



A review of bottom up studies on life cycle carbon emissions for rural dwellings

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Keywords:

Rural dwellings, embodied carbon emission, operational carbon emission, carbon reduction, bottom-up, life cycle assessment

Citation: Huang, Z.; Cheng, M.; Zheng, Y. A review of bottom up studies on life cycle carbon emissions for rural dwellings. *Carbon Footprints* 2026, 5, 36. <https://dx.doi.org/10.20517/cf.2026.23>

Received: 26 Feb 2026

First Decision: 10 Apr 2026

Revised: 18 Apr 2026

Accepted: 12 Jun 2026

Published: 10 Jul 2026

Academic Editors:

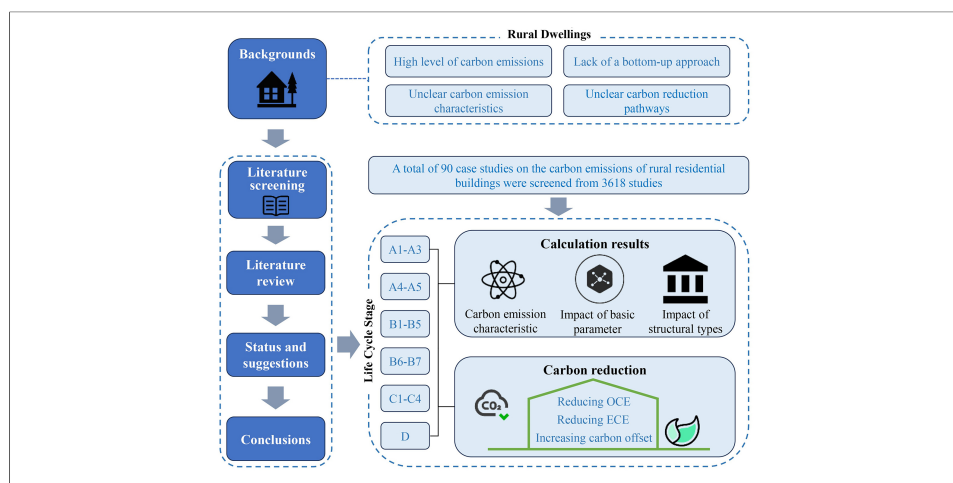
Zhuang Miao, Jukka Taneli Heinonen

Copy Editor:

Fangling Lan

Production Editor:

Fangling Lan



Abstract

The low-carbon transition of the building sector plays a pivotal role in global carbon mitigation, yet rural dwellings remain a critical but underexplored field in decarbonization efforts. In 2024, a substantial population of 42.3% still resides in rural areas where housing contributes significantly to carbon emissions. Unlike standardized urban construction, rural dwellings are characterized by diverse building practices and energy structures, rendering conventional top-down, city-centric assessment methods inadequate for identifying the carbon emission characteristics and targeted reduction pathways of rural dwellings. To address this gap, this study presents a systematic, bottom-up review of 90 scientific studies encompassing 309 rural dwelling cases predominantly located in Asia and Europe (93.8% of cases). We conducted a stage-by-stage statistical analysis of life cycle carbon emissions (LCCE) to quantify contributions across different stages. Our findings revealed that while material production is the most frequently studied stage, the operational stage contributes the highest proportion of total LCCE. Furthermore, the carbon emission factors (CEFs) for materials and energy exhibit order-of-magnitude variations, highlighting a lack of a standardized CEF database. These results underscore the necessity of shifting from macro-level statistics to fine-grained, context-specific assessment frameworks. By synthesizing fragmented data and summarizing strategies for reducing embodied carbon, lowering operational emissions, and enhancing carbon sequestration, this study



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established a foundational roadmap for developing accurate standards and effective decarbonization policies tailored to rural contexts. The implications of this work are vital for guiding low-carbon transitions in rural dwellings.

INTRODUCTION

The excessive emission of greenhouse gases has led to the continuous deterioration of the global climate^[1,2]. In 2023, global carbon emissions (CEs) reached a historic high of 39.02 billion tons^[3]. As one of the key sectors contributing to CEs, the construction and use of buildings can cause many environmental problems^[4,5], and the building sector accounted for 34% of global CEs^[6]. Energy conservation and carbon reduction in the building sector constitute one of the key pillars for achieving global carbon neutrality.

According to statistics, 42.3% of the world's population—approximately 3.44 billion people—still resides in rural areas^[7]. This is a significant figure, indicating the substantial need for rural dwellings to meet the housing demands of these populations. For example, data released by China's National Bureau of Statistics showed that in 2024, 33.0% of the country's total population continued to live in rural areas^[8]. According to the Seventh National Population Census, there were a total of 16.8 million rural dwellings, representing 36.8% of all dwellings nationwide^[9]. Similarly, in India, over 60% of the population lives in rural areas^[10], also requiring a large stock of rural dwellings. Additionally, the issue of excessive construction persists in rural areas. A large number of idle houses in these areas have further added to the total housing stock. Taking a study in Guangdong Province, China, as an example, leveraging remote sensing imagery in conjunction with deep learning algorithms, this study successfully identified 5.2 million new constructions and 4.8 million legacy dwellings across the rural landscapes of Guangdong Province. Comparative analysis revealed a substantial disparity in spatial footprint, indicating that the average floor area of newly constructed residences is more than threefold that of their older counterparts^[11]. As a result, rural areas are plagued by extensive over - construction, along with the squandering of resources and energy. This leads to an alarmingly high level of CEs. Therefore, to achieve global carbon neutrality, there is an urgent need to study the life cycle carbon emission (LCCE) of rural dwellings and formulate corresponding strategies to reduce carbon emissions.

Current research on the dwellings CEs in rural areas predominantly relied on macro-level statistics, employing top-down approaches to derive average CE values at the national or regional scale. For example, according to statistics by the Tsinghua University Building Energy Efficiency Research Centre in 2020, 0.51 billion tCO₂ were emitted from rural dwellings, which accounted for 23.4% of China's total CEs from building operation^[12]. Ottelin *et al.*^[13] adopted a top-down approach to assess CEs in both European urban and rural areas. Their findings revealed that, under comparable economic and household characteristics, the average CEs of dwellings in rural areas is 7% higher than those in urban areas. Pang *et al.*^[14] employed a hybrid top-down and bottom-up approach to calculate the CEs of Swiss households, and the result showed that urban dwellings generally have lower direct CEs than rural dwellings, but higher indirect CEs. Despite highlighting the aggregate CEs of rural dwellings at national or regional levels, top-down approaches lack the resolution to present emission characteristics at the individual building level. In comparison, the bottom-up process can offer detailed CE characteristics across each life cycle stage, and promote the formulation of tailored carbon mitigation strategies.

To bridge this gap, and provide implications for environmental management and policy-making, this study conducted a comprehensive literature review based on bottom-up CE analysis of rural dwellings, and the majority of the case studies (93.8%) are concentrated in Asia and Europe. First, based on the basic framework of ISO 21930, a detailed review was conducted on the CEs at each life cycle stage of 309 cases from 90 studies, revealing issues related to calculation methods and basic parameters. Second, based on the fundamental

principles of building LCCE and carbon reduction, the embodied and operational carbon emissions (OCE) mitigation technologies and their effectiveness adopted in the aforementioned cases were systematically analyzed. Finally, recommendations at a more macro level, including carrying out fundamental research on the LCCE calculation standards and basic parameters, and local technical strategies for carbon reduction were proposed.

METHODOLOGY

Literature search

This study conducted a systematic review of literature related to the CEs of rural dwellings, with a focus on the calculation methods, results, and carbon reduction strategies across the holistic life-cycle stages. The workflow consists of four main stages: (1) literature identification, (2) screening, (3) eligibility assessment, and (4) study inclusion.

A systematic literature search was performed using the Web of Science Core Collection. This database was selected as the sole source because it indexes a comprehensive range of high-impact, peer-reviewed journals in the fields of environmental science and construction engineering, ensuring the academic quality and reliability of the included studies. This study defined the following search keywords: TS = (("carbon emission*" OR "carbon footprint*" OR "greenhouse gas*") AND ("rural*" OR "village*") AND ("residential" OR "housing" OR "dwelling*" OR "detached*" OR "house" OR "home*") AND ("low-carbon" OR "low-energy" OR "passive")).

The screening process was conducted in two stages by two independent reviewers to minimize bias. First, all retrieved records were imported into Zotero (a reference management software), and duplicates were removed. Second, the remaining records were screened based on their titles and abstracts. Finally, the full texts of the potentially eligible articles were assessed against the pre-defined eligibility criteria. Any discrepancies between the reviewers were resolved through discussion or consultation with a third reviewer.

Additionally, a snowballing technique was applied to the reference lists of the initially identified articles to retrieve any potentially relevant studies not captured by the database search. In the first stage, we retrieved a total of 3,618 articles.

Inclusion and exclusion criteria

To further align with the primary research objectives of this review, we screened the titles and abstracts of 3,618 articles, followed by a full-text review of articles. Screening was conducted based on the following criteria:

- (1) Lack of specific case studies: Articles that were purely theoretical, conceptual reviews, or lacked empirical data from actual building cases were excluded.
- (2) Unspecified building function: Studies where the building function was not explicitly defined as residential or housing were excluded to avoid mixing with commercial or public buildings.
- (3) Incompatible building scale: Studies involving high-rise buildings (more than three floors) were excluded, as this review focuses specifically on low-rise rural dwellings.
- (4) Absence of quantitative data: Articles that did not provide explicit numerical results for CE calculations were excluded.

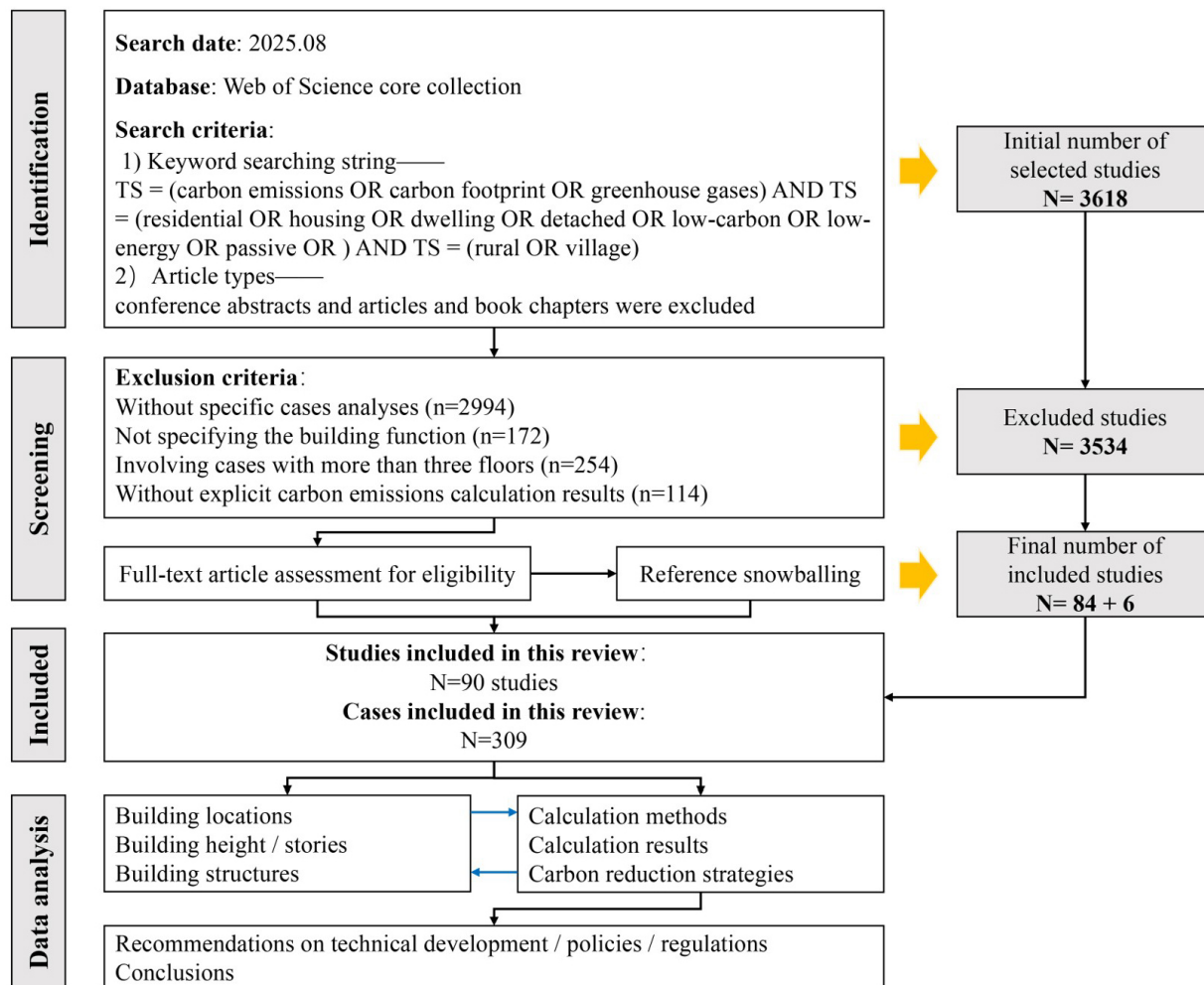


Figure 1. The selection process for the papers and the number of studies within the paper.

After this process, 84 articles that were specifically related to CEs of low-rise rural dwellings were retained. Additionally, 6 more studies were screened using the snowball technique (retrieving new studies through mining the reference lists of the 84 studies). Ultimately, 90 studies were screened [Figure 1]. Subsequent analyses were based on the case data from these 90 studies.

Data extraction

The information extracted from the aforementioned 90 studies is divided into three parts. The first part covers the basic building information, which mainly includes the building's region, climate zone, height or number of stories, structural type, and whether it holds certifications such as green or low-carbon building status. The second part focuses on the LCCE of the building cases, detailing the CEs for each life cycle stage. The third part mainly collects the carbon reduction strategies and carbon reduction effectiveness. It should be noted that since not all studies encompassed a complete life cycle scope, we only extracted the LCCE results as calculated in the respective literature. Furthermore, as the climate zone was not specified in most studies, we inferred the corresponding climate zone based on the specific geographic location of each building case.

The core of this research involves the descriptive statistical analysis of fragmented data from the aforementioned 90 studies. After extracting CE data of each life cycle stage from the selected case studies, descriptive statistics (including median) were calculated to characterize the overall dataset. The median was

selected as the primary measure of central tendency due to the non-normal distribution of life cycle assessment (LCA) data. This approach allowed us to present a robust overview of current practices based on our synthesized dataset, rather than relying on potentially skewed averages from individual source papers.

Data standardization

To facilitate a unified analysis and comparison, we standardized the units of CE results from the literature. Regarding embodied carbon emission (ECE), we calculated the total amount and divided it by the gross floor area, resulting in a unit of $\text{kgCO}_2\text{e}/\text{m}^2$. As for OCE, given that the assumed service lives vary across different studies, we calculated the total OCE over the life cycle and normalized them to an annual per-square-meter basis; therefore, the unit is expressed as $\text{kgCO}_2\text{e}/\text{m}^2/\text{year}$. To maintain the authenticity of the original findings and avoid introducing bias through estimation, life cycle stages that were not reported or calculated in the primary studies were excluded from the corresponding analyses.

To address the variations in system boundaries across the collected studies, we adopted a stage-specific data extraction strategy. Rather than relying on aggregated total values, we disaggregated the CE data into distinct life cycle stages (e.g., product stage, construction, use, and end-of-life). We extracted available data for each specific module as reported in the literature. Consequently, all subsequent statistical analyses were performed separately for each life cycle stage. This approach ensures that comparisons are made between equivalent stages, thereby mitigating the impact of differing system boundaries among the source studies.

Overview of the reviewed cases

The 90 screened studies contain a total of 309 building cases. CE assessment results for 309 building instances were compiled. The geographical location, climate type, structure type, number of floors, floor area, and expected service life of the building cases are summarized in [Supplementary Figures 1-6](#).

According to ISO 21930:2017, the holistic life cycle of a building is structured into five primary stages comprising 17 distinct modules. These include material production (A1-A3), construction (A4-A5), usage (B1-B7), end-of-life (C1-C4), and supplementary benefits (D). Notably, Module D is categorized as voluntary information falling outside the scope of the system boundary. In terms of CE categorization, CEs arising from Modules A1-A5, B1-B5, and C1-C4 are collectively termed ECE. Conversely, emissions from Modules B6-B7 are defined as OCE, with Module D serving as a factor related to both ECE and OCE.

Although ISO 21930 establishes the fundamental framework for defining life cycle stages and system boundaries in building assessments, its strict implementation is not consistently observed in practical applications. As shown in [Table 1](#), the 90 reviewed studies were calculated for production (88, 97.8%), construction (61, 67.8%), use (48, 53.3%), and end-of-life stages (48, 53.3%). The number of studies where B6-B7 was calculated was 60 (66.7%). The number of cases where module D was calculated was only 19 (21.1%). Few studies calculated the specific modules in both the use and end-of-life stages for ECE, with the largest number being 27 (30.0%) for maintenance (B2). Sixty (66.7%) studies calculated the operational energy consumption (B6), while only eight (8.9%) calculated the operational water consumption (B7) for OCE.

CALCULATION OF LCCE

The analysis yielded a total of 255 datasets for ECE, 173 for OCE, and 162 for LCCE. As shown in [Figure 2](#) and [Table 2](#), the calculation results vary significantly across different cases, therefore, in the following analysis, the calculation results are described based on quartiles, including the median (med), first quartile (25%), and third quartile (75%). The ECE_{med} ($ECE_{25\%}$ - $ECE_{75\%}$) were 305.7 (178.3-536.7) $\text{kgCO}_2\text{e}/\text{m}^2$, accounting for 35.0% of LCCE. The OCE_{med} ($OCE_{25\%}$ - $OCE_{75\%}$) was 792.0 (300.0-1,921.5) $\text{kgCO}_2\text{e}/\text{m}^2$, accounting for 66.1%

Jonsson et al. ^[74]	1998	Sweden	●	○	○	●					○	○	●				○	
Citherlet et al. ^[75]	2007	Switzerland	●			○	●	○	●	○	●	○	●					
Bertini et al. ^[76]	2025	Belgium	●	●	●	○	○	○	●	○	●	○	○	○	●	●	○	
Norouzi et al. ^[77]	2025	UK	●	●	●	●					●	○	●				○	
Keyhani et al. ^[78]	2024	UK	●			○	●	●	●	○	○	○	○	○	●	●	○	
Mohammadpourkarbasi et al. ^[79]	2023	UK	○	○	○	○	○	○	○	○	○	●	○	○	○	○	○	
Norouzi et al. ^[80]	2023	UK	●	●	●	●					●	●	●	●	○	●	●	
Newberry et al. ^[81]	2023	UK	●	●		○	○	○	●	○	●	○	●				○	
Cuéllar-Franca et al. ^[82]	2012	UK	●	●	●	○	●	○	○	○	●	⦿	●	●	●	○	●	
Moncaster et al. ^[83]	2013	UK	⦿	⦿	⦿	○	○	⦿	⦿	⦿	○	○	⦿	⦿	⦿	⦿	○	
Monahan et al. ^[84]	2011	UK	●	●	●	○	○	○	○	○	○	○	○	○	○	○	○	
Asif et al. ^[85]	2007	UK	●	○	○	○	○	○	○	○	○	○	○	○	○	○	○	
Iddon et al. ^[86]	2013	UK	●	○	○	○	○	○	○	○	○	○	○	○	○	○	○	
Hacker et al. ^[87]	2008	UK	●	○	○	○	○	○	○	○	⦿	●	○	○	○	○	○	
Essaghouri et al. ^[88]	2023	Morocco	●			○	○	○	○	○	○	●	○	○	○	○	○	
Hansen et al. ^[89]	2024	Denmark	●	○	○	○	○	○	○	○	○	○	○	○	○	●	●	○
Rossi et al. ^[90]	2012	BE + PT + SE	●	○	○	⦿					●	○	○	○	○	○	○	
Rossi et al. ^[91]	2012	BE + PT + SE	●	⦿	⦿	⦿					●	○	○	⦿	○	○	○	
Hafner et al. ^[92]	2017	DE + AT	●	○	○	○	●	○	●	○	○	○	○	○	○	●	●	○
Quintana-Gallardo et al. ^[93]	2021	DE + SI + ES	●	●	●	○	●	○	●	●	●	●	○	●	●	●	○	
Moghayedi et al. ^[94]	2025	South Africa	●	●	●	○	●	○	○	●	●	○	●	●	●	●	●	
Moghayedi et al. ^[95]	2024	Africa	●	●		●	●	○	○	○	○	○	●				●	
Salazar et al. ^[96]	2009	Canada	●	●	●	○	○	●			○	○	○	○	○	●	○	●
Zhang et al. ^[97]	2014	Canada	●	●	●	○	●	○	●	●	●	○	●	●	○	○	○	○
Keoleian et al. ^[98]	2001	USA	●	○	●	○	●	○	○	○	○	●	○	●	○	●	○	
Arvizu-Piña et al. ^[99]	2023	Mexico	●			○	○	○	○	○	○	●	○	○	○	○	○	
Ortiz et al. ^[100,101]	2010	CO + ES	●	●	●	○	●	○	○	○	○	●	○	○	○	○	○	○
Sandanayake et al. ^[102]	2016	Australia	●	●	●	○	○	○	○	○	○	○	○	○	○	○	○	○
Mosteiro-Romero et al. ^[103]	2014	USA + CH	●	●	●	○	⦿	○	⦿	○	○	●	○	●	●	○	○	●
Shi et al. ^[104]	2023	CN + Fin	●	●	○	●					●	○	●				●	

Summary

	Total	88 (97.8%)	61 (67.8%)	48 (53.3%)					60 (66.7%)	48 (53.3%)				19 (21.1%)		
Sum - stages/modules	Calculated (●)	87 (96.7%)	55 (51.1%)	39 (43.3%)					60 (66.7%)	39 (43.3%)				16 (17.8%)		
	Quoted (●)	1 (1.1%)	6 (6.7%)	9 (10.0%)					0 (0%)	9 (10.0%)				3 (3.3%)		
	Total	88 (97.8%)	53 (58.9%)	54 (60.0%)	2 (2.2%)	27 (30.0%)	2 (2.2%)	23 (25.6%)	6 (6.7%)	60 (66.7%)	8 (8.9%)	20 (22.3%)	17 (18.9%)	13 (14.4%)	15 (16.7%)	19 (21.1%)
Sum - items	Calculated (●)	87 (96.7%)	49 (54.4%)	47 (52.2%)	2 (2.2%)	23 (25.6%)	1 (1.1%)	19 (21.1%)	4 (4.4%)	60 (66.7%)	7 (7.8%)	15 (16.7%)	15 (16.7%)	12 (13.3%)	12 (13.3%)	16 (17.8%)
	Quoted (●)	1 (1.1%)	4 (4.4%)	7 (7.8%)	0 (0%)	4 (4.4%)	1 (1.1%)	4 (4.4%)	2 (2.2%)	0 (0%)	1 (1.1%)	5 (5.6%)	2 (2.2%)	1 (1.1%)	3 (3.3%)	3 (3.3%)

China M: China mainland; BE + PT + SE: Belgium + Portugal + Sweden; DE + AT: Germany + Austria; DE + SI + ES: Germany + Slovenia + Spain; CO + ES: Colombia + Spain; USA + CH: USA + Switzerland; CN + Fin: China + Finland; ● represents that the value was obtained by calculating; ● represents that the value was obtained by quoting data from the literature; ○ represents that the study did not calculate the CE value of the stage.

of LCCE, and the $LCCE_{med}$ ($LCCE_{25\%} - LCCE_{75\%}$) was 1,186.2 (546.2-2,104.6) kgCO₂e/m².

For the ECE, 120 sets of results regarding the A1-A3 stages were reported. On the whole, $CE_{A1-A3,med}$ ($CE_{A1-A3,25\%} - CE_{A1-A3,75\%}$) was 200.0 (113.6-395.4) kgCO₂e/m²; For the remaining A4-A5, B1-B5, and C1-C4 stages, the medians were 32.3, 41.9, and 18.8 kgCO₂e/m², respectively. For the OCE, 173 sets of results regarding the B6-B7 stages were provided, and $CE_{B6-B7,med}$ ($CE_{B6-B7,25\%} - CE_{B6-B7,75\%}$) was 792.0 (300.0-1,921.5) kgCO₂e/m². The D module was represented by only 25 sets of calculation results, and the $CE_{D,med}$ ($CE_{D,25\%} - CE_{D,75\%}$) was -118.0 (-166.9 to -50.3) kgCO₂e/m².

Out of the 309 cases, 158 provided calculation results for both ECE and OCE. Among the 158 cases, 63 were explicitly identified as complying with building certification standards, including passive house (PH), nearly Zero Energy Building (nZEB), Active House, and Low-energy House (hereinafter referred to as the certified group, CF). The remaining 95 cases lacked such specifications and were designated as the non-certified group (NC). The P_{med} value for ECE was 53.9%, while that for OCE was 47.8% in group CF, and 23.6% and 76.2%, respectively, in the NC group. The results clearly show that the proportion of ECE significantly increased in group CF [Figure 3].

The proportion was influenced by several factors. For example, the contributing share of OCE was correspondingly low for cases where the carbon emission factor (CEF) of power was low. A study of a wooden single-family house in Sweden showed that the operating energy and water consumption only accounted for 21% and 6%, respectively, of the LCCE over a 100-year calculation period as Sweden’s electricity was mainly composed of renewable energy^[70]. The CEF was only 0.040 kgCO₂e/kWh, whereas building material production, building construction, building maintenance and material replacement, and building demolition accounted for 30%, 4%, 37%, and 2% of the LCCE, respectively^[70].

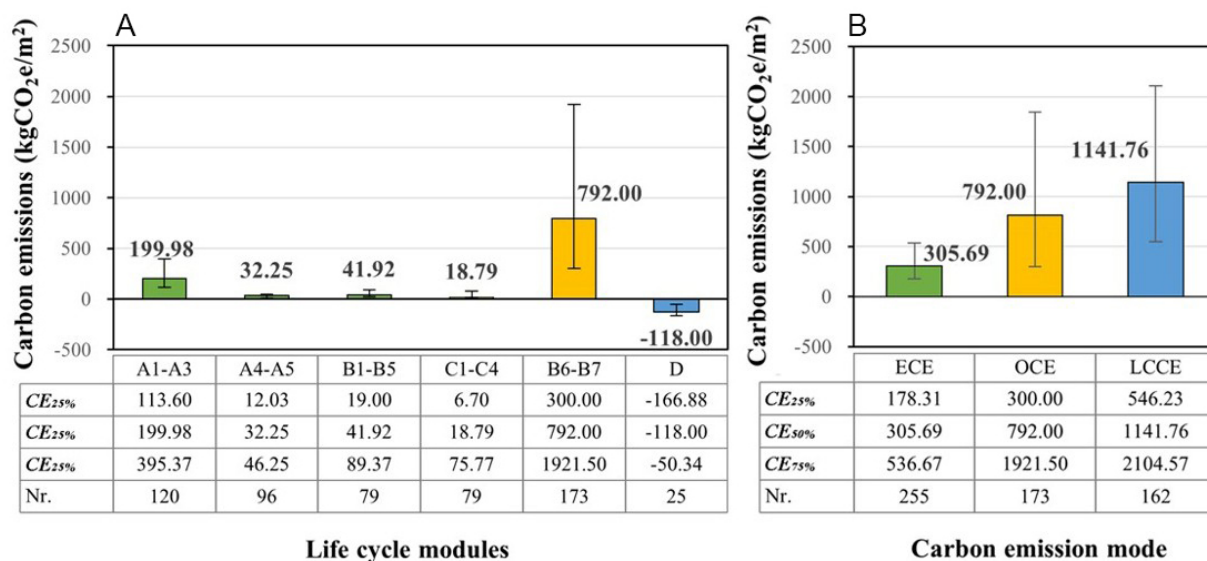


Figure 2. CE values per each life cycle stage within the analyzed case studies. (A) CE calculation results for each life cycle stage in the case studies; (B) ECE, OCE, and LCCE calculation results. Data are presented as median (interquartile range, IQR). The top and bottom of the error bars represent the 75th (Q3) and 25th (Q1) percentiles, respectively. The sample sizes for stages A1-A3, A4-A5, B1-B5, B6-B7, C1-C4, D, ECE, OCE, and LCCE were 120, 96, 79, 173, 79, 25, 255, 173, and 162, respectively.

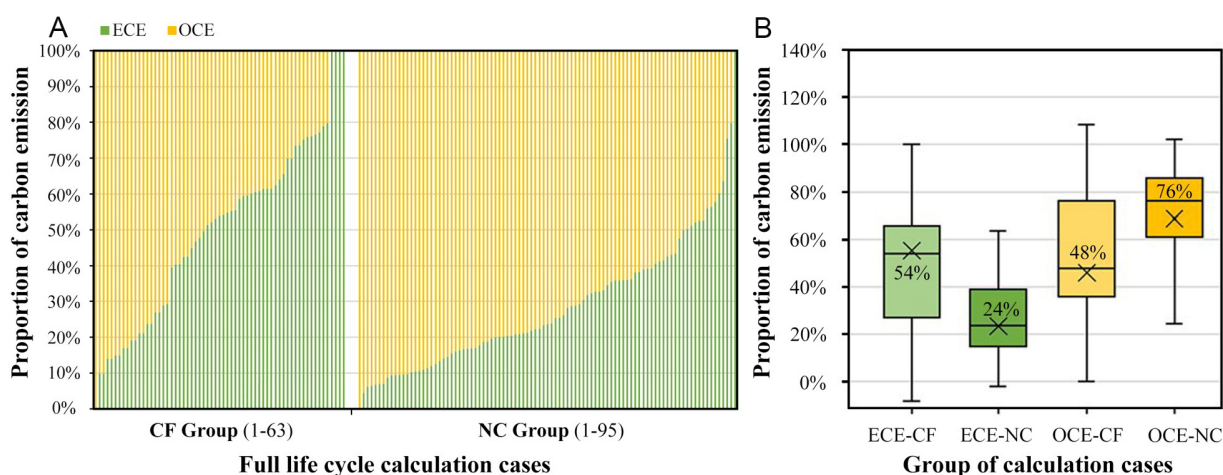


Figure 3. Proportion of CEs in the reviewed case studies. (A) Proportion of ECE and OCE in CF and NC groups; (B) Quartile plot. The box range represents the interquartile range(Q1-Q3), the horizontal line inside the box indicates the median, and the cross symbol (x) denotes the mean value. The sample sizes for the CE and the NCF group were 63 and 95, respectively.

Table 2. CE values per life cycle stage within the analyzed case studies

Items	ECE					OCE	ECE or OCE
Stage	A1-A3	A4-A5	B1-B5	C1-C4	Total	B6-B7	D
Q2 (kgCO ₂ e/m ²)	200.0	32.3	41.9	18.8	305.7	792.0	-118.0
Q1-Q3 (kgCO ₂ e/m ²)	113.6-395.4	12.0-46.2	19.0-89.4	6.7-75.8	178.3-536.7	300.0-1921.5	-166.9--50.3
Number of datasets	120	96	79	79	255	173	25

Q1: Quartile (25%); Q2: median; Q3: quartile (75%). ECE: Embodied carbon emission; OCE: operational carbon emissions.

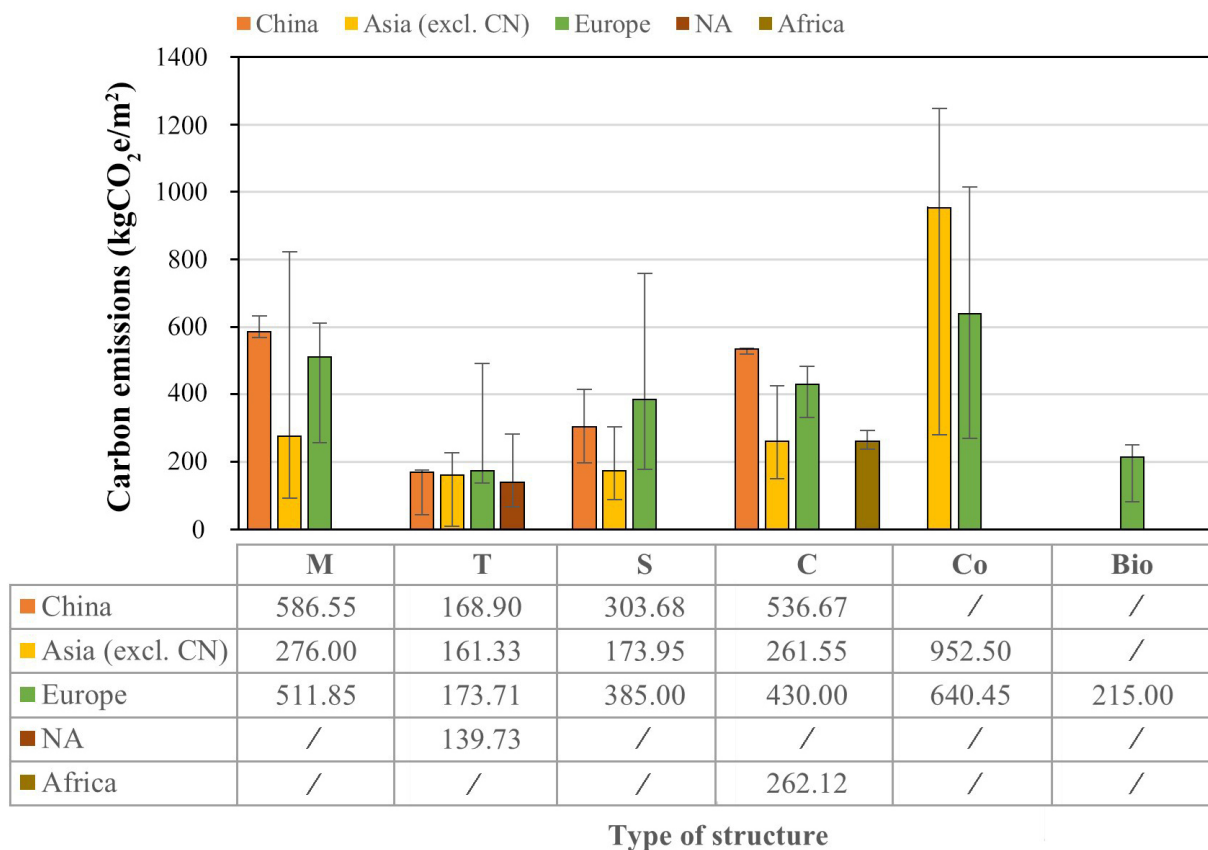


Figure 4. ECE calculation results by types of structure and countries/regions. M, T, S, C, Co, Bio respectively refer to masonry structure, timber structure, steel structure, concrete structure, composite structure, and bio-material building. Data are presented as median (interquartile range, IQR). The top and bottom of the error bars represent the 75th (Q3) and 25th (Q1) percentiles, respectively. The sample sizes for M, T, S, C, Co, and Bo were 66, 83, 18, 63, 26, and 3, respectively.

Calculation of ECE

ECE values are closely related to the buildings’ structural type^[105]. The reviewed studies provided a total of 255 ECE data sets. Among them, there were 66 of masonry, 83 of timber, 18 of steel, 63 cases of concrete structures, and 26 of composite structures. The median statistical results of the ECE are shown in Figure 4. The median ECE for concrete, masonry, timber, steel, and composite structures were 362.50, 359.92, 172.21, 244.86, and 843.00 kgCO₂e/m², respectively, with timber structures having the lowest value. In addition, three bio-based structural buildings from Europe had a median ECE of 178.31 kgCO₂e/m², which was similar to that of wood structures [Figure 4]. It is important to note the varying sample sizes across different structural typologies. While masonry (*n* = 66) and timber (*n* = 83) datasets provide a statistically robust basis for analysis, the results for composite structures (*n* = 26), steel (*n* = 18), and particularly bio-based materials (*n* = 3) should be interpreted with caution. The statistical results for these smaller cohorts may have some limitations and may be more susceptible to outliers.

Due to inconsistencies in basic parameters such as CEFs of energy and building materials, and architectural design codes among different countries and regions, there are also certain variations in building ECE between them. Overall, the median ECE values for the China group and the Europe were 377.42 and 352.20 kgCO₂e/m², respectively, which are higher than those of other regions [Figure 5].

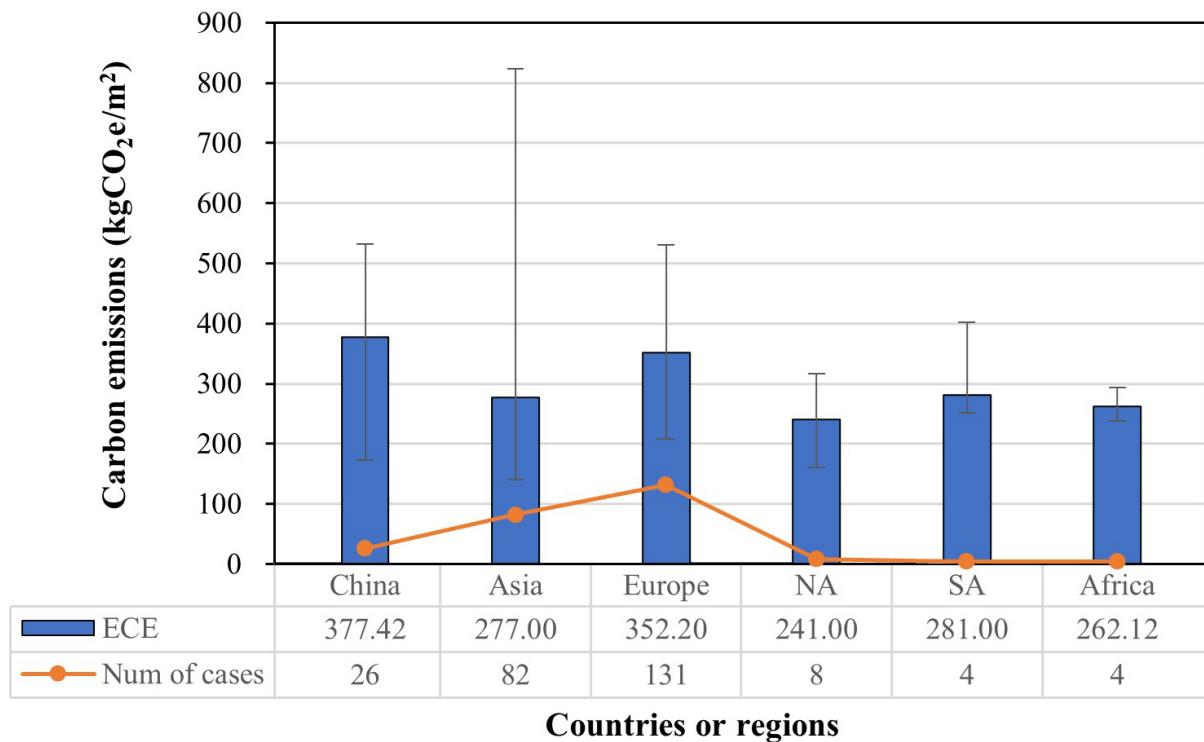


Figure 5. ECE calculation results by countries/regions. Data are presented as median (interquartile range, IQR). The top and bottom of the error bars represent the 75th (Q3) and 25th (Q1) percentiles, respectively. The sample sizes for China, Asia, Europe, NA, SA, and Africa were 26, 82, 131, 8, 4, and 4, respectively.

Building material production stage (A1-A3)

The CEs emitted in stages A1-A3 (CE_{A1-A3}) were obtained from raw material extraction (A1), transportation (A2), and the manufacturing of building materials or components (A3). Among 90 studies, 88 calculated CE_{A1-A3} , and most of which regarded A1-A3 as one. Only 10 (11.4%) of the 88 studies distinguished the three modules, while the rest calculated CE_{A1-A3} as a whole by multiplying the initial consumption of building materials or components with the corresponding CEFs.

The reviewed studies provided 120 sets of CE data from stages A1-A3, with a median value of 200.0 kgCO₂e/m², accounting for 17.7% of the LCCE and 73.0% of the total ECE. CE_{A1-A3} contributed the most to the ECE. The median CE_{A1-A3} values for masonry, concrete, steel, timber, and composite structures are 390.9, 340.0, 305.6, 113.0, and 212.0 kgCO₂e/m², respectively. Among these, timber structures have the lowest CE_{A1-A3} [Figure 6].

It is generally believed that the calculation of CE_{A1-A3} should include the main building materials and equipment. However, only 37 (12.0%) of the 309 cases considered both items, 252 (81.6%) considered only the consumption of the main building materials, and the remaining 20 cases did not specify the scope of calculation. Overlooking the CEs from equipment may lead to an underestimation of the CE_{A1-A3} .

Construction stage (A4-A5)

The CEs emitted in stages A4-A5 (CE_{A4-A5}) mainly include energy and material consumption during on-site construction activities and the transportation of building materials. Transport CEs (CE_{A4}) are conventionally determined through the multiplication of three key factors: the weight of construction materials, the transport distance, and the CEF specific to the transportation mode employed. Transport distance is the

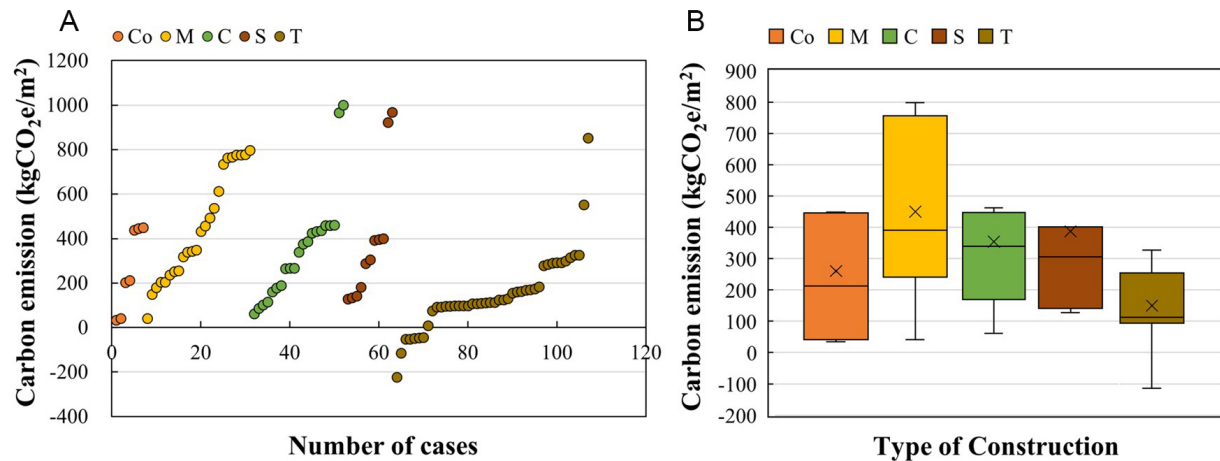


Figure 6. CEs calculation results of stages A1-A3 in the case studies. (A) Distribution of all results; (B) Quartile plot. The box range represents the interquartile range(Q1-Q3), the horizontal line inside the box indicates the median, and the cross symbol (×) denotes the mean value. 13 cases did not provide structural information. The sample sizes for Co, M, C, S, and T were 7, 24, 21, 11, and 44, respectively.

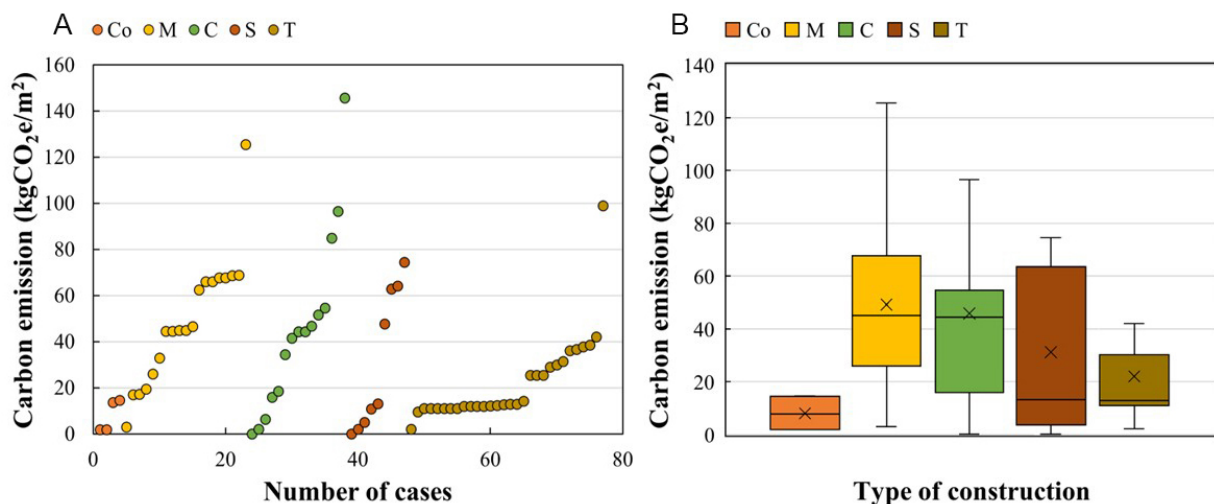


Figure 7. CEs calculation results of stage A4-A5 in the case studies. (A) Distribution of all results; (B) Quartile plot. The box range represents the interquartile range(Q1-Q3), the horizontal line inside the box indicates the median, and the cross symbol (×) denotes the mean value. 19 cases did not provide structural information. The sample sizes for Co, M, C, S, and T were 4, 19, 15, 9, and 30, respectively.

decisive factor for CE_{A4} . When the actual transport distance is unavailable, a hypothetical distance—such as 50 or 300 km^[27]—is typically assumed. On-site construction CE (CE_{A5}) is highly complex and includes direct and indirect CEs from fuel combustion for mechanical power, electricity consumption, assembly and miscellaneous work, transportation of construction equipment, and personnel activities associated with construction. Since the CE sources of CE_{A5} are complex and the calculation process is relatively difficult, some studies refer to data from other studies for the calculation^[47].

The reviewed case studies provided 96 sets of CE data from stages A4-A5 [Figure 7], with a median value of 32.3 kgCO₂e/m², accounting for 3.1% of the LCCE. The median CE_{A4-A5} values for masonry, concrete, steel, timber, and composite structures are 45.0, 44.4, 13.2, 12.9, and 7.8 kgCO₂e/m², respectively. Among these, composite structures have the lowest CE_{A4-A5} . With only four data points on composite buildings, the statistics might be somewhat limited (The stages B1-B5 and C1-C4 also exhibit similar issues).

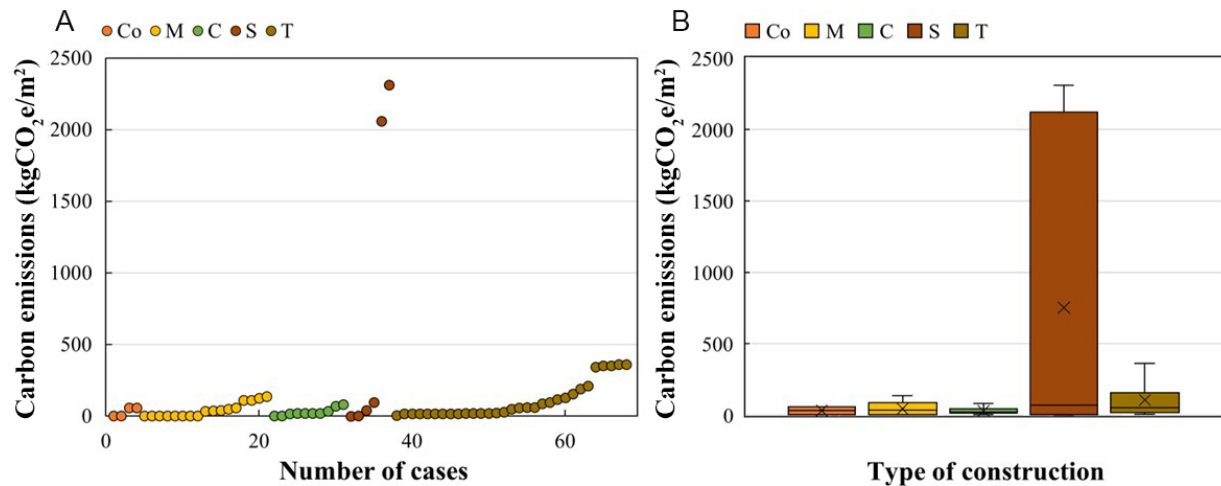


Figure 8. CEs calculation results of stage B1-B5 in the case studies. (A) Distribution of all results; (B) Quartile plot. The box range represents the interquartile range(Q1-Q3), the horizontal line inside the box indicates the median, and the cross symbol (×) denotes the mean value. 11 cases did not provide structural information. The sample sizes for Co, M, C, S, and T were 4, 17, 10, 6, and 31, respectively.

Use stage (B1-B5)

CEs emitted in stages B1-B5 (CE_{B1-B5}) include those from use, maintenance, repair, refurbishment, and replacement (B1-B5, respectively), and the production, transport, and disposal of the involved building materials. This part of CEs was known as the “recurring ECEs”. In contrast, the CEs from the raw material extraction to the end of construction (A1-A5) were referred to as “initial ECEs”. The main method of calculating CE_{B1-B5} determines the number of material replacements over the calculation period based on the expected service life of each building material^[58,83], then calculates the corresponding recurring ECE.

The reviewed case studies provided 79 sets of CE data from stages B1-B5 [Figure 8], with a median value of 41.9 kgCO₂e/m², accounting for 8.0% of the LCCE. The median CE_{B1-B5} values for masonry, concrete, steel, timber, and composite structures are 35.7, 20.5, 69.4, 51.2, and 31.6 kgCO₂e/m², respectively. Among these, concrete structures have the lowest CE_{B1-B5} .

Due to differences in calculation methods, the scope of considered CE sources, and building service life, significant order-of-magnitude variations exist in CE_{B1-B5} values across studies. Huang *et al.*^[26]'s calculations showed CE_{B1-B5} at 36.8 kgCO₂e/m². Parece *et al.*^[59] report 71.43 kgCO₂e/m² for a two-story residential building. However, Davis *et al.*^[61] obtained two significantly higher estimates, 2,059.75 and 2,311.71 kgCO₂e/m², for a single-story dwelling using two different calculation approaches, approximately double the CEs of the stages A1-A5. These notably higher results primarily stem from their comprehensive inclusion of all building components (rather than just non-structural elements like exterior finishes).

End-of-life stage (C1-C4)

CEs emitted in stages C1-C4 (CE_{C1-C4}) were calculated for building demolition (C1), waste transportation (C2), processing (C3), and disposal (C4). The calculations for C1 and C2 were similar to those for A5 and A4. The calculations for C3 and C4 were determined using waste treatment methods, which may greatly vary in different scenarios. In fact, this section is based on certain assumptions owing to the lack of corresponding calculation methods and basic parameters.

The reviewed case studies provided 79 sets of CE data from stages C1-C4 [Figure 9], with a median value of 18.8 kgCO₂e/m², accounting for 2.9% of the LCCE. The median CE_{C1-C4} values for masonry, concrete, steel,

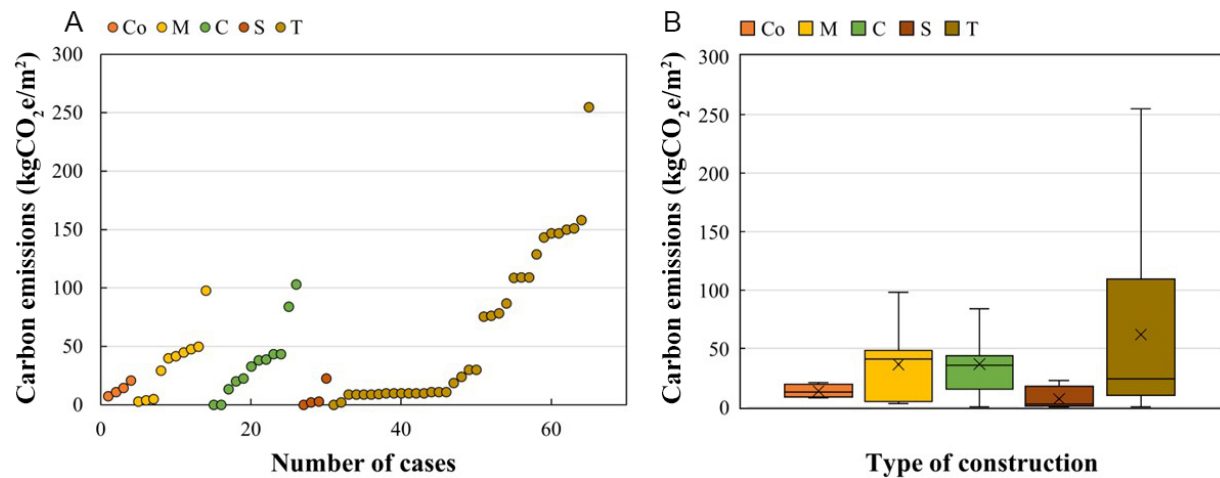


Figure 9. CEs calculation results of stage C1-C4 in the case studies. (A) Distribution of all results; (B) Quartile plot. The box range represents the interquartile range (Q1-Q3), the horizontal line inside the box indicates the median, and the cross symbol (×) denotes the mean value. 14 cases did not provide structural information. The sample sizes for Co, M, C, S, and T were 4, 10, 12, 4, and 35, respectively.

timber, and composite structures are 40.9, 35.6, 2.6, 24.0, and 12.8 kgCO₂e/m², respectively. Among these, steel structures have the lowest CE_{C1-C4} .

Significant differences exist in the calculated CE_{C1-C4} across various studies. Ajay *et al.*^[42] investigated four vernacular buildings in Nepal, finding that CE_{C1-C4} ranged between 3.0–4.0 kgCO₂e/m², accounting for only 0.6%–0.9% of the LCCE. Norouzi *et al.*^[77] calculated the ECE of a two-story residential building in the UK, reporting a CE_{C1-C4} value of 31.32 kgCO₂e/m². Song *et al.*^[27] assessed the LCCE of a traditional single-story courtyard house in Beijing, where CE_{C1-C4} was 97.99 kgCO₂e/m², representing 2.4% of the LCCE.

Calculation of OCE

Building OCE includes operational energy and water consumption. However, most studies only considered energy consumption, and only Huang *et al.*^[26], Davis *et al.*^[65], Cai *et al.*^[22], Passer *et al.*^[44], Petrovic *et al.*^[67], Norouzi *et al.*^[77], Cuéllar-Franca *et al.*^[82], and Quintana-Gallardo *et al.*^[93] explicitly calculated water consumption. The CEs from stage B7 account for a relatively small proportion. For example: Petrovic *et al.*^[67] indicated that Stage B7 accounts for 6% of the OCE over a 100-year building life cycle. Meanwhile, calculations by Cai *et al.*^[22] showed that stage B7 CEs constitute only 0.3% of the building's total LCCE. As shown in [Supplementary Table 1](#), the methods and scopes used for calculating energy consumption in stages B6–B7 varied across different studies.

The reviewed case studies provided 178 sets of CE data from stages B6–B7 [Figure 10], with a median value of 14.8 kgCO₂e/m²/yr, accounting for 66.1% of the LCCE. The median OCE values for masonry, concrete, steel, timber, and composite structures are 20.6, 19.2, 24.6, 4.4, and 10.7 kgCO₂e/m²/yr, respectively. Among these, timber structures have the lowest CE_{B6-B7} . OCE is closely related to the climate zone in which the building is located^[105]. According to the Köppen climate classification method, the world's climates can be divided into five major zones: A, B, C, D, and E. A total of 140 sets of data were collected, including 9 from the B climate zone, 96 from the C climate zone, and 37 from the D climate zone (data for the A and E climate zones are lacking). Statistically, the median OCE value for the B climate zone is 1,208.5 kgCO₂e/m², for the C climate zone it is 902.6 kgCO₂e/m², and for the D climate zone is the lowest, at only 254.5 kgCO₂e/m². Additionally, there are certain differences in OCE among different countries or regions. A comparison was performed of

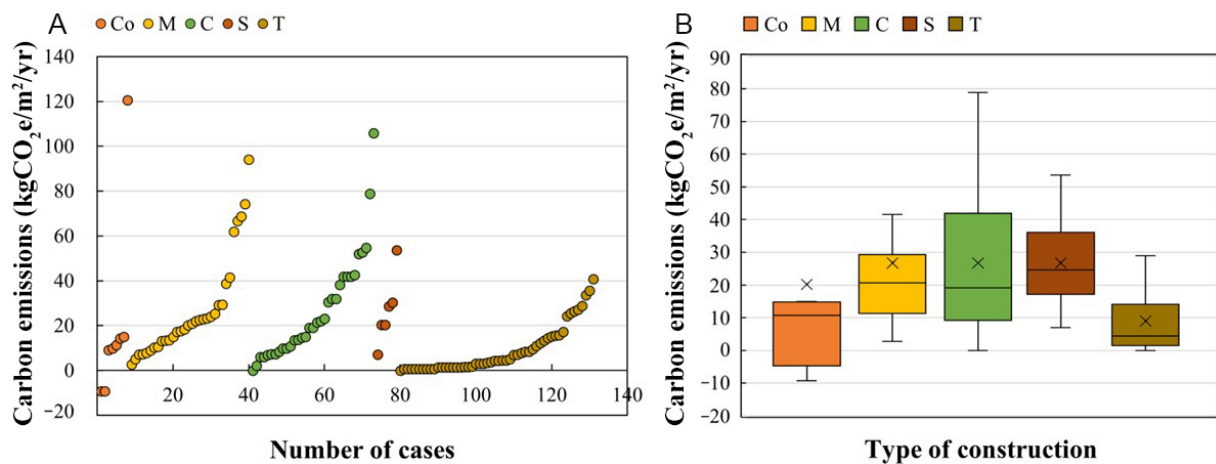


Figure 10. CEs calculation results of stage B6-B7 in the case studies. (A) Distribution of all results; (B) Quartile plot. The box range represents the interquartile range(Q1-Q3), the horizontal line inside the box indicates the median, and the cross symbol (×) denotes the mean value. 42 cases did not provide structural information. The sample sizes for Co, M, C, S, and T were 8, 32, 33, 6, and 52, respectively.

the OCE in China, Asia (excluding China), and Europe. The median OCE value in the China group was the highest, at 910.0 kgCO₂e/m², followed by the Asia group with a median of 881.3 kgCO₂e/m², while the Europe group had the lowest median, at 792 kgCO₂e/m².

Electricity is the main component of the energy consumed during building operations. The electricity CEF changes over time, unlike primary energies. However, most studies tend to overlook the trend of the electricity CEF. The electricity CEF continues to annually reduce in many countries; therefore, the calculation method of annual power consumption × calculation period (such as 50 years) could overestimate the CE due to electricity consumption. Another problem arising from this oversight was that the CE offset was overestimated by the use of renewable energy (such as photovoltaics) in some cases. Replacing grid power with renewable energy decreased the CE offset, as the grid power CEF decreased.

Calculation of supplementary effects (Module D)

The carbon benefit of module D is generated from the recycling and reuse of building materials, components, and energy. Among the 90 studies reviewed, a total of 19 (21.1%) considered this module, of which 16 studies conducted calculations, while the remaining 3 studies used empirical data. Due to the lack of measured data, the recycling or reusing rates of materials or components are usually assumed. For example, Moghayedi *et al.*^[95] assumed that 20% of bricks are recycled after the building's service life ends. In another study^[96], researchers assumed a recycling rate of 30% for wood and tiles, and 50% for steel reinforcement in conventional buildings; whereas for prefabricated buildings, the recycling rate of floor slabs was assumed to be 80%.

The 90 reviewed studies collectively provided 25 data sets for module D [Figure 11]. Overall, the median carbon benefit of module D was -118.0 kgCO₂e/m², accounting for -31.5% of the total ECE and -8.7% of the LCCE. The median CE_D values for masonry, concrete, steel, and timber structures are -109.3, -73.3, -175.3, and -148.1 kgCO₂e/m², respectively. Among these, steel structures have the lowest CE_D . However, it should be noted that, due to the limited amount of available data, the statistical results regarding the carbon benefits of module D for buildings with different structures may have certain limitations.

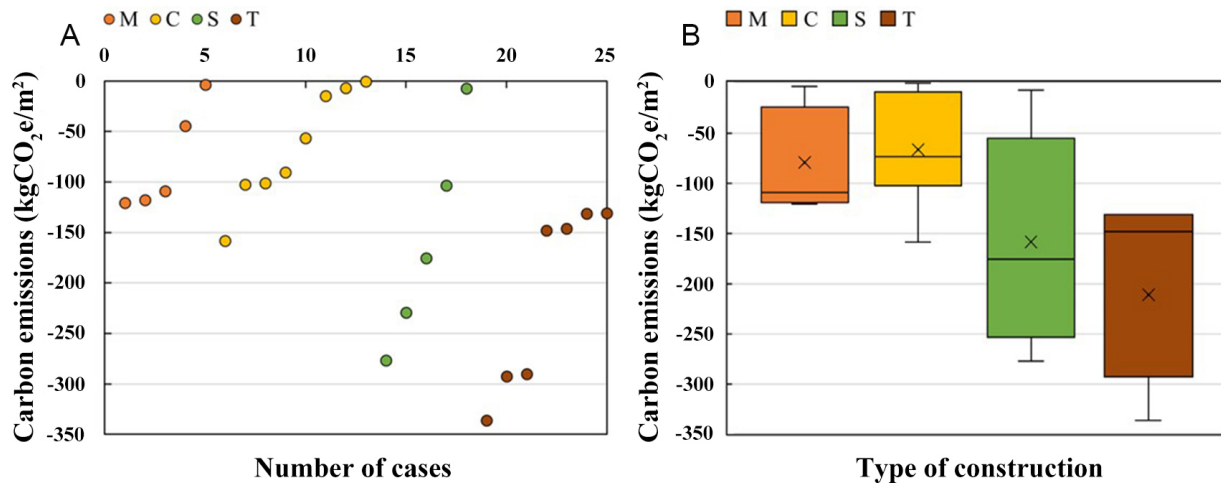


Figure 11. CEs calculation results of module D in the case studies. (A) Distribution of all results; (B) Quartile plot. The box range represents the interquartile range(Q1-Q3), the horizontal line inside the box indicates the median, and the cross symbol (×) denotes the mean value. The sample sizes for M, C, S, and T were 5, 8, 5, and 7, respectively.

Discussion on the LCCE calculation

Most of the pre-use stages were calculated through the design and construction plan in these case studies, or data recorded in the actual construction process, which tended to be in line with the actual conditions. However, many previous cases cited data or empirical formulas in the calculation of the in-use and post-use stages owing to the lack of independent research. Therefore, the calculation processes were full of assumptions and lacked credibility. Blengini *et al.*^[54,55] believed that CEs depend on a complex combination of local building technology, site-specific climatic conditions, local regulations, energy mix, and human behavior patterns in different cases; a single improvement based on oversimplification, generalization, and reliance on friendly tools might be ineffective or even deviate from expectations from a lifecycle perspective. A LCA of rural dwellings in Portugal showed that the use of different assessment tools produces inconsistent comparative results on the same issue, ultimately influencing decision-making^[60]. The resulting CEs for building maintenance varied in the range of 2%-6% of the LCCE in a case study in Spain when different parameters (provided by GaBi and Ecoinvent) were used for calculation^[101].

Inconsistent method for assigning values

Gustavsson *et al.*^[68] calculated CEs from on-site construction based on a review of previous studies, assuming that the energy consumption during the construction stage was 80 kWh/m² and the energy demand for building demolition was 10 kWh/m². Meanwhile, Asdrubali *et al.*^[53]'s calculation assumed that the on-site construction CE was equal to 2% of the energy embodied in the building material, and the transport distance was assumed to be 50 km. Cuéllar-Franca *et al.*^[82] converted construction energy consumption through the weight of building materials and mechanical parameters provided by previous studies. Proietti *et al.*^[57] calculated the amount of building material replacement according to the replacement factors quoted from previous studies. Cuéllar-Franca *et al.*^[82] determined the material replacement in the use stage according to the service life of the building and the material; for example, the service life of windows, doors, and laminate flooring was 25, 20, and 20 years, respectively; therefore, they were considered to be replaced 1, 2, and 2 times over 50 years, respectively. The mechanical energy consumption of demolition activities was determined as the average value based on existing studies in the demolition stage. Asdrubali *et al.*^[53] assumed that glass, aluminum, steel, and copper were 100% recycled, and steel and limestone powder were recycled from the reinforced concrete (RC) at the end-of-life treatment. Cuéllar-Franca *et al.*^[82] considered that the construction waste, concrete, binders, aggregates, and gypsum were 100% recycled, timber was 2% reused

(including 79% recycled and 19% landfilled), while brick was 51% reused (including 36% recycled, and 13% landfilled).

Similar problems were reported in other studies, resulting in very different calculation results. For example, the CEF of straw was given a negative value of $-1.2 \text{ kgCO}_2\text{e/kg}$ owing to the carbon storage of the plant^[46]. In contrast, wood-framed houses were considered that the carbon stored by wood is eventually released; therefore, the impact of carbon storage on CEF was not considered^[18]. The carbon sink in the upstream forest system, separation of wood materials from demolition waste for landfills, and use of wood fuel as a substitute for coal and natural gas in electricity production were all considered in two timber-framed houses in Canada^[97]. Another study on timber houses considered the biomass energy utilization of wood residues to substitute fossil fuels; this resulted in negative CEs of building material production^[69,70].

Uncertain CEF

The following analysis presents the CEFs of the steel, cement, and concrete used in the case studies to demonstrate the uncertainty in these basic parameters. This demonstrates the infeasibility of quoting data from other databases and the need to develop basic parameters for local building materials.

- *Steel.* The reviewed case studies provided 32 sets of steel CEF parameters, including 12, 9, and 11 sets for China, Asia excluding China (excl.CN), and Europe, respectively. They were between $0.36^{[67]}$ - $4.74^{[36]}$ $\text{kgCO}_2\text{e/kg}$, and the lowest and highest values were from Europe and Malaysia, respectively, with a difference of 13.2 times. Regionally, the median CEF of steel in China and Europe are 2.31 and 1.71 $\text{kgCO}_2\text{e/kg}$, respectively. The CEF of steel is affected by many factors, such as its smelting method and the proportion of scrap recycled from raw materials. The CE of crude steel can be reduced by 1 $\text{kgCO}_2\text{e/kg}$ for every additional 1 kg of recycled scrap as raw material according to the World Steel Association^[106]. The CE intensities of crude steel production in China, Germany, Mexico, and the United States were 2,148, 1,708, 1,080, and 1,736 $\text{kgCO}_2\text{/t}$, respectively in 2010. One of the main reasons for the low CE intensity of crude steel in Mexico was the high proportion of steel production by the electric arc furnace method (69.4%) compared with 9.8% in China^[107] [Figure 12A1 and A2].
- *Cement.* Eighteen sets of cement CEF parameters were provided in the reviewed case studies, including seven, nine, and two sets in China, Asia (excl.CN), and Europe, respectively. The values ranged between $0.310^{[38]}$ - $1.047^{[20]}$ $\text{kgCO}_2\text{e/kg}$, and the lowest and highest values were from Asia and China, respectively, with a difference of 3.3 times [Figure 12B1 and B2].
- *Concrete.* Forty-two sets of concrete CEF parameters were provided in the reviewed case studies, including 11, 14, and 17 groups from China, Asia (excl.CN), and Europe, respectively. The values were between $0.070^{[31]}$ - $0.240^{[73]}$ $\text{kgCO}_2\text{e/kg}$ (convert the units using a density of $2,400 \text{ kg/m}^3$), and the lowest and highest values were from Asia (excl.CN) and Europe, respectively, with a difference of 3.4 times. The CE in the concrete life cycle is approximately linearly proportional to its compressive strength, and the CE at 35 MPa is 48% higher than that at 21 MPa^[108]. However, almost no concrete compressive strength was clearly stated in the reviewed literature [Figure 12C1 and C2].

This significant variability in material (steel, cement and concrete) CEFs introduces considerable uncertainty into LCA results. It suggests that differences in ECE between case studies may reflect the regional industrial background (e.g., reliance on scrap or coal) rather than the actual environmental performance of the building design.

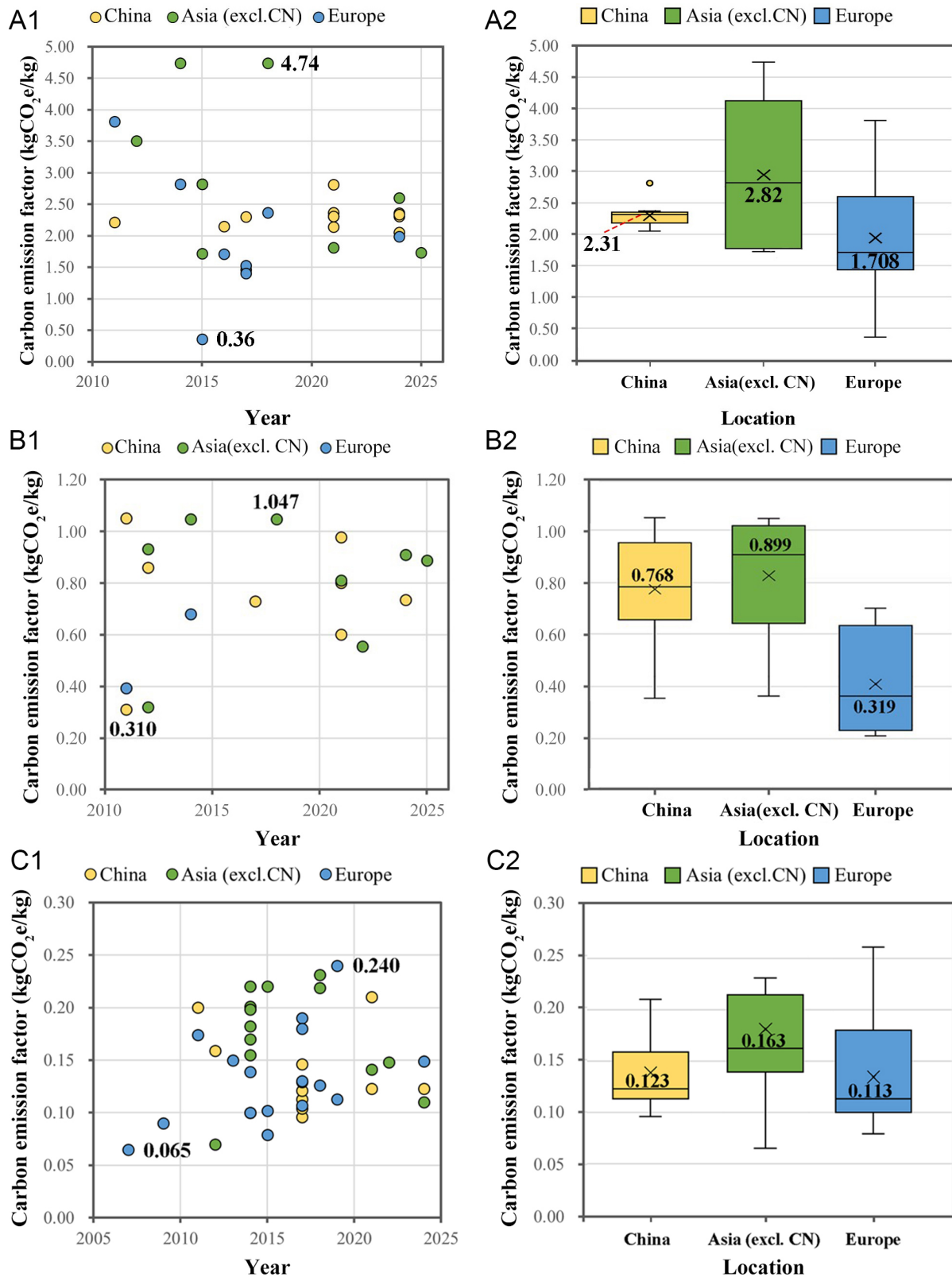


Figure 12. CEF of steel, cement, and concrete used in the reviewed case studies. The box range represents the interquartile range(Q1-Q3), the horizontal line inside the box indicates the median, and the cross symbol (×) denotes the mean value. The sample sizes for (A), (B), and (C) were 32, 18, and 42, respectively. (A1) Distribution of all results, (A2) Quartile plot; (B1) Distribution of all results, (B2) Quartile plot; (C1) Distribution of all results, (C2) Quartile plot.

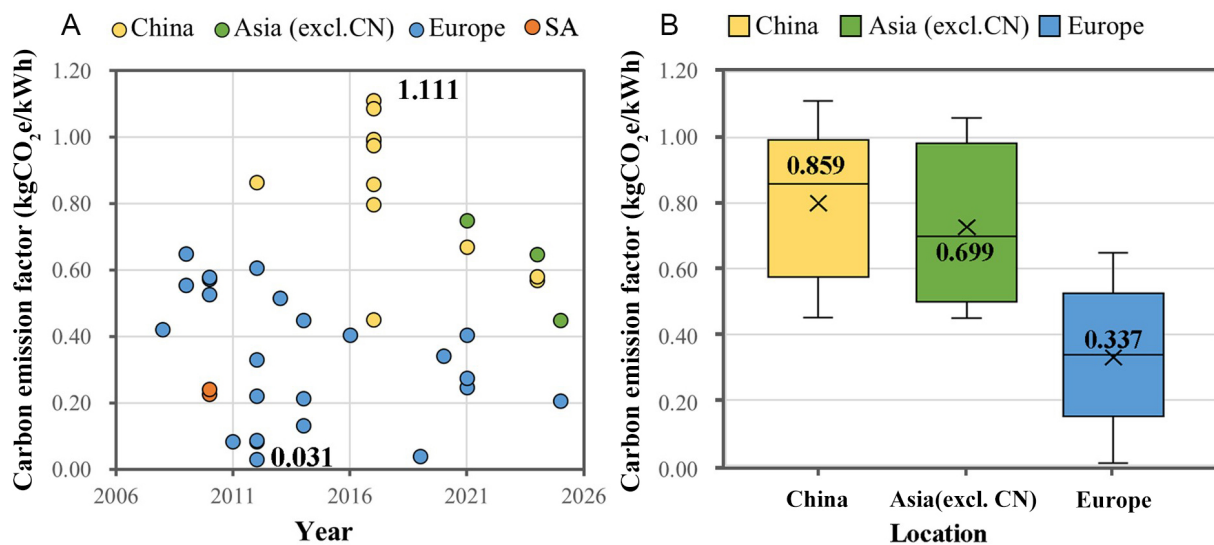


Figure 13. Carbon emission factors of electricity used in the reviewed case studies. (A) Distribution of all results; (B) Quartile plot. The box range represents the interquartile range(Q1-Q3), the horizontal line inside the box indicates the median, and the cross symbol (×) denotes the mean value. The sample size was 41.

Forty-one sets of electricity CEF parameters were provided in the reviewed case studies. The values were between 0.031^[92] and 1.111^[20] kgCO₂e/kWh. The lowest and highest values were from Europe and China, respectively, with an extreme difference of 36.4 times. Electricity CEF dynamically changes and is related to the energy structure used in power generation, which is affected by time and region. Only two sets were from Asia (excl. CN). Here, only China, Asia, and Europe were compared. The median values of the 11 sets of CEF parameters in China and the 24 sets in Europe were 0.859 and 0.337 kgCO₂e/kWh, respectively. The use of different CEFs can lead to significantly different calculation results and decision-making in different countries and regions [Figure 13].

According to the calculation methodology, CE results ($CE = CEF \times \text{Material/Energy Consumption}$) are highly dependent on the CEF as a key parameter. When different studies adopt vastly different CEF for the same building material (e.g., some use regional averages while others rely on global default values; or differences arise from production processes, such as steel produced via the Blast Oxygen Furnace versus the Electric Arc Furnace), such bias at the input stage inevitably leads to in-comparability in the output results.

Therefore, comparability is predicated on a common frame of reference. Different studies often operate within distinct 'evaluation dimensions' due to variations in database sources, geographical boundaries, or technological conditions. This heterogeneity in data sources results in the absence of a unified baseline, thereby severely undermining the reliability of cross-study comparisons of absolute values.

Calculation of CE offset from material reuse/recycling and energy recovery (D module)

The CE offset calculation from material reusing/recycling and energy recovery (hereafter referred to as 3R materials and energy) in module D showed the following problems among the reviewed studies:

- *Overlooked the D stage.* As mentioned in Section "Calculation of supplementary effects (Module D)", only 21.1% of the reviewed studies calculated module D. The statistical results in Section "Calculation of supplementary effects (Module D)" showed that the 3R materials and energy from the D module had a significant impact, especially for materials where the CEFs were significantly affected by the recycling rate of raw materials (such as steel).

- *Repeated carbon offset calculation.* Some studies adopted small CEFs to calculate CE_{A1-A3} on the grounds that recycled raw materials were used to produce the building materials. In contrast, the CE offset by material recycling in the post-use stage was counted in the D module. Consequently, the CE offset was counted twice in the building system, and the building ECE was underestimated.
- *Lack of basic parameters.* Owing to the lack of research on the post-use stage, even in the case of calculating the D module, settings, such as the types of materials for recycling or reuse, material recycling or reuse rate, and recycling or reuse methods, were all based on assumptions. Consequently, the calculation results were extremely uncertain, rendering the calculation of this module unreliable, and a referenceable benchmark value could not be achieved.
- *No consideration for the time factor.* The CE offset by the D module depends on the difference in CE between the 3R materials and energy and the non-3R materials and energy. Unlike ordinary commodities, buildings have a much longer lifespan; therefore, the effect of the time factor must be considered. The CEs of 3R materials and energy and non-3R materials and energy might vary to a large degree after the expected service life of the building (~50 years); However, none of the reviewed studies responded to this question.

The carbon offset benefits associated with Module D essentially occur during the transitional phase between the end-of-life of a preceding building and the beginning of a subsequent building's life cycle. Regarding the allocation of these carbon offsets at the end-of-life stage, there are currently three prevailing allocation paradigms: the World Resources Institute (WRI) 100-0 method (allocating all carbon offsets to the preceding life cycle), and the WRI 0-100 method (allocating all carbon offsets to the subsequent life cycle)^[109].

To avoid the risk of double counting and to account for the uncertainties surrounding building material emission factors over long-term horizons, this study recommends adopting the WRI 0-100 allocation approach. Specifically, this entails attributing the full carbon offset benefit to the subsequent building's life cycle. In practical accounting terms, this means that when calculating the LCCE of a new building, it is necessary to identify and quantify the amount of recycled materials used, and subsequently calculate the resulting carbon reduction.

CARBON REDUCTION STRATEGIES

Based on the study by Huang et al.^[105]. The LCCE can be expressed as:

$$LCCE = \sum_1^i AD_{m,i} \times CEF_{m,i} + \sum_1^i AD_{e,i} \times CEF_{e,i} - CE_D - CE_e \quad (1)$$

where, AD_m , activity data of building materials; AD_e , activity data of operational energy; CEF_m , carbon emission factors of building materials; CEF_e , carbon emission factors of energy; CE_D , supplementary benefits from 3R materials and energy; CE_e is carbon reduction by other technologies.

The technical strategies and carbon reduction benefits mentioned in the case studies reviewed from different regions of low-rise dwellings are shown in Figure 14. These were grouped into the following three categories: decreasing AD_m or CEF_m , reducing AD_e or CEF_e , and enhancing carbon offset from module D through 3R of building materials and energy.

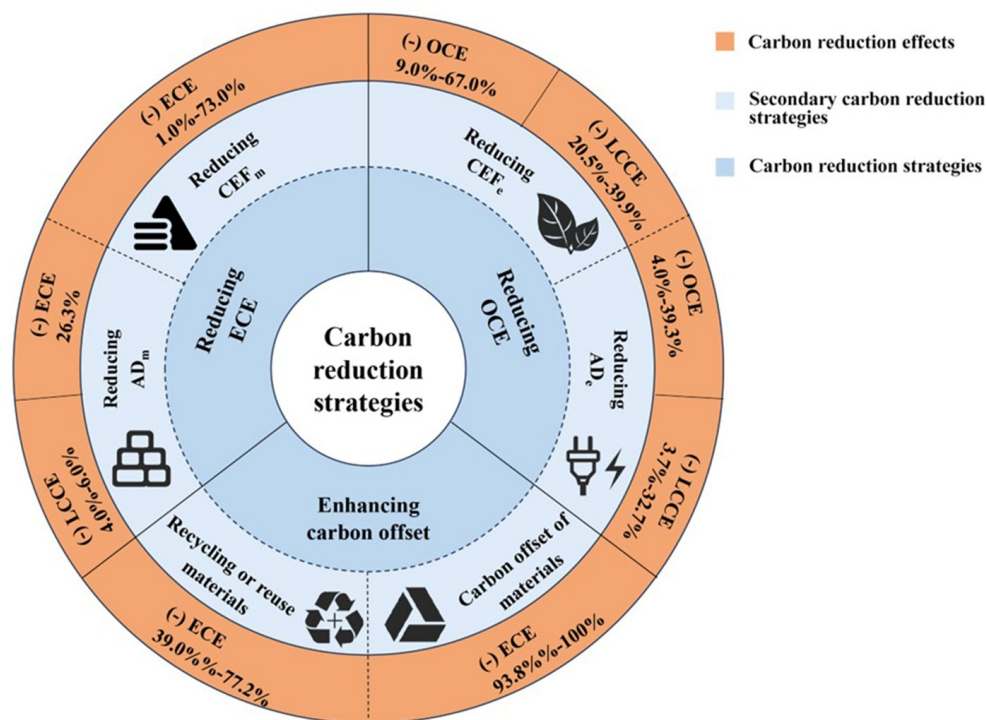


Figure 14. Carbon reduction strategies and effects.

Reduction of building ECE by reducing AD_m and CE_{F_m}

Regulations for load-bearing structure design are well established for small-scale, low-rise buildings, such as the dwellings discussed in this study. The potential for reducing the amount of building materials is limited by their structural safety. In contrast, the substitution of structural systems with low-carbon building materials has a high potential for CE reduction^[110]. The ECE reduction of the optimization schemes was 11.5%-96.5% among the reviewed case studies [Table 3], compared to the corresponding baseline scheme. The ECE reduction was influenced by the difference in CEF and the amount of substitution of building materials between the optimized and baseline structure schemes.

- *Almost all studies involving timber (T) structures have low carbon advantages.* The CE from the production stage of wood-frame houses was reduced by 64.5% compared to a RC scheme^[18]. The ECE of wood-frame rural dwellings was 37.5% lower than that of light-steel-frame houses^[28]. A study of a wooden house in Sweden showed a lower ECE for a wood structure than that for a concrete structure^[69]. The use of a novel off-site panelized modular timber frame system resulted in a 34% reduction in the ECE compared with conventional construction methods^[84]. Hafner *et al.*^[92] demonstrated that the use of wood instead of mineral materials for construction can reduce the ECE.

- *Divergent findings were observed in the comparative analysis of concrete and steel structures.* Analysis of three structural types for a three-storey residence revealed that concrete frameworks generated 44% and 49% higher CEs during the production phase compared to steel and timber alternatives^[17]. When applied to a rural residence in southern Italy, the CEs associated with the cold-formed steel frame and insulated panel wall system were found to be inferior to those of the traditional RC frame with brick walls throughout the pre-use, operational, and end-of-life stages^[56]. According to a statistical assessment of 45 residential units in Iran, concrete structures demonstrated an average ECE reduction of 24.46% compared to their steel counterparts^[32]. This disparity is even more pronounced in prefabricated prefinished volumetric construction, where concrete designs resulted in 54% fewer emissions than steel designs^[34].

Monahan et al., 2011 ^[84]	UK	Cfb	T, M	Panelized timber frame MMC	Conventional masonry construction	•	•	(-) 34%	
Iddon et al., 2013 ^[86]	UK	Cfb	M, T	Using concrete with a 30% PFA mix, timber-framed windows, and a brick slip rainscreen cladding system	Using ordinary concrete, PVC-framed windows, and a brick outer skin		•	(-) 24%	(-) 5%
Rossi et al., 2012 ^[91]	Belgium	Cfb	S, M	Steel frame house	Masonry house	•	•	(-) 12%	
Moghayedi et al., 2025 ^[94]	Africa			Utilizing 3D printing technology	Utilizing cast-in-place method		•	(-) 48%	
Salazar et al., 2009 ^[96]	Canada	Dfb	T, M	Wood-intensive house (system with landfill)	Traditional masonry		•	(-) 72%	
Zhang et al., 2014 ^[97]	Canada	Csb	T	PVC window frame with low-E tin glazing	Aluminum window frame with standard glass		•	(-) 15.3%	
				PVC membrane (PVC-cellulose) roof	4-ply build-up asphalt roof		•	(-) 11.5%	
				Wooden window frame	Using aluminum window frames		•	(-) 9.2%	
Izaola et al., 2023 ^[66]	Spain	NS	NS	Wooden flooring	Using ceramic tiles		•	(-) 2.7%	
				Recycled cork insulated walls	Brick wall		•	(-) 1.0%	

CE: Carbon emissions; ECE: embodied carbon emission; OCE: operational carbon emissions; LCCE: life cycle carbon emissions; AD_m : activity data of building materials; CEF_m : carbon emission factors of building materials; PPVC: prefabricated prefinished volumetric construction; RC: reinforced concrete; PVC: polyvinyl chloride.

• *It is also crucial to investigate the capabilities of alternative low-carbon construction techniques.* Research indicates that substituting conventional rural housing with straw-bale variations can drastically lower ECE; specifically, reductions of 96.5%, 75.5%, and 45% were observed for wood-frame, lightweight steel, and steel-frame straw-bale systems, respectively^[15]. In the context of Iran, a study covering four climatic regions demonstrated that straw-bale dwellings utilizing wooden structures outperformed those with concrete or interior brick walls, achieving ECE decreases of 76.00%, 16.89%, and 13.67% relative to traditional housing^[31]. Furthermore, composite materials show promise; for instance, steel-bamboo frames in East China yielded a 17.6% ECE advantage over concrete frames^[16]. Similarly, switching from an RC framework to a prefabricated concrete panel wall system in a Malaysian two-story residence resulted in a 26.27% reduction in emissions^[37].

• *ECE reduction can be achieved by replacing some of the materials with high CEF used in the buildings.* Research conducted on ten residential units in Malaysia indicates that the adoption of low-carbon components and materials can lower ECE by a range of 16.28% to 41.10%^[35]. Similarly, data from Sweden suggests an inverse relationship between the volume of bio-based materials used and the resulting ECE^[67]. In terms of specific material substitutions, one study on a new residence demonstrated a 24% decrease in ECE by utilizing concrete blended with 30% pulverized fly ash and swapping polyvinyl chloride (PVC) window frames for timber ones^[86]. Furthermore, optimizing wooden rural dwellings—specifically by substituting ordinary glass with tin-plated glass and aluminum frames with PVC—yielded a 15.25% reduction. This figure could be further improved by an additional 11.48% through the replacement of 4-ply asphalt roofing with PVC-cellulose alternatives^[97]. Izaola et al.^[111] found that using a wooden window frame to replace an aluminum window frame resulted in a 9.2% reduction in the ECE.

Reduction of building OCE by reducing AD_e and CEF_e

The implementation of building energy efficiency measures and the optimization of the energy structure to reduce the CEF of the energy supply have great potential. The OCE reduction benefits ranged from 9%-67% among the reviewed case studies [Table 4].

- *Existing comprehensive technologies related to building energy conservation reduce OCE.* A study of the heating scheme in a PH in northwestern France (including the electric heat pump, wood pellet condensing boiler, wood pellet micro-cogeneration unit, and district heating) showed that the PH showed clear advantages over the reference house during the operating stage, regardless of the heating system. The LCCE of the PH was 70.6% lower than that of the reference house following a comparison using the LCA tool, EQUER^[47,49]. A comparison of the OCE using four nZEB schemes and four PH schemes for a two-storey house in Ireland over a 60-year calculation period showed that buildings with high thermal and airtightness and heating systems with low CE (such as biomass boilers or heat pumps) should be prioritized^[52]. A functionally equivalent energy-efficient house reduces the LCCE by 63% compared to a standard home in Michigan^[98]. The study of a wooden house showed that the building ECE increased by 28.5% by improving the building envelope; however, the OCE decreased by 39.3%, which ultimately reduced the LCCE by 32.7%^[18]. A case study of dynamic thermal simulations showed that heavyweight constructions reduce the OCE by 7% compared with lightweight constructions^[87].

- *Decarbonization of the power grid had a significant impact on the reduction of OCE.* The OCE of operating a rural dwelling was reduced by 67% when using the Swiss mix compared to the Union for the Coordination of Transmission of Electricity (UCTE)^[98]. The lower CEF of Colombia's grid resulted in a greatly lower building OCE in Colombia compared with that in Spain; an appropriate energy mix of electricity and natural gas reduces OCE by 25% and 9%, respectively, compared with pure electricity in the Mediterranean and Colombia^[112,113]. The OCE of a rural dwelling in Switzerland was only 13% that of the United States because the Swiss energy source mainly originated from hydropower and nuclear energy^[114]. A case study in Nepal showed that improving the proportion of hydroelectricity from 82.51% to 100% could reduce the LCCE by 20.5%-28.2%^[42].

- *The low-carbon transformation of building heating systems was prominent in Europe.* Comparison of different building envelopes, heating, and PV systems for a concrete-walled house in Finland showed that the heating system had the greatest impact on the LCCE, and the ground source heat pump was the optimal solution^[18]. A study of a rural dwelling in a cold Norwegian climate showed that an all-electric system, heat pump, high-efficiency insulation system, and PV panels achieve zero OCE; however, it was difficult to achieve net zero CEs (ZEB-OM) involving both OCE and ECE^[87]. Research focusing on timber-framed rural housing in Sweden indicates that OCE is significantly influenced by the specific energy supply infrastructure utilized; the OCE of DH + BIG/CC (district heat + biomass-based integrated gasification combined cycle) was approximately 90% lower than that of the RH + CST (electric resistance heating + coal-based steam turbine); the OCE of HP + NGCC (heat pump + natural gas-based combined cycle) was 50% lower than that of the RH + CST. The substitution of fossil fuels with biomass by-product from the wood production chain in a wooden house in Växjö showed that the total CEs during the building material production and building operation were negative when DH + BIG/CC or HP + BIG/CC were used^[70].

- *Strategies showing regional differences.* For example, different local power grids have different CEFs, and the benefits generated by saving the same amount of electricity are different. For example, the CEF of electricity production by PVs showed that the CEFs were 72.4 and 54.6 gCO₂e/kW, respectively, when the US fuel mix and European UCPTE fuel mix were used^[29]. A comparison of wood rural dwellings in five different locations in Europe showed that the OCE still accounted for 65%-76% of the total LCCE, even though the

Table 4. CE reduction technical strategies and benefits by reducing AD_e and CEF_e.

Literature	Location	Climate	Structure	Technical measures		Technical group		CE reduction effects		
				Optimized scheme	Baseline scheme	AD _e	CEF _e	ECE	OCE	LCCE
Yang <i>et al.</i> , 2021 ^[18]	China	Cfa, Cwb, Cwa, Dwa	T	Upgrading energy efficiency to an ultra-low energy building	Ordinary building design	•		(+) 28.5%	(-) 39.3%	(-) 32.7%
				Adding sunrooms	Open-air courtyard	•				(-) 10.3%
				Adding a layer of thermal insulation on the rooftop	Typical roof tiles	•				(-) 3.68%
Song <i>et al.</i> , 2024 ^[27]	China	Dwa	M	Adding a layer of thermal insulation on the outside of the wall	Typical brick walls	•				(-) 19.37%
				Adding a layer of thermal insulation on the inner side	Wooden doors and windows	•				(-) 6.74%
Ajay <i>et al.</i> , 2024 ^[42]	Nepal	ET	M	100% hydroelectric	82.51% hydroelectric		•			(-) 20.5%-28.2%
				Cooking with hydroelectricity	Cooking with liquefied petroleum gas		•			(-) 7.1%-39.9%
Thiers <i>et al.</i> , 2008 ^[47]	France	Cfb	T	Passive house design	Ordinary house design	•	•			(-) 70.6%
Blengini <i>et al.</i> , 2010 ^[54]	Italy	Cfb	RC	Low-energy house design	Ordinary house design	•	•			(-) 55%
Blengini <i>et al.</i> , 2010 ^[55]	Italy	Csa	RC	Passive house design	Ordinary house design	•	•	(+) 12.5%	(-) 71.7%	(-) 53.9%
Citherlet <i>et al.</i> , 2007 ^[75]	Switzerland	Cfb	NS	Using Swiss electricity mix	Using UCTE electricity mix		•			(-) 67%
Norouzi <i>et al.</i> , 2025 ^[77]	UK			Implementing a 4kWp grid-connected PV system	Implementing a 2kWp grid-connected PV system		•			(-) 65%
Iddon <i>et al.</i> , 2013 ^[86]	UK	Cfb	M, T	Improving the thermal envelope	Ordinary building envelope design	•		(+) 1%-13%	(-) 4%-5%	
Keoleian <i>et al.</i> , 2001 ^[98]	USA	Dfb	T	Energy-efficient building design	Ordinary building design	•	•			(-) 63%
Ortiz <i>et al.</i> , 2010 ^[100]	Spain	Csa	NS	Optimal mixing of natural gas plus electricity	Pure electricity		•			(-) 25%
	Colombian	Aw	Co	Optimal mixing of natural gas plus electricity	Pure electricity		•			(-) 9%
Ortiz-Rodríguez <i>et al.</i> , 2010 ^[101]	Spain	Csa	NS	Wind power market penetration reaches 15%	Current electricity mix		•			(-) 10%
	Colombian	Aw	Co	Using hydroelectric plants	Current electricity mix		•			(-) 11%
Peng <i>et al.</i> , 2024 ^[112]	China	Cwa	M	Natural ventilation utilizing a solar chimney	Natural ventilation utilizing windows	•				(-) 16.5 kgCO ₂ /m ²

Houlihan Wiberg <i>et al.</i> , 2023 ^[49]	America	NS	NS	Using a double-glazed window, 102mm brick-fired clay, 19.8mm plywood with CDX sheathing and 90mm fiberglass. Setting the window-to-wall ratio to 0.85	Using a single-glazed window, 25 mm stucco, 16mm gypsum board, exterior wall insulation	•	(-) 35.67%	(-) 17.43%
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CE: Carbon emissions; ECE: embodied carbon emission; OCE: operational carbon emissions; LCCE: life cycle carbon emissions; AD_m : activity data of building materials; CEF_m : carbon emission factors of building materials.

Table 5. CE benefits by enhancing carbon offset from module D

Literature	Location	Climate	Structure	Technical measures		Technical group	CE reduction effects		
				Optimized scheme	Baseline scheme		CE_D	ECE	OCE LCCE
Li <i>et al.</i> , 2021 ^[95]	China	NS	T	CE offset of building materials and construction by carbon sink of wood	Ordinary conditions without carbon sink	•	(-) 93.8%		
Yu <i>et al.</i> , 2011 ^[19]	China	Cfa	T	Recycling of construction and demolition waste	Ordinary conditions without recycling	•	(-) 69.2%		
Cuéllar-Franca <i>et al.</i> , 2012 ^[92]	UK	Cfb	M	Recycling of building materials	Ordinary conditions without recycling	•			(-) 2%-3%
Salazar <i>et al.</i> , 2009 ^[96]	Canada	Dfb	T, M	Wood-intensive house (system with biomass recovery)	Traditional masonry house	•	(-) 100%		
Lei <i>et al.</i> , 2023 ^[115]	China	Dfa	S	Recycle, reuse and remanufacture	Demolition, transportation and landfill	•	(-) 73.75%-77.24%		
	China	Dfa, Cfa	RC	Recycle, reuse and remanufacture	Demolition, transportation and landfill	•	(-) 39%-46.93%		

CE: Carbon emissions; ECE: embodied carbon emission; OCE: operational carbon emissions; LCCE: life cycle carbon emissions; RC: reinforced concrete.

building envelope was well insulated. A cooler climate led to higher OCE owing to greater heating demand; however, differences in electricity and energy could sometimes mask the differences caused by climate. For example, the CEFs of electricity in Germany, Slovenia, and Spain were 0.406, 0.248, and 0.276 kgCO₂e/kWh, respectively, making the OCE in Munich (Germany) much higher than that in Ljubljana (Slovenia), although the energy consumption of the two cases was similar^[95].

Enhancement of carbon offset from module D through 3R of building materials and energy

The CE reduction benefits of module D among the reviewed cases ranged in 39.0%-100% (ECE) or 2%-3% (LCCE) together with other technology strategies [Table 5]. This requires technological support, such as waste recycling and scrapping. The study of a house with a bamboo structure showed that using building materials with renewable content reduces ECE by 18.5%, and the recycling of construction and demolition waste reduces ECE by 69.2%^[29]. A study of Palestinian houses showed that the ECE of traditional houses built with limestone and lime mortar was only 20.3% that of modern houses built with RC and concrete blocks^[43]. A study of three typical types of dwellings showed that recycling building materials at the end of their life reduces the LCCE by 3% for detached and semi-rural dwellings and by 2% for terraced houses^[92]. A case study in Belgium showed that the ECE of steel-frame houses was similar to that of masonry houses; however, when the recycling potential of steel is taken into account, the ECE associated with steel frameworks drops to 12% below that of masonry construction^[100,101].

STATUS, GAPS, AND RECOMMENDATIONS

Status and gaps

Calculation of LCCE

- *Calculation method.* Current evaluations of CE in rural housing predominantly rely on macro-level statistics. Consequently, the use of input-output (IO) analysis yields only average emission figures, failing to capture the specific variations between individual structures. This calculation model collects data from different sources (for example, different sectors) for integration, which might cause errors in the calculation owing to the inconsistent statistical methods of the source data. Few case studies are based on actual recorded data, and most were obtained based on calculations and simulations without verification.

The “bottom-up” process analysis (PA) presents the composition of building LCCE, which helps capture CE reduction hotspots. The IO approach cannot provide detailed information regarding the obtained results for methodological reasons. Recent research on Chinese educational facilities indicates that while the IO method is effective for broad estimations, the PA approach provides a more granular depiction of specific characteristics^[16]. Furthermore, an investigation into residential structures demonstrated that integrating PA with a hybrid framework successfully identifies 64% of carbon mitigation potential—a figure the IO method failed to capture. Consequently, the IO approach is generally deemed inadequate for conducting detailed assessments of individual buildings^[17].

- *Basic parameters.* The CEF database is based on the industrial sector rather than the construction sector, and the data are relatively coarse. A reliable database of CEFs for building materials has not been formed. Therefore, it was necessary to refer to CEFs from other databases, but as shown in Section "Uncertain CEF", CEF data from different sources significantly varied, which caused significant uncertainty in the calculation. Calculations based on such unreliable CEF data might result in incorrect conclusions. CEFs depend on a complex combination of local production technology, site-specific resource conditions, energy mix, and opaque databases, which might pose real threats to truly low-carbon development.

Reduction of LCCE

- *The singularity of the carbon reduction priorities in rural dwellings.* Current research primarily focuses on energy-saving technologies for the operational stage of buildings rather than those aimed at reducing ECE. Compared with other review studies, the statistical results of this study showed that the proportion of OCE in the LCCE of low-rise rural dwellings (66.1%) is significantly smaller than that reported by Huang et al.^[105] for 826 global building cases (75.2%). The study by Huang et al.^[26] showed that the OCE of a rural dwelling in southern China accounts for only 43.2% of the LCCE. The discrepancy may arise from the lower per-unit floor area energy demand with limited potential for further reduction. Consequently, there is restricted scope for optimizing the building envelope to achieve OCE reductions. Furthermore, the grid's carbon intensity is declining steadily due to the rapid expansion of renewable energy. It is anticipated that the impact of operational energy savings on mitigating building OCE will progressively diminish. Conversely, addressing ECE necessitates a heightened emphasis on curtailing material consumption and promoting the adoption of low-carbon alternatives.

- *Insufficient regulatory incentives aimed at promoting low-carbon construction structures.* According to the statistics in this study, the ECE of timber and bio-based structural buildings is significantly lower than that of concrete and masonry structures [Figure 3]. However, these two types of structural buildings account for only 27.8% of all cases, with a concentrated distribution in Europe (69.8% of timber and bio-based structural building cases are in Europe). The lack of such buildings in other regions can be attributed to both climatic factors and, in some areas, the absence of supportive policies for the development of timber structures.

Research recommendations

Technical recommendations

(1) Establishment of a localized database for building material CEF: Priority support should be given to cataloging typical rural building materials and establishing a reliable CEF database that accurately reflects the current state of local production technologies.

(2) Conducting fundamental research on material durability: Acquiring data on the durability and expected service life of various building materials under diverse rural operating conditions is critical for the accurate calculation of initial and recurring ECE.

(3) Accumulation of engineering case study data: Efforts should be made to investigate the demolition, waste disposal, and "3R" (Reduce, Reuse, Recycle) processes of typical rural residential structures. This will facilitate the accumulation of data for Modules C and D, providing a basis for scenario assumptions in future policy-making.

Policy recommendations

(1) Research and promotion of low-carbon structural systems: Policy frameworks should prioritize the research and development of structural systems based on locally sourced plant-based materials, such as fast-growing bamboo and cultivated fir. Key efforts must focus on improving their mechanical properties, physical characteristics, and fire resistance to accelerate the transition of these materials from theoretical research to practical engineering applications.

(2) Removal of policy barriers: To promote the adoption of low-carbon structural systems, it is essential to eliminate existing institutional barriers at the policy level. Simultaneously, upgrading related building material manufacturing technologies is required to stimulate green innovation vitality within the industry.

(3) Incentivizing the recycling of idle housing resources: Addressing the phenomenon of "constructing new houses without demolishing old ones", policies should be introduced to encourage the recycling and reuse of existing idle houses and waste building materials. By reducing the production and consumption of new materials through circular utilization, the ECE of rural dwellings can be effectively lowered.

(4) Aligning with clean energy trends: Policymakers should fully leverage the advantages of rural areas—specifically their low building density and high potential for renewable energy utilization (such as solar and wind power). Aligning with the trend of rapidly decreasing electricity CEFs, policies should vigorously promote the widespread adoption of clean energy in rural regions.

Standardization recommendations

(1) Formulation of specialized calculation and reporting standards: It is recommended that the competent authorities promulgate CE calculation standards specifically tailored for rural residential buildings. These standards should explicitly stipulate the system boundaries and the division of life cycle stages for the accounting process. In particular, the sources of basic parameters (such as CEFs for building materials) must be regulated to enhance the transparency and traceability of the data.

(2) Implementation of a "WRI 0-100" accounting mechanism: Given the current lack of conditions for precisely calculating carbon benefits in modules C and D, it is suggested that the "WRI 0-100" allocation method be introduced at the policy level^[109]. This approach allocates the accounting of recycling benefits (Module D) from the post-demolition stage to the pre-use stage of the next building life cycle. The carbon

reduction effect is calculated by evaluating the quantity of building materials manufactured from recycled content used in the construction. This value serves as the carbon credit for Module D. This method avoids calculation deviations caused by uncertainties in future demolition scenarios. For Module C, Stage C1 involves natural collapse and generates no CEs. The CEs from construction waste transportation in Stage C2 can be calculated using Equation $CE_{C2} = AD_{wei} \times CEF_{tran}$. Currently, there is a lack of data regarding the treatment and degradation processes of construction waste in Stages C3 and C4. Since most existing studies omit calculations for these stages, there is a lack of reliable data support.

Heterogeneous differences

The cases included in this review exhibit significant heterogeneity across multiple dimensions, which to some extent limits the direct comparability of results across studies. Specifically, this heterogeneity is primarily reflected in the following aspects.

In terms of contextual and technical parameters: The reviewed cases are located in different countries and climate zones. This variation directly affects building operational energy consumption and the CEF of electricity, thereby significantly impacting the comparability of OCE calculation results. For instance: for residential buildings with the same three-story masonry structure, the case investigated by Norouzi *et al.*^[77] is located in the UK (with an electricity CEF of 0.207 kgCO₂e/kWh), while the case studied by Huang *et al.*^[26] is in China (0.570 kgCO₂e/kWh). Despite the significant difference in electricity CEF between the two countries, and although the case in Norouzi *et al.*^[77] has a lower energy consumption than that in Huang *et al.*^[21], its OCE remain higher than the latter. On the other hand, differences in building types and structural systems fundamentally alter the consumption intensity of various materials, leading to different baselines for ECE. For instance, in this review, the median CE of steel-structured residential buildings during the A1-A3 stages is 305.6 kgCO₂/m², whereas that of timber-structured cases is only 113.0 kgCO₂/m².

In terms of methodology: First, the definition of system boundaries (e.g., whether Module D is included) directly determines the accumulation scope of CEs. Second, the lack of uniform functional units renders the horizontal comparison of absolute values meaningless; thus, units must be standardized before any comparison can be made. Finally, the selection of CEF databases (as previously discussed regarding regional differences and database sources) introduces systematic biases into the foundational data.

CONCLUSION

To characterize CEs in rural dwellings and develop effective mitigation strategies for low-carbon development. This study reviewed 90 studies with 309 cases of low-rise rural dwellings in Asia, Europe, North America, South America and Africa, with reference to the ISO 21930 standard. This study reviewed and analyzed the calculation methods and results of CEs across each life cycle stage of buildings, and summarized CE reduction strategies. On this basis, corresponding recommendations for the accurate calculation of LCCE and the advancement of CE reduction strategies were proposed.

Based on the reviewed dataset, the analysis suggested that the operation stage (B6) predominantly contributes to LCCE, with a median value of 792.0 kgCO₂e/m², which is approximately four times higher than that of the building material production stage (200.0 kgCO₂e/m²). The production stage (A1-A3) is the most frequently assessed stage (97.8% of cases), however, significant data gaps remain in the construction (A4-A5), maintenance (B1-B5), and end-of-life (C1-C4) stages, which were considered in fewer than 70% of the studies. It should be noted that the geographical distribution of the reviewed cases is heavily concentrated in Asia and Europe. Therefore, the observed dominance of OCE is primarily representative of the contexts covered in this review and may not be universally generalizable to all rural dwellings worldwide.

Our analysis revealed that structural typology and regional context are critical determinants of ECE. Masonry and concrete structures exhibit significantly higher ECE (359.92–362.50 kgCO₂e/m²) compared to wood structures (172.21 kgCO₂e/m²). The substantial variation in reported CEFs for materials like steel and cement across different studies highlights the urgent need for localized, reliable databases. Furthermore, the inconsistency in system boundaries and calculation methods—particularly regarding the exclusion of building equipment and water consumption in many studies—hinders accurate cross-regional comparisons.

In terms of decarbonization measures, suggestions were put forward for advancing standard low-carbon technologies. These encompass low-carbon structural frameworks, the reclamation and repurposing of materials from aging rural residences, high-efficiency electrical and lighting fixtures, as well as sustainable disposal techniques for derelict rural housing.

Despite these insights, this study has certain limitations. First, the regional coverage is insufficient. Building cases are predominantly concentrated in Asia and Europe, accounting for 93.8% of all cases, while there are relatively few cases from the Americas, Oceania, and Africa. Consequently, it is inadequate to generalize the CE characteristics of low-rise buildings in these regions. Second, data for certain structural types (composite structures, steel, and bio-based) are limited, which may lead to statistical limitations. Third, given that a significant proportion of rural buildings are existing rather than newly built, their carbon reduction strategies should differ from those for new constructions. However, the findings of this study are primarily applicable to new building scenarios; carbon reduction strategies specifically for existing buildings warrant further research. Finally, a limitation of this study lies in the disparity of sample sizes among structural types. The statistical findings for bio-based structures are based on a very limited sample ($n = 3$), and thus, these results should be considered preliminary. Similarly, steel and composite categories have smaller sample sizes compared to masonry and timber, which implies a wider confidence interval and lower statistical power for these specific groups. Future research will further strengthen the study of CEs in rural dwellings and promote their low-carbon and sustainable development.

DECLARATIONS

Authors' contribution

Writing - review & editing, validation, supervision, methodology, formal analysis, data curation, conceptualization: Huang, Z.

Methodology, investigation, formal analysis, data curation, conceptualization: Cheng, M.

Formal analysis, data curation: Zheng, Y.

Availability of data and materials

Not applicable.

AI and AI-assisted tools statement

Not applicable.

Financial support and sponsorship

The research has been supported by the National Natural Science Foundation of China (52278020), the State Key Laboratory of Subtropical Building and Urban Science (2023ZB07), and the Fundamental Research Funds for the Central Universities (2024ZYGXZR081).

Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent participate

Not applicable.

Consent for publication

Not applicable.

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Supplementary Materials

[Supplementary Materials](#)

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