % 100 thermal solar heating provide minimize GHG emissions, stating that it has ~ 18 kg CO<sub>2</sub>-eq/year operational carbon while building which is used district heating and electricity network has 72 kg CO<sub>2</sub>-eq/year, for D climate zone (see Appendix 2C) [55].

To further reduce WLC emissions, several studies suggest using renewable energy resources especially the on-site renewable technologies, preferring materials such as lower carbon emissions, optimizing HVAC systems, using technological advancements and efficiency improvements, reducing the area of square meters built [15,50,70,71]. These 25 articles represent clues between embodied and operational carbon trade-offs to reduce environmental impacts.

### 3.1.3. Importance of end-of-life scenarios

Among the 66 articles included in this study, 29 of them cover the importance of EoL scenarios in building LCA. According to the findings the total environmental impact and embodied carbon of building materials and systems are determined in a considerable way by EoL strategies, including reuse, recycling, landfill and disassembly [13,48,67,72]. Although EoL emissions are often a smaller part of the total, strategies such as reuse and recycling can significantly reduce the building's carbon footprint [73]. In many studies, EoL strategies and its environmental outcomes have been represented by using detailed frameworks that focus on Modules C1-C4, which represents the stages of demolition, transport, waste, processing and disposal [13,15,47,63,71,74]. The significant influence of options on greenhouse gas emission and resource efficiency is demonstrated by these analyses which quantify emissions and material flows under several EoL scenarios. In this context, reuse scenarios maintain the biogenic carbon stored in timber, resulting in significantly reduced net emissions as shown by [67]. Some of the studies also emphasize that circular design and disassembly (DfD) play crucial roles in improving material recovery. They focus on both DfD and construction techniques. These studies demonstrate how early design decisions have a significant impact on potential for recycling and reuse which advances the circular economy principles within the built environment [46,58,72,75]. Careful consideration of embodied and recyclable carbon in materials at EoL stage is key to minimizing emissions [76]. Some other studies examine material specific and system-specific impacts, demonstrating that the carbon footprint at the EoL varies by component type. Timber frames, HVAC systems, curtain walls, and facades all have different emission profiles based on how they are maintained at the end of their service life [67,57,55]. Several studies address specific methodological and practical issues on EoL scenarios. These issues include integrating EoL considerations into cost-optimal design strategies [77], investigating data gaps and inconsistencies in EoL modeling [19,75], and highlighting policy and standardization issues that limit comprehensive inclusion of EoL phases in LCA [40,64,53,78]. These 29 studies show that careful consideration of EoL scenarios is critical for accurate environmental assessments and the development of sustainable and circular building practices.

While the inclusion of EoL strategies (modules C1–C4) has become more common in recent years, the degree to which they are considered varies significantly by geographical context. Among the 29 studies addressing EoL:

- Northern and Central Europe (e.g., Sweden, Finland, Germany) consistently integrate EoL phases into both LCA studies and building policies, often emphasizing reuse and disassembly for timber and hybrid buildings.

- North American studies include EoL less consistently; many LCA studies still focus on A1–A3 modules, although timber reuse and recycling strategies are emerging in advanced research projects.
- Developing countries (e.g., Türkiye, Egypt, parts of Eastern Europe) show minimal EoL consideration in literature or policy. Most studies omit modules C or rely on cradle-to-gate approaches.
- UK and Denmark are exceptions where EoL is well-integrated both in policy and practice, with circularity explicitly mentioned in national roadmaps.
- This geographical disparity shows the need for regionally tailored benchmarks and the development of localized data for demolition, recycling, and reuse processes to foster accurate whole-life carbon accounting.

### 3.1.4. Content of nZEB definition

In this study, which comprises a total of 66 articles, 16 of them are concerned with the definition of nZEB. The definition of nZEB has evolved significantly across various studies and regulatory frameworks, reflecting growing ambitions for decarbonization and energy efficiency in the building sector. EPBD has played a central role by requiring member states to develop national nZEB definitions tailored to their specific climatic, economic, and technical conditions [19,39,40,77]. This has led to significant variability across countries in terms of thresholds, metrics, and implementation strategies [79]. While most of these studies concern regulatory sources, a minority of them also provide comparative analyses of national definitions or methodological frameworks [16,19,39,40,64]. One significant study developed specifically detailed cost-optimal design strategies and performance benchmarks for office buildings in cold climates, offering a replicable methodology for countries seeking to define feasible nZEB solutions within their own economic and climatic contexts [77].

Core elements and suggestions about the definition are:

- Focusing on high energy performance and preferring renewable energy sources (often generated on-site) [63]
- Adopting a whole-life cycle perspective by distinguishing between operational and embodied energy and incorporating environmental impact metrics such as carbon and GHG emissions [16,64,69,70,79,80].
- Improving critical assessments for ambiguities or gaps in existing frameworks [40] and proposing refinements or alternative metrics, particularly using LCA approaches [39,64].

### 3.2. Carbon / energy metrics analysis

The 44 original research articles that include LCA of office-building-related energy and/or carbon metrics are first categorized in terms of their building system scope and then presented in 4 separate tables in four categories: (i) structural system only, (ii) building envelope only, (iii) technical systems only (HVAC and/or renewable energy systems), and (iv) multiple building systems in Appendix-2A, 2B, 2C and 2D, respectively. Most of the studies originate from mainland Europe and North America. A few studies consider developing countries or Eastern Europe [16,63,58,57,68,69]. The building system scope of the majority of the studies focuses on building envelopes and structural systems. There are emerging studies on HVAC and technical systems as well. Across the dataset, there is a clear distinction between studies focusing on embodied carbon, those focusing on operational energy, and an increasing number addressing WLC of buildings.

The scope of LCA across studies has been found to vary considerably:

- Many structural-system studies concentrate on upfront “cradle-to-gate” embodied impacts (typically A1–A3) and omit use-phase or EoL modules.

- Studies focusing on envelopes often emphasize the operational energy phase (B6) due to its sensitivity to façade design, sometimes with partial inclusion of material production impacts.
- HVAC and renewable system studies inherently include operational energy use (B6) as a core component, alongside production (A1–A3) and occasionally replacement impacts (some include B4–B5 for equipment lifecycles).
- Studies covering multiple building systems tend to adopt comprehensive cradle-to-grave scope, including initial construction (A1–A3), operational energy use (B6), maintenance/replacement (selected B modules), and EoL stages (C).
- Only a few exceptional cases include EoL or beyond-life modules (D) in otherwise narrow scopes [74]. Seven of the studies [13,14,40,49,63,67,75] included Module D in their assessment. At one study [75], the authors found out that bio-based building scenarios have significantly lower embodied impacts and can also significantly avoid high amounts of embodied carbon emissions via demountability.
- The assumed service life of the building or system also differs: a 50–60-year lifetime is most common, aligning with standard design life, but several studies explore shorter or longer horizons. Notably, few studies prefer study with system lifetimes such as 20 to 25-year periods to reflect system-based cost turnover rather than a building lifetime [70,77]. On the other hand, some extend to 100 years to capture long-term effects [81].

Regarding building typology, there are some key findings which are important benchmark for office buildings as it includes many examples:

- As a result of comprehensive systematic review of more than 650 LCA cases [50], the range of observed embodied GHG emissions for existing office buildings is approximately 17.3 kg CO<sub>2</sub>-eq/m<sup>2</sup>/year, while for new or advanced office buildings, the range is between 11.6 and 12.0 kg CO<sub>2</sub>-eq/m<sup>2</sup>/year. The range of observed operational GHG emissions for existing buildings is approximately 80.20 kg CO<sub>2</sub>-eq/m<sup>2</sup>/year, while for new or advanced office buildings, the range is from 26.52 to 10.79 kg CO<sub>2</sub>-eq/m<sup>2</sup>/year.
- In a recent study about the environmental impacts of nZEB-defined buildings in Türkiye with the evaluation encompassing three different building typologies in four different climate zones [16] show that embodied CO<sub>2</sub> emissions of current nZEB offices are slightly higher than a baseline building, between 182 and 201 kg CO<sub>2</sub>-eq/m<sup>2</sup>. Whereas WLC emissions are 32–43 % lower especially when an improved nZEB regulation is simulated.
- In the study conducted in Poland [69], a carbon classification for office buildings was created and an average GWP value of 5000 kg CO<sub>2</sub>-eq per m<sup>2</sup> was determined for a 60-year life span. Energy consumption in the operational phase represents between 79 % and 93 % of total emissions, and material production and construction phase represent between 6 % and 11 % of total emissions [70,77,81].

Regarding environmental impact and supportive calculation systems, the majority of studies employed building performance simulation to evaluate operational energy or thermal performance as part of the analysis.

- Dynamic building energy modeling software (e.g., EnergyPlus, IES VE, or similar) is commonly used, especially in envelopes and HVAC system studies, to estimate annual energy demand under different design scenarios.
- Programs such as SimaPro and Athena Impact Estimator, especially for life cycle analysis, have been used in the calculations of different LCA modules.
- Self-created programs were utilized in some studies and energy simulation results are then coupled with LCA data to compute

operational carbon impacts. Some use standard usage assumptions or ignore operation altogether.

- Compared to actual office buildings with real design data and archetype models, envelope and system optimization studies frequently favor archetypes so that variables (window-to-wall ratio, insulation levels, system configurations, etc.) can be systematically varied on a consistent baseline. Both approaches yield comparable insights, but archetype-based analyses allow broader parametric exploration, whereas real-building case studies provide context-specific validation.

Additionally, the studies report on a range of carbon and energy metrics, reflecting their different focuses:

- Embodied impacts are typically quantified as greenhouse gas emissions in kg CO<sub>2</sub>-eq, often normalized per square meter of floor area or per component.
- Operational performance is usually expressed either as annual energy use intensity (e.g., kWh/m<sup>2</sup>/year) or as annual operational carbon emissions (e.g., kg CO<sub>2</sub>/year for the building, or kg CO<sub>2</sub>/m<sup>2</sup>/year).

Whole-life metrics, where reported, combine embodied and operational contributions over the analysis period. These may be presented as a cumulative WLC in kg CO<sub>2</sub>-eq over the building's lifetime or normalized, per m<sup>2</sup> or per year, for comparability. For example, several envelope studies optimize designs based on reductions in heating/cooling demand (kWh/m<sup>2</sup>/year), whereas structural studies compare material alternatives by their embodied carbon per m<sup>2</sup> of building area. In terms of building system scope, different approaches show that:

- The studies on structural systems generally focused on the upfront carbon emissions, mainly proceed with cradle-to-gate approach by centering A1-A3 modules [82,83], There is a variety on the carbon metrics; concrete baseline scenarios respectively have 237 and 420 kg CO<sub>2</sub>-eq/m<sup>2</sup> whereas the alternative solutions have 193 and 126 kg CO<sub>2</sub>-eq/m<sup>2</sup>. The improvement rate for CLT is quite significant around 70 %, whereas that of timber scenario is only 35 % [82]. In a study that their carbon metrics for low and mid-rise timber structures are 160,9 and 164,7 kg CO<sub>2</sub>-eq/m<sup>2</sup> whereas those of steel structures are 210,7 and 232,6 kg CO<sub>2</sub>-eq/m<sup>2</sup>. A similar study on archetypes shows [74] that timber, steel and concrete possess 119, 185, and 228 kg CO<sub>2</sub>-eq/m<sup>2</sup> embodied carbon, respectively (Appendix 2A).
- The studies on the envelope are generally engaged in energy consumption values and it is related to building operational phase. The main topic addressed in the envelope studies is based on optimization analysis. Optimization methods for the improvement of the envelope design of office buildings, particularly the transparency ratio and thermal values of the envelope in office buildings examined [62,77,84,85]. In these optimizations, cost and carbon are taken into consideration along with energy. In terms of building envelopes, the impact of building form has also been assessed [80]. A review reveals a lack of emphasis on WLCA in studies of envelopes, with the majority of research focusing on operational phase (Appendix 2B).
- The studies focused only on technical systems include consideration of HVAC whereas [70] considered the impact of renewable energy technologies on embodied and operational carbon emissions of actual nZEBs [15]. All studies showed that technical systems have a significant impact on embodied carbon whereas very few studies focus on this hidden impact (Appendix 2C).

Some studies consider multiple building systems that help to understand the environmental impacts of the design, construction, use and demolition processes of buildings (Appendix D). Five of these studies [13,68,86,87] concentrated on the energy demands and prospective energy savings of buildings. Key findings show that:

- Specific CO<sub>2</sub> emissions related to energy were observed to be 2.7 kg CO<sub>2</sub>-eq/m<sup>2</sup>/year, while specific CO<sub>2</sub> emissions related to materials were found to be 3.2 kg CO<sub>2</sub>-eq/m<sup>2</sup>/yr in the original building. After the implementation of the changes, it was determined that the energy value decreased to 0.8 kg CO<sub>2</sub>-eq/m<sup>2</sup>/year, while the material value decreased to 2.3 kg CO<sub>2</sub>-eq/m<sup>2</sup>/year [88].
- Ylmen et al. [78] in their study found that, the WLC environmental impact varies between 100–250 kg CO<sub>2</sub>-eq/FU according to material selection and environmental impact of HVAC systems.
- The research [64] in Italy was evaluated reinforced concrete 5-storey office building in Italy and they concluded that the material production and construction stage (A1-A5) is 512 kg CO<sub>2</sub>-eq/m<sup>2</sup>, the use stage(B1 – B7) is 54 kg CO<sub>2</sub>-eq/m<sup>2</sup>, and the end of life stage(C1-C4) is 63 kg CO<sub>2</sub>-eq/m<sup>2</sup>. Complete life cycle – yearly environmental impact calculated 65 kg CO<sub>2</sub>-eq/m<sup>2</sup>/year for office building.
- Retrofit strategies were evaluated in studies [13,66,68], which holistically assessed both energy, environmental and economic impacts. The impact of these improvements, especially on operational carbon, has been investigated.
- The study [89] in USA evaluated the production (A1-A3) and construction (A4-A5) stage of concrete, hybrid CLT with fireproofing, hybrid CLT with charring system. Concrete building system was calculated at 450 kg CO<sub>2</sub>-eq/m<sup>2</sup>, hybrid CLT with fireproofing at 334 kg CO<sub>2</sub>-eq/m<sup>2</sup> and hybrid CLT with charring system at 328 kg CO<sub>2</sub>-eq/m<sup>2</sup>.
- The study [65] evaluated A1-A3, B6 and C1-C4 stage for construction system (brick, timber, insulated concrete and steel) together with renewable energy in office buildings and stated that timber system with renewable energy is the lowest life cycle environmental impact with 861,000 kg CO<sub>2</sub>.
- The study [72] conducted WLCA on concrete, wood and hybrid DfD archetypes in Finland. The carbon metrics are significantly lower than that of North America studies; all between 10–14 kg CO<sub>2</sub>-eq/m<sup>2</sup>/year (100–140 kg CO<sub>2</sub>-eq/m<sup>2</sup>). Timber structures display the lowest carbon emissions; on the other hand, there is a discrepancy when mid-rise and tall structures are involved.

### 3.3. Literature gaps identified and addressed in the review articles

11 review articles and an original research study [50] that includes a systematic literature survey, are presented in Table 2. These 12 studies in total are analyzed and compared in terms of the literature gaps they point out, and their proposals to address those gaps. These articles exhibit diverse methodologies and regional emphases, yet they converge on several critical gaps.

Early studies often adopted narrative literature reviews without a review methodology, whereas only two recent studies have employed systematic review protocols with structured inclusion criteria [50,57]. Regionally, the literature has been disproportionately focused on developed countries in Europe and North America, with limited coverage of developing countries or tropical climate zones. One study emphasizes that most available case studies originate from developed and/or cold countries, showing the need for further empirical evaluation in developing and warm-climate contexts [51]. The first identified consistent gap pertains to the global imbalance between operational and embodied carbon assessment [54,58,57]. While operational energy efficiency has historically dominated the discourse, embodied emissions that contribute a significant proportion of WLC remain underrepresented, despite their increasing relative significance in high-performance buildings [50]. The second recurrent issue is the lack of standardization in nZEB and life cycle carbon assessment frameworks, which limits cross-study comparability [51,53,55]. Several studies emphasize the absence of harmonized nZEB definitions and standard metrics for WLC evaluations across EU countries [19,20,50]. Moreover, clear nZEB definitions, practical applications and case studies demonstrating nZEB implementation in developing countries remain scarce,

limiting the transferability of existing findings to these contexts [25].

Out of these 12 studies, 5 of them introduced an original framework or model as a key contribution.

- Two works provide comprehensive WLC frameworks: [54] advocate an integrated policy approach combining operational and embodied building emissions with cost analysis using marginal abatement carbon cost curves, and [19] develop a taxonomy of 11 Carbon Reduction and Removal Strategies (CRRS) covering all life-cycle stages with an assessment of their adoption potential across EU countries.
- Two other studies offer design-oriented guides for energy-efficient buildings. In the first one recommends a  $\sim 10$  kWh/m<sup>2</sup>·year lighting energy target alongside a set of efficiency strategies, such as efficient lamps, controls, daylighting, for future low-energy offices [52]. The second study proposes a three-step framework for achieving nZEBs, emphasizing climate-specific passive design, optimization of energy and cost parameters, and ensuring a net-zero energy balance with renewables [25].
- Lastly, [20] propose a harmonized definition framework for nearly-zero, net-zero, and plus-energy buildings by introducing a complementary energy index to account for buildings that generate surplus energy, thereby clarifying the distinctions between “near zero,” “zero,” and “energy-plus” building standards.
- As a summary, each of these contributions addresses one or more of these three main gaps: (I) integrating embodied carbon in policy, (II) providing practical design procedures, and (III) clear performance definitions.

### 3.4. Analysis of the selected grey literature

The reviewed grey literature sources present a diverse array of national and regional strategies addressing energy and carbon reduction in the built environment, often targeting both operational and embodied emissions (Table 3).

In Türkiye, the Ministry of Environment, Urbanization and Climate Change released multiple policy tools, including the 2020 guidebook for nZEB which aims at a 14–26 % energy reduction in office buildings, and the 2021 Green Certificate Building Evaluation Guide (YES-TR), which requires at least 21 % better energy performance compared to national thresholds as a certification criterion [3,5].

- Denmark’s National Strategy for Sustainable Construction sets a rather clear trajectory toward decarbonization with a 70 % CO<sub>2</sub> reduction by 2030 and net-zero targets by 2050. It includes operational benchmarks such as 12 kg CO<sub>2</sub>-eq/m<sup>2</sup>/year by 2023 and 10.5 kg CO<sub>2</sub>-eq/m<sup>2</sup>/year by 2025 [6].
- At the European level, the World Green Building Council’s EU Policy Roadmap calls for a 40 % reduction in embodied emissions by 2030 across all new buildings and renovations [7]. The European Commission’s Level(s) framework offers a common method to measure the sustainability of buildings, focusing on both embodied and operational carbon across their full life cycle. It guides Member States to use consistent metrics and reporting, especially through GWP indicators that cover stages A1–A3, B4, B6, and C1–C4 [59].
- The Buildings Performance Institute Europe advocates for at least 55 % GHG reductions by 2030 and full climate neutrality by 2050, emphasizing alignment with the EU Renovation Wave and Fit for 55 package [2,52].
- The Royal Institution of Chartered Surveyors contributes a methodological reference for WLCA in the built environment, offering detailed guidance for consistent LCA implementation and benchmarking [8].
- The European Commission has supported the development of a harmonized roadmap for WLC reduction in buildings, focusing on

the integration of carbon performance into policy and market mechanisms [9].

- The EU framework proposes setting performance thresholds through benchmarks that reflect national contexts, aiming for near-zero emissions across the building stock. It emphasizes the zero carbon by 2050, recommending the inclusion of all significant life-cycle stages for comprehensive and comparable WLC assessments [60].

These references collectively illustrate a clear policy evolution from fragmented energy performance goals toward more comprehensive and integrated approaches to whole-life carbon assessment. Earlier grey literature sources tend to reflect less mature frameworks, often limited in scope to operational energy or partial life cycle phases. In contrast, the more recent publications reveal a growing maturity: wider LCA scope, inclusion of both embodied and operational emissions, and stronger alignment with standardized methodologies and regulatory mechanisms. This trend signals an increasing policy sophistication over time, shaped by EU-level initiatives such as Level(s), the Renovation Wave, and Fit for 55. Despite these advancements, notable regional differences remain in terms of scope, enforcement, and benchmark stringency. The cross-analysis of these strategies (Table 3) offers a comparative view of national and regional readiness, forming a foundational dataset for the proposed building decarbonization maturity scale in this study. By structuring these findings, the scale supports the evaluation of current practices and guides the shift toward harmonized, full-scope WLC policy adoption in line with 2050 climate neutrality targets.

### 3.5. Rationale for building decarbonization maturity scale

In the detailed reading of the literature, it was determined that some issues related to the design, renovation, factors affecting energy performance and environmental performance of office buildings were emphasized and they have been presented in Appendix 3. The evolution of nZEB definition discourse reflects a dynamic intersection of policy, performance metrics, and environmental objectives, pointing towards the need for harmonized, yet adaptable, definitions that support effective worldwide carbon reduction strategies for reaching the net zero carbon target by 2050.

To bridge the fragmented landscape of current decarbonization research, this section turns attention to the reported WLC emission ranges across the reviewed studies. Only 15 studies out of the 66 articles included in the review are comparable in terms of WLC results. While earlier sections addressed the methodological and thematic maturity of these works, this presents a quantitative synthesis, illustrating the annualized whole life carbon emissions (kgCO<sub>2</sub>/m<sup>2</sup>/year) reported in both developed and developing countries over time. The graph (Fig. 3) includes data from studies with full or near-complete WLC assessments, normalized across a 50 or 60-year life span where applicable. It enables a comparative view of the scale and variability of reported carbon impacts, revealing several key trends. While developed countries tend to show increasingly consistent and converging values over time, reflecting greater methodological harmonization and policy alignment, developing country contexts exhibit wider variability, including both some of the highest and unexpectedly low values. Importantly, these lower WLC values from developing countries often result from narrower building system scopes. In such cases, the studies’ lower maturity levels restrict their ability to capture the full WLC, meaning that if more comprehensive assessments were applied, the actual values would likely be higher. This insight signals that lower reported emissions from less mature studies do not necessarily indicate better performance but often reflect gaps in methodological depth.

The systematic review not only identified thematic trends and methodological gaps in nZEB and WLC research but also provided a foundation to define maturity indicators across chronological, geographical, and technical dimensions. Recurring patterns observed in

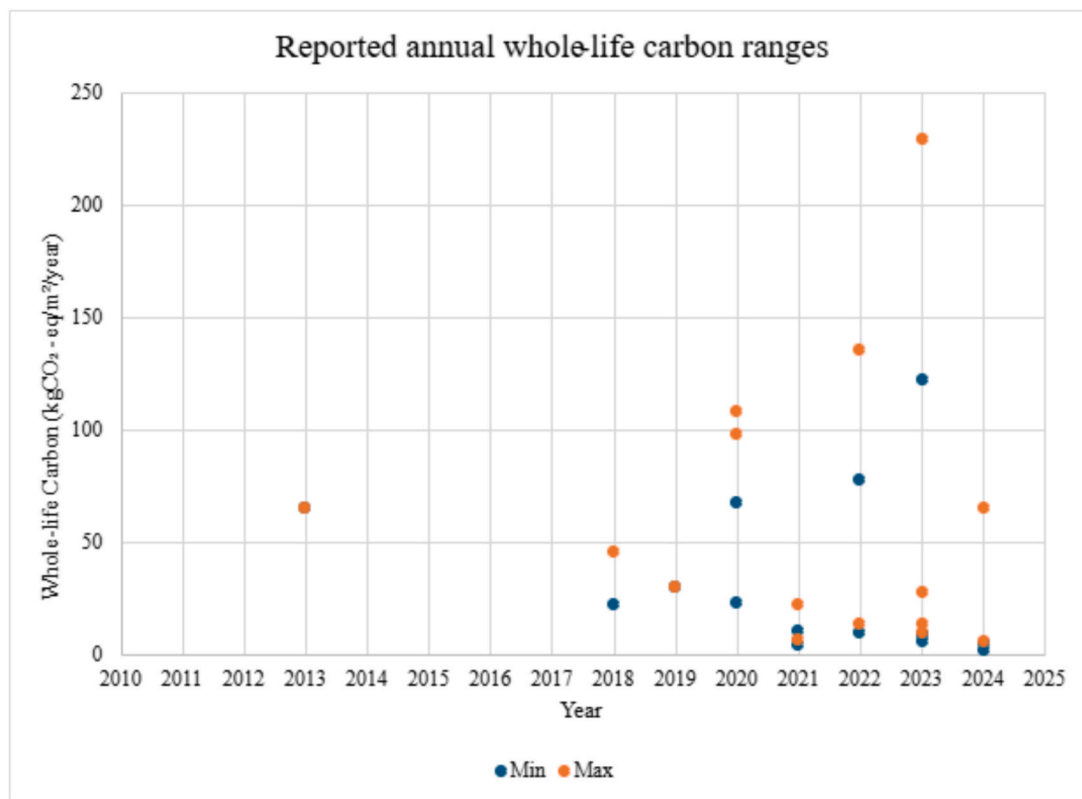


Fig. 3. Reported annual whole life carbon ranges from the literature.

how different countries, building typologies, and policy contexts approached decarbonization allowed for the conceptualization of the Building Decarbonization Maturity Scale. This scale was then used to synthesize these patterns into a structured progression roadmap, offering a sequenced path from low-awareness contexts toward regenerative, carbon-negative practices. For instance, the dominance of operational-carbon-only studies in early literature aligns with “Level 1 – Awareness,” while cradle-to-grave studies with circular design principles align with “Level 5 – Regenerative.” In this way, the review’s findings directly informed the definition of maturity levels, transition indicators, and recommended actions for developing contexts such as Türkiye.

Created on the basis of the research, it is seen that there is a need for a maturity scale and a road map that enables authorities, researchers, designers/constructors to:

- Create a link between the current situation about decarbonization target of countries, policies and their next steps
- Determine what the scope of the new studies should be, applications to be carried out and which parts should be prioritized.
- Understand different decarbonization policies and provide comprehensive tools to ease their comparison.

#### 4. Discussion

The differences and overlaps among the review articles reveal a maturing but uneven research landscape. Although there is growing momentum toward whole life-cycle approaches, targets and harmonized standards, the field remains rooted in developed-world data and assumptions. These findings directly inform the rationale of this study, which targets Türkiye and similar developing countries to bridge these identified gaps and explore feasible pathways for implementing decarbonized nZEB office buildings in underrepresented contexts.

Accordingly, the review results, the maturity evaluation of the

literature and the proposed progression roadmap are discussed in the following subheadings.

##### 4.1. Discussion of the review results

The reviewed literature shows a clear focus on decarbonization goals: nearly all studies invoke net-zero or GHG reduction targets and many explicitly frame their work around WLC strategies.

Almost all of the included articles discuss “decarbonization” explicitly, especially in the 2020–2024 period. However, researchers have often reported outcomes inconsistently. A notable pattern is that some studies present results only as relative savings between scenarios rather than absolute carbon or energy intensities, in % reductions, echoing legacy energy-class conventions. As a consequence, 11 of 66 LCA-based studies included no common metric (kgCO<sub>2</sub>-eq or kWh) undermining cross-comparison and benchmarking against 2050 net-zero limits. This inconsistency necessitates regulators to adopt uniform WLC or energy limits per floor area, a change expected to accelerate international benchmarking [4].

The treatment of operational versus embodied emissions also varies widely. Many analyses are system specific. For example, structural-material LCAs typically consider only cradle-to-gate impacts (modules A1–A3) and omit use-phase or EoL, whereas building envelope studies focus on operational energy (B6) concentration on insulation and glazing effects. HVAC and renewable energy system studies generally include both production and use (A and B modules) and occasionally equipment replacement (B4–B5). Comprehensive, multi-component LCAs tend to be an exception. Only a few studies, which cover cradle-to-grave (A–C) scope, include module D. Historically, this has created an imbalance: operational energy dominated the discourse, while embodied carbon was underemphasized [54,58,57], despite the evidence that embodied impacts gain relative weight in very high-performance buildings [50].

Building lifetime assumptions vary as well. Most studies assume 50 – 60-year building lifetimes, common in codes. On the other hand, some use shorter (20 to 25-year technical system cycles) or very long (100-year) horizons. Methodologically, about half the LCAs are based on actual office buildings and half on archetype models. On one hand, archetype models enable systematic parametric comparison, by varying window-to-wall ratio, insulation, etc., on the other hand, actual building studies provide contextual validation of these trade-offs.

EoL and circular strategies are becoming prominent year by year. Almost half of the included articles specifically examine demolition, reuse, recycling, and disposal scenarios, showing that design-stage decisions strongly affect WLC. For instance, reuse or demountability of timber elements can preserve biogenic carbon and greatly reduce net CO<sub>2</sub> (Greene et al. 2023). Likewise, studies highlight design-for-disassembly and recycled-content approaches [46,72,75] as crucial for circularity. Component-level analyses confirm that EoL footprints differ by element [67,57]. However, the inclusion of end-of-life stages remains uneven: only 7 of 34 LCA studies included module D and many authors note data gaps and methodological barriers to fully account for EoL [19,40,64]. This points to a need for standardizing EoL metric inclusion in future LCAs or nZEB definitions.

The definition of nZEB itself shows significant evolution and diversity. All national definitions emphasize low or ultra-low energy use and on-site renewables, yet thresholds and metrics vary widely by region [79]. Encouragingly, recent work indicates that some frameworks are beginning to adopt a whole-life perspective: for example, [16,79] observe that newer nZEB criteria distinguish operational vs. embodied energy and even include carbon metrics. Several contributions target the identified gaps by suggesting integrating embodied carbon into policy, providing clear design guidance, and clarifying performance criteria [20,39,64]. Many reviews point out the lack of harmonized whole-life carbon or nZEB assessment frameworks. In response, only a handful of studies propose integrated frameworks or unifying building energy categories [19,20,54]. Together, these efforts of combining operational/embodied accounting, practical design steps, and clear definitions, directly address the review-identified gaps in LCA standardization and policy coherence.

Material findings consistently highlight timber’s low-carbon advantage. Several LCAs in temperate contexts show mass-timber or CLT structures substantially cutting embodied impacts [65,72,89]. The EoL

related results reveal the carbon storage benefit of wood and its favorable EoL options. On the other hand, case studies also confirm that operational energy still dominates total emissions. Importantly, simulations of stricter standards demonstrate real impact [75]. This implies that relatively stringent operational requirements can substantially lower total carbon, a finding echoed by the high operational shares.

Overall, the thematic and methodological patterns indicate that the research field is gradually maturing and becoming more aligned with global decarbonization goals. While there is clear progress, such as increased attention to WLC, circular strategies, and proposed frameworks, challenges remain. These include the lack of standardized metrics, limited geographical diversity, and inconsistent scopes across studies. These results of the study provide insights that can help guide the development of more effective and context-specific nZEB policies and design practices, especially in developing countries.

#### 4.2. Decarbonization maturity evaluation of the included literature

The joint interpretation of the results presents that it is mostly difficult to categorize individual studies for comparison, since the methodology varies largely. This finding is also consistent with the findings of a similar recent review study on non-domestic buildings [90]. However, it is also observed there is a pattern in this chaos: The studies, policies, and regulations, especially from developed countries, have evolved over the last 15 years from fragmented, energy-focused, and non-standardized approaches to carbon-oriented, whole-life-cycle-based, and typology- and region-specific frameworks. This evolution can be considered a maturation process that can be categorized into several distinct levels within a decarbonization maturity scale. This mirrors the differentiation presented in the Zero Tracker, a global monitoring platform that tracks the net-zero targets and climate pledges of over 4,000 entities (including countries, regions, cities, and companies) against a robust framework of credibility indicators, which classifies countries by the credibility and implementation of their net-zero targets, thus indirectly indicating their level on a decarbonization maturity scale [91]. Accordingly, the “Building Decarbonization Maturity Scale” proposed within the scope of this study is presented in Fig. 4.

This scale consists of five levels from less mature to more mature, similar to its predecessors from other fields of research [30–32]. The proposed Building Decarbonization Maturity Scale is closely aligned

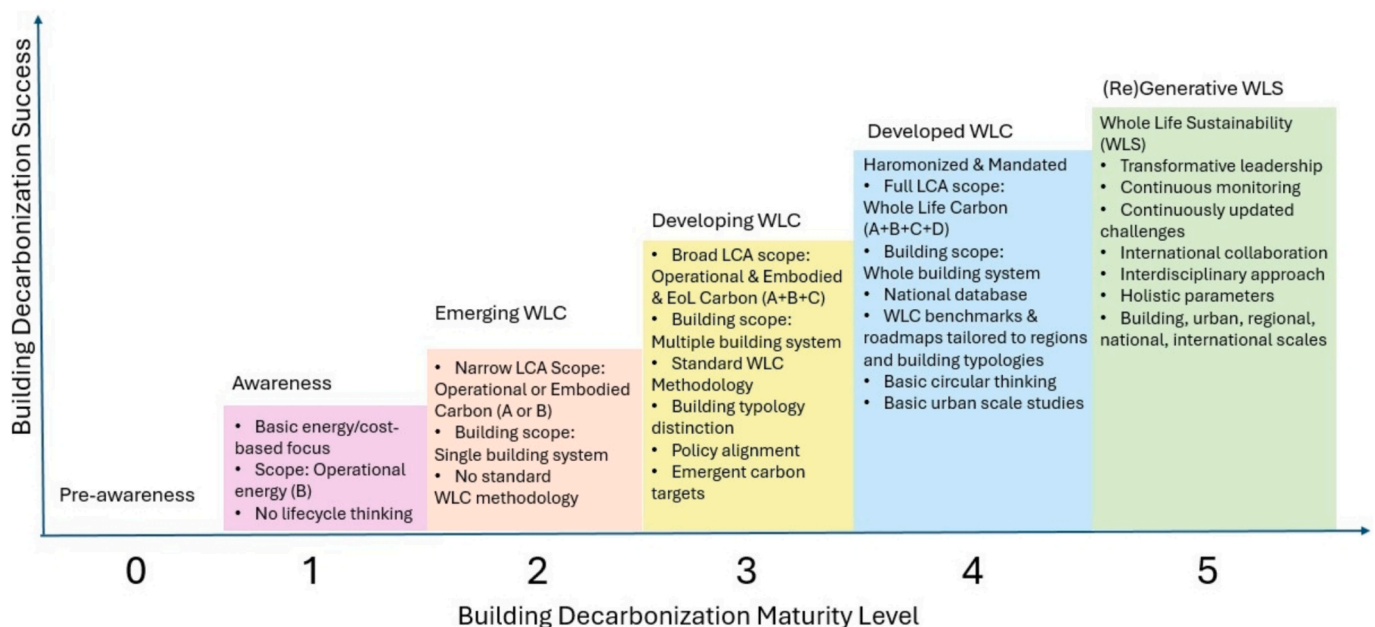


Fig. 4. Building decarbonization maturity scale.

with the progression outlined in the Harmonized Whole-Life Carbon Framework across the EU [60]. The framework emphasizes a gradual yet structured transition toward climate-neutral buildings by 2050, requiring EU Member States to adopt standardized methodologies for WLC calculation and implement both disclosure requirements and limit values over time.

Each maturity level in the proposed scale reflects this staged implementation: from early-stage awareness of energy efficiency (Level 1) and fragmented carbon accounting (Level 2), to structured national WLC methodologies and benchmarking systems (Level 4), and finally to fully integrated, regenerative design thinking and carbon literacy (Level 5). The BPIE framework's call for harmonized system boundaries, consistent GWP metrics, and policy instruments such as delegated acts, disclosure mandates, and public procurement criteria, corresponds directly to the higher levels of maturity in the scale. Moreover, the differentiation in flexibility across components (such as strict methodology requirements versus adaptive national targets) supports the notion of a maturity continuum that varies by national context yet moves toward common EU-wide goals. Thus, the scale not only captures the current landscape of decarbonization policies but also mirrors the strategic roadmap laid out in the BPIE report. The characteristics of each level and their alignment with the Harmonized WLC Framework across EU [60] are explained below.

**Level 0- Pre-awareness:** At this stage no awareness or interest is developed on building decarbonization. According to the Net Zero Emissions Race 2025 Scorecard [91], 11 countries still lack any form of net zero target. These include oil-dependent economies and least developed countries, with no formalized statements, dates, or planning documentation. The platform highlights this as a major gap, particularly in Sub-Saharan Africa, parts of Southeast Asia, and some Central Asian countries, which remain in the pre-policy and pre-awareness stage of net-zero governance.

**Level 1 – Awareness:** Efficiency becomes a target. The focus remains solely on operational energy efficiency, often limited to minimizing utility costs or meeting outdated energy codes. No integration of carbon considerations into the built environment, yet. Neither embodied carbon nor life cycle stages are acknowledged in assessments. Countries such as Pakistan, Egypt, and several Gulf nations flagged by the Zero Tracker [91] as having “low-credibility targets” reflect a fragmented stage of awareness without structured decarbonization. These correspond with Level 1 of the maturity scale, where efficiency is a target, but carbon is not a design or regulatory factor.

**Level 2 – Emerging:** Projects and policies at this level begin to mention carbon-related concerns, typically prompted by external (international) regulations or climate targets. However, responses are fragmented and narrow in scope, focusing either on operational carbon or basic embodied carbon estimates from A1–A3 modules. At this stage, road maps for building decarbonization need to be created on city, regional and national scales. Assessment tools are applied without strategic alignment, and decarbonization is not a core design driver. Germany, Ireland, Czechia and Italy, which are classified under the category “Other non-legislative requirements in place or preparing for WLC measurement and benchmarking” and Iceland, Finland, Estonia and Spain under “WLC legislation (disclosure/limit values) proposed” by BPIE, can be considered representative of this maturity level [60].

**Level 3 – Developing:** This level is marked by an explicit acknowledgment of the importance of both embodied and operational carbon and partial integration of whole-life carbon perspectives. LCA studies begin to expand beyond upfront stages to include selected modules from the use and end-of-life (EoL) phases (e.g., B4–B6, C1–C4), though still inconsistent. Renewable energy systems, envelope optimization, and structural alternatives start to be evaluated from a carbon standpoint. Research begins comparing real case data and archetypes, but standardization and benchmarking are still missing. Sweden and Norway, which are classified under the category “WLC disclosure requirements in force” and relevant regions in UK categorized as “Local jurisdictions

with disclosure requirements linked to permits of public procurement” by BPIE, are representative of Level 3 [60].

**Level 4 – Developed:** Decarbonization becomes a structured design and policy objective. WLC targets and numeric benchmarks are institutionalized in building codes or national policies and integrated into the national LCA database design teams and regulators use harmonized tools and methodologies, and buildings are expected to meet quantified carbon limits per square meter and/or per year, specific to building typology and climate zone. The benefits beyond building systems are considered in the circular construction context. The developments allow for basic urban-scale studies. France, the Netherlands and Denmark under the “WLC regulation with limit values in force” category exemplify this Level 4 maturity [60].

**Level 5 – (Re)Generative:** An aspirational level where decarbonization is no longer seen as a technical constraint but a driving principle of whole-life sustainability (WLS) culture. Projects actively pursue climate-positive outcomes through carbon capture, biogenic materials, and circular design. Building decarbonization is expected to improve over time through continuous monitoring and regularly updated benchmarks through harmonized tools and databases. At this level, cities or countries are aligned with net-zero pathways and global climate goals, embedding carbon literacy across all actors and shareholders. The highest level of building decarbonization maturity is closely aligned with the vision set out in the BPIE framework, which advocates for climate-positive outcomes and the integration of carbon considerations across the entire lifecycle [60]. The emphasis on net-zero pathways, circular construction, carbon literacy, and continuously updated benchmarks directly reflects the aspirational goals of Level 5.

The literature included in the systematic review is evaluated based on the proposed “Building Decarbonization Maturity Scale” to map this specific research area and to help researchers navigate their future studies towards zero carbon targets by 2050. The articles included are presented in Fig. 5 in terms of geographical context, maturity levels and number of articles for three consecutive periods of 5 years in a matrix. In the 2010–2014 period, developed countries have more studies and attention about decarbonization and in the following 5-year periods, developing countries began to improve strategies of decreasing carbon emissions. The included studies from developed countries present a gradual maturation in the past 15 years regarding the building decarbonization by inclusive LCA and building system scopes, and policy alignment. In the last 5 years, most of the studies concentrate on level 3 (developing) while a few developed or (re)generative level studies appear on the stage. Accordingly, the number of future studies with higher maturity from developed countries is predicted to dramatically increase in the next decade. On the other hand, the number and the maturity of the studies from the developing countries are particularly low. This scene signals that the gap between developed and developing countries, in terms of maturity and prevalence of the decarbonization efforts, may grow in the future. Since successful decarbonization is only possible with global engagement, an effective and rapid decarbonization maturation is also necessary for the developing countries.

Consequently, “Building decarbonization maturity scale” proposed in this study steps in as a practical tool to determine the maturity level of a research study, a regulation, a country, or a region, and guides the progression road maps to move higher levels. As the next step, a progression road map (based on this maturity scale) is proposed and further elaborated in the context of Türkiye in the following subheading.

#### 4.3. Progression roadmap

A progression roadmap that outlines the sequential stages through which building decarbonization practices typically evolve, from early awareness to fully integrated, regenerative approaches, is presented in Table 4. It highlights key transition points that characterize each level of maturity, offering a structured understanding of how policies, design practices, and assessment methods become more advanced,

2010-2014						2015-2019						2020-2024					
Country Context	Decarbonization Maturity Level					Country Context	Decarbonization Maturity Level					Country Context	Decarbonization Maturity Level				
	Awareness	Emerging	Developing	Developed	(Re)Generative		Awareness	Emerging	Developing	Developed	(Re)Generative		Awareness	Emerging	Developing	Developed	(Re)Generative
N/A	0	0	0	0	0	N/A	0	0	1	0	0	N/A	0	1	1	0	0
Developing	0	0	0	0	0	Developing	0	1	1	0	0	Developing	0	2	3	0	0
Developing & Developed	1	0	1	0	0	Developing & Developed	1	1	0	0	0	Developing & Developed	0	0	2	0	1
Developed	5	1	3	0	0	Developed	6	2	8	1	0	Developed	2	2	13	3	3
<b>TOTAL</b>	<b>6</b>	<b>1</b>	<b>4</b>	<b>0</b>	<b>0</b>	<b>TOTAL</b>	<b>7</b>	<b>4</b>	<b>10</b>	<b>1</b>	<b>0</b>	<b>TOTAL</b>	<b>2</b>	<b>5</b>	<b>19</b>	<b>3</b>	<b>4</b>

Fig. 5. Summary of the literature on a matrix in terms of geographical context, maturity levels and number of articles for three consecutive periods of 5 years.

comprehensive, and aligned with net-zero carbon goals over time. By identifying these transition stages, the roadmap serves as a practical guide for evaluating the status of regions or actors and for designing targeted strategies that enable advancement toward higher maturity. This framework is particularly valuable for developing contexts, where decarbonization efforts are often novel and require coordinated, step-wise planning.

#### 4.4. Case of Türkiye

In the light of the findings of this study, Türkiye’s context can be considered as a representative example of developing countries, progressing through the early stages of the decarbonization roadmap, from raising awareness and piloting green building initiatives to beginning alignment with international frameworks, can illustrate a model pathway for other developing countries. Türkiye is in the “emerging” stage: climate and carbon are on the radar mostly due to international pressure and voluntary green initiatives, but decarbonization is not yet core driver in mainstream building practice:

- According to the Annex 89 technology readiness assessment for Türkiye, while there is growing awareness of carbon emissions, the practical implementation of building LCA is still voluntary and quite limited [92].
- Operational energy efficiency has been the primary focus, yet, building energy performance certificates has become mandatory only in recent years. The upfront embodied carbon and EoL impacts are largely absent from regulations, and awareness of these issues remains low outside a small expert community.
- On the other hand, tow encouraging indicators of the emerging level of the maturity scale are evident: The “Green Certificate for Buildings and Settlements” (YES-TR), a voluntary national green building rating, and the increase in product-level LCA and EPDs for construction materials.
- The influence of the EU Green Deal is noted as a significant external driver pushing Türkiye to start considering carbon accounting. However, as of now, Türkiye lacks a local building LCA tool or database and has no mandatory requirement for embodied carbon assessment [92].

Advancing along the maturity pathway from “emerging” to “developing” level will require concerted efforts from policymakers, construction professionals, and researchers, such as:

- Policymakers should strengthen and expand the regulatory framework to move beyond voluntary initiatives by establishing intermediate targets and gradually introducing upfront and embodied carbon limits into building codes. Given the current lack of localized

carbon accounting resources, developing a national LCA database and tools is also critical to support these regulations.

- Designers and practitioners can accelerate progress on the ground by voluntarily adopting green building practices and certifications (e.g. YES-TR), engaging in pilot nZEB projects, and incorporating WLCA in projects even before they are mandated. These proactive steps will not only reduce emissions in practice but also build local capacity and exemplify the feasibility of low-carbon designs, thereby informing and pressuring policy.
- Meanwhile, the research community in Türkiye plays a pivotal role in closing knowledge gaps and guiding data-driven decisions. Key priorities for researchers should include developing harmonized WLCA methods and benchmarks suited to Türkiye’s context and creating open-access LCA databases for region-specific materials and building practices. By providing dependable local data and adapting the best global practices, research can inform evidence-based policies and design strategies.
- Therefore, the government should invest in, provide subsidies for, and actively support researchers to advance this field. Together, these targeted actions by government, industry, and academia will help Türkiye overcome its current limitations and more rapidly advance to the next maturity level on the decarbonization roadmap.

#### 5. Conclusion

The construction sector revitalizes different sectors with its production process, while at the same time providing many economic outputs, and therefore, the construction sector has a significant share in the economy, especially in developing countries. In order to create a sustainable construction sector and ensure economic sustainability, energy and carbon-based practices in the construction sector are becoming increasingly important. In today’s world, where energy bottlenecks are experienced and the harsh effects of the climate crisis are felt more, cleaner and more affordable energy production is required, and it needs to be spent more efficiently. At this juncture, applications and studies concerning life cycle and decarbonization in the built environment are acquiring growing importance.

The decarbonization of the building sector is both an urgent climate imperative and a developmental opportunity, especially for emerging economies. Office buildings are the focus of this study due to their outsized role in energy use and carbon emissions in urban contexts. The systematic review revealed that decarbonization and policy discussions are especially prevalent in studies on office buildings, rendering this typology as a strategic sector for carbon mitigation. While residential and public buildings have historically received more attention, office buildings present unique challenges, such as more complex systems, higher operational energy demand, and opportunities such as greater capacity for advanced solutions due to higher financial resources and corporate sustainability goals. Thus, focusing on nearly zero-energy

**Table 4**  
The decarbonization progression road map for the built environment.

Transition Phase	Aims	Actions
Level 0. Pre-awareness ↓ Level 1. Awareness	<ul style="list-style-type: none"> <li>Recognize the building sector's contribution to climate change and the need for decarbonization</li> <li>Promote basic understanding of energy efficiency and NZEB concepts among stakeholders</li> </ul>	<ul style="list-style-type: none"> <li>Training programs on energy efficiency to inform building owners and professionals.</li> <li>Assess current building stock performance and carbon emissions to create a baseline for action.</li> </ul>
Level 1. Awareness ↓ Level 2. Emerging	<ul style="list-style-type: none"> <li>Translate awareness into initial commitments and plans for low-carbon buildings.</li> <li>Foster stakeholder engagement and early leadership in pilot NZEB projects.</li> <li>Build technical and institutional capacity for decarbonization initiatives.</li> </ul>	<ul style="list-style-type: none"> <li>Training and capacity-building for professionals in energy efficient and low carbon design and technologies.</li> <li>Introduce voluntary standards or certifications to encourage early adoption.</li> </ul>
Level 2. Emerging ↓ Level 3. Developing	<ul style="list-style-type: none"> <li>Integrate decarbonization into mainstream building practices and policy frameworks.</li> <li>Scale up from isolated pilots to widespread implementation across new projects and renovations.</li> <li>Establish intermediate targets such as NZEB code requirements to guide market transformation.</li> </ul>	<ul style="list-style-type: none"> <li>Strengthening building codes to mandate higher energy performance, such as requiring all new buildings to meet nZEB standards by a target year.</li> <li>Include embodied carbon targets gradually starting with upfront carbon targets for nZEBs, depending on the market readiness.</li> </ul>
Level 3. Developing ↓ Level 4. Developed	<ul style="list-style-type: none"> <li>Achieve widespread adoption of net-zero energy and low-carbon standards in both new construction and existing stock.</li> <li>Reduce operational and embodied carbon emissions sector-wide.</li> </ul>	<ul style="list-style-type: none"> <li>Mandate WLC disclosure to generate data for representative benchmarking</li> <li>Retrofit programs to upgrade existing buildings to nZEB levels.</li> <li>On-site renewables with smart energy management (smart grids, storage etc.) to minimize buildings' carbon impact.</li> </ul>
Level 4. Developed ↓ Level 5. Regenerative	<ul style="list-style-type: none"> <li>Surpass net-zero goals to achieve regenerative outcomes.</li> <li>Enable buildings to actively improve the environment, rather than merely minimizing harm.</li> <li>Full circularity on resources, aiming for buildings that contribute to ecosystem health and carbon reduction.</li> </ul>	<ul style="list-style-type: none"> <li>Design buildings for producing more clean energy than they use.</li> <li>Adopt regenerative design practices such as carbon-storing materials, rainwater harvesting etc.</li> <li>Make the built environment a life-supporting part of its local ecosystem.</li> <li>Implement continuous monitoring and regular benchmark updates.</li> </ul>

office buildings provides critical insights that can inform broader sustainable design approaches and policies.

However, despite the increasing attention to decarbonization and life cycle practices in the construction sector, the existing body of literature reveals puzzling methodological inconsistencies. Approaches to LCA, carbon accounting, and performance benchmarking differ significantly across studies, countries, and regulatory frameworks. These differences range from variations in the scope of assessed building systems and life cycle stages, to the use of incomparable metrics and non-standardized data sources. As a result, drawing direct comparisons between studies or translating findings into actionable policy becomes challenging. Classifying the existing literature in the "Building Decarbonization Maturity Scale" is useful for: (i) mapping and understanding the global progression toward decarbonization in the built environment, (ii) determining the current maturity level of a specific region, and (iii) designing and managing future studies, initiatives, and policies that enable buildings, cities, regions, and countries (especially the developing) to advance to higher maturity levels, and thus, carbon neutrality by 2050.

The implications of the study are summarized below:

- A decisive knowledge gap exists in developing countries, where only 7 out of 66 reviewed studies focused solely on developing contexts. This signals the urgency of a context-sensitive decarbonization roadmap tailored for these regions.
- Türkiye, as a developing country with a large and rapidly growing building stock, adds approximately 96,000 new buildings per year, totaling 120 million m<sup>2</sup>, with 7 % being office buildings, demonstrates the strategic importance of guiding this growth through a structured road map based on its decarbonization maturity rating.
- Türkiye's nZEB definition currently mandates only a 20 % improvement in primary energy consumption and 10 % renewable energy use, aligning with the Level 2 (Emerging) on the proposed decarbonization maturity scale, and the need for policy advancement toward Level 5.
- The carbon intensity of Türkiye's energy mix is currently 0.697 kgCO<sub>2</sub>-eq/kWh, among the highest in Europe, indicating that

demand reduction and efficiency measures must be prioritized in early roadmap stages.

- The average operational emissions of Türkiye's reported office nZEBs range between 7.5 and 35 kgCO<sub>2</sub>-eq/m<sup>2</sup>/year, and the embodied carbon ranges between 182 and 201 kgCO<sub>2</sub>-eq/m<sup>2</sup>, showing that WLC impacts remain high despite operational improvements, validating the necessity of a structured and tailored decarbonization roadmap.
- International comparisons show that countries like the UK and Denmark are approaching Level 5 with integrated circularity and policy alignment, while Türkiye is in early transition. Thus, the roadmap would provide a mechanism to benchmark and accelerate national policy and practice.

The proposed maturity scale and roadmap, when tested against Türkiye's current state, reveal certain leverage points such as improving carbon benchmarks, revising standards, and enforcing LCA modules, which can guide other developing nations. However, several limitations of this study should be acknowledged. While this study provides a structured synthesis of recent research on nZEB office buildings and proposes a novel decarbonization maturity scale and roadmap, several constraints shape the interpretation of the findings:

- The findings are based solely on office buildings and may not fully generalize to other typologies such as residential, industrial, or healthcare buildings, which have distinct usage patterns and regulatory contexts.
- The review includes studies published up to January 31, 2025. Subsequent developments in fast-evolving regulatory environments are not reflected.
- The Building Decarbonization Maturity Scale was developed through qualitative synthesis. While later validated through case mapping, it remains a conceptual model that would benefit from further quantification or validation.
- Only peer-reviewed journal articles were included in the core review. Policy reports, technical guidelines, and government datasets were reviewed separately but not systematically screened.

- Although efforts were made to include global studies, the review is limited by the availability and accessibility of English-language literature, which may underrepresent certain regions or developing country contexts.

**CRedit authorship contribution statement**

**Başak Yüncü Karanfil:** Writing – original draft, Visualization, Supervision, Methodology, Formal analysis, Conceptualization. **Nuri Cihan Kayaçetin:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Funding acquisition, Conceptualization. **Ayşegül Tereci:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Neslihan Bıyıklı:** Writing – original draft, Visualization, Formal analysis. **Merve Kılınç Gıllısrıhalıoğlu:** Writing – review & editing, Formal analysis, Data curation. **Diğdem Karaer:** Writing – original draft, Formal analysis, Data

curation.

**Declaration of competing interest**

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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**Appendix 1**

- Web of Science:

(TS=(whole life cycle) OR TS=(WLC)OR TS=(whole life carbon)OR TS=(cradle to grave)) AND (TS=(zero energy buildings) OR TS=(zero carbon buildings)OR TS=(nzeb)OR TS=(low energy buildings)OR TS=(net zero energy building)OR TS=(zero emission building)OR TS=(low emission buildings)) AND (TS=(office buildings) OR TS=(offices)OR TS=(office building)OR TS=(administrative building)).

- Scopus:

(TITLE-ABS-KEY (whole AND life AND cycle) OR TITLE-ABS-KEY (wlc) OR TITLE-ABS-KEY (whole AND life AND carbon) OR TITLE-ABS-KEY (cradle AND to AND grave)) AND (TITLE-ABS-KEY (nzeb) OR TITLE-ABS-KEY (zero AND energy AND building) OR TITLE-ABS-KEY (zero AND carbon AND building) OR TITLE-ABS-KEY (low AND energy AND buildings) OR TITLE-ABS-KEY (net AND zero AND energy AND building) OR TITLE-ABS-KEY (zero AND emission AND building) OR TITLE-ABS-KEY (low AND emission AND buildings)) AND (TITLE-ABS-KEY (office AND buildings) OR TITLE-ABS-KEY (office AND building) OR TITLE-ABS-KEY (offices) OR TITLE-ABS-KEY (administrative AND building)).

- TR-Dizin:

(abstract: ((“whole life cycle” OR “WLC” OR “whole life carbon”) AND (“nzeb” OR “zero energy building” OR “zero carbon building” OR “low energy buildings” OR “net zero energy building” OR “zero emission building” OR “low emission buildings”) AND (“office buildings” OR “office building” OR “offices” OR “administrative building”))).

**Appendix 2A. Office building LCA case study articles focused on structural systems only**

Reference	Year	Geographical Context		LCA modules				Actual Building or Archetype	Building Simulation Applied	Compared Scenarios	Carbon / Energy Metrics			Lifetime (years)
		Location	Köppen Climate Zone	A	B	C	D				Embodied / Upfront	Operational	Whole-life	
[83]	2012	Canada	C	A1- A3	N/ A	N/ A	N/ A	Actual Building	Yes	Reinforced concrete (baseline) CLT & glulam	420 kg CO <sub>2</sub> -eq/m <sup>2</sup> 126 kg CO <sub>2</sub> -eq/m <sup>2</sup>	N/A	N/A	50
[81]	2020	Portland, Oregon, US	C	A1- A3	N/ A	N/ A	N/ A	Actual Building	Yes	Timber Concrete	193 kg CO <sub>2</sub> -eq/m <sup>2</sup> 237 kg CO <sub>2</sub> -eq/m <sup>2</sup>	N/A	N/A	100
[74]	2021	N/A	N/A	A1- A3	N/ A	N/ A	N/ A	Archetype	Yes	Timber Steel Reinforced concrete	119 kg CO <sub>2</sub> -eq/m <sup>2</sup> 228 kg CO <sub>2</sub> -eq/m <sup>2</sup> 185 kg CO <sub>2</sub> -eq/m <sup>2</sup>	N/A	N/A	50
[82]	2021	USA	C	A1- A5	N/ A	C1- C4	D	Archetype	Yes	5-storey traditional structural steel frame 5-storey mass timber utilizing engineered wood 12-storey traditional	~211 kg CO <sub>2</sub> -eq/m <sup>2</sup> ~ 161 kg CO <sub>2</sub> -eq/m <sup>2</sup> ~ 233 kg CO <sub>2</sub> -eq/m <sup>2</sup>	N/A	N/A	60

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(continued)

Reference	Year	Geographical Context		LCA modules				Actual Building or Archetype	Building Simulation Applied	Compared Scenarios	Carbon / Energy Metrics			Lifetime (years)
		Location	Köppen Climate Zone	A	B	C	D				Embodied / Upfront	Operational	Whole-life	
										structural steel frame 12-storey mass timber utilizing engineered wood	~ 165 kg CO <sub>2</sub> -eq/m <sup>2</sup>			

**Appendix 2B. Office building LCA case study articles focused on building envelopes only**

Reference	Year	Geographical Context		LCA modules				Actual Building or Archetype	Building Simulation Applied	Compared Scenarios	Carbon / Energy Metrics			Lifetime (years)
		Location	Köppen Climate Zone	A	B	C	D				Embodied / Upfront	Operational	Whole-life	
[84]	2012	Tallinn, Estonia	D	N/A	B6	N/A	N/A	Archetype	Yes	Optimum WWR & Solar Factor (North) Optimum WWR & Solar Factor (East) Optimum WWR & Solar Factor (South) Optimum WWR & Solar Factor (West)	N/A	~75 kWh/m <sup>2</sup> /year ~70 kWh/m <sup>2</sup> /year ~62 kWh/m <sup>2</sup> /year ~65 kWh/m <sup>2</sup> /year	N/A	N/A
[77]	2014	Estonia	D	N/A	B6	N/A	N/A	Archetype	Yes	Glazing type 200 mm Air filling (baseline) 300 mm Argon filling 400 mm Krypton filling 500 mm Krypton filling 500 mm Krypton filling	N/A	N/A 111 kWh/m <sup>2</sup> 109 kWh/m <sup>2</sup> 107 kWh/m <sup>2</sup> 103 kWh/m <sup>2</sup>	N/A	N/A
[85]	2016	US	C	N/A	B6	N/A	N/A	Archetype	Yes	Optimum case	N/A	1805 kg CO <sub>2</sub> -eq/191.123 MJ	N/A	60
[61]	2016	Taiwan	A, C	N/A	B6	N/A	N/A	Actual Building	Yes	Moderate insulation glass and roof Improved insulation with different sunshade design High insulation glass and roof – optimized materials	N/A	87 kWh/m <sup>2</sup> /year 87 kWh/m <sup>2</sup> /year 88 kWh/m <sup>2</sup> /year	N/A	N/A
[62]	2017	Taiwan	C	N/A	B6	N/A	N/A	Actual Building	Yes	Original design (baseline) Southern Climatic Zone Northern Climatic Zone	N/A	~87 kWh/m <sup>2</sup> /year 92 kWh/m <sup>2</sup> /year 64 kWh/m <sup>2</sup> /year	N/A	N/A
[80]	2018	USA	D	N/A	B6	N/A	N/A	Archetype	Yes	Square footprint shaped mass (baseline) Rectangular parallelepiped designs H-shaped designs Cross-shaped design Pyramidal designs, slope of 83-86°	N/A	~668 kWh/year ~ 660–663 kWh/year ~ 664 – 669 kWh/year ~ 668 kWh/year ~ 664 – 702 kWh/year	N/A	N/A
[93]	2018	Italy	C	N/A	B6	N/A	N/A	Actual Building	Yes	Palermo Baseline Turin Baseline Palermo retrofit with PCM layers Turin retrofit with PCM layers	N/A	137 kWh/m <sup>2</sup> /year 206 kWh/m <sup>2</sup> /year 104–115 kWh/m <sup>2</sup> /year 138–155 kWh/m <sup>2</sup> /year	N/A	50

## Appendix 2C. Office building LCA case study articles focused on technical systems (HVAC and/or renewable energy systems) only

Reference	Year	Geographical Context		LCA modules				Actual Building or Archetype	Building Simulation Applied	Compared Scenarios	Carbon / Energy Metrics			Lifetime (years)
		Location	Köppen Climate Zone	A	B	C	D				Embodied / Upfront	Operational	Whole life	
[70]	2019	Southern Finland	D	A1-A4	B4-B6	N/A	N/A	Actual Building	Yes	BAU Annual Net Zero Electricity Off-Grid Electricity 100 % Solar Thermal Heat	– 6,337–14,825kg CO <sub>2</sub> -eq/year 85,268–254,327kg CO <sub>2</sub> -eq/year 20,202–21,445kg CO <sub>2</sub> -eq/year	72,352 kg CO <sub>2</sub> -eq/year 24,821 kg CO <sub>2</sub> -eq/year 0 kg CO <sub>2</sub> -eq/year 18,103 kg CO <sub>2</sub> -eq/year	72,352 kg CO <sub>2</sub> -eq/year	25
[94]	2020	Switzerland	E	A1-A3	B4-B6	C1-C3	N/A	Archetype	Yes	Mechanical Equipment Air Terminals Pipe Accessories Duct Accessories Adjusted LCA and Hot Floor Area (HFA) (at least 10 °C)	51 kg CO <sub>2</sub> -eq/m <sup>2</sup> ~ 1 kg CO <sub>2</sub> -eq/m <sup>2</sup> ~ 3 kg CO <sub>2</sub> -eq/m <sup>2</sup> ~ 7 kg CO <sub>2</sub> -eq/m <sup>2</sup> 40 kg CO <sub>2</sub> -eq/m <sup>2</sup>	N/A	N/A	60
[15]	2024	UK	C	A1-A5	B6	C1-C4	N/A	Archetype	Yes	4-Pipe FCU, Boiler & Chiller 4-Pipe FCU + ASHP Variable refrigerantflow Hybrid variable refrigerant flow Active chilled beam + ASHP Chilled ceiling + ASHP+Radiators Displacement vent. +ASHP + Radiators	151 kg CO <sub>2</sub> -eq/m <sup>2</sup> 146 kg CO <sub>2</sub> -eq/m <sup>2</sup> 288 kg CO <sub>2</sub> -eq/m <sup>2</sup> 162 kg CO <sub>2</sub> -eq/m <sup>2</sup> 136 kg CO <sub>2</sub> -eq/m <sup>2</sup> 145 kg CO <sub>2</sub> -eq/m <sup>2</sup> 89 kg CO <sub>2</sub> -eq/m <sup>2</sup>	202 kg CO <sub>2</sub> -eq/m <sup>2</sup> 58 kg CO <sub>2</sub> -eq/m <sup>2</sup> 47 kg CO <sub>2</sub> -eq/m <sup>2</sup> 44 kg CO <sub>2</sub> -eq/m <sup>2</sup> 40 kg CO <sub>2</sub> -eq/m <sup>2</sup> 31 kg CO <sub>2</sub> -eq/m <sup>2</sup> 23 kg CO <sub>2</sub> -eq/m <sup>2</sup>	353 kg CO <sub>2</sub> -eq/m <sup>2</sup> 204 kg CO <sub>2</sub> -eq/m <sup>2</sup> 335 kg CO <sub>2</sub> -eq/m <sup>2</sup> 209 kg CO <sub>2</sub> -eq/m <sup>2</sup> 175 kg CO <sub>2</sub> -eq/m <sup>2</sup> 176 kg CO <sub>2</sub> -eq/m <sup>2</sup> 112 kg CO <sub>2</sub> -eq/m <sup>2</sup>	60

**Appendix 2D. Office building LCA case study articles focused on multiple building systems of office buildings. Considered building system scopes are coded as; s (structural system), B (building envelope), H (HVAC), R (renewable energy), L (lighting), D (DHWS) and i (interior finished & components). (The numbers given in the articles are rounded up)**

Reference	Year	Geographical Context		Building System Scope						LCA modules				Actual Building or Archetype	Building Simulation Applied	Compared Scenarios	Carbon / Energy Metrics			Lifetime (years)		
		Location	Köppen Climate Zone	S	B	H	D	L	R	I	A	B	C				D	Embodied / Upfront	Operational		Whole life	
[88]	2011	Sweden	D	-	+	+	-	+	+	-	A1-A3	B6	N/A	N/A	Actual Building	Yes	Original building	11,404 kg CO <sub>2</sub> -eq/year	9,572 kg CO <sub>2</sub> -eq/year	N/A	50	
																	Retrofit options	8,141–11,463 kg CO <sub>2</sub> -eq/year	2,867 – 9,490 kg CO <sub>2</sub> -eq/year	N/A		
[64]	2013	Italy	C	+	+	+	+	-	-	+	A1-A5	B1 – B7	C1-C4	N/A	Actual Building	Yes	Reinforced concrete 5-storey office building	512 kg CO <sub>2</sub> -eq/m <sup>2</sup>	54 kg CO <sub>2</sub> -eq/m <sup>2</sup> /year	65 kg CO <sub>2</sub> -eq/m <sup>2</sup> /year	50	
[86]	2013	Spain, UK, Estonia	C, D	-	+	+	+	+	-	-	N/A	B6	N/A	N/A	Archetype A	Yes	Base case	N/ A	80–111 kWh/m <sup>2</sup> -year	N/ A	N/A	
																	Retrofit scenarios		45–107 kWh/m <sup>2</sup> -year			
[87]	2015	Italy	C	-	+	+	-	-	+	-	N/A	N/A	N/A	N/A	Archetype A	Yes	C-0	N / A	126 kWh/m <sup>2</sup> /year	37 kg CO <sub>2</sub> -eq/m <sup>2</sup> /year	N/A	20
																	C-246		77 kWh/m <sup>2</sup> /year	22 kg CO <sub>2</sub> -eq/m <sup>2</sup> /year	N/A	
[40]	2018	Belgium	C	+	+	+	-	-	-	+	A1 – A5	B4, B6	C1 – C4	D	Actual Building	Yes	Rebuild baseline	1,432 kgCO <sub>2</sub> -eq/m <sup>2</sup>	N/ A	1,100–1,200 kgCO <sub>2</sub> -eq/m <sup>2</sup>	50	
																	Retrofit	~810 kgCO <sub>2</sub> -eq/m <sup>2</sup>		~2,100–2,300 kgCO <sub>2</sub> -eq/m <sup>2</sup>		
[89]	2019	USA	C	+	+	-	-	-	-	-	A1-A5	N/A	N/A	N/A	Actual Building	No	Concrete building (baseline)	450 kgCO <sub>2</sub> -eq/m <sup>2</sup>	N/ A	N/ A	N/ A	
																	Hybrid CLT with fireproofing	334 kgCO <sub>2</sub> -eq/m <sup>2</sup>				
																	Hybrid CLT with charring	328 kgCO <sub>2</sub> -eq/m <sup>2</sup>				
[78]	2019	Sweden	D	-	-	+	-	-	-	+	A1-A5	B4, B6	C1 – C4	N/A	Archetype A	Yes	HVAC	N/ A	N/ A	150 kg CO <sub>2</sub> -eq/FU	50	
																	Inside Construction			250 kg CO <sub>2</sub> -eq/FU		
																	Outside Construction			100 kg CO <sub>2</sub> -eq/FU		
[50]	2020	Global	All	+	+	+	-	+	+	-	A1-A3	B6	N/A	N/A	Archetype A	No	New advanced office average	12 kg CO <sub>2</sub> -eq/m <sup>2</sup> /year	11 kg CO <sub>2</sub> -eq/m <sup>2</sup> /year	23 kg CO <sub>2</sub> -eq/m <sup>2</sup> /year	50	
																	New standard office average	27 kg CO <sub>2</sub> -eq/m <sup>2</sup> /year		38 kg CO <sub>2</sub> -eq/m <sup>2</sup> /year		
																	Existing office average	17 kg CO <sub>2</sub> -eq/m <sup>2</sup> /year	80 kg CO <sub>2</sub> -eq/m <sup>2</sup> /year	98 kg CO <sub>2</sub> -eq/m <sup>2</sup> /year		
[63]	2021	Egypt	B	+	+	-	-	-	-	+	A1-A5	N/A	C1, C2	D	Actual Building	Yes	Reinforced Concrete	3 GJ/m <sup>2</sup>	31.60 GJ/m <sup>2</sup>	346 kg CO <sub>2</sub> -eq/m <sup>2</sup>	50	
																	Hot Rolled Steel	5 GJ/m <sup>2</sup>		444 kg CO <sub>2</sub> -eq/m <sup>2</sup>		
																	Light Steel	2 GJ/m <sup>2</sup>		219 kg CO <sub>2</sub> -eq/m <sup>2</sup>		
[68]	2021	Shanghai	C	+	+	+	-	+	+	-	A1-A3	B1, B6	N/A	N/A	Archetype A	Yes	Baseline scenario	N/ A	613 kgCO <sub>2</sub> /year	N/ A	50	
																	Retrofit scenario		307 kgCO <sub>2</sub> /year			
[13]	2021	UK	C	+	+	-	-	+	-	-	A1-A3	B6	C1 – C4	D	Actual Building	Yes	Pre-retrofit	N/A	N/A	17,592,826 kgCO <sub>2</sub>	20	
																	Post-retrofit			14,854,693–17,304,206 kgCO <sub>2</sub>		

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Reference	Year	Geographical Context		Building System Scope				LCA modules				Actual Building or Archetype	Building Simulation Applied	Compared Scenarios	Carbon / Energy Metrics			Lifetime (years)			
		Location	Köppen Climate Zone	S	B	H	D	L	R	I	A				B	C	D		Embodied / Upfront	Operational	Whole life
[14]	2021	UK	C	+	+	-	-	+	-	-	A1-A3	B6	C1 – C4	D	Actual Building	Yes	Pre-retrofit Post-retrofit	N/A	N/A	17,592,826 kgCO <sub>2</sub> 14,852,095–17,206,053 kgCO <sub>2</sub>	60
[79]	2022	Austria	C	+	+	+	-	-	-	-	A1-A4	B4, B6, B7	C1 – C4	N/A	Actual Building	No	building 'be 2226'	N/A	132 kWh/m <sup>2</sup> /year	N/A	60
[72]	2022	Finland	D	+	+	-	-	-	-	-	A4-A5	B2-B3	C1 –C4	N/A	Archetype	No	nZEB building concept Business as usual (BAU) Wood	403 kg CO <sub>2</sub> -eq/m <sup>2</sup> 9 kg CO <sub>2</sub> -eq/m <sup>2</sup> /year 7 kg CO <sub>2</sub> -eq/m <sup>2</sup> /year	67 kWh/m <sup>2</sup> /year 4 kg CO <sub>2</sub> -eq/m <sup>2</sup> /year	14 kg CO <sub>2</sub> -eq/m <sup>2</sup> /year 11 kg CO <sub>2</sub> -eq/m <sup>2</sup> /year	100
[67]	2023	USA	B	+	+	-	-	-	-	-	A1-A5	B6	C1 – C4	D	Actual Building	No	Design for disassembly (DfD) Steel Frame Timber – EOL1 Timber- EOL2 Timber- EOL3	3999 t CO <sub>2</sub> -eq 698 t CO <sub>2</sub> -eq 795 t CO <sub>2</sub> -eq 50 t CO <sub>2</sub> -eq	574 t CO <sub>2</sub> -eq/year	N/A	30
[71]	2023	Denmark	C	-	+	+	-	-	-	-	A1-A3	B4, B6	C3,C4	N/A	Archetype	Yes	Packaged all-air system with reheat Thermally Active Building System + DOAS	360 kgCO <sub>2</sub> -eq/m <sup>2</sup> 370 kgCO <sub>2</sub> -eq/m <sup>2</sup>	19 kWh/m <sup>2</sup> /year 13 kWh/m <sup>2</sup> /year	10 kgCO <sub>2</sub> -eq/m <sup>2</sup> /year 9 kgCO <sub>2</sub> -eq/m <sup>2</sup> /year	50
[75]	2023	Belgium	C	+	+	-	-	-	-	-	A1-A5	B4	C1-C4	D	Actual Building	No	PD1-Masonry PD2-Masonry optimized PD3-Steel post beam PD4-Steel framing PD5-Wood framing PD6-Caisson post beam PD7-Wood SIP – straw PD8- CLT PD9-Modular blocks system	N/A	N/A	28 kg CO <sub>2</sub> -eq/m <sup>2</sup> 22 kg CO <sub>2</sub> -eq/m <sup>2</sup> 24 kg CO <sub>2</sub> -eq/m <sup>2</sup> 20 kg CO <sub>2</sub> -eq/m <sup>2</sup> 27 kg CO <sub>2</sub> -eq/m <sup>2</sup> 6 kg CO <sub>2</sub> -eq/m <sup>2</sup> 8 kg CO <sub>2</sub> -eq/m <sup>2</sup> 13 kg CO <sub>2</sub> -eq/m <sup>2</sup> 10 kg CO <sub>2</sub> -eq/m <sup>2</sup>	60
[16]	2024	Turkey	B,C,D	+	+	+	-	-	+	-	A1-A5	B4-B6	C1-C4	N/A	Archetype	Yes	Baseline nZEB nZEB+	150–165 kg CO <sub>2</sub> -eq/m <sup>2</sup> 182–201 kg CO <sub>2</sub> -eq/m <sup>2</sup> 209–230 kg CO <sub>2</sub> -eq/m <sup>2</sup>	5–33 kg CO <sub>2</sub> -eq/m <sup>2</sup> /year 3–22 kg CO <sub>2</sub> -eq/m <sup>2</sup> /year 1–11 kg CO <sub>2</sub> -eq/m <sup>2</sup> /year	416–3255 kg CO <sub>2</sub> -eq/m <sup>2</sup> 312–1285 kg CO <sub>2</sub> -eq/m <sup>2</sup> 235–780 kg CO <sub>2</sub> -eq/m <sup>2</sup>	50
[66]	2023	Denmark	C	+	+	+	-	-	-	+	A1-A3	B4	C3-C4	N/A	Actual Building	No	Reference (RSP-before renovation) After renovation average Scenarios	N/A 3 kg CO <sub>2</sub> -eq/m <sup>2</sup> /year	14 kg CO <sub>2</sub> -eq/m <sup>2</sup> /year 7 kg CO <sub>2</sub> -eq/m <sup>2</sup> /year	14 kg CO <sub>2</sub> -eq/m <sup>2</sup> /year 9 kg CO <sub>2</sub> -eq/m <sup>2</sup> /year	50
[65]	2019	N/A	N/A	+	+	+	-	-	-	-	A1-A3	B6	C1-C4	N/A	Archetype	Yes	Brick/Block (fossil-based) Brick/Block (renewable-based) Timber Frame (fossil-based) Timber Frame (renewable-based)	508,000 kgCO <sub>2</sub> 624,000 kgCO <sub>2</sub> 167,000 kgCO <sub>2</sub> 283,000 kgCO <sub>2</sub>	1,750,000 kgCO <sub>2</sub> 569,000 kgCO <sub>2</sub> 1,830,000 kgCO <sub>2</sub> 570,000 kgCO <sub>2</sub>	2,270,000 kgCO <sub>2</sub> 1,210,000 kgCO <sub>2</sub> 2,000,000 kgCO <sub>2</sub> 861,000 kgCO <sub>2</sub>	30

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Reference	Year	Geographical Context		Building System Scope				LCA modules				Actual Building or Archetype	Building Simulation Applied	Compared Scenarios	Carbon / Energy Metrics			Lifetime (years)		
		Location	Köppen Climate Zone	S	B	H	D	L	R	I	A				B	C	D		Embodied / Upfront	Operational
[69]	2020	Poland	D	-	+	+	-	+	-	-	A1-A5	B4-B7	C1-C4	N/A	Actual Building	Yes	Insulated Concrete Form (fossil-based)	767,000 kgCO <sub>2</sub>	1,750,000 kgCO <sub>2</sub>	2,540,000 kgCO <sub>2</sub>
																	ICF (renewable-based)	883,000 kgCO <sub>2</sub>	558,000 kgCO <sub>2</sub>	1,480,000 kgCO <sub>2</sub>
																	Steel Frame (fossil-based)	410,000 kgCO <sub>2</sub>	1,830,000 kgCO <sub>2</sub>	2,250,000 kgCO <sub>2</sub>
																	Steel Frame (renewable-based)	526,000 kgCO <sub>2</sub>	571,000 kgCO <sub>2</sub>	1,110,000 kgCO <sub>2</sub>
																	VRF + district heating	631 kg CO <sub>2</sub> -eq/m <sup>2</sup>	3,835 kg CO <sub>2</sub> -eq/m <sup>2</sup>	4,466 kg CO <sub>2</sub> -eq/m <sup>2</sup>
																	high WWR	652 kg CO <sub>2</sub> -eq/m <sup>2</sup>	3,981 kg CO <sub>2</sub> -eq/m <sup>2</sup>	4,633 kg CO <sub>2</sub> -eq/m <sup>2</sup>
																	very high WWR	1,039 kg CO <sub>2</sub> -eq/m <sup>2</sup>	3,927 kg CO <sub>2</sub> -eq/m <sup>2</sup>	4,966 kg CO <sub>2</sub> -eq/m <sup>2</sup>
																	low A/V ratio	671 kg CO <sub>2</sub> -eq/m <sup>2</sup>	4,684 kg CO <sub>2</sub> -eq/m <sup>2</sup>	5,355 kg CO <sub>2</sub> -eq/m <sup>2</sup>
																	Uses trigeneration (CHP), gas-powered	523 kg CO <sub>2</sub> -eq/m <sup>2</sup>	4,133 kg CO <sub>2</sub> -eq/m <sup>2</sup>	4,656 kg CO <sub>2</sub> -eq/m <sup>2</sup>
																	High energy use	441 kg CO <sub>2</sub> -eq/m <sup>2</sup>	6,032 kg CO <sub>2</sub> -eq/m <sup>2</sup>	6,473 kg CO <sub>2</sub> -eq/m <sup>2</sup>
[73]	2022	China	C, D	-	+	+	-	-	+	-	A1-A5	B6	C1-C4	N/A	Actual Building	Yes	High-rise (39 floors)	587 kg CO <sub>2</sub> -eq/m <sup>2</sup>	4,940 kg CO <sub>2</sub> -eq/m <sup>2</sup>	5,527 kg CO <sub>2</sub> -eq/m <sup>2</sup>
																	High glazing ratio	586 kg CO <sub>2</sub> -eq/m <sup>2</sup>	4,846 kg CO <sub>2</sub> -eq/m <sup>2</sup>	5,432 kg CO <sub>2</sub> -eq/m <sup>2</sup>
																	Energy-efficient structure	750 kg CO <sub>2</sub> -eq/m <sup>2</sup>	3,454 kg CO <sub>2</sub> -eq/m <sup>2</sup>	4,204 kg CO <sub>2</sub> -eq/m <sup>2</sup>
																	Electric heating	698 kg CO <sub>2</sub> -eq/m <sup>2</sup>	3,349 kg CO <sub>2</sub> -eq/m <sup>2</sup>	4,047 kg CO <sub>2</sub> -eq/m <sup>2</sup>
																	Mixed HVAC (gas + VRF)	476 kg CO <sub>2</sub> -eq/m <sup>2</sup>	4,780 kg CO <sub>2</sub> -eq/m <sup>2</sup>	5,256 kg CO <sub>2</sub> -eq/m <sup>2</sup>
																	Baseline	685 kg CO <sub>2</sub> -eq/m <sup>2</sup>	6095 kg CO <sub>2</sub> -eq/m <sup>2</sup>	6780 kg CO <sub>2</sub> -eq/m <sup>2</sup>
																	Green building	1033 kg CO <sub>2</sub> -eq/m <sup>2</sup>	4550 kg CO <sub>2</sub> -eq/m <sup>2</sup>	5583 kg CO <sub>2</sub> -eq/m <sup>2</sup>
																	ULEB (ultra-low energy building)	794 kg CO <sub>2</sub> -eq/m <sup>2</sup>	3096 kg CO <sub>2</sub> -eq/m <sup>2</sup>	3890 kg CO <sub>2</sub> -eq/m <sup>2</sup>
																	Pre-retrofit	N/A	N/A	42,220,000kg CO <sub>2</sub>
																	Post-retrofit	N/A	N/A	11020000 kg CO <sub>2</sub>
[76]	2023	UK	C	+	-	+	+	+	-	+	A1-A4	N/A	N/A	N/A	Actual Building	No	22 Office Buildings	N/A	~ 20 kg CO <sub>2</sub> -eq/m <sup>2</sup> /year	~ 30 kg CO <sub>2</sub> -eq/m <sup>2</sup> /year
																	LEED certified office	N/A	125 kWh/m <sup>2</sup> /year	N/A
[95]	2019	Germany	C	+	+	+	-	-	+	-	A1-A3	B4, B6	C3-C4	N/A	Actual Building	No	Non-LEED office	N/A	146 kWh/m <sup>2</sup> /year	N/A
																	LEED certified office	N/A	125 kWh/m <sup>2</sup> /year	N/A
[96]	2021	USA	C	-	-	+	-	+	-	-	N/A	B6	N/A	N/A	Actual Building	Yes	Multi-story buildings	272 kgCO <sub>2</sub> /m <sup>2</sup>	N/A	N/A
																	High-rise buildings	307 kgCO <sub>2</sub> /m <sup>2</sup>	N/A	N/A
[97]	2016	China	B, C, D	+	-	+	+	+	-	+	A1-A4	N/A	N/A	N/A	Actual Building	No	Super high-rise buildings	402 kgCO <sub>2</sub> /m <sup>2</sup>	N/A	N/A
																	low-rise buildings	522.18 kg CO <sub>2</sub> eq/m <sup>2</sup>	N/A	N/A
[98]	2021	Srilanka	A	+	+	-	-	-	-	+	A1-A3	N/A	N/A	N/A	Actual Building	No	medium rise buildings	457.85 kg CO <sub>2</sub> eq/m <sup>2</sup>	N/A	N/A
																	low-rise buildings	522.18 kg CO <sub>2</sub> eq/m <sup>2</sup>	N/A	N/A

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Reference	Year	Geographical Context		Building System Scope					LCA modules				Actual Building or Archetype	Building Simulation Applied	Compared Scenarios	Carbon / Energy Metrics			Lifetime (years)		
		Location	Köppen Climate Zone	S	B	H	D	L	R	I	A	B				C	D	Embodied / Upfront		Operational	Whole life
[99]	2021	Greece	C	-	+	+	-	+	+	-	N/A	B6	N/A	N/A	Actual Building	Yes	high-rise buildings	567.51 kg CO <sub>2</sub> eq/m <sup>2</sup>	N/A	N/A	
																Climate zone B – Reference building	N/A	226–229 kWh/m <sup>2</sup> /year	N/A	30	
																Climate zone B – nZEB range	N/A	75–170 kWh/m <sup>2</sup> /year	N/A		
																Climate zone B – NZEB range	N/A	0–75 kWh/m <sup>2</sup> /year	N/A		
																Climate zone C – Reference building	N/A	201–225 kWh/m <sup>2</sup> /year	N/A		
																Climate zone C – nZEB range	N/A	66–169 kWh/m <sup>2</sup> /year	N/A		
																Climate zone C – NZEB range	N/A	0–74 kWh/m <sup>2</sup> /year	N/A		
[100]	2021	Norway	D	-	+	+	-	-	-	-	A1–A5	B4–B5, B6	C1–C4	N/A	Actual Building	Yes	Reference	315 kg CO <sub>2</sub> eq/m <sup>2</sup>	1025 kg CO <sub>2</sub> eq/m <sup>2</sup>	1340 kg CO <sub>2</sub> eq/m <sup>2</sup>	60
																Passive House retrofit, keeps radiator system.	370 kg CO <sub>2</sub> eq/m <sup>2</sup>	500 kg CO <sub>2</sub> eq/m <sup>2</sup>	870 kg CO <sub>2</sub> eq/m <sup>2</sup>		
																Passive House retrofit, uses efficient all-air system	360 kg CO <sub>2</sub> eq/m <sup>2</sup>	450 kg CO <sub>2</sub> eq/m <sup>2</sup>	810 kg CO <sub>2</sub> eq/m <sup>2</sup>		
																Cost-optimized retrofit, keeps radiator system	350 kg CO <sub>2</sub> eq/m <sup>2</sup>	450 kg CO <sub>2</sub> eq/m <sup>2</sup>	900 kg CO <sub>2</sub> eq/m <sup>2</sup>		
																Cost-optimized retrofit with efficient all-air system	350 kg CO <sub>2</sub> eq/m <sup>2</sup>	280 kg CO <sub>2</sub> eq/m <sup>2</sup>	630 kg CO <sub>2</sub> eq/m <sup>2</sup>		
[101]	2016	China	C	+	+	+	-	+	+	-	A1–A5	B6	C1–C4	D	Actual Building	Yes	Baseline (Existing Design)	N/A	N/A	1464 tCO <sub>2</sub> /year	50
																Enhanced Envelope Insulation	N/A	N/A	1347–1361 tCO <sub>2</sub> /year		
																Reduced Fresh Air Nighttime	N/A	N/A	1258 tCO <sub>2</sub> /year		
																Ventilation Strategy	N/A	N/A	1452–1457 tCO <sub>2</sub> /year		
																Wider Temperature Range	N/A	N/A	1318 tCO <sub>2</sub> /year		

### Appendix 3. Key findings from the literature review

#### Building Design

- High-performance façade systems increase the initial investment cost but reduce the life cycle cost over time due to energy savings [77].
- South orientation provides energy efficiency by increasing natural heat and light gain, but excessive use of glass increases the cooling load in summer, especially in hot locations [84].
- The energy load was 50 % higher in southern buildings in Taiwan due to the warmer climate and higher internal gain [61]. It was recommended that the window ratio be reduced to balance with the northern design [62].
- Among 11 different form alternatives, in the temperate climate of Washington, the implementation of H, plus and high aspect ratio rectangular plans seem to give better results to achieve net zero energy [80].
- Improving the U-value of the envelope should be given special consideration in warm climate zones for office buildings in the EU [ ]while lighting has an important role in achieving energy efficiency for all climate zones [86]. In office NZEB application for a hot climate region such as Italy [87], the application of insulation on the outside and thermal mass on the inside of the envelope gives better results and should be supported with applications such as high efficiency window frames, efficient generation and HVAC systems, and RES. This resulted in a 41 % reduction in carbon emissions at the lowest cost.
- For office building design in Sweden, the key climate change issues are listed as carbon-free electricity, replacing concrete slabs with wood, improving the U-value of the building envelope, and installing low-energy lighting and appliances [88].
- CO<sub>2</sub> emissions during the construction phase account for 5–20 % of the total lifecycle emissions of an office building. Emissions significantly increase with building height, with the majority of these emissions originating from steel, concrete, mortar, and masonry materials [97].
- The study evaluates the embodied carbon content of twenty office buildings in Sri Lanka, classifying the office buildings as low, mid-rise, and high-rise. The substructure, skeleton, upper floors, and external walls accounted for 85–95 % of the total EC. The significance of internal walls, stairs, and roofs was found to be minimal, with their contributions amounting to less than 20 % [98].

#### Renovation

- The study [66] examined 23 different real building renovation examples in Denmark, including 4 office buildings, and concluded that energy efficiency measures implemented in renovation efforts resulted in operational savings of approximately 50 %, with an average annual reduction from 13.5 to 7 kg CO<sub>2</sub>-eq/m<sup>2</sup>/year, savings are between 20 % and 65 %.
- A three-story office building in the UK achieved substantial reductions in life cycle cost (44 %), carbon emissions (74 %), and energy use (68 %) through iterative optimization as an integrated passive and active retrofit strategy, using real data [76].
- The study [40], which compares the renovation and complete reconstruction of office buildings in Belgium, states that retrofitting can be more effective in reducing whole life cycle emissions and the rebuild increases especially embodied carbon.
- The study analyzed the carbon reduction and economic impacts of energy-saving retrofits in an office building located in a cold climate zone in China and found that ultra-low energy buildings achieve significantly more carbon and operational emission reductions than green buildings but face higher carbon and costs and become less economically viable unless local production and cost control are improved [73].
- For a typical Norwegian office building from 1987, various renovation scenarios for a 60-year lifetime were analyzed, and it was determined that renovations using glass wool insulation, district heating, and polycrystalline PVs are the most suitable renovation strategy to achieve nZEB performance in cold climates. The largest sources of tangible emissions during renovation: use of extra materials: 18–23 %, transportation them to site: 25–31 %, End-of-life service: 25 % [100].

#### Material & System Selection

- For a mid-size prototype office building, the radiant system produced less operational carbon and reduced life-cycle carbon by 11 % when compared to an all-air system [71].
- For NZEB offices in Italy the operation phase accounted for 85 % of the total impact, while the construction phase accounted for 14 %. If renewable energy-based electricity increases in the future, this rate will decrease even more [64].
- Focusing on the construction and material production phases of the office building by collecting real-time data, the research emphasized the importance of material choices and the environmental impact of HVAC systems [78].
- For mid-rise offices in US, re-used mass timber together with a steel structure reduce net embodied carbon emissions [67]. In evaluating the environmental impacts of hybrid CLT structures in the U.S. Pacific Northwest and comparing them to conventional reinforced concrete buildings; hybrid CLT structures have lower environmental impacts compared to reinforced concrete structures and offer advantages especially in terms of reducing carbon emissions and storing biogenic carbon [89].
- A study from Egypt [63] compared reinforced concrete, hot rolled steel construction and light steel systems and found that compared to reinforced concrete, the hot rolled steel construction system had 41 % more life cycle embodied energy, while the latter had 34 % less life cycle embodied energy 62 % lower greenhouse gas emissions.
- The study [65], which evaluates both the structural system and the renewable energy source together in the case of an office building, found that the use of high emission materials such as steel and concrete in the building system increases the embedded carbon, while low emission materials such as wood reduce these effects. In addition, the use of energy based on fossil fuels increases embedded carbon, while the use of renewable energy sources reduces these effects.
- The study examines the relationship between primary energy consumption and life cycle cost of various interventions in five-story office buildings in Greece. Different heating/cooling systems for older buildings met almost zero energy targets, while newly constructed buildings required VRV systems for optimum performance. Lighting systems, especially LED technology, are crucial to achieving NZEB levels. Exterior insulation types with lower U-value materials led to higher costs, especially in older buildings. Advanced automation systems proved to be not cost-effective. PV systems are suitable for achieving NZEB targets, especially in older buildings [99].
- Cascone, Capozzoli, and Perino (2018) reported that PCM layer in opaque wall assemblies reduces primary energy and heating/cooling demands in office renovations in Mediterranean climates and balances them with investment and life cycle costs [93].

#### Energy Efficiency

- A recent study [50] reveals that the share of embedded emissions in high energy efficient buildings increases to 45–50 % and in some extreme cases even over 90 %.
- The study in Austria [79] evaluates an innovative passive building concept “BE 2226” for WLC emissions using an office building case. Although this passive building standard reduces energy demand, it does not provide a significant reduction in the nZEB concept. However, it does provide significant emission reductions in the conventional standard. Furthermore, it has been observed that the incorporation of high thermal mass materials appears to result in an increase in embedded emissions.
- A study was conducted to assess the potential for utilizing data from the German Sustainable Building Council (DGNB) to develop automated LCA benchmarks for buildings. The study found that meaningful environmental metrics can be derived from the available data for early planning stages throughout the life cycle phases, as evidenced by the first harmonized dataset of 22 office buildings [95].
- LEED-certified office buildings in Washington, D.C., compared to their non-LEED counterparts using municipal energy benchmarking data published in 2019, indicate lower performance than non-LEED-certified buildings [96].
- In Peng’s (2016) analysis for a typical office building in Nanjing, China, approximately 85.4 % of total lifecycle CO<sub>2</sub> emissions occur during the operational phase, primarily from heating, cooling, lighting, and equipment [101].

### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.enbuild.2025.116443>.

## Data availability

Data will be made available on request.

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