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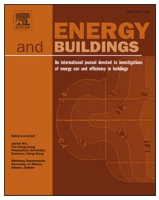

Achieving carbon neutrality at single and multi-building complex levels – A review

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ABSTRACT

Achieving carbon–neutral building stock by 2050 contributes to coping with the detrimental impacts of global warming since buildings account for almost 37% of final energy-related CO_2 emissions. This paper reviews the publications on carbon neutrality (CN) feasibility at both single and multi-building complex scales. Publications are retrieved from the Scopus database, and the snowball method is used to find the most relevant studies. The paper addresses the primary question: "Is it possible to reach the life cycle carbon neutrality of buildings?". Various information such as building life cycle carbon assessment, building characteristics (usage type and number of stories), climate type, mitigation measures, and simulation results are extracted, classified, and analyzed. Technically, reaching CN is feasible, but it is challenging given the need to implement multiple mitigation measures simultaneously, especially in the regions with low emissions intensity of the electricity grid, and may not always be economically feasible. A lack of successful case studies for large multi-building complexes, such as cities, is evident in the literature. It can be attributed to the limited availability of input data for carbon assessments as well as the complexity of simulations. Knowledge gaps in the literature and suggestions for future works are also discussed in detail. Due to the small number of studies on the topic, conclusive paths to reach the CN of buildings, specific to different climates and types of buildings, remain unclear, and thus, further research is necessary.

1. Introduction

Due to the drastic increase in anthropogenic CO_2 emissions, the earth's atmosphere is getting warmer continuously. This global warming trend has created unprecedented harmful environmental impacts, such as melting glaciers, rising sea levels, and unexpected flash floods [1]. Since 1850, the atmospheric CO_2 concentration has increased from 280 PPM to 450 PPM (about 60.7 % increase), global temperature has raised by 0.9–1.2 ℃, and sea level has increased by 20 cm [2–4]. In the past 30 years, the rate of these adverse effects of climate change has increased. By the end of this century, if the global temperature rise reaches 2 ℃ above pre-industrial levels (around 1750–1850), the sea level is expected to rise by 36 to 87 cm; about 13 % of the ecological system on the earth could vanish; many plants and animals might be in danger of extinction [4].

Among all sectors, buildings are responsible for almost 37 % of annual worldwide energy-related CO_2 emissions [5]. Emissions associated with buildings occur throughout their entire life cycle, and thus, the assessment of their environmental impacts should encompass this entire life cycle.

1.1. Categorizing building emissions

Buildings emit greenhouse gases (GHGs) throughout their life cycle, which comprises several major chronological stages: production, construction, use, and end-of-life. Common types of building-related GHGs emissions are [6]: CO_2, CH_4, N_2O, CFC-11, CFC-12, HCFC-22, and hydrofluorocarbons (HFCs). There is a massive global effort to ban the use of Chlorofluorocarbons (CFC) products [7]. CO_2 is the predominant GHG associated with buildings in terms of quantity emitted [8]. While GHGs have the potential to remain in the atmosphere for extended

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Nomenclature

Symbols

a	Building lifetime (years)
C	Carbon equivalent emissions (kg CO_2 eq.)
CC	Emissions factor for the operational energy use (kg CO_2 eq. per kWh)
CM	Emissions factor for the energy embodies building materials (kg CO_2 eq. per kg or m^3)
CT	Emissions factor for the transportation of building materials per unit of distance (kg CO_2 eq. $kg^{-1}.km^{-1}$)
e	Building operational energy use (kWh, MJ)
I	Environmental impact
l	Transportation distance (km)
m	Unit of building material (kg, m^3, etc.)
Q	Energy use at construction site (kWh)
TW	Emissions of transportation of waste materials (kg CO_2 eq.).

Abbreviations

CN	Carbon neutrality
CNB	Carbon neutral building
EE	Embodied emissions
GHG	Greenhouse gas
LCA	Life cycle assessment
OE	Operational emissions

periods of time, often lasting hundreds of years [9], the average lifespan of a building is approximately 30 to 100 years [10].

Building emissions are generally classified as either operational emissions (OE) or embodied emissions (EE) based on when and how they occur during various phases of the building life cycle. The OE encompasses those emissions resulting from the day-to-day energy consumption required to maintain a comfortable indoor environment. These include energy used by HVAC systems, hot water supply, lighting, and indoor appliances [11,12]. For instance, the energy required to heat and cool a building throughout its occupancy or the electricity consumed by lighting fixtures are OE. On the other hand, EE pertains to emissions associated with the construction and materials of the building itself, including the production, transportation, and assembly of building materials. For example, emissions generated during the manufacture of concrete or steel used in buildings' structure are EE.

Furthermore, emissions from buildings can also be classified as direct and indirect emissions. Direct emissions are released directly from buildings into the atmosphere, for instance, from the combustion in boilers or furnaces on-site [13]. Indirect emissions refer to those associated with the EE in building construction materials, on-site construction processes [14], and with the use of electricity from the grid, heat, steam, and cooling generated off-site (e.g., from the district heating and cooling) [13] used to operate buildings.

1.2. Does carbon neutrality have an exact definition?

Carbon neutrality (CN) is defined as net zero CO_2 emissions when human-caused CO_2 emissions reach zero levels [15] or are counterbalanced globally by CO_2 removal actions over a specific period [16,17]. It may appear that "carbon neutrality" means no CO_2 emissions, but significant amounts of other greenhouse gases are also emitted into the atmosphere. The other similar terms to "net zero CO_2 emissions" are "climate neutral" and "net zero GHG emissions". "Climate neutral" and "net zero GHG emissions" carry a similar definition and cover all types of GHGs. This does not necessarily mean that each GHG must individually reach zero emissions. Rather, the objective is to achieve a net-zero effect by balancing the collective impact of all emitted GHGs. This means that any emissions produced need to be offset by an equivalent amount of emissions reductions to achieve a net-zero effect [18].

Defining carbon neutrality is not as straightforward as previously discussed. Even though the terms "carbon neutrality", "net zero emissions", and "climate neutral" have clear definitions, they are not always used with the same definitions discussed above [19]. CO_2 is the most common type of GHGs emitted in terms of quantity [20]. Based on its dominance, GHG emissions are often reported by the equivalent CO_2 [15], although it can cause misunderstandings. Similarly, carbon (C) has also been used ambiguously. Specifically, the term "carbon emission" is sometimes used to refer to just CO_2 emissions [15,20], or just the amount of carbon (as the chemical element C) in CO_2 emissions (this is less common) [15,20], or sometimes is used to describe the emissions of all GHGs, even though not all of them contain carbon in their chemical composition [20]. According to the guidelines presented by the Intergovernmental Panel on Climate Change (IPCC) [21], the assessment of carbon neutrality includes all forms of greenhouse gas emissions [15].

1.3. Time horizon and life cycle boundary of carbon–neutral buildings (CNBs)

To achieve net-zero carbon buildings by 2050, the direct CO_2 emissions from buildings must be reduced by approximately 50 % by 2030, while the indirect building emissions must be reduced by 60 % [5]. The goal of CNBs is to minimize emissions over their lifetime and offset any residual emissions through different activites such as on-site production from renewable energy sources [22]. Like "carbon neutrality" which lacks a universally accepted definition, the term "carbon-neutral building" also lacks a widely agreed-upon definition. Various definitions are employed, depending on factors such as the time horizon and the specific phase of the building's life cycle. These definitions may vary accordingly:

- Zero yearly OE refers to buildings with zero operational emissions on a yearly basis [23–33].
- Life cycle zero OE is used when the time horizon of assessment is the lifetime of the building [34,35]. The analysis for reaching life cycle zero operational emissions can be more challenging as future scenarios (e.g., grid emissions intensity, weather conditions, etc.) can affect results.
- Zero emissions by combining EE of the on-site construction and the life cycle OE [36].
- Zero emissions of the EE of building materials and life cycle OE [35,37]. In a more complete definition, emissions related to travel of all employees and visitors to or from a building, using different means from different distances, should also be included [22,38].
- Zero emissions of both life cycle EE and OE [39].

This paper uses interchangeably the terms "emissions" and "carbon emissions" to refer to all types of greenhouse gas emissions from buildings. The present review addresses the research gaps in previous literature regarding carbon–neutral buildings (CNBs) and aims to provide insights into successful case studies that achieved carbon neutrality at both single and multi-building complex levels. The key questions include the feasibility of achieving single-building carbon neutrality, considering factors such as the time horizon, climate, and building types. Additionally, the review explores the extension of carbon neutrality to multi-building complexes, analyzing their size and type. The paper stands out by offering an in-depth analysis of lessons learned, presenting case studies, and identifying knowledge gaps for future research. In summary, it synthesizes existing knowledge, provides new perspectives, and aims to advance the understanding of carbon–neutral buildings.

The rest of the paper is organized as follows:

- Section 2 presents the methodology applied in this review paper, contributions of previous reviews, as well as the current work's motivations and objectives.
- Section 3 reviews details about building life cycle carbon emission assessment and mitigation methods.
- Sections 4 and 5 present successful case studies of CNB at single and multi-building complex levels, respectively. The knowledge gaps in the literature are also discussed in detail.
- Section 6 presents the conclusions of the present study.

2. Review paper overview

In this section, we describe the methodology for extracting information from the literature, highlight the contributions made by prior studies in the field, and identify the unique contributions of present study.

2.1. Methodology of collecting papers

This subsection describes the methodology adopted to collect the most relevant papers related to our review. Table 1 displays six groups of keywords used in the Scopus search engine. The Scopus database provides access to a wide range of resources, including journals, conference proceedings, patents, and more. The asterisk (*) is used to return different variations of a word. Moreover, by enclosing a phrase in quotation marks, the search results are narrowed down to only include instances in the exact order specified. Without using quotation marks, the search engine will look for instances of those words regardless of their order or proximity to each other.

All papers retrieved from searches have been imported into Mendeley (Mendeley is a free reference manager software [40]) in separate folders. Fig. 1 illustrates the general steps undertaken to gather final candidate papers and remove those out of the scope. A similar approach has been taken in other reviews [41]. In addition to a comprehensive list of keywords used to refine searches, the applied restrictions include (step 3 shown in the figure): subject area (limited to Engineering, Energy, Chemical Engineering, Environmental Science, and Multidisciplinary), document type (limited to Article, Conference paper, and Review), and language (limited to English).

In our methodology, we systematically assessed and selected papers by carefully examining titles, keywords, and abstracts. The criteria for this evaluation (steps 6–9 in Fig. 1) are outlined in detail as:

- Title evaluation: We initiated the analysis by evaluating the content of each paper's title to exclude those that fell outside the scope of carbon–neutral buildings.
- Keyword criteria: Papers lacking explicit usage of keywords such as "building" or "built environment" in their title, keywords or abstract were deemed likely to be outside of our scope and were subsequently excluded.
- Carbon emissions focus: To further refine our selection, we removed papers that did not incorporate keywords such as "carbon," "CO_2," "greenhouse gas," "GHG," "emissions," or similar expressions, because their content was not aligned with our focus on net-zero carbon emissions.
- Carbon neutrality emphasis: Papers without explicit utilization of terms like "neutral," "neutrality," "zero," "net zero," "nearly-zero," or "free" in their title and abstract were also excluded, as these did not align with our objective of addressing carbon–neutral buildings.

Table 1
Search for relevant papers from the Scopus database.

Group	Group of keywords used in searches
1	"life cycle" *OR* "life cycle assessment" *OR* "life cycle analysis" *OR* LCA *OR* "life cycle emission""*OR* "life cycle carbon emission"
2	carbon* *OR* CO_2 *OR* "carbon dioxide" *OR* GHG *OR* "greenhouse gas"
3	"zero carbon" *OR* "zero emission" *OR* "carbon free" *OR* "emission free" *OR* "net zero carbon" *OR* "net zero emission" *OR* "nearly zero carbon" *OR* "nearly zero emission" *OR* "carbon neutral" *OR* "emission neutral" *OR* "low carbon" *OR* "low emission"
4	emission *OR* emit* *OR* footprint *OR* reduc* *OR* mitigat* *OR* "carbon neutral" *OR* "zero carbon" *OR* "low carbon" *OR* decarbon*
5	building *OR* "built environment"
6	city *OR* urban *OR* "city scale" *OR* "urban scale" OR "city level" *OR* "urban level" *OR* large *OR* "large scale" *OR* neighborhood *OR* complex *OR* community *OR* "urban community" *OR* "city community"

Moreover, a brief examination of the methodology, results, and conclusion sections was also conducted (steps 10 and 11 in Fig. 1), ensuring the selected case studies aligned with the scope of our study.

We have done three main searches to find the most appropriate papers: (1) previous review papers on the topic and (2–3) research papers on CN of buildings at single and multi-building complex levels. Table 2 summarizes the findings by listing the total number of retrieved papers and the number of final candidates. These three distinct searches yielded 109, 92, and 22 papers, respectively, totaling 223 papers. In Table 2, when a group of keywords (shown in Table 1) is set to exist in Title, Keywords, and Abstract, one of the group members should exist at least in Title, Keywords, and Abstract of papers retrieved. The keyword group #5 (building OR "built environment") must appear in the title of the papers retrieved. No restrictions were imposed on the years of publication during the paper collection process, ensuring that all relevant papers, regardless of their publication year, were included in the study. Moreover, duplications for retrieved papers in different searches were removed.

Despite applying a comprehensive set of relevant keywords in Scopus to retrieve most of the related papers, it is possible that we may have missed some articles that used different keywords in the title, abstract, or keywords section.

The Snowball method [42] was also used to find other relevant papers by reading all the references cited in the final candidate papers. This process led to the identification of 7 more relevant papers. More searches have been manually conducted in some selected journals using the keywords "carbon neutral building," "zero carbon building," and "zero emission building," revealing more than 5 additional papers related to the topic.

2.2. Contributions of previous review papers

Our search in the Scopus database, along with the subsequent filtration process, identified a total of 26 relevant review papers, as indicated in the first row of Table 2. Most of these papers focused on building life cycle carbon emissions and mitigations, with the ideas discussed in Fig. 2. The following abbreviations are used in this figure: LCA (life cycle assessment/analysis) LCE (life cycle emissions), ECE (embodied carbon emissions), and LCCE (life cycle carbon emissions).

These review papers aimed to determine the most influential stages of a building life cycle in relation to emissions [43]. They also underlined the idea that EE of buildings needs to be incorporated into the LCA [44,45], because it shares a significant portion of total emissions from buildings. They summarized the methods available for evaluating embodied life cycle emissions [6,46,47]. Important factors affecting the EE [48] and databases and tools for the carbon assessment of buildings were explored [49]. Some researchers reviewed the challenges of incorporating the calculation of life cycle emissions at the early-design stage of buildings [50,51], and others reviewed the strategies to mitigate emissions from buildings [52–56]. Different definitions of carbon–neutral buildings were also discussed [57].

2.3. Motivations and objectives of present review

Although previous reviews have addressed a variety of aspects, several questions remain unanswered. The main purpose of this paper is

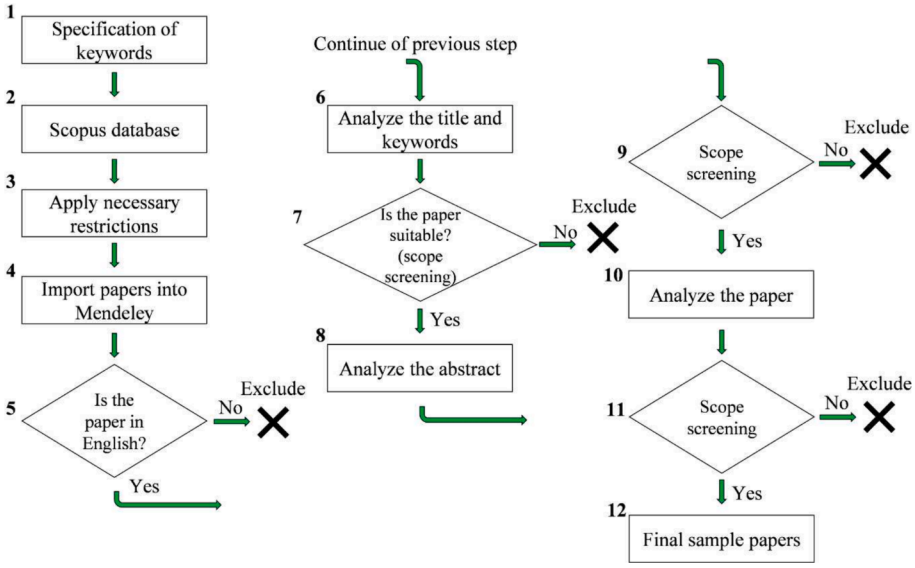

Fig. 1. Steps followed to filter the papers extracted from the Scopus database.

Table 2
Total number of papers found and selected as final candidates for three different searches.

Search number	Folder name in Mendeley	Group of keywords used (Table 1)	Keywords in at least one of the following sections:			Number of papers retrieved	Number of final candidates (Fig. 1)
			Title	Keywords	Abstract		
1	Review papers about building emissions and carbon neutrality	1	✓	✓	✓	109	26
		2	✓	✓	✓		
		4	✓	✓	✓		
		5	✓	×	×		
2	Research papers on the carbon neutrality of single buildings	1	✓	✓	✓	92	20
		2	✓	×	×		
		3	✓	✓	✓		
		5	✓	×	×		
3	Research papers on the carbon neutrality of multi-building complex	1	✓	✓	✓	22	8
		2	✓	✓	✓		
		3	✓	✓	✓		
		5	✓	×	×		
		6	✓	×	×		

to discuss the successful stories toward carbon–neutral buildings, at both single and multi-building complex levels, to address the following questions:

Question 1: Can single building carbon neutrality be achieved?

In order to respond to the above question, the answers to the following questions need to be gathered from publications:

a) What were the time horizon and life cycle phase of buildings considered for single CNB?
b) Was it possible to reach single CNB in all climates?
c) Was it possible to reach single CNB for all types of buildings?
d) What mitigation measures were applied to reach single CNB?
e) What were the main conclusions of previous studies about the single CNB?

Question 2: Was it feasible to go beyond single CNB and reach CN of buildings at the multi complex level?

Question 3: What were the size and type of carbon–neutral multi-building complex?

Question 4: What are the main knowledge gaps to be addressed in future research regarding CNBs?

Although previous review papers have provided contributions to the understanding of life cycle carbon emissions within the context of buildings, the aim of this paper is to provide a fresh perspective on the subject and provide answers to remaining questions discussed above. The distinctive features of this review paper are as follows:

- An in-depth analysis of single building carbon neutrality (CN): Previous reviews have stressed the importance of reducing building emissions; however, we have examined this concept in greater detail, examining issues such as the feasibility of achieving CN across a range of building types, climates, and lifecycle stages, as well as the challenges and opportunities associated with this ambitious goal.
- Beyond single building CN: We extend our scope beyond single building CN to examine the possibility of achieving CN at multi-building complex level.
- Case studies and practical insights: We have presented comprehensive case studies of successful carbon–neutral buildings and multi-building complexes. By analyzing these examples, we aim to provide deeper insights into the strategies, technologies, and approaches that have enabled these projects to achieve carbon neutrality.

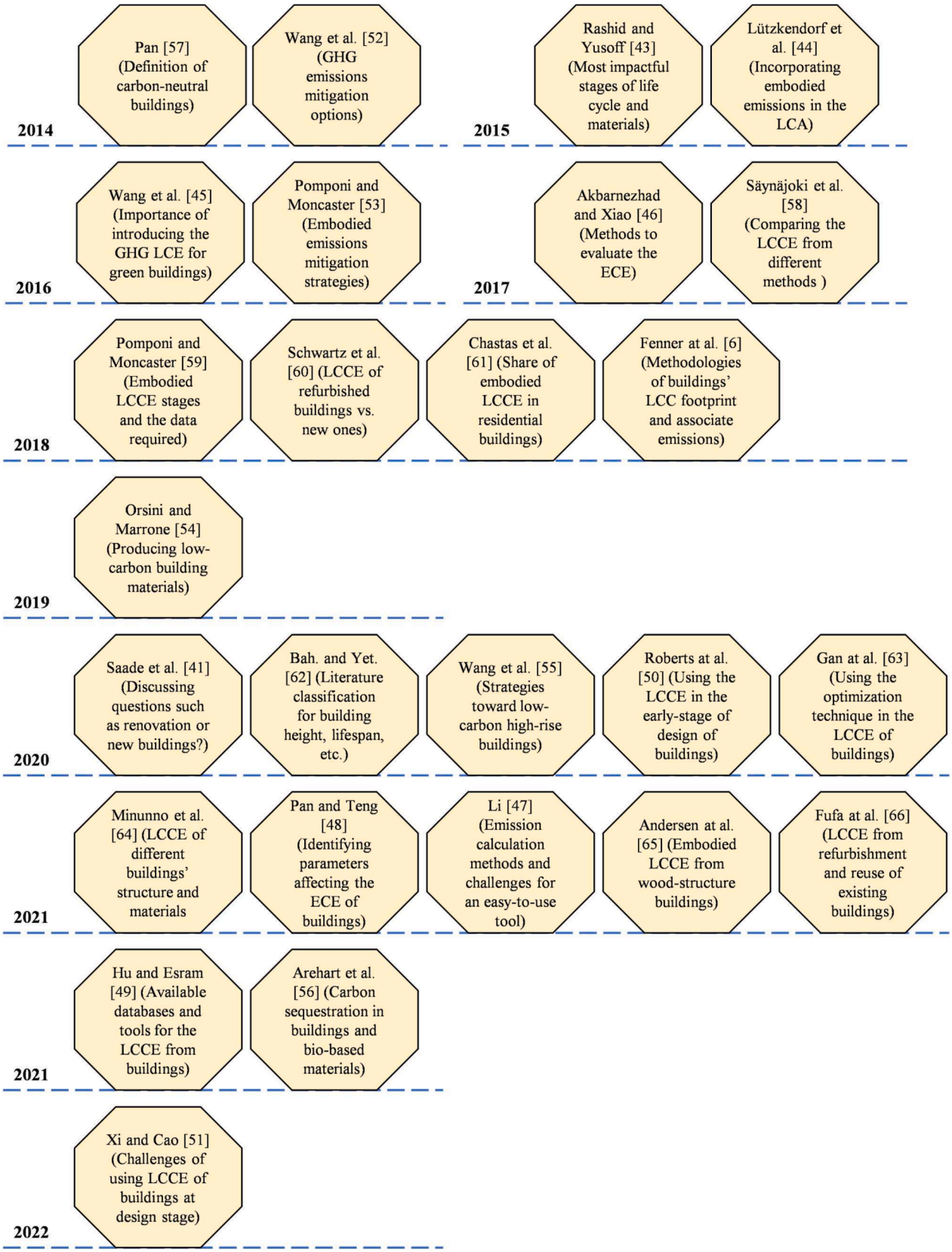

Fig. 2. Most important topics covered in previous review papers concerning life cycle carbon emissions and carbon neutrality of buildings. (See above-mentioned references for further information.)

- Identifying knowledge gaps: To provide guidance for future research efforts, we have critically reviewed the existing literature and identified knowledge gaps in the field of carbon–neutral buildings.

In summary, this review paper synthesizes existing knowledge, while also offering a novel perspective on specific questions related to CN in buildings. We strive to advance the understanding of carbon–neutral building practices in order to contribute to a sustainable future by addressing these questions and providing new and practical insights.

3. Building life cycle carbon emissions

3.1. Building emissions: stages and details

Life cycle stages of buildings are shown in Fig. 3 based on the standard EN 15804 [67]. Stages A1-A3 refer to the emissions from the production of building materials. Stage A4 refers to the emissions related to the transportation of construction materials to on-site, and A5 represents the emissions due to on-site construction activities. Emissions that occur during stages A1 to A5 are called the pre-use/initial embodied emissions (EE) [68].

Stage B1 refers to the emissions from the use of installed products, services, or appliances. Stages B2 to B4 refer to the emissions due to the maintenance, repair, and replacement of products, and stage B5 refers to the emissions from the refurbishment of construction products [67]. Stages B6 and B7 refer to the emissions due to the operational energy and water use, respectively. In addition to the emissions resulting from the energy consumption by HVAC systems, hot water supply, lighting, and indoor appliances, operational emissions (OE) can also include emissions associated with the transportation of occupants to and from buildings [69]. All emissions occurring during the utilization phase of buildings, except B6 and B7, as depicted in Fig. 3, are referred to as recurrent embodied emissions [11,12].

According to some studies, emissions from buildings at the end-of-life stage (C1-C4) are classified as end-of-life/demolition emissions rather than embodied emissions. In some studies, however, embodied emissions are defined as the sum of the emissions generated at the initial, recurrent, and end-of-life stages of building's life cycle [70]. The emissions occurring beyond the building lifetime are not commonly included in the life cycle assessment of buildings. This last stage shows the potential avoidance of embodied emissions through certain actions, such as reuse, recovery, and recycling of building materials and subsystems.

In general, life cycle emissions from current buildings can range from as low as 10 kg CO_2 eq.·m^{-2}·$year^{-1}$ to as high as 110 kg CO_2 eq.·m^{-2}·$year^{-1}$, with an average of about 50 kg CO_2 eq.·m^{-2}·$year^{-1}$ [6]. OE typically accounts for over 70 % of a building's life cycle emissions and can even reach as high as 90 % in some cases, leaving EE to make up the remaining 10 % to 30 % [71,72]. However, highly energy-efficient buildings exhibit a different pattern. EE can constitute a significant share, ranging from 45 % to 50 % of a building's overall life cycle emissions, with extreme cases exceeding 90 % [71]. Emissions associated with construction activities are relatively low, making up only about 2 % of a building's total life cycle emissions [73]. Within the construction stage, transportation of materials is the primary contributor, accounting for approximately 90 % of emissions [73]. Finally, demolition emissions, occurring at the end of a building life cycle, represent a negligible share, estimated to be around 0.2–0.3 % of the total life cycle emissions [72].

3.2. Building life cycle carbon emissions quantification

In our context, life cycle assessment (LCA) refers to a systematic evaluation of the overall environmental impact of buildings in terms of GHGs emissions. In general, the four phases of a LCA are: (1) the goal specification, (2) the life cycle inventory analysis, (3) the environmental impact assessment, and (4) the life cycle impact explanation and interpretation [74]. In order to quantify the carbon emissions throughout the life cycle of buildings, it is essential to establish a clear boundary and to collect the necessary inventory data.

The LCA of buildings can have different boundaries as cradle to gate, cradle to site, cradle to handover, gate to end-of-use, gate to grave,

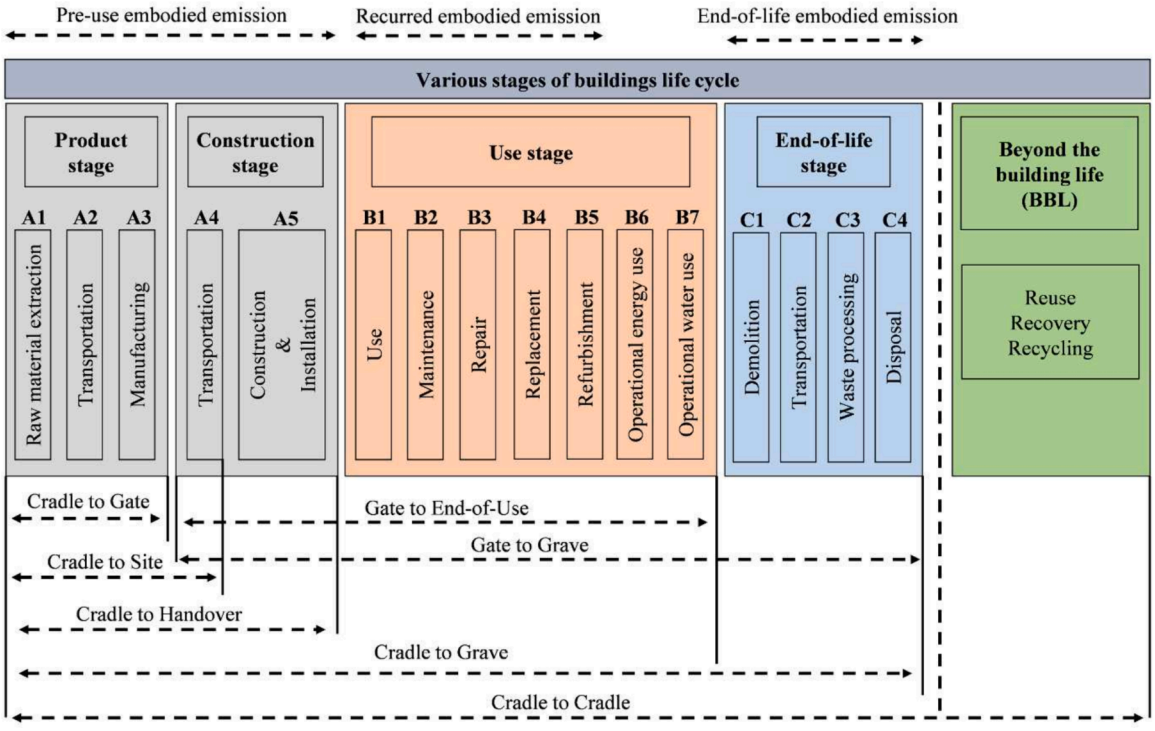

Fig. 3. Various stages of emissions from buildings over their life cycle [67].

cradle to grave, and cradle to cradle [75–78] (shown in Fig. 3). Other life cycle boundaries, such as cradle to operations, have also been adopted [75,79]. Four types of life cycle inventory data are used to calculate life cycle emissions: statistical data, process-based data, economic input–output data, and data derived from a hybrid method (combining the advantages of both process-based and input–output methods). Reference [6] provides details regarding the development of inventory data, their accessibility, and popularity for the evaluation of building life cycle assessments. Life cycle inventory data are not easy to obtain and are accompanied by measurement and calculation uncertainties. Moreover, the inventory data obtained from different methods for the same product are in general not equivalent [80]. Some studies have compiled databases for life cycle carbon inventory data [81,82], including Eco-Invent [83] (primarily used in Western Europe), Athena Impact Estimator for Buildings [84] (used in USA and Canada), USLCI [85] (primarily used in the USA), Australian LCI (Australia), Canadian database [86] (used in Canada), and Inventory of Carbon & Energy [87].

The life cycle carbon emissions from buildings can be formulated as follows [47,72,88]:

$$C = C_{extraction} + C_{manufacture} + C_{on-site} + C_{operation} + C_{demolition} + C_{recycling} + C_{disposal} \quad (1)$$

where C is the carbon-equivalent emissions of all greenhouse gases (in kg CO_2 eq.), and subscripts represent various stages of the building lifetime. Other stages shown in Fig. 3 can also be included in Eq. (1).

The embodied emissions from building materials can be calculated as [72]:

$$C_{m,i} = \sum_{i=1}^{n} CM_i m_i \quad (2)$$

where $C_{m,i}$ is the carbon equivalent emissions (in kg CO_2 eq.) of i^{th} building material; CM_i is emissions factor for material type i (e.g., kg CO_2 eq. per kg or m^3) in different stages such as extraction, manufacture, demolition, waste processing, and disposal; m_i is unit of that material (e.g., kg or m^3), and n is the number of building materials.

In the construction stage, emissions are usually associated with energy used in equipment as well as the transportation of waste materials. Emissions associated with the building construction can be calculated as (in kg CO_2 eq.) [89]:

$$C_{const.i} = \sum_{i=1}^{n} CC_i Q_i + TW \quad (3)$$

where CC_i is the emission factor for energy source type i used at construction (e.g., kg CO_2 eq. per kWh), Q_i is the energy use of source type i (e.g., kWh), n is the number of energy sources used at the construction stage, and the term TW is for emissions related to transportation of waste materials to their designated place for landfill or other recycling processes (in kg CO_2 eq.).

The emissions due to the transportation of materials at the construction stage can be calculated as (in kg CO_2 eq.) [47]:

$$C_t = \sum_{i=1}^{n} CT_i \times m_i \times l_i \quad (4)$$

where CT_i is equivalent carbon emissions of transportation of one unit of i^{th} building material per unit of distance (e.g., kg CO_2 eq. $kg^{-1}{\cdot}km^{-1}$), and l_i is the transportation distance associated with building material type i (km).

The building operational energy use (in kg CO_2 eq.) can be obtained as [47]:

$$C_{OEU} = \sum_{i=1}^{n} CE_i \times e_i \times a \quad (5)$$

where, CE_i is the emission factor for energy source type i per unit of energy use (e.g., kg CO_2 eq. per kWh), e_i is i^{th} energy source consumption (e.g., kWh), a is building lifespan (in years), and n is numbers of energy sources used in that building. Usually, the operational energy use of the first year is assumed to be maintained over the building lifespan.

To report the environmental impact of buildings, many functional units are used to normalize results per a defined unit to produce comparable results. Some examples of functional units for buildings are as follows: gross floor area, heated floor area, net floor area, usable area, gross volume, and heated volume. Other functional units are reported in the literature [72]. Sometimes comparing results from different studies can be difficult because they use different functional units. To present environmental impact findings, the majority of authors opted for the global warming potential (GWP) indicator from the various available impact categories. GWP estimates the impact of all greenhouse gases emissions relative to the impact of 1 kg of CO_2 over the same time horizon. For instance, 1 kg of methane (CH_4) emitted today will have the same damaging effect on the environment as 25 kg of CO_2 emitted today and over the next 25 years.

There are two classes of LCA methods: the static and dynamic. Static LCA disregards temporal variation of parameters, activities, and information over the building lifespan [90], while dynamic LCA considers these variations for a more comprehensive analysis. Dynamic LCA is an emerging research topic and more studies need to be conducted [91]. Some impactful parameters that can change over time are occupants' density and their behaviors, grid emissions intensity, and weather data [90]. For more details, the following research articles can be referred to [92–94].

Following is a summary of the main information discussed so far regarding the LCA of buildings:

- There is no general agreement about the life cycle boundaries to assess the environmental impact of buildings, which makes it difficult to compare the results of different studies.
- Various functional units are used to normalize the environmental impact of buildings, making the comparison of results from different studies difficult.
- Different types of life cycle inventory data are available, which affect the final assessment of the environmental impact of buildings.
- Dynamic LCA is in its early stages, and requires further studies to assess the environmental impact of buildings more accurately over their lifetime.

3.3. Building carbon mitigation

Carbon mitigation strategies related to operational energy use can be classified as either active or passive. Passive strategies can reduce emissions using appropriate building design and operation, nature-based solutions, and local climate [95], while active strategies require mechanical systems, which operate and control the thermal comfort and indoor air quality, and artificial lighting to provide visual comfort [96]. Examples of building-related active and passive strategies to reduce OE from buildings are listed in Table 3.

There are design and construction options to reduce EE from buildings, such as using natural materials (e.g., wood, stone, clay); local and durable materials; reusable, recycled, and waste materials; and avoiding waste [54]. Furthermore, increasing the efficiency of the production process of building materials, including the use of renewable energy sources, can also be another option.

There are additional techniques, such as carbon sequestration and building electrification, that do not fall within the previous categories. As the GHGs emissions intensity of the grids is gradually reduced by using more renewable energy sources such as hydro-power, solar, and wind, building electrification is promising for reaching CNB [97]. Carbon sequestration through vegetation is one viable solution [98], though various other carbon sequestration methods exist. A previous study

Table 3
Active and passive strategies to reduce the operational carbon emissions from buildings.

Approach	Class	Subclass	Types	Information
Active	On-site energy harvesting facilities	Photovoltaic (PV) panel	Polycrystalline (P) Monocrystalline (M) Thin film (Tf)	- Efficiency [101]: (P: 12–15 %, M: 15–25 %, and Tf: 12–15 %) - Price [101]: (P: low, M: high, and Tf: low) - Lifespan [101]: (P: short, M: long, and Tf: short) - PV panels can also be integrated into building façades or roof, (BIPV) systems [102]
		Solar thermal collector	Flat plate Evacuated tube	- Cost payback period: 7–11 years [101] - Thermal efficiency: 60–70 % [103,104] - Can be integrated into building façades or roof [105]
		Wind turbine	Horizontal axialVertical axial Vertical axial Savonius	- Operation dependency: terrain type, local wind, urban environment and building architecture [106] - Vertical axis types are more suitable for buildings and produce less noise [106] - Local power generation can be much higher than the average in urban areas [106] - Debates on whether micro generators are successful in urban environments [106–110]
	Energy-efficient ventilation systems		Direct/indirect evaporative cooling [111,112] Nocturnal cooling [113] Ground source cooling [114] Desiccant cooling [115,116] Heat pumps CCHP system etc.	- Integrated desiccant systems can have 80 % lower energy consumption compared to conventional systems [117] - Variable refrigerant flow (VRF) heat pumps can save up to 70 % energy compared to conventional systems [118] - CCHP systems have energy saving potential of 45 % compared to conventional systems [119] - District heating and cooling can save energy consumption by 30–50 % [120]
	Energy storage system		Storage tanks [121] Aquifer systems Borehole thermal storage [122] Ice storage systems integrated with HVAC systems [123] Phase change materials (PCM) integrated with HVAC systems	- Benefits: Increasing the potential of using renewable energies and reducing energy demand for cooling and heating - Storage tanks can meet 50 % of heating and domestic hot water demands [122] - Aquifer systems can meet about 50–62 % of heating and cooling demands [124,125] - PCM integrated HVAC system energy saving potential: 40–60 % [126]
	Water facilities	Reclaiming water system	Physical treatment Chemical treatment Biological treatment [127,128]	- 50–80 % of wastewater from buildings can be reclaimed [127] - Can reduce non-potable water needs by 50 % [129]
	Others	Efficient lighting and appliances		- LEDs and improved lighting controls greatly reduce lighting energy [130,131] - The growing share of appliances in building energy consumption [132,133]
Passive	Building materials	Envelope material	Insulation materials Phase change materials (PCMs)	- Insulation energy saving potential: 10—80 % [134] Insulation cost payback period: 1–8 years [134] - PCM integrated envelope energy saving: 10–87 % [135] - Increasing thermal resistance of buildings may have adverse effects in energy use [136]
	Building characteristics	Building shape and orientation	–	- The compact shape of buildings has better energy efficiency than other possible shapes [137] - The north-to-south orientation in different climate zones has better energy efficiency [138]
		Envelope-related options	Air tightness Glazing type Window-to-wall ratio (WWR) Window shading/overhangs Skylight	- Their proper design would increase the natural lighting level; however, their impact on building energy can be positive or negative [139] - Smart windows are able to regulate the throughput of radiant solar energy - Smart windows are respectively 50–75 % and 10–30 % energy efficient than static windows without and with blinds [140]
	Passive cooling/heating	Natural ventilation	Stack ventilation (thermal force) Cross ventilation (wind force) ventilation Their combination (hybrid) [141,142]	- Benefits: building energy reduction, better indoor air quality and comfort - Affected by window size and position, number of windows, door position, and building orientation [141,143] - Energy saving potential: 8–78 % for cooling [144,145]
		Thermal Mass		- Energy saving potential: 10 % to 60 % [146]
		Heat recovery ventilation	Crossflow HRV Plate Heat Exchange etc.	- Energy saving potential: 10 % to 60 % [147]
		Green roof and green walls	Green roof [148,149]: Intensive Semi-intensive Extensive Green walls [149]: Green façades Living walls	- Energy saving potential: 22 %-84 % [149] - Can sequester carbon and affect urban microclimate [150] - Other advantages: controlling sound transmission, increasing envelope durability, improving PV panels production, etc. [149]

assessed the carbon uptake potential of trees based on trunk diameter and height [99]. It is shown that urban trees possess a significant capacity to capture GHGs emissions [99,100].

4. Successful case studies of carbon neutrality of single building

It is essential to highlight that out of all the papers we examined and analyzed, we identified 15 case studies specifically focused on the carbon neutrality of individual buildings. In contrast, there were only six case studies that pertained to the carbon neutrality of building complexes. Sections 4 and 5 of our work primarily rely on these case studies.

We carefully selected these case studies from existing literature that demonstrated the potential for achieving life cycle carbon neutrality in both single and multi-building complexes. We prioritized studies that provided explicit simulations (methodology, assumptions, and inputs) along with quantified results to ensure a thorough evaluation of carbon neutral buildings. To ensure diversity among case studies, we considered factors such as building usage types (residential, office, commercial, educational, etc.), structural characteristics (building height/number of stories), geographical locations with distinct climates, varied carbon mitigation options, and the LCA methodologies adopted. This perspective contributes to a detailed understanding of successful carbon neutrality practices within the built environment.

4.1. Data analysis and discussion

There are four categories of carbon neutrality for buildings:

i. 100 % carbon neutrality (CN) based on the operationl emissions (OE);
ii. 100 % CN based on OE, and partial CN based on the embodied emission in materials (EE);
iii. 100 % CN based on EE; and
iv. 100 % life cycle CN based on both OE and EE.

It should be noted that zero-source energy buildings can be technically carbon–neutral buildings if based only on the operation energy use. Our research, however, focuses on building life cycle carbon neutrality, rather than such studies.

Table 4 summarizes case studies of CNBs published from 2011 to 2022 (first column of the table). It includes data on building type, climate type (based on Köppen climate classification [151]), emissions during various building life cycle stages, and the time horizon used in the calculations. Table 5 summarizes various active and passive carbon mitigation strategies used in the case study buildings for achieving carbon neutrality. According to the Köppen climate system [151], different climates can be classified into five broad types as: A (tropical climates), B (arid climates), C (temperate climates), D (continental climates), and E (polar climates).

Additionally, Fig. 4 illustrates the carbon emissions associated with various stages of the life cycle of buildings in these case studies, normalized per floor area and lifespan. Note that this figure is based on studies where data was accessible and quantified values were available. In this figure, negative values depict carbon emissions avoidance resulting from different practices, including the reuse, recovery, and recycling of building materials during the beyond the building life (BBL) stage, on-site electricity generation through PV systems, and other activities such as on-site production using wind turbines and carbon sequestration through trees. The magnitude of carbon emissions avoidance through PV systems significantly outweighs others, indicating its substantial contribution to carbon footprint mitigation.

The key insights from the case studies presented in Tables 4 and 5, along with the data illustrated in Fig. 4, are summarized below:

a) The studies we reviewed consistently demonstrated the feasibility of achieving 100 % life cycle CN if based on the OE [152,156,161,164].

Table 4
Information from case studies of carbon–neutral single buildings.

Pub. Yr	Ref.	Building type[a]					No. of stories	Climate type[b]					Life cycle stages of emissions (same color codes in Fig. 3)										CN[c] category	TH[d] (years)
		R	O	C	E			A	B	C	D	E	A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1-C4	BBL	
2011	[152]	✓					3			✓			✓								✓				i	1
2014	[153]	✓					2				✓		✓						✓		✓				ii	60
2015	[154]			✓			1			✓			✓								✓				iv	30
2016	[155]		✓				2			✓			✓		✓						✓		✓		iv	50
2017	[156]	✓					1				✓										✓				i	1
2018	[157]	✓					2				✓		✓	✓	✓				✓		✓				iv	60
2018	[158]	✓	✓				1–5				✓		✓	✓	✓				✓		✓		✓		ii	60
2018	[159]	✓					2				✓		✓						✓		✓				ii	60
2019	[160]	✓					3			✓			✓		✓			✓	✓		✓	✓	✓		ii	60
2019	[161]	✓					2		✓												✓	✓			i	1
2020	[162]	✓					4			✓			✓	✓	✓	✓				✓	✓				iv	50
2021	[163]				✓		2				✓		✓	✓	✓				✓		✓				iv	100
2021	[164]	✓					6			✓											✓				i	1
2022	[165]	✓					4–15			✓			✓	✓			✓	✓	✓	✓			✓	✓	iii	50
2022	[166]		✓				3			✓			✓								✓				iv	50

[a] Building type: R (residential), O (office), C(commercial), E (educational).
[b] Climate types: A (tropical), B (arid), C (temperate), D (continental), E (polar).
[c] i (100% CN based on the OE), ii (100% CN based on OE, and partial CN based on the EE in materials), iii (100% CN based on EE), iv (100% life cycle CN based on both OE and EE).
[d] Time horizon

Table 5
Carbon mitigation strategies adopted in case studies of carbon–neutral single buildings.

Ref.	Climate type	Mitigations adopted																				
		Active[a]									Passive[b]											
		RPV	FPV	RSC	FSC	PVT	WT	HVC	HW	ES	RW	EM	GR	BS	BO	NV	AT	WR	GL	WS	L	SL	V	LC[c]	Oth[d]
[152]	C	✓		✓			✓	✓								✓				✓					
[153]	D	✓			✓							✓													✓
[154]	C	✓										✓		✓		✓		✓				✓			
[155]	C	✓						✓				✓			✓		✓	✓							
[156]	D	✓		✓			✓	✓																	
[157]	D	✓	✓		✓			✓				✓		✓				✓							
[158]	D	✓		✓				✓																✓	
[159]	D	✓		✓				✓				✓		✓											
[160]	C	✓		✓			✓				✓	✓									✓		✓		
[161]	B	✓										✓					✓	✓			✓		✓		
[162]	C	✓	✓	✓				✓				✓									✓				
[163]	D	✓		✓				✓		✓		✓				✓									
[164]	C	✓	✓	✓		✓		✓				✓							✓	✓					
[165]	C											✓												✓	
[166]	C	✓		✓			✓	✓				✓							✓		✓				

[a] Active strategies: RPV (roof PV panel), FPV (façade PV panel), RSC (roof solar collector), FSC (façade solar collector), PVT (photovoltaic-thermal panel), WT (wind turbine), HVC (heating, ventilation, and air conditioning), HW (hot water), ES (energy storage), RW (water recovery).

[b] Passive strategies: EM (envelope materials), GR (green roof/wall), BS (building shape), BO (building orientation), NV (natural ventilation), AT (air tightness), WR (window-to-wall ratio), GL (glazing), WS (window shading/overhangs), L (lighting), SL (skylight), V (vegetation).

[c] LC: low-carbon materials.

[d] Other methods: All-electric buildings, carbon sequestration etc.

However, as OE decreases due to the adoption of active and passive solutions, the contribution of EE increases over time [70,153,167]. According to Fig. 4, EE accounts for approximately 50 % of the total life cycle carbon emissions, ranging from 27 % to 75 %. These emissions exhibit a wide range, measured in kg CO_2 eq.·m^{-2}·$year^{-1}$, with a minimum of 5, a maximum of 48, and an average of 22. These values are significantly lower than those reported in the literature for non-carbon–neutral buildings [6]. This highlights the importance of including EE associated with mitigation measures like PV panels, solar thermal collectors, and HVAC systems within the system boundary [163,168]. Research findings, as seen in reference [162], indicate that PV systems may take several years, such as 7 years, to offset their own embodied carbon. Furthermore, the full compensation for the EE of the building and PV systems may require even much more time, such as 28 years. Despite these initial EE investments, PV systems are promising in achieving carbon neutrality in the long term. Similar trends are observed in other references [159].

b) Some studies claimed that life cycle CN can be reached at 100 % based on the OE, but only 65–75 % based on the EE [153,158–160]. Another study showed that reaching the 100 % life cycle CN based on the EE is feasible through major renovations [165]. The on-site renewable energy production from PV panels is critical to reaching CN in buildings [157]. The case studies with small ratios of roof surface area to building volume failed to reach CN [154]. A proposed solution was to increase the area of the south-facing façades for PV panels installation, since roof PV panels were not sufficient to reach CN [154]. Other possible solutions include the installation of solar panels integrated into building façades, which can provide additional opportunities for generating electricity [157,162,164].

c) At the most ambitious level, it was shown that the goal of 100 % life cycle carbon neutrality (CN) was feasible [154,155,157,162,163,166]. The literature review highlights that achieving CNB is ambitious, necessitating both on-site renewable energy production and emissions reduction across all building life cycle stages. Some research results may have practical challenges when applied to real-world situations. Reference [166], for example, indicated that achieving carbon neutrality for a three-story building with an area of 4300 m^2 would necessitate 7500 m^2 of PV panels. This extensive PV installation would exceed the building's footprint, presenting practical challenges, especially in urban areas with limited space. There was a similar challenge in another reference [161], where achieving CNB was highly dependent on trees' long-term capacity to sequester carbon. As these examples illustrate, practicality and feasibility aspects must be considered alongside ambitious objectives related to CNB.

d) In previous studies, CNBs have been shown to have promising future prospects, but their viability depends on the future trend in the grid's emissions intensity [159,162,163]. The amount of on-site renewable energy exported to the grid has a relatively small mitigation effect when the grid emissions intensity is low, compared to a grid with higher emissions intensity. As a result, on-site renewable energy production cannot completely offset emissions, especially the EE. In regions with low grid emissions intensity, stricter approaches are required, and reaching CN will become more difficult.

e) Case studies have primarily focused on residential and low- to mid-rise buildings, which face significant challenges in their pursuit of carbon neutrality, considering both OE and EE. High-rise buildings, with their substantial EE, pose an even greater challenge in this regard. Achieving CN is significantly more difficult when EE is included [153]. In particular, building elements like structure, envelope, and foundation contribute significantly to EE, especially in the context of multi-residential buildings [158,164,169]. Research findings indicate that it typically takes 20 to 50 years to offset total life cycle emissions from buildings using on-site production methods [154,162,165,166] or carbon sequestration through trees [161].

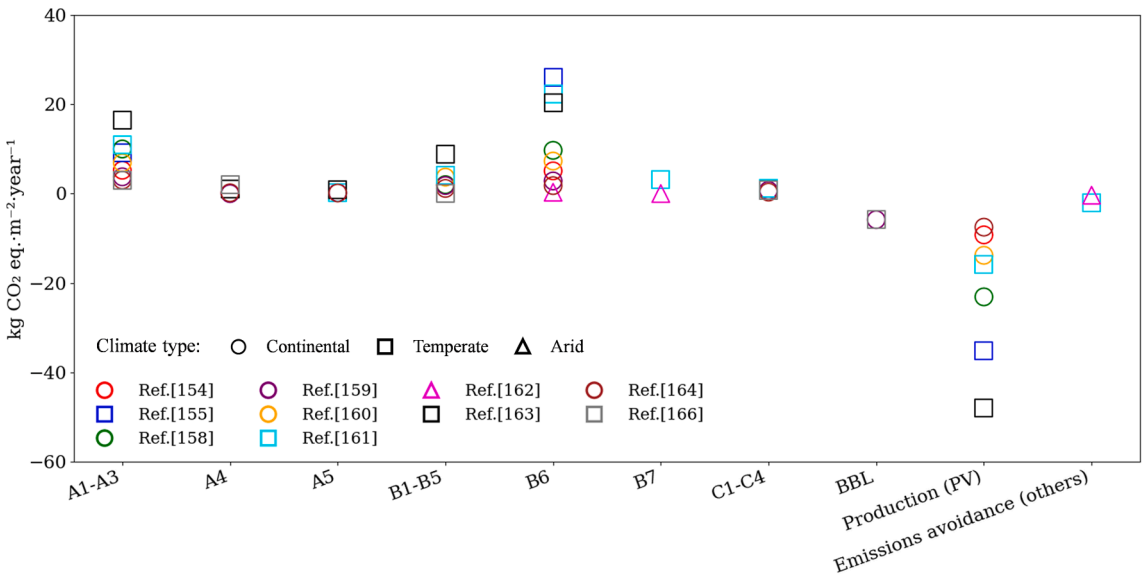

Fig. 4. Normalized carbon emissions from various stages of life cycle of carbon neutral building case studies along with emissions avoidance activities.

Noted that trees can both sequestrate carbon and reduce heating loads through shading on façades, thereby reducing associated OE. As a result of these insights, it has become clear that achieving carbon neutrality in the built environment is a complex undertaking.

f) Climate types can have a significant impact on the CN performance of buildings [155]. Achieving CN may vary from region to region, and the mitigation solutions required may also differ. There are no general rules that can be established with respect to climate types. Successful case studies of CNBs are reported for warm temperate and continental/snow climates. There are no studies for equatorial climates with intense solar radiation, high temperature and humidity, and there is only one study for arid climates with intense solar radiation, high summer temperature, and low relative humidity. The feasibility of reaching the goal of CNB in equatorial and arid climates is still under question.

g) Buildings and landscape design can have a significant effect on buildings' operational energy consumption and carbon neutrality [161]. For example, optimizing the building shape can lower material usage, and thus the EE, reduce operational energy consumption by controlling solar exposure on façades, and increase on-site electricity production via PV panels by maximizing available area. Reference [157] suggested the most appropriate building shape for a constant building volume that maximizes the on-site electricity production from PV panels, maximizes daylight, minimizes the amount of materials used, and minimizes the OE.

h) The energy use intensity (EUI) values observed in the case studies of carbon–neutral buildings (CNBs) range from 21 to 110 $kWh{\cdot}m^{-2}{\cdot}year^{-1}$, with an average EUI of 60 $kWh{\cdot}m^{-2}{\cdot}year^{-1}$. In contrast, non-carbon–neutral buildings exhibit significantly higher EUIs, with reported values ranging from 147 to 814 $kWh{\cdot}m^{-2}{\cdot}year^{-1}$, as evidenced by reference [136]. Moreover, reference [170] highlighted that non-carbon–neutral office buildings typically fall within the range of 300 to 650 $kWh{\cdot}m^{-2}{\cdot}year^{-1}$, while non-carbon–neutral schools and hotels have average EUIs of 50 to 200 $kWh{\cdot}m^{-2}{\cdot}year^{-1}$ and 270 to 427 $kWh{\cdot}m^{-2}{\cdot}year^{-1}$, respectively. Recent findings from reference [171] suggest that net-zero energy buildings maintain an average EUI of approximately 57 $kWh{\cdot}m^{-2}{\cdot}year^{-1}$. These comparisons emphasize that the EUIs of CNBs are significantly lower than those of both non-carbon–neutral and zero-energy buildings. For the calculation of building energy use and associated EUI and OE, most studies have used software such as EnergyPlus [154,157,161], TRNSYS [156,164], SIMIEN [153,158,163], IDA-ICE [158,159], IES [155], and DEROB-LTH [162].

i) Some studies did not account for all life cycle emissions stages. For example, reference [155] conducted their life cycle emissions analysis while including stages C1-C4, whereas reference [157] included stage A4 but omitted stages C1-C4. Consequently, comparing the findings of these case studies poses challenges due to their utilization of different lifetime stages, reporting results with distinct functional units, and variations in building usage types and climates. Furthermore, the scarcity and uncertainty surrounding life cycle inventory data have led most authors to exclude specific building life cycle stages when assessing carbon emissions. Stages A1-A3, A4, A5, B4, and B6 are commonly included in these studies. Reference [160] extended their analysis by incorporating emissions related to occupant transportation, in addition to the life cycle stages outlined in Table 4. The types of inventory data used for the life cycle carbon assessment are sometimes not disclosed, further complicating the comparison of results across studies, while references [162,163,165] explicitly detailed their inventory data within their studies.

j) The majority of studies considered active mitigation measures such as PV panels, solar thermal collectors, and energy-efficient HVAC systems. CNBs require low-energy HVAC systems, particularly in regions with high cooling demands [155]. A study conducted in the US on commercial buildings found that HVAC systems accounted for an average of 32 % of total site energy use [172]. Another study by European Union estimated that this share could reach 65 % for residential buildings [173]. Furthermore, building envelope insulation was a popular passive mitigation strategy, along with optimizing the window-to-wall ratio (WWR) and utilizing energy-efficient lighting systems such as LEDs and occupant-sensitive control systems.

k) Most of the previous studies have adopted static LCA to assess the CN in buildings. Only some scenarios of future grid emissions intensity [159,162–164] and some scenarios of improvements in future technologies, such as PV panels, have been studied [153,158,159,163].

l) Life cycle cost analysis should be conducted with life cycle carbon assessments. Reference [164] concluded that there are cost-effective mitigation solutions for reducing building emissions, while reference [165] found that some mitigation scenarios are not currently cost-effective. It has been argued, for example, that building renovation using specific materials is capable of decarbonizing buildings,

however their current high costs make them less practical in comparison with other alternatives [174].

4.2. Knowledge gaps in the literature regarding the carbon neutrality of single building

It was discovered that the knowledge gaps can be classified into three categories: building-related information (e.g., building usage type, height, etc.), carbon mitigation methods (e.g., the simultaneous implementation of different types of mitigations and universally accepted frameworks for LCA), as well as methodology challenges (e.g., transparency in inventory data and uncertainty analysis, etc.). Details about these classes of knowledge gaps are discussed below:

a) Building-related information
- High-rise buildings pose greater challenges in terms of carbon neutrality (CN) due to their smaller footprint as compared with the total conditioned floor area, which limits the amount of renewable energy produced on-site relative to the building's energy needs. One potential solution is to maximize on-site production by incorporating PV panels into the building's façade, in addition to the roof area. As urban downtown areas often contain many high-rise buildings, further research is needed.
- A majority of previous studies have primarily focused on specific types of buildings and geographic locations, which can limit the relevance of their findings to broader contexts. Many factors such as climate type, usage type of buildings, and location of buildings (e.g., dense high-rise buildings in downtown areas) affect the type and level of mitigation scenarios required to reach CN. For example, buildings in cold climates require more energy for heating, while buildings in hot climates require more energy for cooling, and different building usage types have distinct energy usage patterns and requirements. In order to ensure practicality and wide-reaching implications, future research should include a diverse range of building types and geographical regions.
- There are not enough case studies to answer the following questions: "Is it possible to achieve carbon neutrality in all usage types of buildings?" and "Is carbon neutrality of high-rise buildings feasible?"

b) Carbon mitigation methods
- It has been shown that by minimizing the amount of materials used, maximizing recycled and local materials, and using low-carbon materials, it is feasible to reach the CN in terms of EE [165]. Further studies are needed on the topic.
- Various energy-efficient heating and cooling technologies were applied in these case studies (Table 5). However, many other active and passive mitigation technologies remain unexplored. Further study will be necessary to determine their impact on the achievement of carbon neutrality.
- There have been a few studies that have examined the life cycle cost of carbon mitigations [156,162,164–166].
- The effects of dynamic inputs over the lifespan of buildings have not been accounted for in the assessment and design of carbon–neutral buildings. Such inputs are the forecasts of (i) weather data, (ii) EE of new materials for renovation, (iii) global warming potential of GHGs, (iii) changes in human behavior, and (iv) natural gas use. The dynamic LCA is still not addressed properly.
- There is no reliable or accessible life cycle inventory data for building materials in several regions [81]. To facilitate reliable research on the carbon neutrality of buildings, organizations should make available life cycle inventory data and construction material information.
- At present, a universally accepted framework for assessing carbon neutrality in the context of buildings is conspicuously absent. This is evident from the variations observed in life cycle boundaries and building lifespans considered across different references [167]. Additional research is essential to advance the field of CN in buildings.

c) Methodology challenges:
- Except for some of the studies listed here [162,163,165], most of the above studies failed to disclose transparently the sources of their data to ensure research transparency and reproducibility. Furthermore, the discussion of data uncertainty and its potential impact on research outcomes is an essential aspect that is often overlooked. The uncertainty analysis is essential for quantifying the degree of variability and reliability associated with simulation results. It is possible to undermine the scientific credibility of proposed solutions by neglecting these aspects. References [162,163] did a preliminary uncertainty analysis on the input data, and this practice should be further developed and continued in the context of building life cycle carbon assessment.
- The optimization approaches commonly used in references [157,164,165] often present problems when it comes to replicability in terms of time and complexity of the workflow, especially for a large number of building designs. In addition, optimization processes should be adapted to account for construction challenges and associated costs to ensure that CNBs remain practical and cost-effective compared with conventional ones.
- Although some of the above studies have acknowledged the mismatch between on-site energy production and demand, references [153,157] only briefly discussed grid integration challenges. A more comprehensive examination of grid-related issues and on-site exploration would significantly enhance the practicality of the results. Additionally, none of the studies mentioned above included simulations of on-site energy storage. In some scenarios, surplus energy generated cannot be efficiently exported to the grid due to grid complexities. By utilizing batteries, it may be possible to store this surplus energy for use or export during peak hours. These studies can be enhanced by incorporating battery operation modeling in terms of practical points of view.
- The design of CNBs is undoubtedly crucial, but achieving carbon neutrality by 2050 requires not only new construction, but also renovation and upgrade of existing buildings. While previous studies have predominantly concentrated on the design of new CNBs, there has been limited attention given to retrofitting existing buildings to achieve carbon neutrality [162–166]. Retrofitting existing buildings for carbon neutrality presents a greater challenge compared to designing new CNBs.

5. Successful cases toward carbon neutrality of multi-building complex

5.1. Data analysis and discussion

Studies focusing on the life cycle carbon assessment of multi-building complexes, particularly at city level, are quite limited in number. Table 6 summarizes key information from case studies that addressed the carbon neutrality of buildings within multi-building complex levels.

The information presented in Table 6 is summarized as follows:

a) Only a limited number of studies have employed detailed transient energy modeling to evaluate OE and city-level EE for multi-building complexes, city neighborhoods, and cities [181]. Only few studies have specifically addressed the carbon neutrality of smaller multi-building complexes, such as university campuses, focusing solely on OE and neglecting EE. It has been shown that CN based only on the OE could be obtained.
b) Reaching carbon neutrality is not currently economically attractive in all regions due to the low cost of fossil fuels or electricity [178]. Updated policies are necessary to motivate the building industry to become as energy efficient as possible. It is argued that the CN cannot

Table 6
Information from case studies of carbon–neutral multi-building complex.

Year	Ref.	Region	Scale[a]	Boundary of carbon LCA[b]					Mitigation strategies[c]														
				YOE	YOW	LOE	OTE	EEM	PV	SC	WT	DH	HR	HP	CCHP	RW	SS	EI	BS	IW	GR	EL	PE	EV	FE	OB
2022	[175]	Australia	CN			✓	✓	✓	✓															✓		✓
2022	[176]	USA	HC	✓	✓				✓		✓										✓					
2020	[177]	USA	UC			✓			✓				✓	✓		✓						✓	✓	✓	✓	
2019	[178]	USA	UC			✓			✓	✓		✓		✓	✓		✓						✓			
2017	[179]	India	UC	✓					✓																	
2017	[180]	Germany	UC	✓					✓			✓			✓			✓	✓	✓		✓				

[a] Scale: CN: City neighborhood, HC: Hospital complex, UC: University campus.
[b] Boundary of carbon LCA: YOE: Yearly operational emissions of energy use, YOW: Yearly operational emissions of water use, LOE: Life cycle operational emissions of energy use, OTE: Occupants traveling emissions, EEM: Embodied emissions of mitigations.
[c] Mitigation strategies: PV: PV panel, SC: Solar collector, WT: Wind turbine, DH: District heating, HR: Heat recovery in HVAC systems, HP: Heat pump, CCHP: Combined heat and power, RW: Rainwater harvesting, SS: Seasonal storage, EI: Envelope insulation, BS: Building shape, IW: Improved window, GR: Green roof, EL: Efficient lighting and occupant-sensitive sensor, PE: Purchasing clean electricity generated off-site, EV: Electric vehicle, FE: Full electrification, OB: Occupants behavior (low carbon behavior).

be achieved currently without purchasing off-site clean energy at multi-building complex level [177].

c) Implementation of active and passive carbon mitigation measures increases the share of EE and causes a delay in reaching CN. Thus, the building energy-efficiency is not a quick response to CN, rather they are a part of long-term plan [175]. Moreover, as a result of the best building design, such as the optimized building shape, and shading interaction of façades on each other or shading effects by neighbor buildings, the energy use for cooling and heating can be further reduced [180].
d) The on-site electricity generation through PV panels is the key to reaching the CN [175,176,179]. Nonetheless, the mismatch between supply and demand of electricity poses a challenge when massive on-site production is undertaken [178]. Besides, heat pumps and combined heat and power systems are both promising technologies for achieving carbon neutrality in multi-building complexes. These systems can be integrated with low-temperature renewable energy sources like solar and geothermal [177,180].
e) People must be sensitized to adopt low-carbon behavior, as it impacts building OE [175]. Examples of low-carbon habits are [182,183]: energy-efficient practices (e.g., turning off lights when not in use), efficient use of heating and cooling systems (e.g., properly managing thermostat settings), responsible use of water, waste management, and low-carbon transportation choices.

5.2. *Knowledge gaps in the literature regarding carbon neutrality of multi-building complex*

The knowledge gaps discussed in section 4.2 for single buildings apply to multi-building complex and larger scales as well. In general, building complexes and bigger areas such as cities have challenges in conducting life cycle carbon assessments due to limited building characteristics data, local weather data, and necessary software framework to handle these wide range of data, etc. Detailed critical knowledge gaps regarding the carbon neutrality of multi-building complexes are listed below:

a) A limited number of studies have examined the life cycle emissions of buildings at larger scales, such as multi-building complexes and cities, with a focus on the use stage. Full life cycle carbon assessments in these contexts are rare due to challenges in assessing construction material mass for EE evaluations. Additionally, dealing with larger scales, like cities, poses challenges in accessing data related to building characteristics, such as window-to-wall ratio, glazing type, envelope U-value, occupants' schedule, HVAC system type, and energy source used. Consequently, most studies have primarily conducted life cycle carbon assessments for single buildings [184]. Further research is required to generate life cycle carbon results for multi-building complexes and cities. This entails creating detailed archetypes to model the energy performance of buildings using more realistic building-related data and identifying the construction materials and their associate EE.
b) To accurately model building energy performance in larger areas and the associate EE, another challenge arises due to the influence of nearby buildings on the incident solar radiation reaching building façades. Research has shown that shading effects from neighboring buildings can significantly impact both daylighting efficiency and building energy consumption [185]. However, dynamically modeling these shading effects from surrounding buildings in large areas, such as cities, is computationally intensive and time-consuming [186]. Therefore, there is a need for new tools to rapidly calculate shading effects in urban areas and provide inputs for urban energy building modelers.
c) In addition to the challenges mentioned earlier, accurate building energy modeling and the assessment of OE also require high-resolution weather data or actual weather data specific to the

location of the building. Neglecting to account for downscaled or urban microclimate weather data (e.g., temperature and wind profile), can result in an underestimation of building energy consumption [187]. Various factors like vegetation and land surface materials such as asphalt and concrete can affect the urban micro-climate. While high-resolution weather data can improve the accuracy of energy performance simulations, obtaining such data can be a daunting task. Accessing real-time and localized weather data, especially at the level of detail needed for precise modeling, can be limited or require significant resources. This challenge is further exacerbated when dealing with larger areas, like cities, where variations in microclimates and weather patterns can be substantial. In future works, high-resolution weather data or weather data obtained from microclimate simulations or local weather stations need to be incorporated.

d) The integration and interoperability of data is another challenge. To create a holistic life cycle carbon assessment, it may be necessary to integrate data sources and tools. This can include data on building design, construction materials, occupancy patterns, energy consumption, urban microclimate, and more. The integration and utilization of these diverse datasets and tools for modeling purposes can prove to be a significant challenge, especially when dealing with larger scales such as urban areas. A multi-scale framework for standardization, compatibility, accessibility, and modeling is a potential solution to address this challenge in the future.

e) Different carbon mitigation approaches should be studied when conducting life cycle carbon assessment of buildings in cities, such as (i) the modification of building envelope, (ii) the use of energy efficient HVAC systems with heat pumps, (iii) green roofs and walls, (iv) roof or façade PV panels, and (v) building wind turbines. Only a few attempts have been made in this direction.

f) Since the climate greatly influences the pathway to the CNB, studies of multi-building complexes in regions of different climates should be undertaken.

g) On-site generation of electricity from renewable sources is one of the most important solutions for achieving CN at multi-building complex level, although it poses numerous challenges, especially when large scale buildings generate electricity on-site [188–191]. Further interdisciplinary studies are required to consider the impact on the electricity grid when on-site electricity production is implemented massively.

h) The long-term impacts of carbon mitigation measures on weather data in cities, e.g., trees, vegetation, PV panels, etc., and the relationship with the life cycle operational emissions are not studied. The vegetation contributes to carbon sequestration, affects the urban microclimate, and reduces the building heating and cooling energy use in urban areas [98,192].

i) The morphology of buildings and structures in cities, which change over time, can be predicted [193,194]. Thus, in order to conduct a more reliable life cycle carbon assessment of buildings in larger scales such as cities, future urban patterns and land covers need to be included as inputs. So it is essential to develop advanced technologies, such as digital twins, digital constructions, and large-scale LCAs for achieving CN at both single and multi-building complex levels.

6. Conclusions

Striving for a carbon–neutral building stock by 2050 is crucial in addressing the adverse effects of global warming, considering that buildings contribute nearly 37 % to the total energy-related CO_2 emissions. Our review investigated successful case studies asserting the feasibility of achieving carbon neutrality in buildings at both single and multi-building complex levels across various dimensions, such as building characteristics, climate types, mitigation measures, lessons learned, limitations in studies, and ideas for future research works. Our aim was to unravel the complexities surrounding carbon neutrality with the fundamental question we initially posed: "Is it possible to achieve carbon neutrality at both single and multi-building complex levels?"

Our work synthesizes and classifies valuable insights from existing literature and contributes to shaping the trajectory of future research by shading lights on limitations and existing knowledge gaps. Present review involves a critical examination of methodologies, identification of assumptions, and exploration of overlooked factors, providing a basis for refining and advancing current knowledge and approaches.

We summarize the main findings of our review in three categories: current research findings, recommendations for improving research trend, and future research directions, as follows:

Current research findings:

- Reaching carbon neutrality of single buildings is feasible but is challenging as multiple carbon mitigation measures need to be incorporated and are not always cost-effective. The energy use intensity (EUI) of carbon neutral buildings is significantly lower than those of non-carbon–neutral.
- Carbon neutrality in buildings is influenced by climate types, necessitating tailored mitigations for each specific climate. Warm temperate and continental snow climate types are mostly studied, and there are few or no case studies for equatorial and arid climates.
- It is more difficult to reach carbon neutral buildings in regions where the emissions intensity of the electricity grid is low.
- For the assessment of carbon neutrality, only small multi-building complexes have been introduced, such as university campuses.
- Photovoltaic (PV) systems are being thoroughly examined as a sustainable and long-term approach towards achieving carbon neutrality, acknowledging that their initial embodied emissions make them more of a gradual than an immediate solution.
- Heat pumps and combined heat and power systems, when combined with low-temperature renewable energy sources like solar and geothermal, hold promise for achieving carbon neutrality in multi-building complexes.

Recommendations for improving research trend:

- Currently, there are no universally recognized standards for the design of carbon–neutral buildings. The establishment of widely accepted guidelines could contribute to generating more concrete and comparable results in this field.
- In many regions, accessible and reliable life cycle inventory data are not available. To support credible research on the carbon neutrality of buildings, it is crucial for public data on life cycle inventory and construction materials to be readily available.
- Integrating data sources and tools may be essential to develop a comprehensive life cycle carbon assessment. A potential solution to address this challenge could involve implementing a multi-scale framework focused on standardization, compatibility, accessibility, and modeling.

Future research directions:

- Carbon neutrality in the downtown areas of cities demands further rigorous approaches. Case studies for the assessment and design of high-rise carbon neutral buildings are very rare; thus, more studies need to be undertaken.
- Case studies claiming carbon neutrality of multi-building complex are limited in number, and there are no case studies for cities. Future research needs to focus on the carbon neutrality of larger areas.
- Achieving carbon neutrality by 2050 requires both new construction and the retrofitting of existing buildings. Prior studies mainly focused on designing new carbon–neutral buildings; thus, increased attention should be directed towards retrofitting existing buildings.
- The long-term impacts of carbon reduction measures on life cycle operational energy use and the associated carbon emissions have not

been examined. Comprehensive studies should address this knowledge gap.
- The morphology of buildings and structures in cities evolves over time. Future research should incorporate forthcoming urban patterns and land covers as inputs in life cycle carbon assessments to produce more reliable results and recommendations.

In summary, achieving carbon neutrality at single and multi-building complex levels still need a lot more research activities and efforts while the horizon of success looks promising, and the work should be conducted systematically, cooperatively, and multi-disciplinarily.

CRediT authorship contribution statement

Saeed Rayegan: Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Liangzhu Leon Wang:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing. **Radu Zmeureanu:** Formal analysis, Project administration, Supervision, Writing – original draft, Writing – review & editing. **Ali Katal:** Methodology, Resources, Visualization, Writing – review & editing. **Mohammad Mortezazadeh:** Investigation, Resources, Writing – review & editing. **Travis Moore:** Conceptualization, Resources, Writing – review & editing. **Hua Ge:** Funding acquisition, Methodology, Resources, Writing – review & editing. **Michael Lacasse:** Funding acquisition, Resources, Writing – review & editing. **Yurong Shi:** Investigation, Visualization, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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