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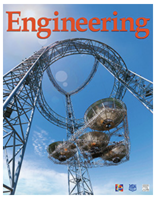

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Life-Cycle Carbon Emissions (LCCE) of Buildings: Implications, Calculations, and Reductions

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ABSTRACT

The life-cycle assessment method, which originates from general products and services, has gradually come to be applied to investigations of the life-cycle carbon emissions (LCCE) of buildings. A literature review was conducted to clarify LCCE implications, calculations, and reductions in the context of buildings. A total of 826 global building carbon emission calculation cases were obtained from 161 studies based on the framework of the building life-cycle stage division stipulated by ISO 21930 and the basic principles of the emission factor (EF) approach. The carbon emission calculation methods and results are discussed herein, based on the modules of production, construction, use, end-of-life, and supplementary benefits. According to the hotspot distribution of a building's carbon emissions, carbon reduction strategies are classified into six groups for technical content and benefits analysis, including reducing the activity data pertaining to building materials and energy, reducing the carbon EFs of the building materials and energy, and exploiting the advantages of supplementary benefits. The research gaps and challenges in current building LCCE studies are summarized in terms of research goals and ideas, calculation methods, basic parameters, and carbon reduction strategies; development suggestions are also proposed.

1. Introduction

As part of global efforts to address climate change, a considerable amount of research has investigated the carbon emissions of buildings during construction and operation. After the industrial revolution, mechanized production activities by humans increased rapidly, resulting in a significant increase in greenhouse gas (GHG) emissions and a gradual deterioration of the dynamic balance between the emissions and natural absorption of GHGs. To address this issue, the Kyoto Protocol, which was adopted in Japan in 1997, formally obliges signatories to control their GHG emissions. In November 2021, the United Nations (UN) Framework Convention on Climate Change conducted the 26th UN Climate Change Conference of the Parties and completed the implementation rules of the Paris Agreement, which stipulates "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels" as a global mission [1]. In this way, a global temperature target was legally enacted for the first time [2]. According to a report from the UN's Intergovernmental Panel on Climate Change (IPCC) in 2018, achieving a 1.5 °C target requires a reduction of 40%–50% in global carbon emissions as compared with the levels in 2010, which must be achieved by 2030; additionally, carbon neutrality should be achieved by 2050 [3]. According to a report from the United Nations Environment Programme (UNEP), the global construction sector constituted 37% of the total carbon dioxide (CO_2) emissions in 2020, including 27% from building operations and 10% from the production of building materials. Among the 27% from building operations, 9% were direct emissions, whereas the remaining 18% were indirect emissions from electricity and commercial heat consumption [4].

The IPCC classifies sources of carbon emissions into four sectors: industry, electricity, construction, and transportation. To

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provide statistics regarding carbon emissions at the macro level, emissions from building operations, including direct and indirect emissions, are classified as coming from the construction sector, whereas emissions from the production of building materials are generally classified as coming from the industrial sector. However, a building's life-cycle carbon emissions (LCCE) include both the production of building materials and their consumption in the construction sector. The production and transportation of building materials are determined by the demand of the construction sector. Therefore, measures to reduce building LCCE should account for the direct and indirect emissions generated by building operations, as well as the emissions generated by the production and transportation of building materials.

Investigating building LCCE is an effective approach for identifying carbon emission hotspots and formulating carbon reduction plans. However, the methods currently used in various studies vary significantly, and comparability between different cases is low. In some cases, completely opposite conclusions can be inferred from the same question, which hinders the formation of a consensus on the carbon emission intensity of typical buildings and the formulation of future carbon reduction goals. Therefore, this study was conducted to obtain a general idea regarding the present research progress pertaining to building LCCE (i.e., implications), the methods used to calculate building LCCE (i.e., calculation methodologies), and the methods used to realize low carbon emissions (i.e., carbon reduction strategies) via a literature review. In addition, this study summarizes current research gaps and challenges and proposes corresponding development suggestions (Fig. S1 in Appendix A).

2. The reviewed studies

In this study, 161 published reports pertaining to studies on buildings' carbon emissions are reviewed, including 85 building LCCE studies, 69 building embodied carbon emissions (ECE) studies, and seven building operational carbon emissions (OCE) studies. The calculation of building life-cycle stages and the sub-items of the cases are introduced in Section 3.1.2. The 161 studies involved 826 calculation cases. The geographical location, climate type, building function, structure, number of floors, floor area, and expected service life of the case studies are summarized in Fig. S2 in Appendix A.

3. Implications of building LCCE

3.1. Building life-cycle assessment

3.1.1. Differences and correlations among life-cycle assessment, life-cycle energy assessment and life-cycle carbon emission assessment

Concepts related to life-cycle carbon emission assessment (LCCEA) include life-cycle assessment (LCA) and life-cycle energy assessment (LCEA) [5]. LCA, which was the earliest proposed method, has been applied to the construction industry and other related industries [6]. In a building system, an LCA is performed to evaluate all resource loads, including land, energy, water, and materials, as well as environmental loads, including global warming, ozone depletion, acidification, eutrophication, and photochemical smog. Both LCEA and LCCEA can be regarded as constituents of the LCA. In particular, LCEA focuses primarily on energy consumption at the input, including the total energy demand, primary energy consumption, and renewable energy utilization [5], whereas LCCEA focuses on the environmental effect at the output, particularly GHG emissions that contribute to global warming (Fig. 1).

3.1.2. Categorization of a building's life-cycle stages

ISO 21930 was issued by the International Organization for Standardization (ISO) in 2017 as a formal international rule for building LCA [7]; it specifies the principles, codes, and requirements for formulating an environmental product declaration for construction activities, establishes product category rules for construction products and services, and proposes calculation rules for life-cycle inventory analysis and life-cycle impact assessment in environmental product declaration reports. ISO 21930 categorizes the entire building life cycle into five modules or stages and 17 sub-stages: building material production (A1–A3), construction (A4–A5), use (B1–B7), end-of-life (C1–C4), and supplementary information beyond the system boundary (D). This provides a basis for the classification of life-cycle stages and the definition of system boundaries for calculating buildings' LCCE (Fig. 2).

The D module involves the potential net benefits from reuse, recycling, and/or energy recovery beyond the system boundary. For ease of explanation, the following discussion considers only the "recycling of building materials" as a representative. In terms of building LCCE calculations, this module has important carbon reduction benefits for buildings that use recyclable materials. The recycling of building materials occurs between two building life cycles: the end of the previous life cycle and the beginning of the next one. This particular location creates the problem of allocating the carbon reduction benefits between the two cycles involved. This problem is mentioned to some degree in existing LCA-related standards/guidelines, but a uniform method for allocating the benefits is still lacking.

In essence, recycled building materials refer to recyclable waste generated in the previous life cycle that can be used as the raw material for the next cycle. The World Resources Institute and the World Business Council for Sustainable Development proposed a method that allocates all benefits to the previous cycle and another method that allocates all benefits to the later cycle [8]. The European Commission proposed a method for the Product Environmental Footprint that allows the environmental benefits of material recycling to be divided equally in half for each of the two life cycles [9]. Jiang et al. [10] proposed an improved method that could distinguish between mixed recycling and independent recycling routes, and demonstrated its feasibility in an LCA of steel production. In this approach, the differences among various recyclable materials should be considered.

3.1.3. Integrity of building life-cycle stages in the reviewed studies

The statistical results showed that ISO 21930 was not strictly implemented in the reviewed studies. In fact, adjustments were performed based on factors such as calculation goals and data availability for specific cases. Among the 85 LCCE studies, only seven (8.2%) involved calculations that included ECE (A1–A3, A4–A5, B1–B5, and C1–C4), OCE (B6–B7), and supplementary benefits (D), whereas 23 (27.1%) involved calculations for all stages except module D. Among the 69 ECE studies, three completely considered the four stages of ECE, whereas only two considered module D in addition to the aforementioned stages (Table 1 [11–173]).

3.2. Carbon emissions

3.2.1. GHG types and building emission sources

In general, carbon emissions include only emissions of CO_2; however, the current practice is to refer to GHG emissions. The IPCC distinguishes dozens of GHGs and ensures that they are supplemented and updated [174]. The Kyoto Protocol stipulates six GHGs that exert significant effects: CO_2, methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs),

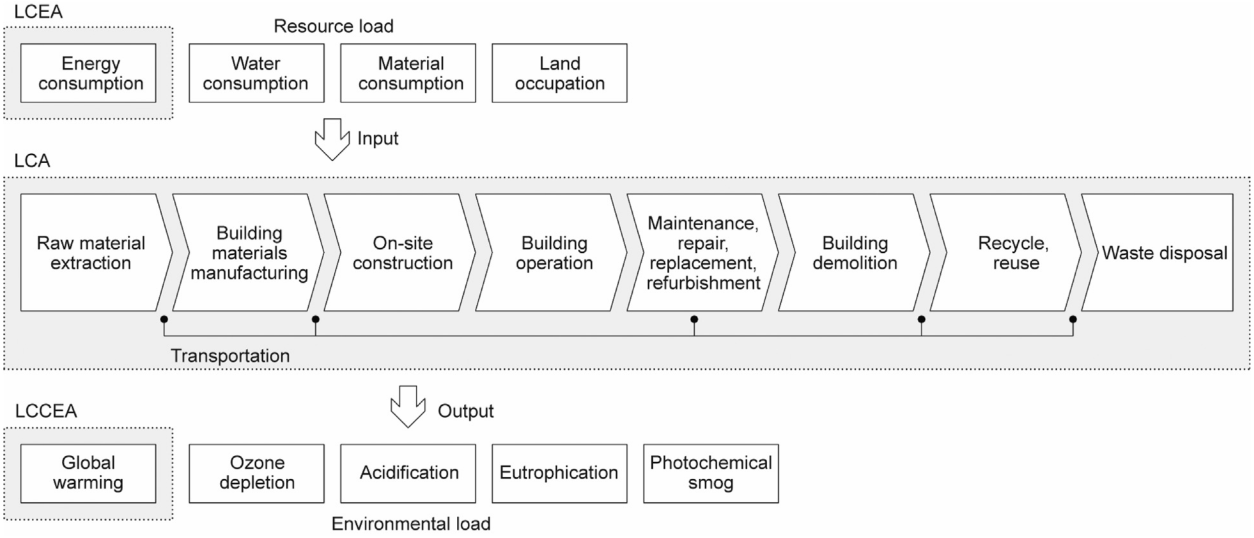


Fig. 1. Relation among the LCA, LCEA, and LCCEA.

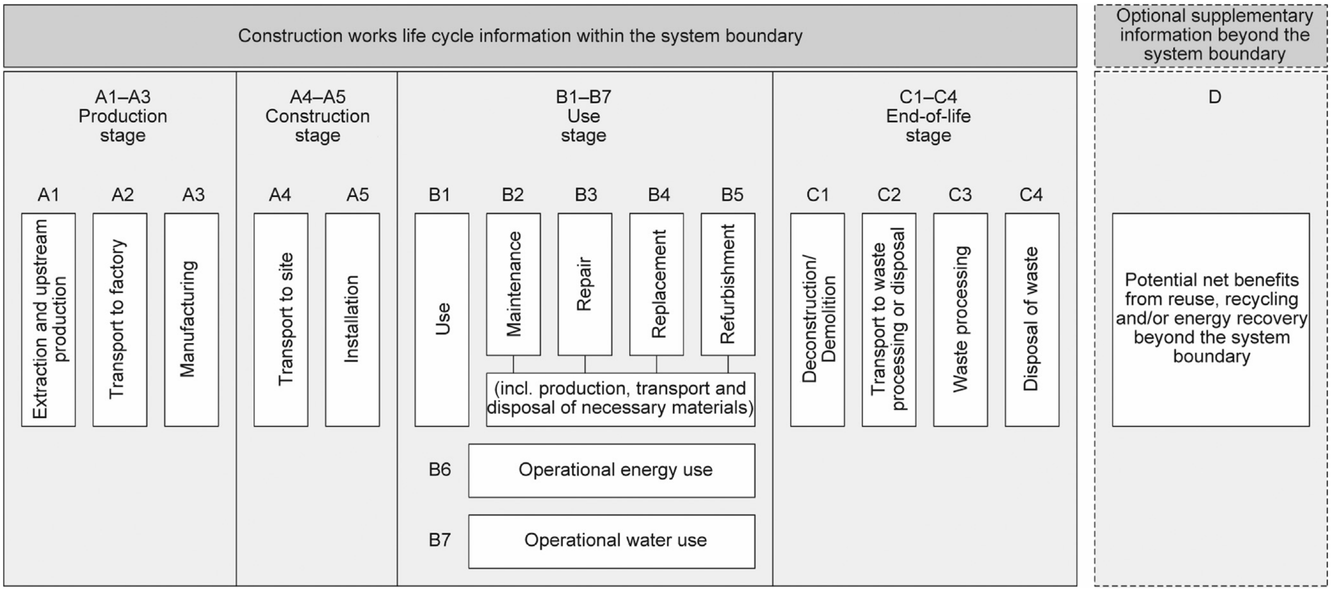


Fig. 2. Building life-cycle stages. Reproduced from Ref. [7] with permission of ISO, ©2017.

and sulfur hexafluoride (SF_6). Among them, CO_2 constitutes the largest proportion in the atmosphere; hence, it is given top priority when addressing control and reduction. While other GHGs have a lower concentration, their global warming potential (GWP) exceeds that of CO_2 by tens to tens of thousands of times.

Experts have reached an informal consensus regarding the GWP values of all GHGs and building-related emission sources; however, there is still no consensus regarding their inclusion when investigating the carbon emissions from buildings. All calculation cases include the amount of CO_2, which is generated in all life-cycle stages of a building. In addition to CO_2, two other GHGs, CH_4 and N_2O, have attracted great attention. N_2O is generated from the burning of fossil fuels and biomass, such as for cooking. These fossil fuels include coal, oil, and natural gas, whereas biomass includes crop straw, bark, sawdust, and peanut shells. CH_4 primarily originates from kitchen waste, fresh garbage, domestic sewage, biogas digesters, and landfills. According to the Hong Kong Environmental Protection Department [175], CO_2, CH_4, and N_2O constitute more than 95% of all GHGs. Sim et al. [69] investigated the ECE of a high-rise residential building in Republic of Korea and reported the amounts of the abovementioned three GHGs; the results suggested that concrete was the primary contributor of CO_2, whereas steel was the primary contributor of CH_4 and N_2O. A case study in Hong Kong involved the abovementioned three GHGs and showed that 65.6% of CH_4 was from the use stage, whereas 33.8% was from the production of building materials [56]. For wood-frame buildings, CH_4 is one of the most important carbon emission sources in the end-of-life stage, such as during landfill treatment [152,176]. Dodoo et al. [128] reported that CO_2 and CH_4 accounted for 50% of the calculated carbon emissions from wood landfill treatment.

Fluorinated gases are another important type of non-CO_2 GHGs, which originate from building air conditioners, refrigerants, fire-extinguishing systems, and some insulation-related aerosols and foaming agents [174]. Jiang and Hu [177] reported that emissions of HFCs and hydrochlorofluorocarbons from buildings in China

Table 1
Life-cycle stages considered in the case studies.

Literature		Production stage	Construction stage		Use stage					End-of-life stage				D module	Use stage	
		A1 A2 A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4		B6	B7
Stages/modules	Total	149 (92.5%)	100 (62.1%)		59 (36.6%)					70 (43.5%)				28 (17.4%)	92 (57.1%)	
	Calculated	146 (90.7%)	91 (56.5%)		43 (26.7%)					53 (32.9%)				22 (13.7%)	92 (57.1%)	
	Quoted	3 (1.9%)	9 (5.6%)		16 (9.9%)					17 (10.6%)				6 (3.7%)	0 (0%)	
Items	Total	149 (92.5%)	92 (57.1%)	89 (55.3%)	6 (3.7%)	44 (27.3%)	9 (5.6%)	32 (19.9%)	15 (9.3%)	61 (37.9%)	44 (27.4%)	30 (18.6%)	33 (20.5%)	28 (17.4%)	92 (57.1%)	9 (5.6%)
	Calculated	146 (90.7%)	83 (51.6%)	75 (46.6%)	3 (1.9%)	32 (19.9%)	3 (1.9%)	21 (13.0%)	9 (5.6%)	44 (27.3%)	36 (22.4%)	23 (14.3%)	22 (13.7%)	22 (13.7%)	92 (57.1%)	8 (5.0%)
	Quoted	3 (1.9%)	9 (5.6%)	14 (8.7%)	3 (1.9%)	12 (7.5%)	6 (3.7%)	11 (6.8%)	6 (3.7%)	17 (10.6%)	8 (5.0%)	7 (4.3%)	11 (6.8%)	6 (3.7%)	0 (0%)	1 (0%)

The above statistics are based on Refs. [11–173], as detailed in Table S1 in Appendix A.

due to refrigerant leakage amount to 100 million tonnes CO_2 equivalent (tCO_2e). Owing to its extremely high GWP, the leakage of fluorine-containing refrigerants can result in considerable CO_2-equivalent emissions; however, this issue is not discussed in the reviewed studies (Table 2 [174,178–180]).

3.2.2. Modes of building carbon emissions

A building's carbon emissions can be classified into three modes: direct, indirect, and embodied emissions. Direct and indirect carbon emissions are primarily generated by building operations. Direct carbon emissions are primarily caused by the burning of fossil fuels, such as gas and loose coal, for heating, cooking, and producing domestic hot water; they may also include GHG emissions from the chemical reactions of carbonaceous building materials. Indirect carbon emissions refer to carbon emissions that are due to purchased electricity, heating, and cooling. ECE are primarily generated by building materials and components; they are emitted during raw material extraction; building material manufacturing, installation, use, maintenance, repair, replacement, and refurbishment; building demolition; waste disposal, recycling, and reuse; and transportation in all stages (Table 2).

3.3. Discussion regarding LCCE system boundaries

As suggested in previous publications, the study results from different sources vary significantly, owing to different definitions of the system boundary. For example, Anand and Amor [181] determined the development status and challenges of buildings' LCA; the findings revealed that different definitions and scopes of the building life cycle were adopted in different studies and that different models were developed for system boundaries. Similarly, Vilches et al. [182] and Schwartz et al. [183] reported that differences in building maintenance and renovation reported among study cases were caused by inconsistent interpretations of the LCA system boundary.

In practice, not all studies are required to adopt the same temporal dimension or GHG content, because the study objects are different. For example, the development of building materials by manufacturers primarily involves the "cradle-to-gate" stage; for landfills, it is necessary to consider CH_4 emissions from wood but not those from concrete or steel. However, the findings should include relevant details so that the preconditions and application scope can be determined. The authors clarified the system boundary to investigate building LCCE and concluded that the following three dimensions should be defined (Table 3 [38,44,51,56,58,97,101,138,140,160,184–189]):

(1) The spatial boundary, that is, the study object or emitter of carbon emissions, including the building materials, components, systems, and surrounding environment.

(2) The temporal boundary, including the length and stage classification of the building's life cycle. The former pertains primarily to the service life of a building, whereas the latter involves five different spans: "cradle to gate", "cradle to site", "cradle to operation", "cradle to grave", and "cradle to cradle". Alternatively, these can be categorized into three modules: before, during, and after use.

(3) The carbon emission boundary, including the GHG type, carbon emission source, and carbon emission mode, as described in Section 3.2.2.

4. Calculation of building LCCE

4.1. Basic approaches to emissions measurement

The basic approaches to carbon emissions measurement include the experimental, mass–balance, and emission factor (EF) approaches, all of which are based on carbon flow analysis.

Table 2
Building-related GHGs.

Types of GHGs	Atmospheric lifetime (a)	GWP100	Main sources in building	Emission mode			Be calculated?
				direct	indirect	embodied	
CO_2	50–200	1	Energy production and consumption	●	●	○	yes
			Material production and consumption	○	○	●	yes
			Chemical reactions of carbonaceous materials	●	○	○	partial
CH_4	12	25	Energy production and consumption	●	●	○	yes
			Material production and consumption	○	○	●	yes
			Chemical reactions of carbonaceous materials	●	○	○	partial
N_2O	114	298	Energy production and consumption	●	●	○	yes
			Material production and consumption	○	○	●	yes
HFCs	≤270	≤14 800	Air conditioning, refrigerants, aerosols, foam-blowing agents for insulation, fire extinguishing systems	●	○	○	no
CFC-11 (CCl_3F)	45	4750	Air conditioning, refrigerants, aerosol insulation, propellants, solvents	●	○	○	no
CFC-12 (CF_2Cl_2)	100	10 900					
CFC-22 ($CHClF_2$)	12	1810					
SF_6	3200	23 900	None	/			/

GWP100: GWP of the GHGs over 100 years; energy consumption includes primary energy, electricity, heat, and other forms. GHGs' atmospheric lifetime, GWP100, and sources are adapted from Refs. [174,178–180].

Table 3
System boundary of LCA for buildings' carbon emissions.

Dimension	Item	Content	Example references
Spatial boundary	Geographic scope	Building materials	[44]
		Building components (including building structure, building envelope)	[51]
		Whole building	[140]
		Building with site	[184]
Temporal boundary	Lifespan	Commercial buildings: commonly used 50 (40–100) years	[185]
		Residential buildings: commonly used 50 (40–75) years	[186]
	Life-cycle stages	"Cradle to the gate" from A1 to A3	[44]
		"Cradle to site" from A1 to A5	[160]
		"Cradle to operation" from A1 to B7	[101]
		"Cradle to grave" from A1 to C4	[187]
		"Cradle to cradle" from A1 to D, then returning to A, forming a closed loop	[188]
		"Before use" from A1 to A5	[160]
		"Use" from B1 to B7	[58]
		"After use" from C1 to D	[38]
Carbon emission boundary	Emission sources	Products (including building materials, equipment)	[97]
		Processes (including manufacturing, construction, demolition, etc.)	
		Building operation	
		Human emissions (including food waste, sewage, excretion, etc.)	[189]
	Emission mode	ECE	[138]
		Direct carbon emissions	
		Indirect carbon emissions	
	Types of GHG	Only CO_2	Most cases
		CO_2, CH_4, N_2O	[56]
		According to the Kyoto Protocol: CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6	Not found
		According to the IPCC: numerous	Not found

(1) **The experiment approach**. This measurement-based carbon emission method includes on- and off-site measurements. The former directly calculates the GHG concentration and flow–rate data obtained via a continuous emission-monitoring system. The latter calculates carbon emissions via sampling, testing, and quantitative analysis by professionals.

(2) **The mass–balance approach**. This approach monitors the carbon emitter to analyze the balance of the overall carbon flow, where the internal reaction process is disregarded. CO_2 emissions can be calculated by multiplying the difference in carbon content between the input and output of a system by the CO_2/C mass conversion coefficient, 44/12.

(3) **The EF approach**. This approach is based on the principle of "activity data (AD) × carbon EF". The EFs reflect the carbon emission intensity of various activities. The AD refers to the quantitative measure of a level of activity that directly or indirectly result in carbon emissions, such as the consumption of fossil fuels, electricity, heat, and building materials.

In practice, the experimental approach can only yield direct emission data and is thus limited to fields that generate direct emissions, such as the initial stage of cement production when limestone is calcined. In addition, capturing data for different GHG concentrations is technically demanding. The mass–balance approach is feasible for the production of a specific building material; however, owing to the various material inputs and outputs of the system and the unstable carbon content, this approach is unsuitable for accurately calculating the carbon flow of building systems. In contrast, the EF approach is more feasible for construction projects. Two key parameters, AD and EF, must be determined for the calculation. In the absence of primary data, the parameters of the relevant databases can be obtained from previous studies (Fig. 3).

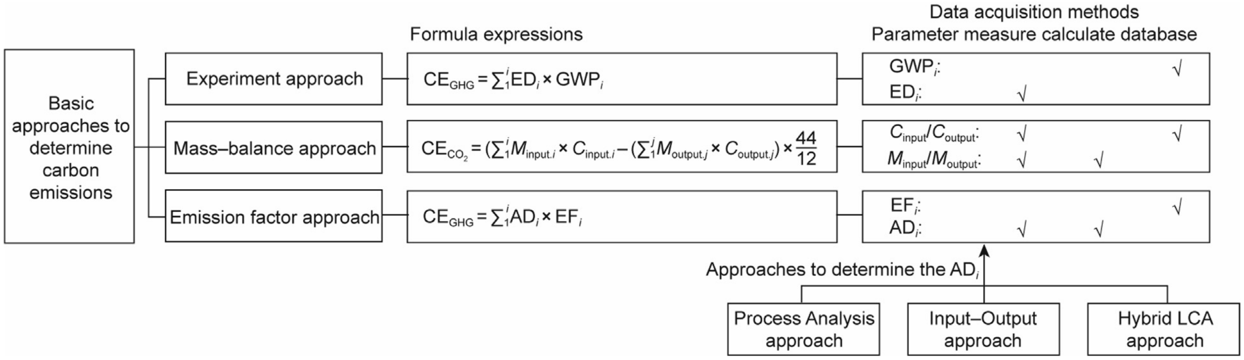


Fig. 3. Methods to determine the amount of carbon emissions. CE_{GHG}: carbon emissions, kilogram CO_2 equivalent (kgCO_2e); ED_i: emission data of the GHG i, kg; GWP_i: GWP of the GHG i, kilogram CO_2 equivalent per kilogram gas ($\text{kgCO}_2\text{e}\cdot\text{kg}^{-1}$). CE_{CO2}: CO_2 emissions, kilogram CO_2 (kgCO_2); $M_{\text{input},i}/M_{\text{output},i}$: mass of the input/output material i, kg; $C_{\text{input},i}/C_{\text{output},i}$: carbon content per unit mass of the input material i/output material material j, %; 44/12: ratio of the molecular weights of CO_2 and carbon. CE_{GHG}: carbon emissions, kgCO_2e; AD_i: activity data of the activity i, unit; EF_i: carbon emission factor of the activity i, kilogram CO_2 equivalent per unit ($\text{kgCO}_2\text{e}\cdot\text{unit}^{-1}$).

To determine AD, a process analysis (PA), input–output (IO) information, and a hybrid LCA are required. PA and IO are basic methods. Among the 161 reviewed studies, 180 methods were mentioned, including 138 PA-based (76.7%) and 29 IO-based (16.1%) methods. For a single building, the PA is particularly important for identifying carbon emission sources and developing carbon reduction plans. Moreover, 13 cases (7.2%) adopted a hybrid LCA, which combines both PA and IO information. The IO approach is applicable to investigating carbon emissions at the macro level. However, the results obtained using the IO approach are unlikely to provide detailed information. In a study on residential buildings, Zhang et al. [25] showed that combining a PA with a hybrid method captured 64% of the carbon reduction potential, which was otherwise not achievable via the IO approach; therefore, the IO approach alone was deemed inappropriate for the detailed assessment of individual buildings. Based on an analysis of an educational building in China, Chang et al. [27] considered that the IO approach could be used to estimate the overall situation of typical construction projects, whereas the hybrid model based on PA could reveal the project's characteristics more effectively.

4.2. Selection of functional units

Various functional units (FUs) specific to the research objects were used in the case studies. For building materials, the unit volume or weight is typically regarded as the FUs (e.g., the carbon emission calculation of concrete, steel, and bamboo products by Dong et al. [51], Gan et al. [44], and Xu et al. [190], respectively). For building components, the unit building component is often regarded as the FUs (e.g., the carbon emission calculation of prefabricated concrete stair products, piles, earth walls, and straw–bale walls by Li et al. [30], Liu et al. [32], and González [162]). Multiple FUs are used for building systems, although the primary ones used are the "whole building", "unit floor area", and "unit floor area per year", which can be mutually converted using the floor area and expected service life.

The FUs used can affect the understanding of the carbon emission calculation results. Filimonau et al. [137] investigated hotel buildings and showed that the carbon emission intensity of large hotels was 14% higher than that of small hotels, based on "unit floor area" as the FUs; furthermore, this value increased to 67% when "per guest × night" was used as the FUs. Bastos et al. [116] compared three residential buildings in Portugal and found that the carbon emission intensity of large-scale buildings was lower when "per floor area × per year" was used as the FUs, whereas it was higher when "per capita × per year" was used as the FUs. In this study, "unit floor area" and "unit floor area per year" were used as the FUs.

4.3. Activity data calculation methods, results, and effects

An analysis of variance (ANOVA) was carried out for the above cases. The LCCE was divided into two components: ECE and OCE. The cases were grouped according to the structure and function related to the building itself, as well as the country and climate related to the external conditions. The function and climate were further divided into subcategories. The ANOVA results are shown in Table 4, and the number of groups and the total number of datasets are shown in Table S2 in Appendix A. These ANOVA results were adopted as the basis for the grouping analysis of the ECE and OCE calculation results presented in Sections 4.3.1 and 4.3.2.

The ANOVA results showed that the ECE among the groups of structure types, country/regions, and climate zones were significantly different. The P value of the group of structure types was only 6.43×10^{-15}, and the groups of country/regions and climate zones had P values of 1.10×10^{-06} and 3.79×10^{-06}, respectively. All the values indicated statistical significance. Conversely, the P value of the building function group was 0.202, showing no significant difference. In addition, the ANOVA results showed no significant difference among the OCE in the structure type group. Conversely, significant differences were observed in the groups of building function, country/regions, and climate zones, all of which

Table 4
ANOVA results for the carbon emission datasets.

Group	ECE				OCE			
	No. of S	No. of G	*F*	*P*	No. of S	No. of G	*F*	*P*
Structure	511	8	12.59	6.43×10^{-15}	242	8	1.886	0.0727
Function	479	2	1.636	0.202	327	2	108.0	$< 2 \times 10^{-16}$
Function (subcategories)	409	6	8.089	2.75×10^{-07}	257	6	19.55	$< 2 \times 10^{-16}$
Country/region	548	5	8.536	1.10×10^{-06}	354	5	32.27	$< 2 \times 10^{-16}$
Climate	497	4	9.563	3.79×10^{-06}	308	4	38.65	$< 2 \times 10^{-16}$
Climate (subcategories)	480	8	8.297	1.45×10^{-09}	298	7	37.07	$< 2 \times 10^{-16}$

No. of S: total number of datasets; No. of G: number of groups; *F*: variance ratio; *P*: *P* value.

had P values < 2×10^{-16}. The differences among the subcategories of building function and the climate zones were also significant.

As described in Section 3.1.2, the LCCE was not completely calculated in most of the 826 cases in the 161 studies. Based on the data obtained from the cases, the calculation methods, results, and effects on the AD at each stage are analyzed below. The statistics reveal significantly different calculation results among the cases. Therefore, in the following analysis, the calculation results and effects are described based on quartiles, including the median, first quartile, and third quartile (Figs. 4 and 5, Tables 5 and 6).

4.3.1. ECE of buildings

The total number of ECE datasets used in the reviewed studies was 564. Of these, concrete, steel, timber, and mortar structures were considered in 267, 63, 99, and 46 sets, respectively. The statistical results are shown in Fig. 6 and Table S3 in Appendix A. The median values of ECE (ECE_{med}) for global cases with concrete, steel, timber, and mortar structures were 436.0, 297.9, 182.1, and 338.8 $kgCO_2e \cdot m^{-2}$, respectively, with timber structures having the lowest values. In addition, the ECE_{med} of the six cases with Bio (built using bio-based construction methods) structures in Europe was 101.0 $kgCO_2e \cdot m^{-2}$; this type of structure seemed to be more low-carbon than the other types of structures.

The ECE of buildings differs among countries/regions due to differences in building design and differences between the carbon emission intensities of the energy and building materials in each country/region. Overall, the ECE_{med} ($ECE_{25\%}$–$ECE_{75\%}$) value for the cases in China was 448.0 (366.6–566.4) $kgCO_2e \cdot m^{-2}$. This value was lower than that in Australia but obviously higher than those of the cases in Europe, North America, and other Asian countries.

The ECE were affected by the type of structure because they are closely related to activities associated with building materials, such as production and construction. The ANOVA also showed the lowest P value for the difference in the group of building structures. Therefore, the concrete, steel, and timber structure groups were selected to analyze the calculation methods, results, and effects in each life-cycle stage related to the ECE.

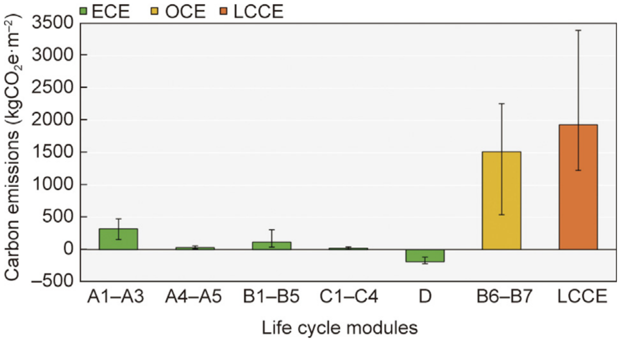


Fig. 4. Carbon emission calculation results for each life-cycle stage in the case studies.

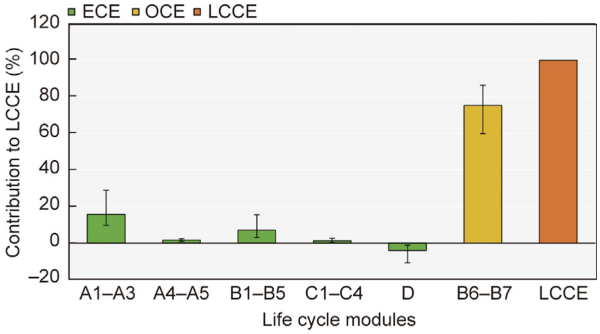


Fig. 5. Carbon emission proportion of each life-cycle stage in the case studies.

(1) **Building material production stage (A1–A3).** ① Calculation method. The carbon emissions from the building material production stage (ECE_{A1-A3}) include the emissions from the extraction of raw materials, the transport of raw materials to factories, and the manufacturing of building materials. Among the 161 studies investigated, 149 included the calculation of ECE_{A1-A3}, most of which (82.6%) regarded A1–A3 as one and calculated ECE_{A1-A3} by multiplying the carbon EF by the consumption of building materials. In the remaining 26 studies (17.4%), the three sub-stages were separated in order to calculate and analyze the carbon emission intensity of raw material extraction, transportation, and building material production [44,76,190]. ② Calculation result and effect. The reviewed case studies provided 234 sets of carbon emission calculation results for A1–A3. In general, ECE_{med} ($ECE_{25\%}$–$ECE_{75\%}$) was 321.2 (155.2–476.3) $kgCO_2e \cdot m^{-2}$, which constituted 15.6% (9.7%–28.9%) of the LCCE (Figs. 4 and 5). For the cases involving concrete, steel, and timber structures, the ECE_{med} values were 419.3, 182.2, and 130.8 $kgCO_2e \cdot m^{-2}$, respectively (Fig. 7, Table S4 in Appendix A).

The calculation items should include the load-bearing structures, building envelopes, and technical equipment systems. However, among the 826 calculation cases, excluding 138 cases that did not specify the calculation content, only 65 (9.4%) of the remaining 691 cases presented complete calculations of all three items [97,101], while 554 (80.2%) cases presented calculations of the main building materials, and the remaining 69 (10.0%) cases presented only calculations of material consumption for load-bearing structures. As shown in Table 7, the ECE_{A1-A3} of the primary building materials contributes significantly to the total building ECE [14,16,104,121,194]. The load-bearing structure, foundation, and building envelope are the main contributors to carbon emissions. However, disregarding the technical equipment systems will result in underestimated ECE values [41].

(2) **Construction stage (A4–A5).** ① Calculation method. Carbon emissions in the construction stage (ECE_{A4-A5}) were considered in 100 (62.1%) of the 161 studies, among which calculations were performed in 91 studies, and data from the literature were used for the remaining nine studies. The calculated carbon emissions from building material transportation (ECE_{A4}) were relatively uniform because the carbon EFs for various transportation activities were sufficient. The other parameters for this calculation are the weight and transportation distance of the building materials. The transportation was assumed to be a certain distance, such as 50 km [88,110] or 300 km [195]. The calculation of carbon emissions from onsite construction (ECE_{A5}) is more complex, as it includes the onsite energy consumption, emissions from assembly and miscellaneous activities, indirect emissions from construction equipment transportation, and emissions from personnel activities related to offsite construction [40,156]. In addition to performing calculations for targeted buildings, the researchers used certain formulas or data from previous studies [62,110,138,157]. ② Calculation result and effect. The reviewed case studies provided 172 sets of carbon emission calculation data for stages A4–A5. In general, the ECE_{med} ($ECE_{25\%}$–$ECE_{75\%}$) was 32.2 (14.4–56.7) $kgCO_2e \cdot m^{-2}$, which constituted 1.6% (0.9%–2.4%) of the LCCE (Figs. 4 and 5). For the cases involving concrete, steel, and timber structures, the medians of ECE_{A1-A3} were 46.3, 15.7, and 31.5 $kgCO_2e \cdot m^{-2}$, respectively (Fig. 8, Table S5 in Appendix A).

Table 5
Carbon emission calculation results for each life-cycle stage in the case studies.

Life-cycle stage (kilogram CO_2 equivalent per square meter ($kgCO_2e\cdot m^{-2}$))	A1–A3	A4–A5	B1–B5	C1–C4	D	B6–B7	LCCE
CE_{med}	321.2	32.2	114.9	20.9	−188.6	1515.0	1931.9
$CE_{25\%}$	155.2	14.4	38.3	5.0	−219.0	540.0	1225.5
$CE_{75\%}$	476.3	56.7	308.8	41.3	−115.5	2260.5	3392.5

CE_{med}, $CE_{25\%}$, $CE_{75\%}$: the median, first quartile, and third quartile of carbon emissions.

Table 6
Carbon emission proportion of each life-cycle stage in the case studies.

Life-cycle stage (%)	A1–A3	A4–A5	B1–B5	C1–C4	D	B6–B7	LCCE
P_{med}	15.6%	1.6%	7.1%	1.2%	−4.1%	75.2%	100.0%
$P_{25\%}$	9.7%	0.9%	3.1%	0.3%	−10.8%	59.9%	100.0%
$P_{75\%}$	28.9%	2.4%	15.5%	2.6%	−1.2%	86.3%	100.0%

P_{med}, $P_{25\%}$, $P_{75\%}$: the median, first quartile, and third quartile of carbon emission proportion of each life-cycle stage.

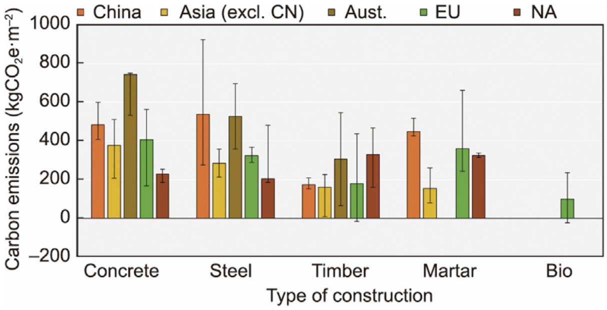
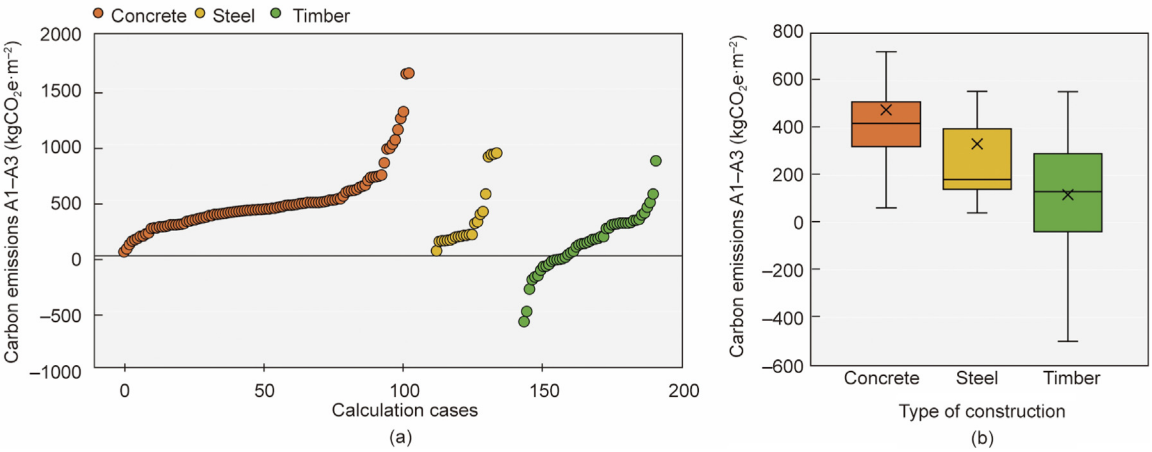


Fig. 6. ECE calculation results by type of structure and countries/regions. Asia (excl. CN): Asia excluding China, Aust.: Australia, EU: Europe, NA: North America.

Based on a literature review, Gustavsson et al. [123] showed that previous studies provided more energy consumption data than carbon emission data and that most of those data were not specified as either the final or primary energy. Personnel-related carbon emissions were often disregarded in a previous study [11], but Williams et al. [136] and Cole and Kennan [196] performed case studies in Canada and the UK and demonstrated that carbon emissions due to workers' commutes were not negligible. Furthermore, owing to differences in the conditions and calculation methods of actual projects, the calculated results may differ by up to two orders of magnitude. Cole [156] investigated different structures in Canada and reported their carbon emissions in the construction stage; Guggemos and Horvath [161] reported that the energy consumed for constructing steel and concrete structures was 418 and 939 $MJ\cdot m^{-2}$, respectively, which were much higher than the values of 3–7 and 20–120 $MJ\cdot m^{-2}$, respectively, in the study by Cole [156].

(3) **Use stage (B1–B5).** ① Calculation method. The ECE in the use stage ($ECE_{B1–B5}$) includes the carbon emissions from the maintenance, repair, renovation, replacement, and transportation of building materials, facilities, and equipment. These types of carbon emissions are known as "recurring ECE"; correspondingly, carbon emissions from material extraction to the end of construction (A1–A5) are known as "initial ECE." Among the 161 studies investigated, 59 (36.6%) accounted for the use-stage carbon emissions, among which 43 of the studies performed calculations, whereas the remaining nine studies used data from the literature. To determine $ECE_{B1–B5}$, the most typical method is to calculate the replacement of building materials during the use stage based on the expected service life of the building and the building materials, and then to further calculate the corresponding recurring ECE. Suzuki and Oka [59], Kofoworola and Gheewala [88], Petrovic et al. [129], Iddon and Firth [143], and Mosteiro-Romero et al. [172] used the expected lifespan of building materials to estimate $ECE_{B1–B5}$ during the use stage. In other studies, $ECE_{B1–B5}$ was estimated based on empirical data from previous studies [95,115]. ② Calculation result and effect. The reviewed case studies provided 72 sets of carbon emission calculation



(a)

(b)

Fig. 7. Carbon emission calculation results for stages A1–A3 in the case studies. (a) Distribution of all results, (b) quartile plot.

Table 7
Contribution of primary building materials to the total ECE.

Building cases	Items	Contribution to the total ECE	References
Two types of residential buildings and six types of nonresidential buildings in Republic of Korea	Primary building materials	78.68%–97.76%	[191]
Six residential buildings in Republic of Korea	Pre-mixed concrete, steel bars, insulation, concrete bricks, glass, and gypsum board	> 95%	[67]
Residential buildings in Republic of Korea	Primary building materials	> 82%	[70]
129 residential buildings in China	Steel, wall materials, mortar, and commercial concrete	> 80%	[36]
High-rise residential buildings in Hong Kong	Concrete + steel	59.2% + 20.1%	[52]
An office building in Hong Kong	Concrete + steel bars	52.8% + 41.2%	[47]
A low-rise residential building in the United Kingdom (UK)	Concrete and mortar	99%	[142]
Low-rise residential areas in the UK	Building materials	50%	[139]
Low-rise residential areas in Malaysia	Building materials	99%	[86]
A school building in Republic of Korea	Building material production	93.4%	[66]
An insurance office building in Sri Lanka	Steel bars, clay bricks, and ready-mixed concrete	70%	[93]
A high-rise office building in Thailand	Concrete + steel rebars	64% + 17% of $\text{ECE}_{\text{A1–A3}}$	[192]
Two buildings in Australia	Building materials	58.1%/49.1%	[171]
A high-rise residential building in Australia	Building materials	88%	[165]
78 office buildings in China	Steel, concrete, mortar, and wall materials	> 60%	[193]

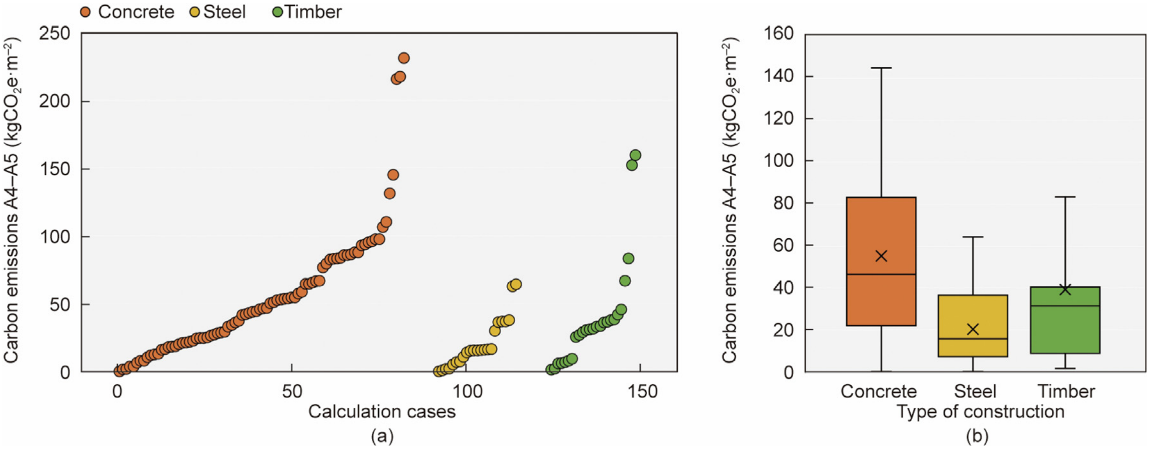


Fig. 8. Carbon emission calculation results for stages A4–A5 in the case studies. (a) Distribution of all results, (b) quartile plot.

results for stages B1–B5. In general, the ECE_{med} ($\text{ECE}_{25\%}$–$\text{ECE}_{75\%}$) was 114.9 (38.3–308.8) kgCO$_2$e·m^{-2}, which constituted 7.1% (3.1%–15.5%) of the LCCE (Figs. 4 and 5). For the cases involving concrete, steel, and timber structures, the median of $\text{ECE}_{\text{B1–B5}}$ was 232.6, 23.0, and 243.4 kgCO$_2$e·m^{-2}, respectively. Because only four sets of data were obtained for steel structures, the statistical results presented might be limited (Fig. 9, Table S6 in Appendix A). The case studies

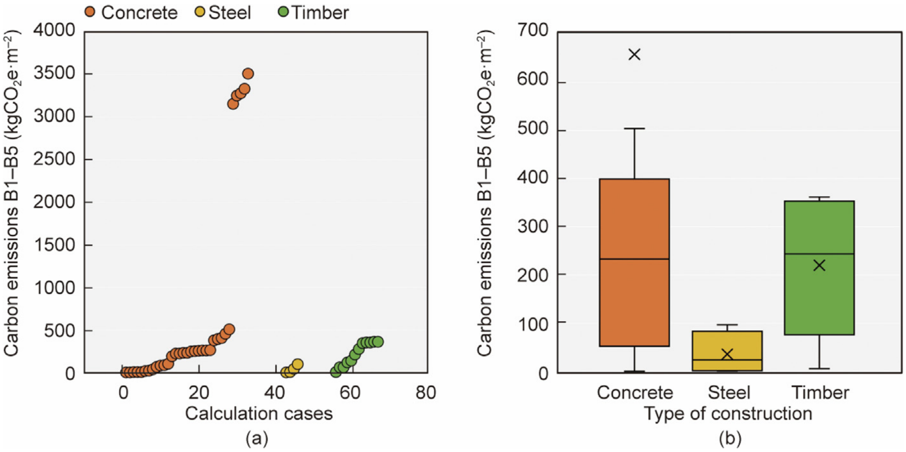


Fig. 9. Carbon emission calculation results for stages B1–B5 in the case studies. (a) Distribution of all results, (b) quartile plot.

by Marzouk et al. [81], Kumanayake and Luo [92], and Ortiz et al. [120] showed that the ECE_{B1-B5} contributed 0.05%, 3.23%, and 1.7% of the LCCE, respectively. Based on the investigations by Bastos et al. [116], Petrovic et al. [129], Williams et al. [136], Moncaster and Symons [139], and Fay et al. [197], the ECE_{B1-B5} contributed 28.1%–29.3%, 37%, 44%, 17%, and 40% of the total ECE, respectively.

(4) **End-of-life stage (C1–C4).** ① Calculation method. In the end-of-life stage, the carbon emission calculation includes the emissions from building demolition, waste transportation, and disposal. Of the 161 studies investigated in this study, carbon emissions in the end-of-life stage C1–C4 (ECE_{C1-C4}) were considered in 70 of the studies (43.5%); among these, calculations were performed for 53 of the studies, whereas empirical data were used for the remaining 17. Calculations pertaining to building demolition and the transportation of dismantled materials were similar to those made for onsite construction and transportation in the pre-use stage, being based on summarizing the relevant mechanical energy consumption and transportation. Different carbon emission calculation methods correspond to different waste disposal methods. Owing to the dearth of carbon emission calculation methods and basic parameters for the disposal stage, the calculations performed in most cases were based on different assumptions [63,95,138]. ② Calculation result and effect. The reviewed case studies provided 150 sets of carbon emission calculation data for stages C1–C4. In general, the ECE_{med} ($ECE_{25\%}$–$ECE_{75\%}$) was 20.9 (5.0–41.3) $kgCO_2e·m^{-2}$, which constituted 1.2% (0.3%–2.6%) of the LCCE (Figs. 4 and 5). For the cases involving concrete, steel, and timber structures, the median of ECE_{C1-C4} was 26.3, 4.1, and 24.3 $kgCO_2e·m^{-2}$, respectively (Fig. 10, Table S7 in Appendix A). Similar to sub-stages B1–B5, different cases presented substantial differences in terms of the calculation results and effects. The case studies by Wu et al. [13], Li et al. [42], and Cuéllar-Franca and Azapagic [138] showed that ECE_{C1-C4} constituted approximately 13.67%, 1%, and 1% of the LCCE, respectively. Li et al. [31] and Moncaster and Symons [139] concluded that ECE_{C1-C4} constituted 3%–21% and 21% of the total ECE, respectively.

4.3.2. OCE stage (B6–B7)

(1) **Calculation method.** The OCE of a building is composed of two items: the operational energy consumption and the water consumption. However, water consumption was only considered in nine of the reviewed studies—namely, those by Li et al. [29], Kofoworola and Gheewala [88], Passer et al. [97], Junnila and Horvath [99], Pons and Wadel [122], Petrovic et al. [129], Cuéllar-Franca and Azapagic [138], Quintana-Gallardo et al. [151], and Scheuer et al. [157]. Most of these studies only involved the energy consumption data and used two main statistical methods. In one of the methods, the data are categorized based on energy-consuming items, such as heating, ventilation, and air conditioning (HVAC), hot water, lighting, electrical appliances, and cooking; in the other method, the data are categorized by energy types, such as electricity, natural gas, and oil. Energy consumption data are primarily acquired via two methods: simulation and monitoring. Few studies used actual energy consumption data [53,57,95] (Table S8 in Appendix A).

(2) **Calculation result and effect.** The reviewed case studies provided 143 sets of carbon emission calculation results for stages B6–B7. In general, the ECE_{med} ($ECE_{25\%}$–$ECE_{75\%}$) was 1515.0 (540.0–2260.5) $kgCO_2e·m^{-2}$, which constituted 75.2% (59.9%–86.3%) of the total LCCE (Figs. 4 and 5). The OCE was related to building function. The reviewed studies provided a total of 380 OCE datasets, of which 215 sets were for residential buildings; 138 were for nonresidential buildings, including commercial buildings, offices, hotels, and educational institutes; seven were for mixed-use buildings; and the remaining 20 sets were unspecified. The OCE calculation results are shown in Fig. 11 and Table S9 in Appendix A. The ECE_{med} ($ECE_{25\%}$–$ECE_{75\%}$) for the residential group was 21.8 (9.0–38.8) kilogram CO_2 equivalent per square meter per year ($kgCO_2e·m^{-2}·a^{-1}$), which was generally lower than the value of 85.1 (22.1–198.7) $kgCO_2e·m^{-2}·a^{-1}$ for the non-residential group.

The OCE exhibited geographical differences. According to the Köppen climate classification method [198], the cases were divided into four groups: namely, climate zones equatorial, arid, warm temperate, and snow. The number of OCE data under climate zones equatorial and arid was relatively small (33 and 8 sets, respectively), while warm temperate and snow had 208 and 80 sets, respectively. The 33 sets under climate zone A had an ECE_{med} value of 214.9 $kgCO_2e·m^{-2}·a^{-1}$, which is substantially higher than the values in the range of 8.1–32.2 $kgCO_2e·m^{-2}·a^{-1}$ for the cases in zones B, C, and D. All the cases under climate zone A were from low-latitude regions in Asia. In addition, the OCE exhibited differences among different countries/regions (Fig. 11, Table S10 in Appendix A). The ECE_{med} ($ECE_{25\%}$–$ECE_{75\%}$) for residential buildings in China was 23.8 (21.7–30.7) $kgCO_2e·m^{-2}·a^{-1}$, which was lower than the value of 41.9 (36.2–52.5) $kgCO_2e·m^{-2}·a^{-1}$ for the rest of Asia. The values for both the China and Asia (excluding China) groups were significantly higher than the value for the European

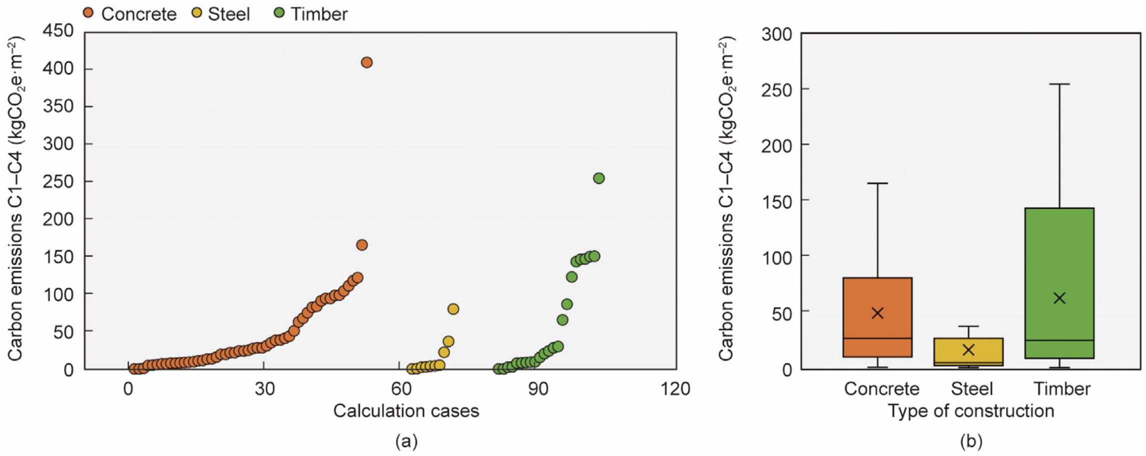


Fig. 10. Carbon emission calculation results for stages C1–C4 in the case studies. (a) Distribution of all results, (b) quartile plot.

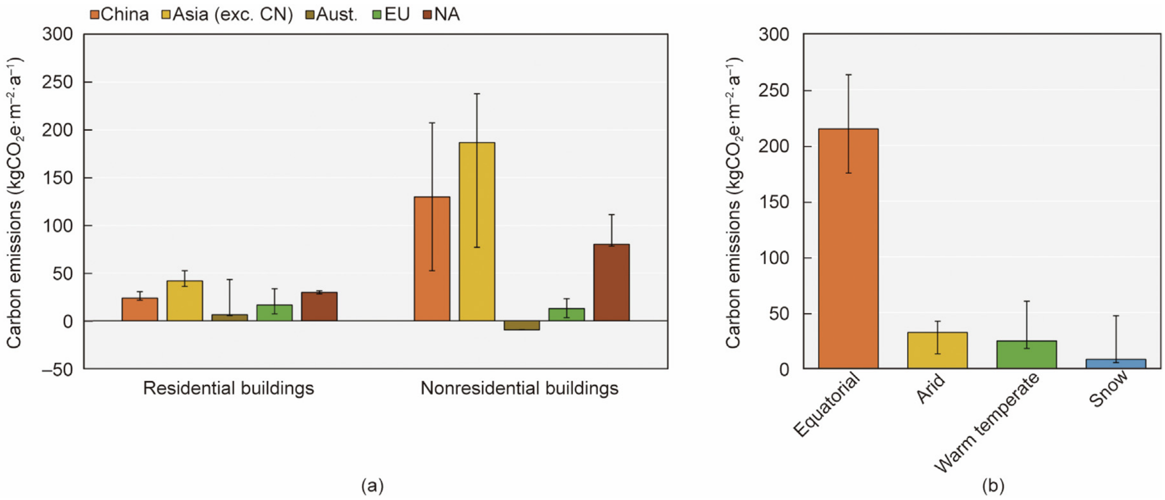


Fig. 11. Carbon emission calculation results for stages B6 and B7 in the case studies. (a) Building function, (b) Köppen climate zone.

group, which was 16.7 (7.3–33.8) $kgCO_2e·m^{-2}·a^{-1}$. Nonresidential buildings showed similar characteristics.

The composition of the OCE varies for different types of buildings. Kofoworola and Gheewala [192], Adalbert [199], and Buyle et al. [200] investigated standard buildings and reported that the environmental effect of the operation stage constituted 60%–90% of the LCCE, primarily from the GWP value contributed by carbon emissions. Studies pertaining to residential buildings by Cuéllar-Franca and Azapagic [138], Radhi and Sharples [201], and You et al. [202] in the UK and China showed that the OCE contributed 80%–90% of the LCCE. Heating, cooling, and lighting are the main sources of OCE, together contributing 82%, 92.7%, 88.2%, and 93.4% of the total OCE in the case studies by Jing et al. [53], Zabalza Bribián et al. [119], van Ooteghem and Xu [153], and Scheuer et al. [157], respectively. The non-consideration of water consumption in most studies may result in underestimated OCE. For example, Petrovic et al. [129] investigated a single-family house in Sweden and showed that water consumption over a 100 year lifespan contributed to 6% of the OCE.

4.3.3. Supplementary effects (module D)

(1) **Calculation method.** Module D included the benefits of recycling and reusing building materials, as well as energy recovery. Because this module is not classified into stages A, B, and C, it is defined as "supplementary information beyond the system boundary". Among the 161 studies investigated in this review, 28 (17.4%) considered the carbon emissions in module D, with calculations being performed for 22 (13.7%) of the studies, and empirical data being used for the remaining six. The cases presented in this section are based on scenario assumptions.

(2) **Calculation result and effect.** Because module D pertains to carbon reduction benefits, the analysis performed is described in Section 5.2.5. The reviewed case studies provided 58 datasets for module D. In general, ECE_{med} ($ECE_{25\%}$–$ECE_{75\%}$) was −188.6 (−219.0–−115.5) $kgCO_2e·m^{-2}$, which constituted −4.1% (−10.8%–−1.2%) of the total LCCE (Figs. 4 and 5). For cases involving concrete, steel, and timber structures, the median of the CE_D was −201.7, −139.4, and −208.0 $kgCO_2e·m^{-2}$, respectively. Because only four sets of data were obtained for steel structures, the presented statistical results were limited (Fig. 12, Table S11 in Appendix A).

4.4. Carbon emission factor

4.4.1. Energy (EF_e)

(1) **Primary energy**. For fossil fuels, the EF_e is generally calculated using the fuel's carbon content and the carbon oxidation rate during the combustion process. According to

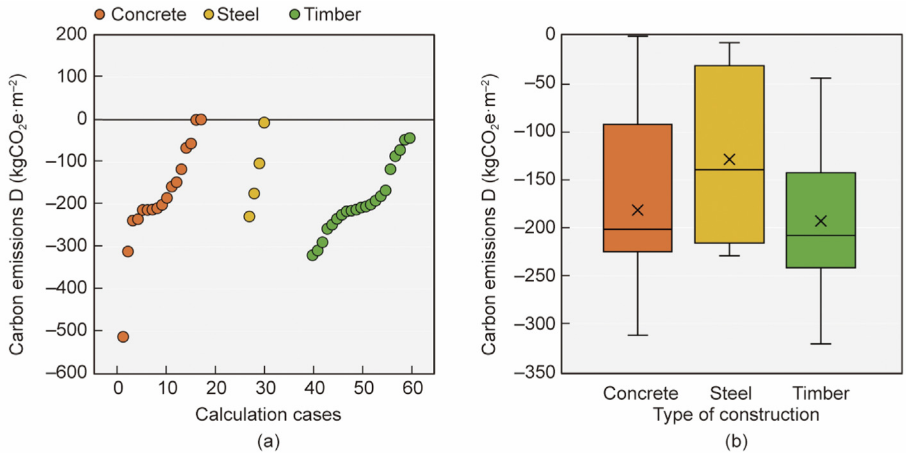


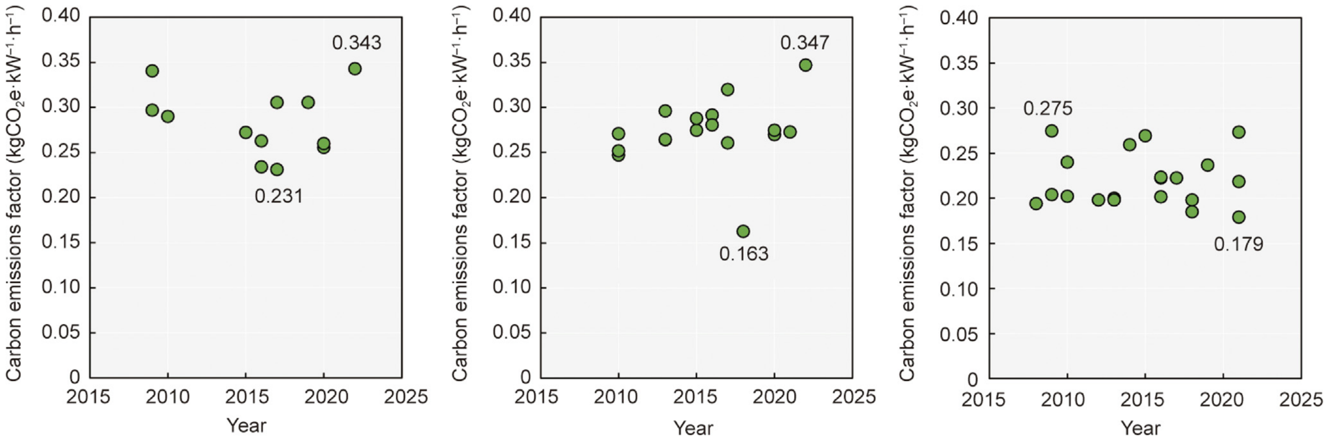
Fig. 12. Carbon emission calculation results for module D in the case studies. (a) Distribution of all results, (b) quartile plot.

Chau et al. [6], the EF_e ranges of gasoline, diesel, kerosene, coal, and natural gas are 0.249–0.252, 0.248–0.340, 0.248–0.259, 0.341–0.486, and 0.18–0.231 kilogram CO_2 equivalent per kilowatt per hour ($kgCO_2e{\cdot}kW^{-1}{\cdot}h^{-1}$), respectively. In the reviewed case studies, most of the basic parameters of the primary energy were not provided. The FUs of the 15 gasoline, 20 diesel, and 22 natural gas carbon datasets were unified, and the respective EF_e ranges obtained were 0.231–0.343, 0.163–0.347, and 0.179–0.275 $kgCO_2e{\cdot}kW^{-1}{\cdot}h^{-1}$, which are similar to the results obtained by Ref. [6] (Fig. 13).

(2) **Electricity**. The EF of electricity is related to the energy mix used in electricity generation, which changes dynamically and is affected by time and region. Among the 100 datasets extracted from the case studies, the EF_e was 0.006–1.127 $kgCO_2e{\cdot}kW^{-1}{\cdot}h^{-1}$, with Sweden and Australia having the lowest and highest values, respectively. From a regional perspective, Australia had the highest average EF_e value (i.e., 0.871 $kgCO_2e{\cdot}kW^{-1}{\cdot}h^{-1}$) from four datasets, followed by China (i.e., 0.783 $kgCO_2e{\cdot}kW^{-1}{\cdot}h^{-1}$) based on the 57 datasets obtained. The average value from the 15 datasets from other Asian countries (excluding China) was 0.600 $kgCO_2e{\cdot}kW{\cdot}h^{-1}$. The European electricity EF_e was significantly lower, with an average value of 0.329 $kgCO_2e{\cdot}kW^{-1}{\cdot}h^{-1}$ based on 23 datasets. The use of different electricity EF_e values can result in significantly different calculation results and can thus affect decision-making (Fig. 14).

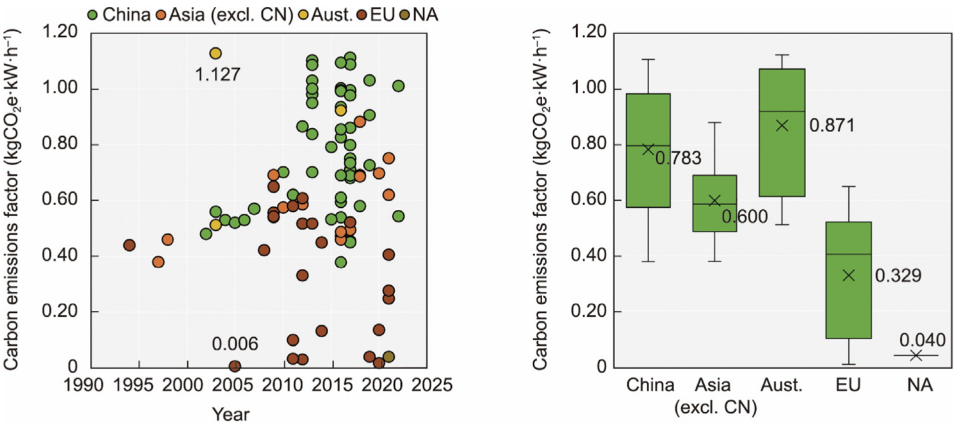
4.4.2. Building materials (EF_m)

(1) **Cement**. In the case studies, 69 sets of cement EF_m parameters were obtained, ranging between 0.320 and 1.350 $kgCO_2e{\cdot}kg^{-1}$. Among these parameters, the values of 45 sets (65.2%) ranged between 0.6 and 1.0 $kgCO_2e{\cdot}kg^{-1}$. In terms of geographical distribution, the average value for the 45 sets of parameters in China was 0.904 $kgCO_2e{\cdot}kg^{-1}$, which was higher than the values in Australia, Europe, and Asia (excluding China), at 0.881, 0.774, and 0.502 $kgCO_2e{\cdot}kg^{-1}$, respectively (Fig. 15). During limestone calcination, a significant amount of direct CO_2 is emitted, making calcination a primary contributor of the carbon emissions from cement production. Feiz et al. [203] investigated the production of carbon emissions from German cement and showed that the calcination of limestone was the most significant contributor to the carbon emissions with a maximum value of 0.541 $kgCO_2{\cdot}kg^{-1}$, constituting 64% of $ECE_{A1–A3}$.



(a) (b) (c)

Fig. 13. Carbon emission factors of the primary energy used in the case studies. (a) Gasoline, (b) Diesel, and (c) Nature gas.



(a) (b)

Fig. 14. Carbon emission factors of the electricity used in the case studies.

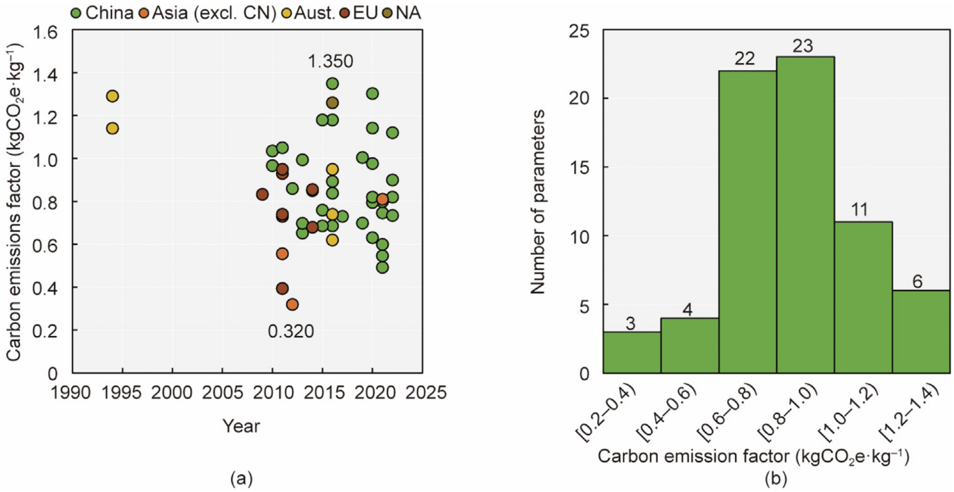


Fig. 15. Carbon emission factors of the cement used in the case studies.

In contrast to limestone calcination, carbonation during cement use and post-use periods can reabsorb CO_2. Several researchers [204–206] have indicated that the carbon intensity of cement is significantly overestimated when this process is disregarded. However, the quantification of this process varies significantly. Xi et al. [205] estimated that the global CO_2 absorption by carbonization was 43% of the carbon emissions released from cement production between 1930 and 2013. Based on a concrete frame house, Dodoo et al. [206] showed that the amount of carbon released by calcination was 23 tCO_2e, which constituted 16% of the total building ECE, whereas the carbon absorption via carbonization during 100-year use and post-use periods was 5.4 and 4.7 tCO_2e, respectively. However, Lee et al. [207] considered that CO_2 uptake via the carbonation of concrete in the use stage would not exceed 5% of the CO_2 emissions in the production stage.

(2) **Concrete**. A total of 279 sets of concrete EF_m parameters were obtained from the case studies, among which 157 sets did not include the composition and strength of the concrete. In 32 sets, supplementary cementitious materials were added based on ordinary Portland cement, and 90 sets specified the compressive strength information. In the first group of 157 datasets, the average EF_m value was 0.144 $kgCO_2e\cdot kg^{-1}$, with the lowest and highest values being recorded in the North America (0.05 $kgCO_2e\cdot kg^{-1}$) and China (0.485 $kgCO_2e\cdot kg^{-1}$), respectively. The second group of 32 ordinary Portland cement and supplementary cementitious materials concrete datasets had an average EF_m of 0.105 $kgCO_2e\cdot kg^{-1}$, which was 27% lower than that of the first group. The third group comprised concrete datasets with strength information; it clearly indicated a positive correlation between the EF_m and the compressive strength of concrete (Fig. 16).

(3) **Steel**. In the cases reviewed here, 172 sets of EF_m parameters for steel were obtained, among which 119 (69.2%) did not include information pertaining to the steel type and recycling content. The values of the parameters ranged from 0.341 to 6.100 $kgCO_2e\cdot kg^{-1}$, with a difference of 17.9 times between the maximum and minimum values. The maximum and minimum values were used in case studies by Kyriakidis et al. [208] and Choi et al. [209] in Cyprus and Republic of Korea, respectively. Based on a histogram constructed, the values were primarily distributed in the range of < 4 $kgCO_2e\cdot kg^{-1}$, where 110 (92.4%) sets were in the range of < 3 $kgCO_2e\cdot kg^{-1}$. In addition, 19 and 34 sets were denoted as virgin and recycled steels, respectively. The average EF_m of the virgin steel was 2.565 $kgCO_2e\cdot kg^{-1}$, whereas the average EF_m of the recycled steel was 1.336 $kgCO_2e\cdot kg^{-1}$ (Fig. 17). According to the World Steel Association, for every additional 1 kg of recycled scrap steel used as raw material, the carbon emissions of steel can be reduced by 1 $kgCO_2e\cdot kg^{-1}$ [210].

(4) **Timber**. In the case studies, 78 sets of timber EF_m parameters were obtained. The EF_m of wooden products is affected by the raw materials and processing methods and can vary significantly from one product to another. However, in 37 (47.4%) cases, the specific wood type was not specified. The remaining 41 cases included seven types: hardwood, softwood, glulam, cross-laminated timber, oriented strand board, raw bamboo, and glued bamboo. In general, the EF_m parameters ranged from −1.665 to 2.570 $kgCO_2e\cdot kg^{-1}$, with an average value of 0.404 $kgCO_2e\cdot kg^{-1}$ (Fig. 18). Compared with the carbon emissions generated during processing, carbon storage in raw wood and post-use treatment may have a more significant effect on carbon flow, resulting in a negative carbon footprint in the product life cycle [23,123,152]. However, this was not considered in some cases, because the carbon absorbed by photosynthesis was assumed to be re-released into the atmosphere through combustion or natural oxidation [26]. The consideration/non-consideration of these carbon flows significantly affects the calculation results.

(5) **Aluminum**. In the reviewed cases, 36 sets of EF_m parameters for aluminum were obtained, among which three sets were denoted as virgin aluminum, three sets as recycled aluminum, while the rest 30 sets were unspecified as primary or recycled aluminum. The distribution of the EF_m parameters for the 36 sets of aluminum is shown in Fig. 19. The average value was 10.686 $kgCO_2e\cdot kg^{-1}$. The values of the parameters ranged from 0.666 to 29.850 $kgCO_2e\cdot kg^{-1}$, with a 44.8 fold difference between the maximum and minimum values. Both the minimum and maximum values were recorded in China [47,173]. The EF_m value was influenced by the recycling condition. In case study by Yan et al. [47], the EF_m values of virgin and recycled aluminum were 8.566 and 0.666 $kgCO_2e\cdot kg^{-1}$, respectively. In Purnell's [211] study, the corresponding EF_m values were taken as 11.5 and 1.7 $kgCO_2e\cdot kg^{-1}$, respectively.

(6) **Glass**. In the cases reviewed here, 36 sets of EF_m parameters for glass were obtained, which ranged from 0.550 to 2.820 $kgCO_2e\cdot kg^{-1}$, with a 5.1 fold difference between the maxi-

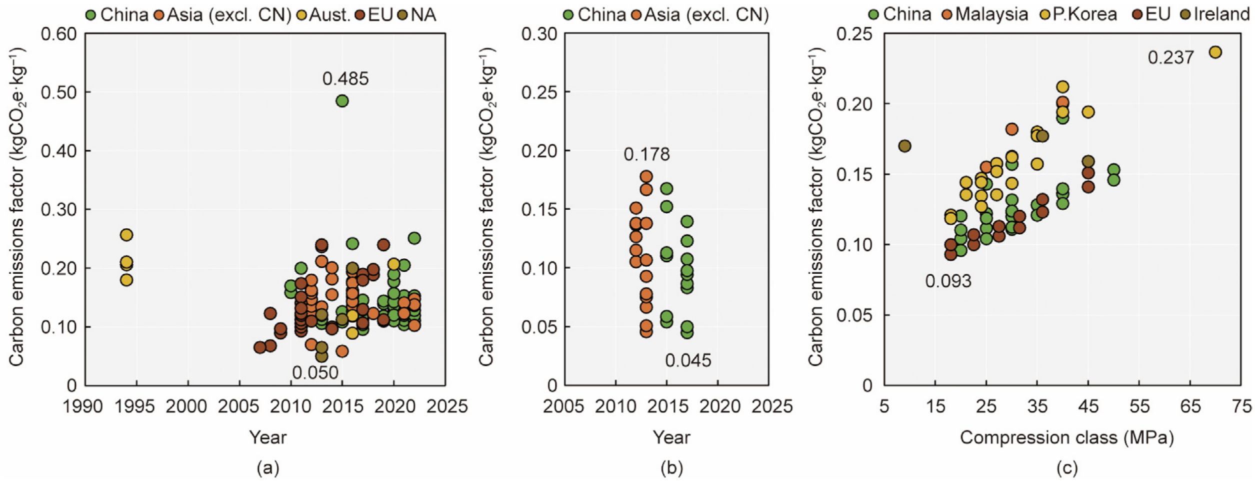


Fig. 16. Carbon emission factors of the concrete used in the case studies. (a) Concrete without specified information, (b) Concrete with supplementary cementitious materials, and (c) Concrete specified with compressive strength information. P.Korea: Republic of Korea.

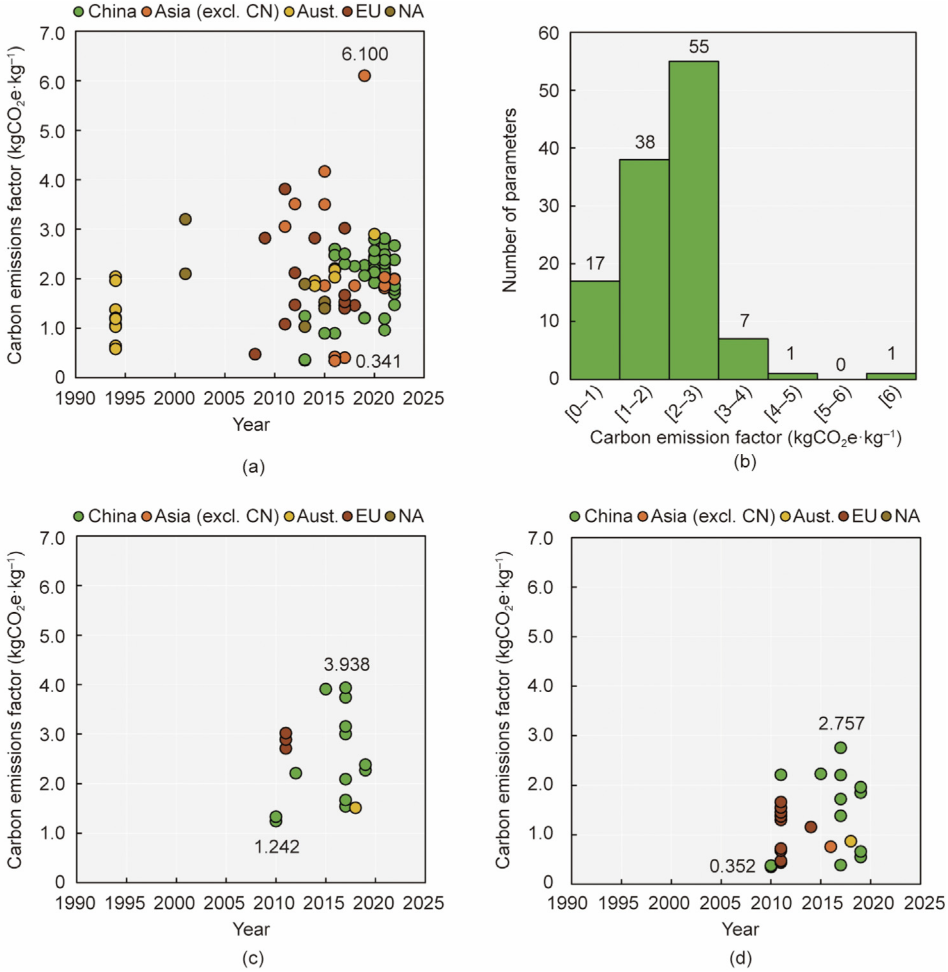


Fig. 17. Carbon emission factors of the steel used in the case studies. (a) Steel, unspecified virgin or recycled (scatterplot), (b) Steel, unspecified virgin or recycled (histogram), (c) Steel, virgin, and (d) Steel, recycled.

mum and minimum values. The distribution of the EF_m parameters is shown in Fig. 20. The average was 1.267 $kgCO_2e{\cdot}kg^{-1}$, with the maximum and minimum values recorded in China and Australia, respectively [173]. Most of the cases did not provide specific information about the glass. However, even for the same type of glass, there were differences in the values taken in each case. For example, for float glass in China, Gong et al. [26] and Yan et al. [47] used EF_m values of 2.588 and 1.858 $kgCO_2e{\cdot}kg^{-1}$, respectively.

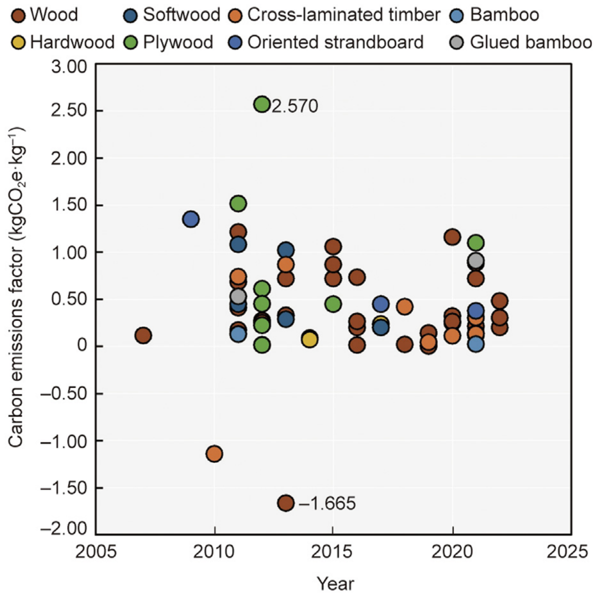


Fig. 18. Carbon emission factors of the timber used in the case studies.

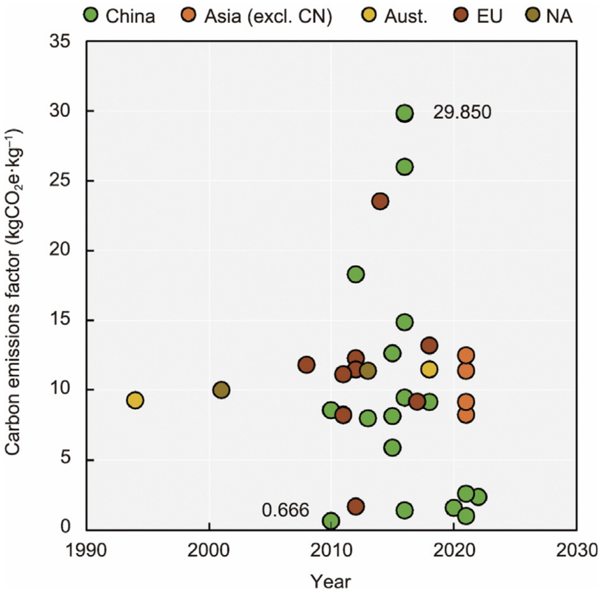


Fig. 19. Carbon emission factors of the aluminum used in the case studies.

4.5. Discussion of factors affecting LCCE calculation

4.5.1. Impact of the carbon emission calculation method

Moncaster et al. [145] and Saade et al. [212] performed comparative studies and reported that differences in life-cycle stages, material boundaries, and fundamental parameters were the primary contributors to differences in the calculations of carbon emissions. Pomponi and Moncaster [213] showed that the methods used in case studies differed significantly, resulting in differences of up to two orders of magnitude, which rendered it impossible to compare the calculation results. Piccardo and Gustavsson [131] investigated the effects of different modeling methods on the analysis of building carbon. The results showed that the material calorific value, biochar, calcination and carbonization processes, electricity production scenarios, impact distribution of multifunctional processes, and post-use disposal options affected the LCA of buildings, particularly those constructed using timber and cement.

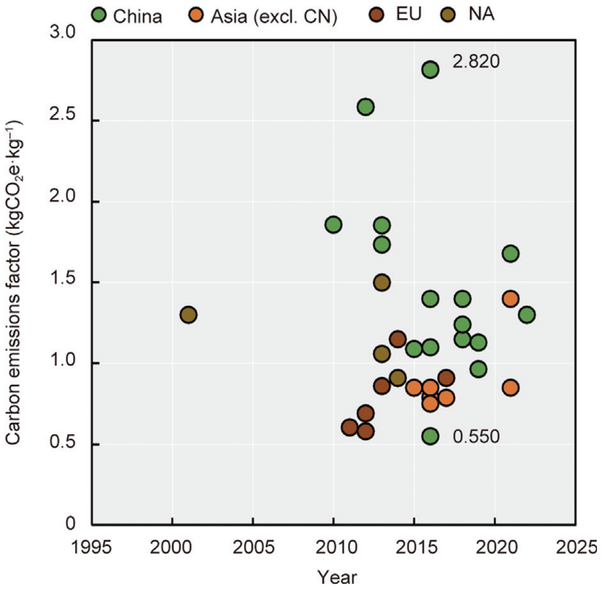


Fig. 20. Carbon emission factors of the glass used in the case studies.

The calculation results of the carbon emissions over the entire life cycle of buildings significantly depend on the life-cycle modeling and construction scenarios used. Unlike general products, buildings are complex systems and—according to general assumptions—have a lifespan of decades; as such, more advanced mathematics must be utilized when applying LCA fundamentals to models for calculating the carbon emissions of buildings, in order to address key issues at the corresponding stages. This can easily result in a loss of calculation accuracy, rendering the results unpredictable; furthermore, diametrically opposite results may be obtained for the same problem, making it difficult to obtain conclusions that are conducive to low-carbon decision-making.

4.5.2. Impact of basic carbon emission parameters

Hossain and Ng [214] analyzed the effects of parameters from different sources on the carbon emission calculation results. The evaluation results deviated even when the same system boundaries and materials were used. Furthermore, differences in the basic parameters were found to result in a 284%–1044% variation in the calculation results of ECE [213]. In the case study by Ortiz-Rodríguez et al, [164] in Spain showed that, when different parameters from the life cycle databases GaBi and Ecoinvent were selected for calculation, the proportion of OCE to LCCE was 84%–89%, whereas the proportion of carbon emissions in the maintenance stage varied from 2% to 6%. A statistical analysis of 35 existing studies showed that using certain upstream databases resulted in significant differences in the evaluation results; in particular, a difference of 22% was shown for cases in Hong Kong [215].

The carbon emission calculation process is complex and thus is difficult to trace and reproduce. As mentioned in Section 4.4.2, the EF values from existing cases differ significantly; moreover, in most studies, the material variety, content, recycled content, strength, and other information regarding concrete, steel, and timber have not been reported. The calculations performed in these studies thus lack transparency and reliability in terms of the basic parameters. We consider that, in future studies, researchers must establish a basic database suitable for a local area and prioritize its evaluation, improve the transparency of the parameter value selection for calculating building carbon emissions, consider carbon emission calculation through professional institutions, and conduct data quality analysis to clarify the reliability of the results obtained.

5. Reducing building LCCE

5.1. Carbon emission hotspots and carbon reduction principles

5.1.1. Distribution of carbon emissions from buildings

The proportions of the ECE and OCE in LCCE depend on several factors, such as the building function, materials used, building envelope performance, building energy efficiency, and building lifespan. A review by Ibn-Mohammed et al. [216] showed that ECE constituted 2%–80% of the total LCCE. Studies on traditional residential buildings with a lifespan of 50–60 years by Mao et al. [217], Ramesh et al. [218], Harris [219], and Cole and Wong [220] showed that ECE constituted 11%–40% of the LCCE; in comparison, the proportion for traditional nonresidential buildings with a lifespan of 50–60 years was found to be 10%–27% [18,217,221]. The proportion can be significantly affected by the energy carbon intensity, which can result in different priorities in terms of carbon reduction. For example, a study on a high-rise building in Australia by Robati et al. [169] showed that the proportion of ECE in LCCE increased from 27% to 58% when different electricity EF_e parameters were used.

In low-energy buildings, the proportion of ECE increases significantly and can exceed the OCE [15,105]. Chastas et al. [222] analyzed 95 housing cases and reported that the proportions of ECE in the LCCE were 9%–22%, 32%–38%, 21%–57%, and 71% for traditional buildings, passive houses, low-energy buildings, and net-zero energy consumption buildings, respectively. Röck et al. [223] analyzed 238 building LCA cases worldwide and showed that the average proportion of ECE in the LCCE was 20%–25% for buildings designed based on existing energy–efficiency regulations; for high-energy-efficiency buildings, this proportion increased to 45%–50% and could exceed 90% in extreme cases. Kristjansdottir et al. [106] investigated the carbon emissions of eight detached houses in Oslo, Norway, including one active house, two passive houses, four net-zero energy consumption buildings, and one reference house designed based on the Norwegian Building Code 2010, reporting that ECE comprised 60%–75% of the LCCE. In another study pertaining to an Australian green building, the contribution of ECE was assumed to be 100% due to the realization of net-zero emissions in the operation stage [173].

The reviewed case studies provided 309 sets of data, including calculation results for the ECE, OCE, and LCCE. Of these, 43 sets qualified for certification as low-energy buildings, green buildings, net-zero energy consumption buildings, active houses, or passive houses. In the following analysis, these 43 sets were classified as the certification group (group C), whereas the remaining 266 sets were classified as the non-certification (NC) group. Considering the effect of lifespan, the FUs was unified as "per building floor area × per year".

In terms of the LCCE, the $LCCE_{med}$ ($LCCE_{25\%}$–$LCCE_{75\%}$) of group C was 10.00 (6.76–26.57) $kgCO_2e{\cdot}m^{-2}{\cdot}a^{-1}$, which was significantly lower than that of group NC, at 32.17 (22.04–55.08) $kgCO_2e{\cdot}m^{-2}{\cdot}a^{-1}$. The ECE_{med} ($ECE_{25\%}$–$ECE_{75\%}$) of groups C and NC was 4.50 (3.40–13.80) $kgCO_2e{\cdot}m^{-2}{\cdot}a^{-1}$ and 8.16 (4.19–12.01) $kgCO_2e{\cdot}m^{-2}{\cdot}a^{-1}$, respectively. Thus, the ECE of group C is lower than those of the NC group, although a better thermal performance of the building envelope is generally required for group C. This might be because 46.5% (20 of 43 cases) of group C were timber structures, whereas the proportion of timber structures was only 16.2% (43 of 266 cases) for the NC group. The OCE_{med} ($OCE_{25\%}$–$OCE_{75\%}$) of group C and the NC group were 6.30 (3.95–11.95) $kgCO_2e{\cdot}m^{-2}{\cdot}a^{-1}$ and 24.35 (14.33–41.81) $kgCO_2e{\cdot}m^{-2}{\cdot}a^{-1}$, respectively. The proportion of ECE—that is, P_{med} ($P_{25\%}$–$P_{75\%}$)—for group C was 47.4% (29.4%–59.2%), which was much higher than that for the NC group, at 24.3% (14.1%–36.0%) (Figs. S3 and S4 in Appendix A).

5.1.2. Principles for reducing buildings' carbon emissions

Based on the implications and calculation methods for LCCE presented in Sections 3 and 4, the LCCE can be expressed as follows:

$$LCCE = \sum_{1}^{i} AD_{m.i} \times EF_{m.i} + \sum_{1}^{i} AD_{e.i} \times EF_{e.i} - CE_D - CE_e$$

\Where, $AD_{m.i}$ is activity data of the building material i, unit; $EF_{m.i}$ is carbon emission factor of the building material i, $kgCO_2e{\cdot}unit^{-1}$; $AD_{e.i}$ is activity data of the operational energy i, unit; $EF_{e.i}$ is carbon emission factor of the operational energy i, $kgCO_2e{\cdot}unit^{-1}$; CE_D is carbon reduction by supplementary benefits (module D), $kgCO_2e$; CE_e is carbon reduction by other technologies, $kgCO_2e$.

In the following analysis, technologies for reducing buildings' carbon emissions are classified into six groups: reducing the activity data of building materials (AD_m) and operational energy (AD_e); decreasing the carbon EFs of EF_m and EF_e; using supplementary benefits (CE_D); and using other carbon reduction technologies (CE_e). Technical content and carbon reduction benefits are prioritized.

5.2. Reducing buildings' carbon emissions: Technical content and benefits

5.2.1. Reducing AD_m

Methods to reduce AD_m include optimizing the lectotype and size of building structures; using building materials with higher strength, lower replacement frequency, and longer life expectancy; applying industrialized building systems; and adopting lean construction techniques (Table S12 in Appendix A).

Reducing the use of concrete and steel can significantly reduce carbon emissions during the construction of conventional reinforced concrete structures. In studies pertaining to high-rise buildings with reinforced concrete structures, Gan et al. [46], Teng and Pan [54], and Choi et al. [62] optimized the construction lectotype and component size, which resulted in a 13.5%–31.6% ECE reduction. Gan et al. [49], Tae et al. [68], and Choi et al. [209] compared structural design schemes with different material strength levels and discovered that the ECE was reduced by 11%–16.7% after improving the strength of steel rebars and concrete. Mequignon et al. [224] evaluated the effect of buildings' service life on their carbon emissions and showed that service life was equally as important as technical solutions. Heravi et al. [77] demonstrated that the use of lean techniques in the production and construction of a prefabricated steel frame reduced the ECE by 4.4% in a residential building in Iran. Robati et al. [169] achieved an 8% reduction in ECE by implementing post-tensioned concrete structural systems in high-rise buildings in Australia.

The advantages of prefabricated concrete over cast-in-place concrete include less usage of raw materials, less construction waste, and less resource consumption during construction. At the material level, Dong and Ng [50] and Dong et al. [51] showed that the carbon emissions per unit volume of prefabricated concrete were 10% lower than those of cast-in-place concrete. At the component level, Ding et al. [37], Wan Omar et al. [86], and Li et al. [225] investigated the components of prefabricated concrete and reported a carbon reduction of 19%–26.27% compared with the corresponding cast-in-place concrete components. At the building system level, the effect of prefabricated concrete on reducing carbon emissions are affected by factors such as the prefabrication rate; it is generally accepted that the carbon reduction effect intensifies as the prefabrication rate increases. However, researchers remain doubtful regarding the effect of prefabrication on carbon emissions [72]. Teng et al. [226] analyzed 27 prefabricated buildings and showed that three and five cases indicated increased ECE and OCE, respectively; moreover, further analysis showed that the ECE would increase if the materials used in prefabricated buildings were not reused. In addition, an increase in transportation demand may diminish the advantages of prefabricated concrete [19,52,227].

5.2.2. Reducing EF_m

EF_m can be reduced using two approaches: One is to use existing material products with a low carbon footprint, while the other is to optimize the building material production during stages A1–A3.

(1) **Using low-carbon building materials**. Concrete, steel, and timber are the most frequently investigated low-carbon building materials, owing to their wide range of applications in the construction sector. Typically, timber structures exhibit lower ECE compared with structures composed of the other two materials [26,60,82,87,117,124,128,140, 145,150, 169,170,228–233]. However, the carbon reduction benefits of timber depend on several prerequisites, such as onsite assembly and appropriate forest management, production methods, transportation distances, and selection of adhesives [152,195,228–230]. Studies on buildings in Australia [130], the United States [160], and Sweden [167] showed that the ECE of timber structures was 26.5%–34% lower than those of reinforced concrete structures. Comparisons between concrete and steel structures have reached diametrically opposing conclusions. In the case studies by Su et al. [12], Gong et al. [26], Vitale et al. [114], and Jönsson et al. [134], the ECE of steel-structure buildings was 10.4%–48.1% lower than those of reinforced concrete structures. However, previous studies [73,74,76,85,161,168,234] concluded that the ECE of steel-structure buildings were 12.7%–54% higher than those of reinforced concrete structures.

In addition, the low-carbon potential of fast-growing plants, such as bamboo and straw, as well as of conventional materials such as adobe, is receiving increasing attention [235,236]. Comparative studies by Pittau et al. [237] and Pittau et al. [238] showed that fast-growing plants can store a significant amount of carbon in a growth cycle and that building materials composed of these plants exhibit greater carbon-sink potential than wood, which is characterized by a relatively longer growth cycle. Similar carbon reduction benefits have been demonstrated in case studies of the use of bamboo [24] and straw bales [23,75,98,162] as building materials in China, Iran, the Balkans, and the Andean Patagonia region. Compared with using modern systems and materials, case studies of conventional technologies and materials—including the use of adobe and fly ash blocks [239,240] and limestone and lime mortar [79,80] in India, Sri Lanka, Palestine, and Iran—exhibited carbon reduction benefits (Table S13 in Appendix A).

(2) **Reducing carbon emissions during the production of building materials**. Measures for reducing carbon emissions during building material production include the substitution of high-carbon raw materials, optimization of production processes, and utilization of process carbon emissions. Rai et al. [141] evaluated the carbon reduction potential of main building materials and reported that 34.7%–45.9% of ECE_{A1-A3} was reduced when 50% of the cement was composed of ground granulated blast furnace slag as the raw material, and that 75.7% of the steel carbon emissions were prevented when secondary steel was used. Turner and Collins [241] developed a concrete composed of geopolymers that reduced ECE_{A1-A3} by 9%, which is an improvement over conventional ordinary Portland cement concrete. In addition, Xu et al. [190] reduced the average ECE_{A1-A3} of bamboo components by 15.7% via product optimization. The development of scrap-made electric arc furnace process steel is regarded as one of the major low-carbon measures for producing steel structure components in China [242].

Because building materials are the primary contributor to the total ECE, optimizing the production of building materials is crucial. In a study pertaining to reinforced concrete structure buildings in Hong Kong, Gan et al. [49] showed that using supplementary cementitious materials (35% fly ash or 75% ground granulated blast furnace slag), 100% recycled scrap steel, ecological cement, and 40 mm aggregates reduced the building ECE by 9%–39%. Similarly, Teng and Pan [52] investigated the reinforced concrete structures of high-rise residential buildings in Hong Kong and showed that partially replacing OPC with blast furnace slag reduced the ECE by 22.8%, whereas using cement substitutes (25% polyfluoroalkoxy) reduced the ECE by 9.8%. Purnell and Black [243] showed that fly ash and ground granulated blast furnace slag could reduce the ECE_{A1-A3} of plain ordinary Portland cement by 20%–30%. Iddon and Firth [143] assessed four typical construction options in the UK and showed that using concrete composed of a 30% polyfluoroalkoxy mixture reduced the ECE of new housing by 24% (Table S14 in Appendix A).

5.2.3. Reducing AD_e

The operational energy consumption contributes significantly to the total LCCE of a building. Existing energy-saving technologies for buildings, whether passive measures or active system optimization, directly affect buildings' energy consumption and the corresponding OCE [127,133,244]. Kneifel [245,246] conducted multiple sets of combined simulations for 12 prototype buildings in 228 cities and showed that the OCE was reduced by 9%–33% when conventional energy-saving measures were implemented. The carbon reduction benefits of low-energy buildings, green buildings, and passive houses over the full life cycle of a building have been recognized in studies in China [17,173], France [102,103,247], Ireland [108], Italy [112], Switzerland [135], the United States [159], and Australia [173]. For a campus building in the UK, Korsavi et al. [147] showed that using a photovoltaic system reduced the OCE by 30%. Atmaca et al. [96] evaluated a historic building renovation project in Turkey and showed that the use of high-efficiency HVAC systems reduced the LCCE by 43%. Legorburu and Smith [248] proposed a discrete multi-objective optimization framework to determine the optimal HVAC system for each campus building. These optimal HVAC systems reduced the LCCE by 15%.

The building envelope, which consumes energy, significantly affects the OCE of a building. Li et al. [249] evaluated the effect of phase-change material walls on the emissions of typical rural houses in Northeast China and showed that the LCCE was reduced by up to 52.7 $kgCO_2{\cdot}m^{-2}{\cdot}a^{-1}$ when reasonable phase-change material wall settings were used. Hacker et al. [146] investigated the 100-year LCCE of low-rise residential buildings in the UK and showed that a building with a heavy building envelope exhibited up to 7% reduced LCCE compared with a building with a light building envelope. In another study, the outer walls of two houses in Turkey were installed with an 80-mm insulation layer, which reduced the LCCE by 23.4% [94]. Karami et al. [126] reduced the OCEs released from heating a house in Europe by applying vacuum insulation technology. Pomponi et al. [250] compared 128 double skin façade configurations and showed that the double skin façade generated lower carbon emissions than a single-story façade in 85% of the cases investigated (Table S15 in Appendix A).

5.2.4. Reducing EF_e

Aside from energy consumption, another important factor that determines the OCE of a building is EF_e, which depends on the energy composition. Mosteiro-Romero et al. [172] compared two detached houses in the United States and Switzerland. Their results showed that the OCE in Switzerland was only 279 kilogram CO_2 equivalent per square meter heated floor area ($kgCO_2e·heated\ m^{-2}$), which was much lower than the 2147 $kgCO_2e·heated\ m^{-2}$ in the United States because the energy in Switzerland was primarily hydropower and nuclear energy. Ortiz et al. [163] compared two low-rise residential buildings in Spain and Colombia; owing to the low electricity EF_e, the OCE in Colombia was significantly lower. Furthermore, a comparison between pure electricity and a combination of electricity and natural gas as the energy supply revealed that an appropriate energy mix reduced the OCE by 25% and 9% in Spain and Colombia, respectively.

In cold-climate regions, the OCE is primarily derived from the heating system. In general, biomass-based and resistance-heating systems have the lowest and highest carbon emissions, respectively. Integrated biomass-based district heating can reduce carbon emissions [123,124]. Based on a large Australian retail mall, Braslavsky et al. [251] showed that only modest investments in combined cooling, heating, and power (CCHP) reduced carbon emissions by 29.6%, whereas strengthened CCHP investments combined with onsite solar power generation reduced the OCE by approximately 72%. A study pertaining to a timber building in Växjö, Sweden, showed that district heating combined with biomass-based integrated gasification combined-cycle systems (BIGCC) or heat pumps combined with BIGCC enabled negative building material production and total LCCE [124]. Zhang and Wang [22] compared several heating schemes for a high-rise residential building in a cold area of China and showed that the OCE was sequentially reduced when a coal-fired boiler, oil-fired boilers, gas-fired boilers, and solar-assisted heat pumps were used (Table S16 in Appendix A).

5.2.5. Exploiting the advantages of CE_D

CE_D includes the carbon reduction benefits from the recycling and reuse of building materials and energy recovery. For example, Blengini [113] investigated a concrete low-rise house in Italy and showed that compared with landfilling, material recycling after building demolition reduced the ECE by 18%. Coelho and de Brito [118] evaluated five constructions waste–disposal methods and showed that the separation, recovery, and reuse of core materials reduced carbon emissions in the demolition phase by 77%. Ghose et al. [252] showed that improving onsite recycling and reusing construction waste reduced the carbon emissions from building renovations by 5%–15% in New Zealand. For a high-rise residential building in China, Wang et al. [38] showed that onsite recycling was better than factory recycling or landfilling. However, research and technology pertaining to CE_D are insufficient, which hinders the utilization of the associated benefits. Wang et al. [253] investigated nine cities in China and found that 95% of decoration and renovation waste was disposed of via landfilling.

The effect of CE_D is particularly pronounced in timber buildings [254]. For a multistory timber apartment in Sweden, Gustavsson et al. [123] reported that, during the construction phase, the energy generated from biomass residue owing to wood processing was higher than the energy consumed during the construction process, which resulted in negative net carbon emissions during the production of the building materials [124]. Recycling dismantled timber elements as biofuels to replace fossil fuels can significantly reduce net carbon emissions [123,167]. Dodoo et al. [206] showed that the carbon reduction benefits of replacing fossil fuels with dismantled timber were more significant than those of using recycled concrete or steel. However, the carbon reduction effect primarily depends on the upstream forest management, production, construction, and treatment of dismantled timber [132,228]. Sathre and O'Connor [255] and Churkina et al. [256] clarified the range of carbon reduction benefits afforded by timber substitution and highlighted sustainable forest management and the rational use of wood residues as prerequisites (Table S17 in Appendix A).

5.2.6. Exploiting the potential of CE_e

The following measures target carbon emissions that are not generated by the production and use of building materials and energy and are thus generally excluded from calculations of buildings' carbon emissions. However, these emissions should be identified because they can potentially promote the carbon reduction of buildings in a broader scope.

(1) **Carbon sinks of green plants**. Based on a literature review, Besir and Cuce [257] concluded that green roofs can capture and store carbon and that the annual carbon accumulation of a vertical greening system is 13.41–97.03 $kgCO_2·m^{-2}·a^{-1}$. Regarding carbon cost, Seyedabadi et al. [258] showed that the process of replacing traditional roofs with green roofs generated 4.6 $kgCO_2·m^{-2}$ of carbon emissions. Similarly, the carbon reduction performances of green walls and spaces have been identified [259,260].

(2) **Carbon emission control for personnel activities**. GHG emissions from daily activities can be reduced via the appropriate management of daily activities. Cheung and Fan [189] investigated a hotel in Hong Kong and discovered that approximately 1900 tCO_2e of emission was avoided over the years by implementing strategies involving lighting, air conditioning, and waste recycling. Among these strategies, the most prominent was food waste recycling, which reduced the carbon emissions by 500–700 tCO_2e annually.

(3) **CO_2 capture, utilization, and storage**. CO_2 capture, utilization, and storage are regarded as the only cost-effective alternative for achieving deep decarbonization for industries that generate CO_2 during their production processes, such as cement and ceramics [261]. Accelerating CO_2 absorption through carbonation can reduce the carbon emissions from cement and concrete [205,262]. For example, Qian et al. [263] attempted to increase the absorption of CO_2 and its conversion to carbonate in cement-based materials, steel slag, and waste concrete using carbon-trapping bacteria.

(4) **Disposal of non-CO_2 GHGs**. As mentioned in Section 3.2.1, the GWP of non-CO_2 GHGs is typically tens to tens of thousands of times higher than that of CO_2, and the leakage of fluorinated refrigerants can be equivalent to high levels of carbon emissions. Instead of relying on the maturation of fluorine-free refrigeration technology, researchers can convert the related fluorides into CO_2 through recycling or combustion [177], which can reduce the GWP value to 1 and thus significantly diminish the corresponding GHG effect.

5.3. Discussion on the combined reduction of building ECE and OCE

5.3.1. Achieving a balance between ECE and OCE

Many carbon–reduction building technologies increase the ECE but reduce the OCE during building operations, ultimately reducing the total LCCE. Blengini and Di Carlo [111] compared detached houses designed as low-energy and standard buildings in Italy. The results showed that the ECE of the low-energy buildings increased by 12.5% and their OCE decreased by 71.7%, while the LCCE of the low-energy buildings was 46.1% of those of the standard buildings during a 70 year lifespan. Yang et al. [28] investigated seven representative demonstration timber buildings in China. By improving the building envelope, the ECE increased by 28.5%, the OCE decreased by 39.3%, and the LCCE decreased by 32.7%.

Notably, not all OCE reductions are predicated on ECE increases. The use of natural ventilation, expanded thermostat settings, CCHP and photovoltaic systems, 10% lighter reinforced concrete redesigns, 30% fly ash and recycled brick, cork board insulation, and wood-based interior finishes in an office building in the UK reduced the LCCE by up to 16%, including 32% and 14% reductions in the ECE and OCE, respectively [144]. Through renovations based on the passive houses standard in a low-rise apartment in Sweden, a 50%–82% reduction in OCE was obtained. By optimizing material usage, particularly by using more wood materials, the ECE can be reduced by 68% [264] (Table S18 in Appendix A).

5.3.2. Carbon payback period

The carbon payback period is typically used to characterize the time for offsetting the increase in ECE by a decrease in OCE. An analysis of a building rehabilitation project in Canada showed that the ECE caused by retrofits would be balanced by energy savings within a carbon payback period of 3–13 years [155]. To support low-carbon decision-making, carbon payback period was used to judge the carbon reduction efficiency of carbon payback period elements in Europe [265], as well as energy-saving retrofits for multi-unit dwellings and office buildings in Canada [266,267].

However, these calculations ignored the fact that the ECE had already been emitted before the building was used, and achieving a carbon balance by means of OCE offsetting would take years or even decades during the building operation. In almost all cases, the existing static EF_e was used for future calculation. Considering that the future grid EF_e drops year by year, the annual amount of OCE offsetting will decrease correspondingly, which may extend the carbon payback period and even lead to eventual failure to achieve a carbon balance.

6. Research gaps and recommendations

6.1. Gaps and challenges

Based on our analysis of the implications, calculations, and carbon reduction strategies for the LCCE of buildings, the following gaps and challenges were identified:

(1) Research goals and ideas pertaining to LCCE are mismatched. According to the IPCC, direct and indirect carbon emissions from buildings are classified as coming from the construction sector, whereas carbon emissions from building material production are classified as coming from the industrial sector. Therefore, this classification will result in an inaccurate understanding of carbon emission sources and may hinder the implementation of effective carbon reduction technologies, because reducing buildings' LCCE requires industry collaboration, particularly between the building material industry and the construction sector. Hence, LCCE calculation methods and reduction divisions should not be based on those specified by the IPCC.

(2) Calculating a building's ECE requires a detailed data list, whose acquisition is labor-intensive. Current methods for calculating the carbon emissions of building materials in the production and use stages require the analysis of building material consumption by querying technical data such as design drawings, procurement lists, and project budgets, while methods for calculating carbon emissions in the construction and demolition stages require the number of mechanical shifts for each subproject, as well as the materials and components produced onsite. However, the building materials used in actual projects and the energy-consuming facilities used during construction and demolition are diverse. Thus, the relevant data are extremely difficult to identify and measure accurately.

(3) Significant differences in the calculation results of carbon emissions among cases in the literature render it difficult to reach a consensus regarding the carbon emission intensity of typical buildings and carbon emission reduction targets. The different settings of system boundaries made it difficult to summarize and compare the results of different case studies. The EF values of the primary energy used in each case were similar. However, the EFs of electricity differed significantly, and differences by orders of magnitude were indicated in the EFs of cement, concrete, steel, and timber. In most studies, the sources of EFs were ambiguous, and the data quality and transparency were dubious.

(4) Asia—particularly China—has not yet perfected a basic database of local building materials for calculating a building's ECE. A reliable database of building materials has not yet been established in China. Databases from Europe, even though they are unsuitable for China, have been cited in numerous case studies. Calculations based on unreliable data can result in misleading conclusions and hinder the discovery of effective low-carbon options. However, establishing a database based on the measurement of a single activity within a single enterprise is difficult [268], because building materials from raw material extraction, transportation to product manufacturing, and other activities are often performed in multiple enterprises.

(5) Changes in the electricity carbon EFs as a basic parameter and its effect on the LCCE of buildings are not considered. Typically, existing energy EFs are used to calculate future building OCE. Only individual case studies [242,269] considered the reduction in the electricity EFs due to the gradual decarbonization of the electricity mix during a building's life cycle. The EFs of electricity changes with time. Disregarding this changing trend in the electricity mix renders it impossible to accurately perform future carbon emission calculations and benefit assessments pertaining to carbon emission reduction technology.

(6) Most buildings are operated in a "full space × fixed time" mode, whereas the potential of "partial space × partial time" for OCE reduction has not been exploited. The OCE can be calculated as follows: [(energy demand intensity × area × time)/energy efficiency] × energy carbon EFs. Due to the multiplicative effect, compressing the actual time and space of energy demand has a magnified carbon reduction effect. However, the potential of "partial space × partial time" for OCE reduction has not been exploited. In extreme cases, excessive full-time constant temperature and humidity regulations are imposed for the entire space of a building, which leads to an unnecessary increase in OCE.

(7) Uncertainty regarding the benefits and costs of low-carbon building technologies poses challenges in formulating carbon reduction pathways. External factors, such as climate change, cause changes to the sources of carbon emissions from building operations, changing the focus of carbon reduction for buildings [136]. Raw materials, energy, resource endowments, and technical conditions differ by location; therefore, borrowing low-carbon technologies from other locations may not be appropriate. Changes in the basic parameters of energy and materials will affect the costs and benefits of carbon reduction technologies. These uncertainties pose challenges for the further development of carbon reduction approaches.

(8) Basic research pertaining to building use, end-of-life, reuse, and recycling stages is insufficient, resulting in technical gaps. As summarized in Section 3.1.2, calculations for stages B, C, and D were performed in only 26.7%, 32.9%, and 13.7% of the cases, respectively, and comprehensive investigations into the LCCE of buildings are rare. Insufficient information

regarding the expected service life of building materials renders it impossible to calculate and evaluate recurring ECE. Construction waste during and after use is currently disposed of in landfills due to inadequate research on low-carbon disposal and recycling technologies, which hinders the potential to reduce LCCE with supplementary effects.

6.2. Development proposals

To address these research gaps and challenges, the following recommendations regarding industry standards, calculation methods, basic parameters, and carbon reduction strategies are proposed:

(1) Based on the carbon reduction effect of the entire building life cycle, synergize building materials and building standards and promote industry cooperation between the building material and building sectors. Revision or partial modification is recommended for relevant standards to enable coordination between carbon emission calculation methods and indicators in the building material and building sectors. Based on synergistic standards, a step-by-step and phased mandatory carbon emission accounting for building materials and construction enterprises is recommended. Based on massive carbon emission accounting practices and a carbon emission database, it is possible to delineate carbon emission baselines and label assessment standards for the building materials and building sectors.

(2) Based on the synergistic standards recommended above, integrate the boundaries of and methods for calculating carbon emissions from building materials and buildings, and improve data transparency and calculation reproducibility. Due to the large number of influencing elements involved, it is difficult to avoid numerical differences in each building case; thus, it is more realistic to develop a unified calculation method in addition to the related reporting and communication rules. This requires the reporting of calculation results with information transparency, including transparency regarding the LCCE system boundary (Table 3), the calculation steps, and the basic parameters used, in order to prevent misinterpretation of the results.

(3) Investigate the carbon emission boundaries of typical building material products in different regions for the entire process, and establish a basic EF_m database for typical building material products. Leading enterprises producing building materials must take the lead in clarifying the boundaries of carbon emissions; standardizing the data-collection methods for the sourcing of raw materials, production, processing, and factory transportation; and establishing carbon emissions inventories for typical building material products. Therefore, technical guidelines should be compiled and promoted for the entire industry. A product labeling method for EF_m should be implemented to ensure that all links of carbon emission data can be sourced, traced, and updated.

(4) Promote refined and information-based management of the entire construction process and establish a process-based basic database of carbon emissions from building construction and demolition. Leading construction and demolition enterprises must comprehensively sort out the typical construction and demolition processes of typical building structures, clarify the carbon emission sources and boundaries of each process, standardize their data collection methods, and establish a process for creating carbon emission inventories. Through standards, policy guidance, and demonstration by leading enterprises, refined and information-based management of materials, processes, and machinery related to construction and demolition would be comprehensively promoted to the whole industry.

(5) Based on existing building energy management platforms and building simulation technology, monitor and predict building OCE and form an OCE database for typical buildings. The energy consumption data collected by existing building energy management platforms can be converted into building OCE by combining various energy EFs. It is particularly necessary to predict the development trend of power grid carbon EFs and to release regional dynamic electricity EF_e data in a timely manner. Based on popularized data collection and simulation prediction, a target value for a building's OCE can be set, which provides basic data support for the further promotion of low-carbon policies, regulations, and technologies.

(6) Continue to promote green building certification in order to guide the reduction of OCE. The comparison in Section 5 showed that, for the group that possessed various green building certifications (low-energy buildings, green buildings, net-zero energy consumption buildings, active houses, passive houses, etc.), the LCCE was significantly lower than for the non-certified group. This finding illustrates the positive contribution of existing green building technologies to achieving low-carbon goals. Therefore, energy–efficiency standards for civil buildings should be continually enforced in order to control energy consumption. In addition, the energy mix supplied to buildings should be optimized, especially by developing local renewable energy sources for local use to reduce energy EF_e.

(7) Strengthen collaboration among stakeholders in building design, technology integration, and engineering application demonstrations to reduce building ECE. The impact of ECE will increase further as the OCE decreases. Based on the analysis in Section 5, the following aspects should be focused on: a lightweight building structure system with new low-carbon building materials as the carrier; a modular manufacturing system, assembled buildings, and industrialized construction technology; strategies and technologies for construction waste reduction, high-quality recycling, and service life extension of existing buildings; and integration with typical construction project types in the use, end-of-life, recycling, reuse, and development stages of carbon emission reduction technologies for each link.

7. Conclusion

In this study, a literature review was conducted on the implications, calculation methods, and low-carbon technology relating to LCCE. A total of 161 global studies involving 826 calculation cases were reviewed and investigated, including 85, 69, and 7 studies pertaining to LCCE, only ECE, and only OCE, respectively. Finally, research gaps and challenges in existing building LCCE studies were clarified in terms of the research goals and ideas, calculation methods, basic parameters, and carbon reduction strategies, and corresponding development suggestions were proposed.

A review of carbon emission calculation methods showed that the division of building life-cycle stages provided by ISO 21930 has not been strictly adhered to in practice. The number of case studies wherein carbon emissions were calculated in stages A1–A3, A4–A5, B1–B5, B6–B7, C1–C4, and D constituted 90.7%, 56.5%, 26.7%, 57.1%, 32.9%, and 13.7%, respectively, of the total. Only 9.4% of the cases considered the technical equipment system in the calculation. The recurring ECE generated in stages B1–B5 was not considered, and specialized calculations for the actual project were not performed in stages C1–C4 and module D; assumptions were primarily used instead.

Carbon emission values for each life-cycle stage was extracted from the cases. In general, the median carbon emissions in stages

A1–A3, A4–A5, B1–B5, B6–B7, C1–C4, and D were 321.2, 32.2, 114.9, 20.9, 1515.0, and −188.6 $kgCO_2e·m^{-2}$, respectively, and the corresponding contribution to the LCCE were 15.6%, 1.6%, 7.1%, 1.2%, 75.2%, and −4.1%, respectively. Among the ECE-related items, none of the stages' contributions to the total ECE were negligible (< 5%). The ECE of the cases differed depending on the construction type. Timber structures were unanimously regarded as the most low-carbon structure, whereas the conclusions regarding steel and concrete structures differed in different case studies.

Based on an analysis of the distribution of buildings' carbon emissions and carbon reduction hotspots, strategies and corresponding benefits were categorized into six groups: reducing activity data and carbon EFs (AD_m, AD_e, EF_m, and EF_e), exploiting supplementary benefits (CE_D), and others (CE_e). In the reviewed cases, AD_e- and EF_e-related technologies successfully reduced OCE. Compared with the benchmark scheme, an optimized scheme could reduce the OCE by 10%–72% for active and passive building energy-saving technologies, and replacing high-carbon electricity with low-carbon electricity could reduce the OCE by 9%–67%. Biomass-based energy, in combination with district heating or heat pumps, could reduce the OCE by up to 90%. Recycling wooden materials for biomass production and replacing fossil fuels can ideally achieve net-zero carbon or even negative carbon.

AD_m- and EF_m-related technologies are primarily used to reduce the ECE. Compared with the benchmark scheme, an optimized scheme could reduce the ECE by 11%–29.2% by optimizing the structure lectotype and size and by using building materials with higher strength, lower replacement frequency, and longer life expectancy; moreover, it could reduce the ECE by 1.5%–26.3% via concrete prefabrication. Substituting wood for concrete or steel as the main building material could reduce the ECE by 13%–96.5%. The low-carbon potential of rapidly progressing plant-based building materials, adobes, and other conventional building materials has garnered significant attention. Replacing high-carbon raw materials, optimizing production processes, and utilizing carbon emissions in the building material production stage can reduce the EF of building materials.

Notably, the benchmark scenarios were set differently in each case study; therefore, the quantitative results of the carbon reduction benefits cannot be used as a direct basis for horizontal comparisons between different strategies. Each case involves specific factors that are sensitive to building LCCE; thus, it is necessary to avoid using the conclusions of one case for another or to present conclusions based on generalization and deduction. Systematic carbon reduction strategy optimization can only be performed after a detailed and specific analysis of all situations is conducted, based on the entire life cycle of a building. Under a consistent framework, it is necessary to continue to collect data from practical scenarios and to gradually improve the current situation of poor-quality basic data for research on the LCCE of buildings.

CRediT authorship contribution statement

Zujian Huang: Methodology, Investigation, Data curation, Writing – original draft. **Hao Zhou:** Methodology, Investigation, Writing – original draft. **Zhijian Miao:** Methodology, Writing – review & editing. **Hao Tang:** Data Curation, Writing – review & editing. **Borong Lin:** Conceptualization, Methodology, Supervision. **Weimin Zhuang:** Conceptualization, Methodology, Supervision.

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Compliance with ethics guidelines

Zujian Huang, Hao Zhou, Zhijian Miao, Hao Tang, Borong Lin, and Weimin Zhuang declare that they have no conflict of interest or financial conflicts to disclose.

Appendix A. Supplementary data

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References

[1] United Nations Framework Convention on Climate Change (UNFCCC). The Paris Agreement. UN Climate Change Conference; 2021 Oct 31–Nov 13; Glasgow, Scotland. New York: UNFCCC; 2021.

[2] Gao Y, Gao X, Zhang XH. The 2 °C global temperature target and the evolution of the long-term goal of addressing climate change—from the United Nations framework convention on climate change to the Paris agreement. Engineering 2017;3(2):272–8.

[3] Masson-Delmotte V, Zhai P, Pörtner, HO, Roberts D, Skea J, Shukla PR, editors. Global warming of 1.5 °C: special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Report. Cambridge: Cambridge University Press; 2018.

[4] United Nations Environment Programme (UNEP). 2021 Global status report for buildings and construction: towards a zero-emission, efficient and resilient buildings and construction sector. Report. Kenya: UNEP; 2021 Oct.

[5] Chau CK, Leung TM, Ng WY. A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings. Appl Energy 2015;143:395–413.

[6] Cabeza LF, Rincón L, Vilariño V, Pérez G, Castell A. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: a review. Renew Sustain Energy Rev 2014;29:394–416.

[7] ISO 21930:2017: Sustainability in buildings and civil engineering works—Core rules for environmental product declarations of construction products and services. International Organization for Standardization (ISO) standard. Geneva: International Organization for Standardization; 2017.

[8] World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). Greenhouse gas protocol: product life cycle accounting and reporting standard. Final report. Washington and Geneva: WRI and WBCSD; 2011 Dec.

[9] Manfredi S, Allacker K, Chomkhamsri K, Pelletier N, de Souza DM. Product environmental footprint (PEF) guide. Report. Italy: European Commission–Joint Research Centre; 2012 Jul. Report No.: N 070307/2009/552517.

[10] Jiang ZL, Wang HT, Liao WJ, editors. Comparison and improvement of life-cycle-modelling methods for recycling. In: The 27th Annual Meeting of the Society of Environmental Toxicology and Chemistry Europe (SETAC Europe); 2017 May 7–11; Belgium. Brussels: Curran Associates; 2018.

[11] Hong J, Shen GQ, Feng Y, Lau WST, Mao C. Greenhouse gas emissions during the construction phase of a building: a case study in China. J Clean Prod 2015;103:249–59.

[12] Su X, Zhang X, Gao J. Inventory analysis of LCA on steel-and concrete-construction office buildings. Energy Build 2008;40(7):1188–93.

[13] Wu HJ, Yuan ZW, Zhang L, Bi J. Life cycle energy consumption and CO_2 emission of an office building in China. Int J Life Cycle Assess 2012;17(2):105–18.

[14] Zhang X, Wang F. Assessment of embodied carbon emissions for building construction in China: comparative case studies using alternative methods. Energy Build 2016;130:330–40.

[15] Wu X, Peng B, Lin B. A dynamic life cycle carbon emission assessment on green and non-green buildings in China. Energy Build 2017;149:272–81.

[16] Su X, Zhang X. A detailed analysis of the embodied energy and carbon emissions of steel-construction residential buildings in China. Energy Build 2016;119:323–30.

[17] Su X, Tian S, Shao X, Zhao X. Embodied and operational energy and carbon emissions of passive building in HSCW zone in China: a case study. Energy Build 2020;222:110090.

[18] Peng C. Calculation of a building's life cycle carbon emissions based on Ecotect and building information modeling. J Clean Prod 2016;112:453–65.

[19] Mao C, Shen Q, Shen L, Tang L. Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods: two case studies of residential projects. Energy Build 2013;66:165–76.

[20] Hong J, Shen GQ, Peng Y, Feng Y, Mao C. Uncertainty analysis for measuring greenhouse gas emissions in the building construction phase: a case study in China. J Clean Prod 2016;129:183–95.

[21] Ji Y, Li K, Liu G, Shrestha A, Jing J. Comparing greenhouse gas emissions of precast *in-situ* and conventional construction methods. J Clean Prod 2018;173:124–34.

[22] Zhang X, Wang F. Analysis of embodied carbon in the building life cycle considering the temporal perspectives of emissions: a case study in China. Energy Build 2017;155:404–13.

[23] Li H, Luo Z, Xu X, Cang Y, Yang L. Assessing the embodied carbon reduction potential of straw bale rural houses by hybrid life cycle assessment: a four-case study. J Clean Prod 2021;303:127002.

[24] Zhang X, Xu J, Zhang X, Li Y. Life cycle carbon emission reduction potential of a new steel–bamboo composite frame structure for residential houses. J Build Eng 2021;39:102295.

[25] Zhang X, Liu K, Zhang Z. Life cycle carbon emissions of two residential buildings in China: comparison and uncertainty analysis of different assessment methods. J Clean Prod 2020;266:122037.

[26] Gong X, Nie Z, Wang Z, Cui S, Gao F, Zuo T. Life cycle energy consumption and carbon dioxide emission of residential building designs in Beijing. J Ind Ecol 2012;16(4):576–87.

[27] Chang Y, Ries RJ, Lei S. The embodied energy and emissions of a high-rise education building: a quantification using process-based hybrid life cycle inventory model. Energy Build 2012;55:790–8.

[28] Yang X, Zhang S, Wang K. Quantitative study of life cycle carbon emissions from 7 timber buildings in China. Int J Life Cycle Assess 2021;26(9):1721–34.

[29] Li XJ, Xie WJ, Xu L, Li LL, Jim CY, Wei TB. Holistic life-cycle accounting of carbon emissions of prefabricated buildings using LCA and BIM. Energy Build 2022;266:112136.

[30] Li XJ, Lai JY, Ma CY, Wang C. Using BIM to research carbon footprint during the materialization phase of prefabricated concrete buildings: a China study. J Clean Prod 2021;279:123454.

[31] Li H, Deng Q, Zhang J, Xia B, Skitmore M. Assessing the life cycle CO_2 emissions of reinforced concrete structures: four cases from China. J Clean Prod 2019;210:1496–506.

[32] Liu G, Gu T, Xu P, Hong J, Shrestha A, Martek I. A production line-based carbon emission assessment model for prefabricated components in China. J Clean Prod 2019;209:30–9.

[33] Cao X, Li X, Zhu Y, Zhang Z. A comparative study of environmental performance between prefabricated and traditional residential buildings in China. J Clean Prod 2015;109:131–43.

[34] Yu D, Tan H, Ruan Y. A future bamboo–structure residential building prototype in China: life cycle assessment of energy use and carbon emission. Energy Build 2011;43(10):2638–46.

[35] Zhang X, Zheng R. Reducing building embodied emissions in the design phase: a comparative study on structural alternatives. J Clean Prod 2020;243:118656.

[36] Cang Y, Yang L, Luo Z, Zhang N. Prediction of embodied carbon emissions from residential buildings with different structural forms. Sustain Cities Soc 2020;54:101946.

[37] Ding Z, Liu S, Luo L, Liao L. A building information modeling-based carbon emission measurement system for prefabricated residential buildings during the materialization phase. J Clean Prod 2020;264:121728.

[38]\ Wang J, Wu H, Duan H, Zillante G, Zuo J, Yuan H. Combining life cycle assessment and building information modelling to account for carbon emission of building demolition waste: a case study. J Clean Prod 2018;172:3154–66.

[39] Ma JJ, Du G, Zhang ZK, Wang PX, Xie BC. Life cycle analysis of energy consumption and CO_2 emissions from a typical large office building in Tianjin. China. Build Environ 2017;117:36–48.

[40] Li L, Chen K. Quantitative assessment of carbon dioxide emissions in construction projects: a case study in Shenzhen. J Clean Prod 2017;141:394–408.

[41] Li XL, Yong RZ, Lin D. An investigation on life-cycle energy consumption and carbon emissions of building space heating and cooling systems. Renew Energy 2015;84:124–9.

[42] Li D, Cui P, Lu Y. Development of an automated estimator of life-cycle carbon emissions for residential buildings: a case study in Nanjing, China. Habitat Int 2016;57:154–63.

[43] Li DZ, Chen HX, Hui ECM, Zhang JB, Li QM. A methodology for estimating the life-cycle carbon efficiency of a residential building. Build Environ 2013;59:448–55.

[44] Gan VJL, Deng M, Tse KT, Chan CM, Lo IMC, Cheng JCP. Holistic BIM framework for sustainable low carbon design of high-rise buildings. J Clean Prod 2018;195:1091–104.

[45] Gan VJL, Chan CM, Tse KT, Lo IMC, Cheng JCP. A comparative analysis of embodied carbon in high-rise buildings regarding different design parameters. J Clean Prod 2017;161:663–75.

[46] Gan VJL, Wong CL, Tse KT, Cheng JCP, Lo IMC, Chan CM. Parametric modeling and evolutionary optimization for cost-optimal and low-carbon design of high-rise reinforced concrete buildings. Adv Eng Inform 2019;42:100962.

[47] Yan H, Shen Q, Fan LC, Wang Y, Zhang L. Greenhouse gas emissions in building construction: a case study of One Peking in Hong Kong. Build Environ 2010;45(4):949–55.

[48] Gan VJL, Cheng JCP, Lo IMC, Chan CM. Developing a CO_2-e accounting method for quantification and analysis of embodied carbon in high-rise buildings. J Clean Prod 2017;141:825–36.

[49] Gan VJL, Cheng JCP, Lo IMC. A comprehensive approach to mitigation of embodied carbon in reinforced concrete buildings. J Clean Prod 2019;229:582–97.

[50] Dong YH, Ng ST. A life cycle assessment model for evaluating the environmental impacts of building construction in Hong Kong. Build Environ 2015;89:183–91.

[51] Dong YH, Jaillon L, Chu P, Poon CS. Comparing carbon emissions of precast and cast-in-situ construction methods—a case study of high-rise private building. Constr Build Mater 2015;99:39–53.

[52] Teng Y, Pan W. Systematic embodied carbon assessment and reduction of prefabricated high-rise public residential buildings in Hong Kong. J Clean Prod 2019;238:117791.

[53] Jing R, Wang M, Zhang R, Li N, Zhao Y. A study on energy performance of 30 commercial office buildings in Hong Kong. Energy Build 2017;144:117–28.

[54] Teng Y, Pan W. Estimating and minimizing embodied carbon of prefabricated high-rise residential buildings considering parameter, scenario and model uncertainties. Build Environ 2020;180:106951.

[55] Lai JHK. Carbon footprints of hotels: analysis of three archetypes in Hong Kong. Sustain Cities Soc 2015;14:334–41.

[56] Zhang X, Shen L, Zhang L. Life cycle assessment of the air emissions during building construction process: a case study in Hong Kong. Renew Sustain Energy Rev 2013;17:160–9.

[57] Lai J, Lu M. Analysis and benchmarking of carbon emissions of commercial buildings. Energy Build 2019;199:445–54.

[58] Huang KT, Wang JC, Wang YC. Analysis and benchmarking of greenhouse gas emissions of luxury hotels. Int J Hospit Manage 2015;51:56–66.

[59] Suzuki M, Oka T. Estimation of life cycle energy consumption and CO_2 emission of office buildings in Japan. Energy Build 1998;28(1):33–41.

[60] Suzuki M, Oka T, Okada K. The estimation of energy consumption and CO_2 emission due to housing construction in Japan. Energy Build 1995;22(2):165–9.

[61] Gerilla GP, Teknomo K, Hokao K. An environmental assessment of wood and steel reinforced concrete housing construction. Build Environ 2007;42(7):2778–84.

[62] Choi SW, Oh BK, Park HS. Design technology based on resizing method for reduction of costs and carbon dioxide emissions of high-rise buildings. Energy Build 2017;138:612–20.

[63] Roh S, Tae S, Suk SJ, Ford G, Shin S. Development of a building life cycle carbon emissions assessment program (BEGAS 2.0) for Korea's green building index certification system. Renew Sustain Energy Rev 2016;53:954–65.

[64] Moon HS, Hyun CT, Hong T. Prediction model of CO_2 emission for residential buildings in Republic of Korea. J Manage Eng 2014;30(3):04014001.

[65] Roh S, Tae S. An integrated assessment system for managing life cycle CO_2 emissions of a building. Renew Sustain Energy Rev 2017;73:265–75.

[66] Jang M, Hong T, Ji C. Hybrid LCA model for assessing the embodied environmental impacts of buildings in Republic of Korea. Environ Impact Assess Rev 2015;50:143–55.

[67] Roh S, Tae S, Suk SJ, Ford G. Evaluating the embodied environmental impacts of major building tasks and materials of apartment buildings in Korea. Renew Sustain Energy Rev 2017;73:135–44.

[68] Tae S, Baek C, Shin S. Life cycle CO_2 evaluation on reinforced concrete structures with high-strength concrete. Environ Impact Assess Rev 2011;31(3):253–60.

[69] Sim J, Sim J, Park C. The air emission assessment of a Republic of Korean apartment building's life cycle, along with environmental impact. Build Environ 2016;95:104–15.

[70] Jeong YS, Lee SE, Huh JH. Estimation of CO_2 emission of apartment buildings due to major construction materials in the Republic of Korea. Energy Build 2012;49:437–42.

[71] Lee D, Lim C, Kim S. CO_2 emission reduction effects of an innovative composite precast concrete structure applied to heavy loaded and long span buildings. Energy Build 2016;126:36–43.

[72] Jeong J, Hong T, Ji C, Kim J, Lee M, Jeong K, et al. An integrated evaluation of productivity, cost and CO_2 emission between prefabricated and conventional columns. J Clean Prod 2017;142:2393–406.

[73] Kim S, Moon JH, Shin Y, Kim GH, Seo DS. Life comparative analysis of energy consumption and CO_2 emissions of different building structural frame types. Sci World J 2013;2013:175702.

[74] Ranjbar N, Balali A, Valipour A, Yunusa-Kaltungo A, Edwards R, Pignatta G, et al. Investigating the environmental impact of reinforced-concrete and structural-steel frames on sustainability criteria in green buildings. J Build Eng 2021;43:103184.

[75] Mehravar M, Veshkini A, Veiseh S, Fayaz R. Physical properties of straw bale and its effect on building energy conservation and carbon emissions in different climatic regions of Iran. Energy Build 2022;254:111559.

[76] Hosseinian SM, Faghani M. Assessing the effect of structural parameters and building site in achieving low carbon building materialization using a life-cycle assessment approach. J Build Eng 2021;44:103318.

[77] Heravi G, Rostami M, Kebria MF. Energy consumption and carbon emissions assessment of integrated production and erection of buildings' pre-fabricated steel frames using lean techniques. J Clean Prod 2020;253:120045.

[78] Zomorodian ZS, Tahsildoost M. Energy and carbon analysis of double skin façades in the hot and dry climate. J Clean Prod 2018;197:85–96.

[79] Pakdel A, Ayatollahi H, Sattary S. Embodied energy and CO_2 emissions of life cycle assessment (LCA) in the traditional and contemporary Iranian construction systems. J Build Eng 2021;39:102310.

[80] Piroozfar P, Pomponi F, El-Alem F. Life cycle environmental impact assessment of contemporary and traditional housing in Palestine. Energy Build 2019;202:109333.

[81] Marzouk M, Abdelkader EM, Al-Gahtani K. Building information modeling-based model for calculating direct and indirect emissions in construction projects. J Clean Prod 2017;152:351–63.

[82] Balasbaneh AT, Bin-Marsono AK. Strategies for reducing greenhouse gas emissions from residential sector by proposing new building structures in hot and humid climatic conditions. Build Environ 2017;124:357–68.

[83] Wan Omar WMS. A hybrid life cycle assessment of embodied energy and carbon emissions from conventional and industrialised building systems in Malaysia. Energy Build 2018;167:253–68.

[84] Jia Wen T, Chin Siong H, Noor ZZ. Assessment of embodied energy and global warming potential of building construction using life cycle analysis approach: case studies of residential buildings in Iskandar Malaysia. Energy Build 2015;93:295–302.

[85] Balasbaneh AT, Ramli MZ. A comparative life cycle assessment (LCA) of concrete and steel-prefabricated prefinished volumetric construction structures in Malaysia. Environ Sci Pollut Res Int 2020;27(34):43186–201.

[86] Wan Omar WMS, Doh JH, Panuwatwanich K, Miller D. Assessment of the embodied carbon in precast concrete wall panels using a hybrid life cycle assessment approach in Malaysia. Sustain Cities Soc 2014;10:101–11.

[87] Bin-Marsono AK, Balasbaneh AT. Combinations of building construction material for residential building for the global warming mitigation for Malaysia. Constr Build Mater 2015;85:100–8.

[88] Kofoworola OF, Gheewala SH. Environmental life cycle assessment of a commercial office building in Thailand. Int J Life Cycle Assess 2008;13(6):498–511.

[89] Kua HW, Wong CL. Analyzing the life cycle greenhouse gas emission and energy consumption of a multi-storied commercial building in Singapore from an extended system boundary perspective. Energy Build 2012;51:6–14.

[90] Wu XC, Priyadarsini R, Lee SE. Benchmarking energy use and greenhouse gas emissions in Singapore's hotel industry. Energy Policy 2010;38(8):4520–7.

[91] Sharma VA, Shree V, Nautiyal H. Life cycle environmental assessment of an educational building in Northern India: a case study. Sustain Cities Soc 2012;4:22–8.

[92] Kumanayake R, Luo H. A tool for assessing life cycle CO_2 emissions of buildings in Sri Lanka. Build Environ 2018;128:272–86.

[93] Kumanayake R, Luo H, Paulusz N. Assessment of material related embodied carbon of an office building in Sri Lanka. Energy Build 2018;166:250–7.

[94] Atmaca A. Life-cycle assessment and cost analysis of residential buildings in South East of Turkey: part 2—a case study. Int J Life Cycle Assess 2016;21(7):925–42.

[95] Atmaca A, Atmaca N. Life cycle energy (LCEA) and carbon dioxide emissions ($LCCO_2A$) assessment of two residential buildings in Gaziantep. Turkey. Energy Build 2015;102:417–31.

[96] Atmaca N, Atmaca A, İhsan ÖA. The impacts of restoration and reconstruction of a heritage building on life cycle energy consumption and related carbon dioxide emissions. Energy Build 2021;253:111507.

[97] Passer A, Kreiner H, Maydl P. Assessment of the environmental performance of buildings: a critical evaluation of the influence of technical building equipment on residential buildings. Int J Life Cycle Assess 2012;17(9):1116–30.

[98] Krasny E, Klarić S, Korjenić A. Analysis and comparison of environmental impacts and cost of bio-based house versus concrete house. J Clean Prod 2017;161:968–76.

[99] Junnila S, Horvath A. Life-cycle environmental effects of an office building. J Infrastruct Syst 2003;9(4):157–66.

[100] Takano A, Winter S, Hughes M, Linkosalmi L. Comparison of life cycle assessment databases: a case study on building assessment. Build Environ 2014;79:20–30.

[101] Pal SK, Takano A, Alanne K, Siren K. A life cycle approach to optimizing carbon footprint and costs of a residential building. Build Environ 2017;123:146–62.

[102] Thiers S, Peuportier B. Energy and environmental assessment of two high energy performance residential buildings. Build Environ 2012;51:276–84.

[103] Thiers S, Peuportier B. Thermal and environmental assessment of a passive building equipped with an earth-to-air heat exchanger in France. Sol Energy 2008;82(9):820–31.

[104] Dimoudi A, Tompa C. Energy and environmental indicators related to construction of office buildings. Resour Conserv Recycling 2008;53(1–2):86–95.

[105] Houlihan Wiberg A, Georges L, Dokka TH, Haase M, Time B, Lien AG, et al. A net zero emission concept analysis of a single-family house. Energy Build 2014;74:101–10.

[106] Kristjansdottir TF, Heeren N, Andresen I, Brattebø H. Comparative emission analysis of low-energy and zero-emission buildings. Build Res Inform 2018;46(4):367–82.

[107] Moschetti R, Brattebø H, Sparrevik M. Exploring the pathway from zero-energy to zero-emission building solutions: a case study of a Norwegian office building. Energy Build 2019;188–189:84–97.

[108] Famuyibo A, Duffy A, Strachan P. Achieving a holistic view of the life cycle performance of existing dwellings. Build Environ 2013;70:90–101.

[109] Moran P, Goggins J, Hajdukiewicz M. Super-insulate or use renewable technology? Life cycle cost, energy and global warming potential analysis of nearly zero energy buildings (NZEB) in a temperate oceanic climate. Energy Build 2017;139:590–607.

[110] Asdrubali F, Baldassarri C, Fthenakis V. Life cycle analysis in the construction sector: guiding the optimization of conventional Italian buildings. Energy Build 2013;64:73–89.

[111] Blengini GA, Di Carlo T. The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. Energy Build 2010;42(6):869–80.

[112] Blengini GA, Di Carlo T. Energy-saving policies and low-energy residential buildings: an LCA case study to support decision makers in Piedmont (Italy). Int J Life Cycle Assess 2010;15(7):652–65.

[113] Blengini GA. Life cycle of buildings, demolition and recycling potential: a case study in Turin. Italy. Build Environ 2009;44(2):319–30.

[114] Vitale P, Spagnuolo A, Lubritto C, Arena U. Environmental performances of residential buildings with a structure in cold formed steel or reinforced concrete. J Clean Prod 2018;189:839–52.

[115] Proietti S, Sdringola P, Desideri U, Zepparelli F, Masciarelli F, Castellani F. Life cycle assessment of a passive house in a seismic temperate zone. Energy Build 2013;64:463–72.

[116] Bastos J, Batterman SA, Freire F. Life-cycle energy and greenhouse gas analysis of three building types in a residential area in Lisbon. Energy Build 2014;69:344–53.

[117] Monteiro H, Freire F. Life cycle assessment of a house with alternative exterior walls: comparison of three impact assessment methods. Energy Build 2012;47:572–83.

[118] Coelho A, de Brito J. Influence of construction and demolition waste management on the environmental impact of buildings. Waste Manag 2012;32(3):532–41.

[119] Zabalza Bribián I, Aranda Usón A, Scarpellini S. Life cycle assessment in buildings: state-of-the-art and simplified LCA methodology as a complement for building certification. Build Environ 2009;44(12):2510–20.

[120] Ortiz O, Bonnet C, Bruno JC, Castells F. Sustainability based on LCM of residential dwellings: a case study in Catalonia. Spain. Build Environ 2009;44(3):584–94.

[121] Pacheco-Torres R, Jadraque E, Roldán-Fontana J, Ordóñez J. Analysis of CO_2 emissions in the construction phase of single-family detached houses. Sustain Cities Soc 2014;12:63–8.

[122] Pons O, Wadel G. Environmental impacts of prefabricated school buildings in Catalonia. Habitat Int 2011;35(4):553–63.

[123] Gustavsson L, Joelsson A, Sathre R. Life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building. Energy Build 2010;42(2):230–42.

[124] Gustavsson L, Joelsson A. Life cycle primary energy analysis of residential buildings. Energy Build 2010;42(2):210–20.

[125] Nässén J, Holmberg J, Wadeskog A, Nyman M. Direct and indirect energy use and carbon emissions in the production phase of buildings: an input–output analysis. Energy 2007;32(9):1593–602.

[126] Karami P, Al-Ayish N, Gudmundsson K. A comparative study of the environmental impact of Swedish residential buildings with vacuum insulation panels. Energy Build 2015;109:183–94.

[127] Wallhagen M, Glaumann M, Malmqvist T. Basic building life cycle calculations to decrease contribution to climate change—case study on an office building in Sweden. Build Environ 2011;46(10):1863–71.

[128] Dodoo A, Gustavsson L, Sathre R. Lifecycle carbon implications of conventional and low-energy multi-storey timber building systems. Energy Build 2014;82:194–210.

[129] Petrovic B, Myhren JA, Zhang X, Wallhagen M, Eriksson O. Life cycle assessment of a wooden single-family house in Sweden. Appl Energy 2019;251:113253.

[130] Sathre R, Gustavsson L. Using wood products to mitigate climate change: external costs and structural change. Appl Energy 2009;86(2):251–7.

[131] Piccardo C, Gustavsson L. Implications of different modelling choices in primary energy and carbon emission analysis of buildings. Energy Build 2021;247:111145.

[132] Peñaloza D, Erlandsson M, Falk A. Exploring the climate impact effects of increased use of bio-based materials in buildings. Constr Build Mater 2016;125:219–26.

[133] Andersson M, Barkander J, Kono J, Ostermeyer Y. Abatement cost of embodied emissions of a residential building in Sweden. Energy Build 2018;158:595–604.

[134] Jonsson A, Bjorklund T, Tillman AM. LCA of concrete and steel building frames. Int J Life Cycle Assess 1998;3(4):216–24.

[135] Citherlet S, Defaux T. Energy and environmental comparison of three variants of a family house during its whole life span. Build Environ 2007;42(2):591–8.

[136] Williams D, Elghali L, Wheeler R, France C. Climate change influence on building lifecycle greenhouse gas emissions: case study of a UK mixed-use development. Energy Build 2012;48:112–26.

[137] Filimonau V, Dickinson J, Robbins D, Huijbregts MAJ. Reviewing the carbon footprint analysis of hotels: life cycle energy analysis (LCEA) as a holistic method for carbon impact appraisal of tourist accommodation. J Clean Prod 2011;19(17–18):1917–30.

[138] Cuéllar-Franca RM, Azapagic A. Environmental impacts of the UK residential sector: life cycle assessment of houses. Build Environ 2012;54:86–99.

[139] Moncaster AM, Symons KE. A method and tool for 'cradle to grave' embodied carbon and energy impacts of UK buildings in compliance with the new TC350 standards. Energy Build 2013;66:514–23.

[140] Monahan J, Powell JC. An embodied carbon and energy analysis of modern methods of construction in housing: a case study using a lifecycle assessment framework. Energy Build 2011;43(1):179–88.
[141] Rai D, Sodagar B, Fieldson R, Hu X. Assessment of CO_2 emissions reduction in a distribution warehouse. Energy 2011;36(4):2271–7.
[142] Asif M, Muneer T, Kelley R. Life cycle assessment: a case study of a dwelling home in Scotland. Build Environ 2007;42(3):1391–4.
[143] Iddon CR, Firth SK. Embodied and operational energy for new-build housing: a case study of construction methods in the UK. Energy Build 2013;67:479–88.
[144] Azzouz A, Borchers M, Moreira J, Mavrogianni A. Life cycle assessment of energy conservation measures during early stage office building design: a case study in London. UK. Energy Build 2017;139:547–68.
[145] Moncaster AM, Pomponi F, Symons KE, Guthrie PM. Why method matters: temporal, spatial and physical variations in LCA and their impact on choice of structural system. Energy Build 2018;173:389–98.
[146] Hacker JN, De Saulles TP, Minson AJ, Holmes MJ. Embodied and operational carbon dioxide emissions from housing: a case study on the effects of thermal mass and climate change. Energy Build 2008;40(3):375–84.
[147] Korsavi SS, Jones RV, Bilverstone PA, Fuertes A. A longitudinal assessment of the energy and carbon performance of a Passivhaus university building in the UK. J Build Eng 2021;44:103353.
[148] Rossi B, Marique AF, Reiter S. Life-cycle assessment of residential buildings in three different European locations, case study. Build Environ 2012;51:402–7.
[149] Rossi B, Marique AF, Glaumann M, Reiter S. Life-cycle assessment of residential buildings in three different European locations, basic tool. Build Environ 2012;51:395–401.
[150] Hafner A, Schafer S. Comparative LCA study of different timber and mineral buildings and calculation method for substitution factors on building level. J Clean Prod 2017;167:630–42.
[151] Quintana-Gallardo A, Schau EM, Niemelä EP, Burnard MD. Comparing the environmental impacts of wooden buildings in Spain, Slovenia, and Germany. J Clean Prod 2021;329:129587.
[152] Salazar J, Meil J. Prospects for carbon-neutral housing: the influence of greater wood use on the carbon footprint of a single-family residence. J Clean Prod 2009;17(17):1563–71.
[153] Van Ooteghem K, Xu L. The life-cycle assessment of a single-storey retail building in Canada. Build Environ 2012;49:212–26.
[154] Zhang W, Tan S, Lei Y, Wang S. Life cycle assessment of a single-family residential building in Canada: a case study. Build Simul 2014;7(4):429–38.
[155] Opher T, Duhamel M, Posen ID, Panesar DK, Brugmann R, Roy A, et al. Life cycle GHG assessment of a building restoration: case study of a heritage industrial building in Toronto. Canada. J Clean Prod 2021;279:123819.
[156] Cole RJ. Energy and greenhouse gas emissions associated with the construction of alternative structural systems. Build Environ 1998;34(3):335–48.
[157] Scheuer C, Keoleian A, Reppe P. Life cycle energy and environmental performance of a new university building: modelling challenges and design implications. Energy Build 2003;35(10):1049–64.
[158] Nadoushani ZSM, Akbarnezhad A. Effects of structural system on the life cycle carbon footprint of buildings. Energy Build 2015;102:337–46.
[159] Keoleian G, Blanchard S, Reppe P. Life-cycle energy, costs, and strategies for improving a single-family house. J Ind Ecol 2000;4(2):135–56.
[160] Pierobon F, Huang M, Simonen K, Ganguly I. Environmental benefits of using hybrid CLT structure in midrise non-residential construction: an LCA comparative case study in the US PNW. J Build Eng 2019;26:100862.
[161] Guggemos AA, Horvath A. Comparison of environmental effects of steel- and concrete-framed buildings. J Infrastruct Syst 2005;11(2):93–101.
[162] González AD. Energy and carbon embodied in straw and clay wall blocks produced locally in the Andean Patagonia. Energy Build 2014;70:15–22.
[163] Ortiz O, Castells F, Sonnemann G. Operational energy in the life cycle of residential dwellings: the experience of Spain and Colombia. Appl Energy 2010;87(2):673–80.
[164] Ortiz-Rodríguez O, Castells F, Sonnemann G. Life cycle assessment of two dwellings: one in Spain, a developed country, and one in Colombia, a country under development. Sci Total Environ 2010;408(12):2435–43.
[165] Sandanayake M, Zhang G, Setunge S. A comparative method of air emission impact assessment for building construction activities. Environ Impact Assess Rev 2018;68:1–9.
[166] Sandanayake M, Zhang G, Setunge S. Environmental emissions at foundation construction stage of buildings—two case studies. Build Environ 2016;95:189–98.
[167] Jayalath A, Navaratnam S, Ngo T, Mendis P, Hewson N, Aye L. Life cycle performance of cross laminated timber mid-rise residential buildings in Australia. Energy Build 2020;223:110091.
[168] Aye L, Ngo T, Crawford RH, Gammampila R, Mendis P. Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules. Energy Build 2012;47:159–68.
[169] Robati M, Oldfield P, Nezhad AA, Carmichael DG, Kuru A. Carbon value engineering: a framework for integrating embodied carbon and cost reduction strategies in building design. Build Environ 2021;192:107620.
[170] Lu HR, El Hanandeh A, Gilbert BP. A comparative life cycle study of alternative materials for Australian multi-storey apartment building frame constructions: environmental and economic perspective. J Clean Prod 2017;166:458–73.
[171] Sandanayake M, Lokuge W, Zhang G, Setunge S, Thushar Q. Greenhouse gas emissions during timber and concrete building construction—a scenario based comparative case study. Sustain Cities Soc 2018;38:91–7.
[172] Mosteiro-Romero M, Krogmann U, Wallbaum H, Ostermeyer Y, Senick JS, Andrews CJ. Relative importance of electricity sources and construction practices in residential buildings: a Swiss—US comparison of energy related life-cycle impacts. Energy Build 2014;68:620–31.
[173] Wang T, Seo S, Liao PC, Fang D. GHG emission reduction performance of state-of-the-art green buildings: review of two case studies. Renew Sustain Energy Rev 2016;56:484–93.
[174] Fenner AE, Kibert CJ, Woo J, Morque S, Razkenari M, Hakim H, et al. The carbon footprint of buildings: a review of methodologies and applications. Renew Sustain Energy Rev 2018;94:1142–52.
[175] Hong Kong Environmental Protection Department (HKEPD). Study of climate change in Hong Kong: feasibility study. Report. Hong Kong: HKEPD; 2010 Dec. Contract No.: CE 45/2007 (EP).
[176] Börjesson P, Gustavsson L. Greenhouse gas balances in building construction: wood versus concrete from lifecycle and forest land-use perspectives. Energy Policy 2000;28(9):575–88.
[177] Jiang Y, Hu S. Paths to carbon neutrality in China's building sector. J HV AC 2021;51(5):1–13. Chinese.
[178] The United States Environmental Protection Agency (EPA). Inventory of U.S. greenhouse gas emissions and sinks: 1990–2016. Final report. Nairobi: EPA; 2018 Apr.
[179] Pachauri R, Reisinger A. Intergovernmental Panel on Climate Change (IPCC) fourth assessment report: climate change 2007. Report. Geneva: IPCC; 2007 Apr. Contract No.: 2300.
[180] The United States Environmental Protection Agency (EPA). Greenhouse Gases (GHG) emissions. Report. Nairobi: EPA; 2017.
[181] Anand CK, Amor B. Recent developments, future challenges and new research directions in LCA of buildings: a critical review. Renew Sustain Energy Rev 2017;67:408–16.
[182] Vilches A, Garcia-Martinez A, Sanchez-Montañes B. Life cycle assessment (LCA) of building refurbishment: a literature review. Energy Build 2017;135:286–301.
[183] Schwartz Y, Raslan R, Mumovic D. The life cycle carbon footprint of refurbished and new buildings—a systematic review of case studies. Renew Sustain Energy Rev 2018;81:231–41.
[184] Kuo NW, Chen PH. Quantifying energy use, carbon dioxide emission, and other environmental loads from island tourism based on a life cycle assessment approach. J Clean Prod 2009;17(15):1324–30.
[185] Pan W, Li K, Teng Y. Rethinking system boundaries of the life cycle carbon emissions of buildings. Renew Sustain Energy Rev 2018;90:379–90.
[186] Chastas P, Theodosiou T, Bikas D. Embodied energy in residential buildings—towards the nearly zero energy building: a literature review. Build Environ 2016;105:267–82.
[187] Häfliger IF, John V, Passer A, Lasvaux S, Hoxha E, Saade MRM, et al. Buildings environmental impacts' sensitivity related to LCA modelling choices of construction materials. J Clean Prod 2017;156:805–16.
[188] Himpe E, Trappers L, Debacker W, Delghust M, Laverge J, Janssens A, et al. Life cycle energy analysis of a zero-energy house. Build Res Inform 2013;41(4):435–49.
[189] Cheung M, Fan J. Carbon reduction in a high-density city: a case study of Langham Place Hotel Mongkok Hong Kong. Renew Energy 2015;250:433–40.
[190] Xu X, Xu P, Zhu J, Li H, Xiong Z. Bamboo construction materials: carbon storage and potential to reduce associated CO_2 emissions. Sci Total Environ 2022;814:152697.
[191] Kang G, Kim T, Kim YW, Cho H, Kang KI. Statistical analysis of embodied carbon emission for building construction. Energy Build 2015;105:326–33.
[192] Kofoworola OF, Gheewala SH. Life cycle energy assessment of a typical office building in Thailand. Energy Build 2009;41(10):1076–83.
[193] Luo Z, Yang L, Liu J. Embodied carbon emissions of office building: a case study of China's 78 office buildings. Build Environ 2016;95:365–71.
[194] Huang PJ, Huang SL, Marcotullio PJ. Relationships between CO_2 emissions and embodied energy in building construction: a historical analysis of Taipei. Build Environ 2019;155:360–75.
[195] Huang Z. Resource-driven sustainable bamboo construction in Asia-Pacific bamboo areas. In: The green energy and technology. Berlin: Springer; 2021. p. 1–40.
[196] Cole RJ, Kennan PC. Life-cycle energy use in office buildings. Build Environ 1996;31(4):307–17.
[197] Fay R, Treloar G, Iyer-Raniga U. Life-cycle energy analysis of buildings: a case study. Build Res Inform 2000;28(1):31–41.
[198] Kottek M, Grieser J, Beck C, Rudolf B, Rubel F. World map of the Köppen-Geiger climate classification updated. Meteorol Z 2006;15(3):259–63.
[199] Adalberth K. Energy use during the life cycle of single-unit dwellings: examples. Build Environ 1997;32(4):321–9.
[200] Buyle M, Braet J, Audenaert A. Life cycle assessment in the construction sector: a review. Renew Sustain Energy Rev 2013;26:379–88.
[201] Radhi H, Sharples S. Global warming implications of facade parameters: a life cycle assessment of residential buildings in Bahrain. Environ Impact Assess Rev 2013;38:99–108.
[202] You F, Hu D, Zhang H, Guo Z, Zhao Y, Wang B, et al. Carbon emissions in the life cycle of urban building system in China—a case study of residential buildings. Ecol Complex 2011;8(2):201–12.

[203] Feiz R, Ammenberg J, Baas L, Eklund M, Helgstrand A, Marshall R. Improving the CO_2 performance of cement, part I: utilizing life-cycle assessment and key performance indicators to assess development within the cement industry. J Clean Prod 2015;98:272–81.
[204] Pade C, Guimaraes M. The CO_2 uptake of concrete in a 100 year perspective. Cement Concr Res 2007;37(9):1348–56.
[205] Xi F, Davis SJ, Ciais P, Crawford-Brown D, Guan D, Pade C, et al. Substantial global carbon uptake by cement carbonation. Nat Geosci 2016;9(12):880–3.
[206] Dodoo A, Gustavsson L, Sathre R. Carbon implications of end-of-life management of building materials. Resour Conserv Recycling 2009;53(5):276–86.
[207] Lee SH, Park WJ, Lee HS. Lifecycle CO_2 assessment method for concrete using CO_2 balance and suggestion to decrease $LCCO_2$ of concrete in South-Korean apartment. Energy Build 2013;58:93–102.
[208] Kyriakidis A, Michael A, Illampas R, Charmpis DC, Ioannou I. Comparative evaluation of a novel environmentally responsive modular wall system based on integrated quantitative and qualitative criteria. Energy 2019;188:115966.
[209] Choi SW, Oh BK, Park JS, Park HS. Sustainable design model to reduce environmental impact of building construction with composite structures. J Clean Prod 2016;137:823–32.
[210] World Steel Association (WSA). Life cycle assessment methodology report. Report. Belgium: WSA; 2011.
[211] Purnell P. Material nature versus structural nurture: the embodied carbon of fundamental structural elements. Environ Sci Technol 2012;46(1):454–61.
[212] Saade MRM, Guest G, Amor B. Comparative whole building LCAs: How far are our expectations from the documented evidence? Build Environ 2020;167:106449.
[213] Pomponi F, Moncaster A. Scrutinising embodied carbon in buildings: the next performance gap made manifest. Renew Sustain Energy Rev 2018;81:2431–42.
[214] Hossain MU, Ng ST. Strategies for enhancing the accuracy of evaluation and sustainability performance of building. J Environ Manage 2020;261:110230.
[215] Hossain MU, Ng ST. Critical consideration of buildings' environmental impact assessment towards adoption of circular economy: an analytical review. J Clean Prod 2018;205:763–80.
[216] Ibn-Mohammed T, Greenough R, Taylor S, Ozawa-Meida L, Acquaye A. Operational vs. embodied emissions in buildings—a review of current trends. Energy Build 2013;66:232–45.
[217] Mao XK, Wang LX, Li JW, Quan XL, Wu TY. Comparison of regression models for estimation of carbon emissions during building's lifecycle using designing factors: a case study of residential buildings in Tianjin, China. Energy Build 2019;204:109519.
[218] Ramesh T, Prakash R, Shukla KK. Life cycle energy analysis of buildings: an overview. Energy Build 2010;42(10):1592–600.
[219] Harris DJ. A quantitative approach to the assessment of the environmental impact of building materials. Build Environ 1999;34(6):751–8.
[220] Cole RJ, Wong KS. Minimising environmental impact of high-rise residential buildings. In: Proceedings of housing for millions: the challenge ahead; 1996 May 20–23; Hong Kong. Hong Kong: Housing Authority; 1996. p. 262–5.
[221] Kotaji S, Schuurmans A, Edwards S, editors. Life-cycle assessment in building and construction: a state-of-art report. Pensacola: Society of Environmental Toxicology and Chemistry (SETAC); 2003.
[222] Chastas P, Theodosiou T, Kontoleon KJ, Bikas D. Normalising and assessing carbon emissions in the building sector: a review on the embodied CO_2 emissions of residential buildings. Build Environ 2018;130:212–26.
[223] Röck M, Saade MRM, Balouktsi M, Rasmussen FN, Birgisdottir H, Frischknecht R, et al. Embodied GHG emissions of buildings—the hidden challenge for effective climate change mitigation. Appl Energy 2020;258:114107.
[224] Mequignon M, Ait Haddou H, Thellier F, Bonhomme M. Greenhouse gases and building lifetimes. Build Environ 2013;68:77–86.
[225] Li XJ, Xie WJ, Jim CY, Feng F. Holistic LCA evaluation of the carbon footprint of prefabricated concrete stairs. J Clean Prod 2021;329:129621.
[226] Teng Y, Li K, Pan W, Ng T. Reducing building life cycle carbon emissions through prefabrication: evidence from and gaps in empirical studies. Build Environ 2018;132:125–36.
[227] Chau CK, Hui WK, Ng WY, Powell G. Assessment of CO_2 emissions reduction in high-rise concrete office buildings using different material use options. Resour Conserv Recycling 2012;61:22–34.
[228] Asdrubali F, Ferracuti B, Lombardi L, Guattari C, Evangelisti L, Grazieschi G. A review of structural, thermo-physical, acoustical, and environmental properties of wooden materials for building applications. Build Environ 2017;114:307–32.
[229] Buchanan AH, Honey BG. Energy and carbon dioxide implications of building construction. Energy Build 1994;20(3):205–17.
[230] Buchanan AH, Levine SB. Wood-based building materials and atmospheric carbon emissions. Environ Sci Policy 1999;2(6):427–37.
[231] Gustavsson L, Sathre R. Variability in energy and carbon dioxide balances of wood and concrete building materials. Build Environ 2006;41(7):940–51.
[232] Petersen AK, Solberg B. Greenhouse gas emissions, life-cycle inventory and cost-efficiency of using laminated wood instead of steel construction.: case: beams at Gardermoen airport. Environ Sci Policy 2002;5(2):169–82.
[233] Yang X, Hu M, Zhang C, Steubing B. Key strategies for decarbonizing the residential building stock: results from a spatiotemporal model for Leiden, the Netherlands. Resour Conserv Recycling 2022;184:106388.
[234] Hart J, D'Amico B, Pomponi F. Whole-life embodied carbon in multistory buildings: steel, concrete and timber structures. J Ind Ecol 2021;25(2):403–18.
[235] D'Alessandro F, Bianchi F, Baldinelli G, Rotili A, Schiavoni S. Straw bale constructions: laboratory, in field and numerical assessment of energy and environmental performance. J Build Eng 2017;11:56–68.
[236] Cabeza LF, Boquera L, Chàfer M, Vérez D. Embodied energy and embodied carbon of structural building materials: worldwide progress and barriers through literature map analysis. Energy Build 2021;231:110612.
[237] Pittau F, Lumia G, Heeren N, Iannaccone G, Habert G. Retrofit as a carbon sink: the carbon storage potentials of the EU housing stock. J Clean Prod 2019;214:365–76.
[238] Pittau F, Krause F, Lumia G, Habert G. Fast-growing bio-based materials as an opportunity for storing carbon in exterior walls. Build Environ 2018;129:117–29.
[239] Shukla A, Tiwari GN, Sodha MS. Embodied energy analysis of adobe house. Renew Energy 2009;34(3):755–61.
[240] Jayawardana AS, Perera NGR, Perera LASR. "Cradle to Gate" assessment of material related embodied carbon: a design stage stratagem for mid-rise housing in Sri Lanka. Energy Build 2021;230:110542.
[241] Turner LK, Collins FG. Carbon dioxide equivalent emissions: a comparison between geopolymer and OPC cement concrete. Constr Build Mater 2013;43:125–30.
[242] Huang ZJ, Zhou H, Tang H, Zhao Y, Lin BR. Carbon emissions of prefabricated steel structure components: a case study in China. J Clean Prod 2023;406:137047.
[243] Purnell P, Black L. Embodied carbon dioxide in concrete: variation with common mix design parameters. Cement Concr Res 2012;42(6):874–7.
[244] Slorach PC, Stamford L. Net zero in the heating sector: technological options and environmental sustainability from now to 2050. Energy Convers Manage 2021;230:113838.
[245] Kneifel J. Beyond the code: energy, carbon, and cost savings using conventional technologies. Energy Build 2011;43(4):951–9.
[246] Kneifel J. Life-cycle carbon and cost analysis of energy efficiency measures in new commercial buildings. Energy Build 2010;42(3):333–40.
[247] Peuportier BLP. Life cycle assessment applied to the comparative evaluation of single family houses in the French context. Energy Build 2001;33(5):443–50.
[248] Legorburu G, Smith AD. Incorporating observed data into early design energy models for life cycle cost and carbon emissions analysis of campus buildings. Energy Build 2020;224:110279.
[249] Li Q, Ma L, Li D, Arıcı M, Yıldız Ç, Wang Z, et al. Thermoeconomic analysis of a wall incorporating phase change material in a rural residence located in northeast China. Sustain Energy Technol Assess 2021;44:101091.
[250] Pomponi F, Piroozfar PAE, Southall R, Ashton P, Farr ERP. Life cycle energy and carbon assessment of double skin façades for office refurbishments. Energy Build 2015;109:143–56.
[251] Braslavsky JH, Wall JR, Reedman LJ. Optimal distributed energy resources and the cost of reduced greenhouse gas emissions in a large retail shopping centre. Appl Energy 2015;155:120–30.
[252] Ghose A, Pizzol M, McLaren SJ. Consequential LCA modelling of building refurbishment in New Zealand—an evaluation of resource and waste management scenarios. J Clean Prod 2017;165:119–33.
[253] Wang J, Teng Y, Chen Z, Bai J, Niu Y, Duan H, et al. Assessment of carbon emissions of building interior decoration and renovation waste disposal in the fast-growing Greater Bay Area. China. Sci Total Environ 2021;798:149158.
[254] Pauliuk S, Heeren N, Berrill P, Fishman T, Nistad A, Tu Q, et al. Global scenarios of resource and emission savings from material efficiency in residential buildings and cars. Nat Commun 2021;12(1):5097.
[255] Sathre R, O'Connor J. Meta-analysis of greenhouse gas displacement factors of wood product substitution. Environ Sci Policy 2010;13(2):104–14.
[256] Churkina G, Organschi A, Reyer CPO, Ruff A, Vinke K, Liu Z, et al. Buildings as a global carbon sink. Nat Sustain 2020;3(4):269–76.
[257] Besir AB, Cuce E. Green roofs and facades: a comprehensive review. Renew Sustain Energy Rev 2018;82:915–39.
[258] Seyedabadi MR, Karrabi M, Nabati J. Investigating green roofs' CO_2 sequestration with cold- and drought-tolerant plants (a short- and long-term carbon footprint view). Environ Sci Pollut Res Int 2022;29(10):14121–30.
[259] Charoenkit S, Yiemwattana S. Living walls and their contribution to improved thermal comfort and carbon emission reduction: a review. Build Environ 2016;105:82–94.
[260] Jo HK, McPherson EG. Carbon storage and flux in urban residential greenspace. J Environ Manage 1995;45(2):109–33.
[261] Lin QY, Zhang X, Wang T, Zheng C, Gao X. Technical perspective of carbon capture, utilization, and storage. Engineering 2022;14:27–32.
[262] Kashef-Haghighi S, Shao Y, Ghoshal S. Mathematical modeling of CO_2 uptake by concrete during accelerated carbonation curing. Cement Concr Res 2015;67:1–10.
[263] Qian C, Yu X, Zheng T, Chen Y. Review on bacteria fixing CO_2 and bio-mineralization to enhance the performance of construction materials. J CO_2 Util 2022;55:101849.
[264] Piccardo C, Dodoo A, Gustavsson L. Retrofitting a building to passive house level: a life cycle carbon balance. Energy Build 2020;223:110135.

[265] Zhang C, Hu M, Laclau B, Garnesson T, Yang X, Tukker A, et al. Energy–carbon–investment payback analysis of prefabricated envelope-cladding system for building energy renovation: cases in Spain, the Netherlands, and Sweden. Renew Sustain Energy Rev 2021;145:111077.

[266] Vakalis D, Patino EDL, Opher T, Touchie MF, Burrows K, MacLean HL, et al. Quantifying thermal comfort and carbon savings from energy-retrofits in social housing. Energy Build 2021;241:110950.

[267] Charles A, Maref W, Ouellet-Plamondon CM. Case study of the upgrade of an existing office building for low energy consumption and low carbon emissions. Energy Build 2019;183:151–60.

[268] De Wolf C, Pomponi F, Moncaster A. Measuring embodied carbon dioxide equivalent of buildings: a review and critique of current industry practice. Energy Build 2017;140:68–80.

[269] Yu FW, Ho WT. Tactics for carbon neutral office buildings in Hong Kong. J Clean Prod 2021;326:129369.