Dynamic multi-factor approach for deriving embodied carbon limit of building structures: Methodology and application in China

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Abstract: Establishing scientifically grounded embodied carbon limits is essential for guiding low-carbon structural design and translating macro-level decarbonization targets into actionable regulatory parameters. Here we propose a dynamic, multi-factor methodology for deriving embodied carbon limits of building structures, accounting for evolving carbon budgets and shifts in their allocation to embodied carbon-related activities in regions with a transitioning construction sector. This methodology integrates top-down budget decomposition with bottom-up benchmarking to respectively determine upper and lower bounds of embodied carbon limits for new construction, renovation, and maintenance. Furthermore, multi-factor adjustments are introduced to customize limits according to building type, regulatory stringency, regional conditions, and lifecycle design requirements. The proposed methodology is demonstrated through an analysis of urban residential building structures in China from 2026 to 2060, which reveals a declining trend in embodied carbon limits over time, and provides reasonable limit ranges corresponding to China's Five-Year Plans (FYPs), e.g., 320.8–360.8 kg CO_2/m^2 for new construction, 0.90–1.02 kg $CO_2/(m^2 \cdot year)$ for maintenance, and 56.3–63.0 kg CO_2/m^2 for renovation during the 2026–30 FYP. The analysis also highlights the benefits of construction management in providing a buffer period for limit relaxation, examines the impact of regional disparities on carbon mitigation feasibility-based adjustments, and offers recommendations for low-carbon lifecycle design to ensure compliance with mitigation targets while providing further design flexibility.

Keywords: Low-carbon structural design; Embodied carbon limit; Top-down decomposition; Bottom-up benchmarking; Feasibility adjustments; Lifecycle design

Nomenclature

Abbreviations

BAU	Business as usual
BFS	Building floor space
BIPV	Building-integrated photovoltaics
CV	Coefficient of variation
FYP	Five-year plan
GDP	Gross domestic product
HVAC	Heating ventilation and air conditioning
HVR	Housing vacancy rate
RN-D	Renovation and demolition restriction
RVR-D	Combined implementation of HVR reduction, renovation and demolition restriction
SSP	Shared socioeconomic pathway
URB	Urban residential building
VR	HVR reduction

Symbols

A	Cumulative BFS of occupied buildings during a time interval
A_0	Annual BFS of occupied buildings
ΔA	Incremental BFS demand for occupied buildings
A_B	BFS of occupied buildings in the year of benchmarking
ΔA_B	BFS of newly completed buildings in the year of benchmarking
ΔA_r	Planned BFS of renovation
B_c	Carbon intensity benchmark for new construction
B_m	Carbon intensity benchmark for a single maintenance action
B_{m0}	Average annual carbon intensity benchmark for maintenance
B_r	Carbon intensity benchmark for renovation
C_C	Collective carbon budget for building structures
C_G	Global carbon budget
C_N	National carbon budget
C_{NB}	National carbon emissions in the year of carbon emission benchmarking
E	Embodied carbon of a proposed design
L	Embodied carbon limit
L_c	Embodied carbon limit for new construction
L_{LC}	Lifecycle embodied carbon limit for building structure
L_m	Embodied carbon limit for a single maintenance action
L_{m0}	Average annual embodied carbon limit for maintenance
L_r	Embodied carbon limit for renovation
N_r	Number of regions divided for analysis of differentiated embodied carbon limits
N_y	Number of years for a time interval
P^C	China's population
P^G	Global population
R	BFS of buildings planned to be renovated
S_o	Annual saving of operational carbon compared to conventional practice
T_d	Designed structural service life
T_m	Average maintenance cycle
T_r	Average age of buildings to be renovated
Y_0	The year since which buildings completed are available for renovation
Y_d	Year of structural design
Y^e	End year of a time interval

Y^s	Start year of a time interval
a_j	Ratio of the mean carbon intensity benchmark of new construction in the j^{th} region to the nationwide mean benchmark
p	Uniform probability of keeping structural embodied carbon below the limit across regions
$r_{B,j}$	Proportion of newly completed urbs in the j^{th} region to the national total in the year of benchmarking
$r_{i,j}$	The share of planned new construction in the j^{th} region relative to the total planned construction across all analyzed regions during the time interval i
r_n	Ratio of ΔA to A
r_r	Ratio of ΔA_r to ΔA
α_m	Ratio of the average annual carbon intensity of maintenance to the carbon intensity of construction
α_r	Ratio of carbon intensities of renovation to new construction
β_b	The status-quo share of embodied carbon from building structures in national annual carbon emissions
γ_L	Regulation-level factor
γ_R	Regional adjustment factor
λ_f	Coefficient characterizing feasibility disparities in reducing embodied carbon of new construction across regions
λ_m	Relative carbon intensity compared to the national average value due to the changes in construction proportions across various regions

Subscripts

i	Counter for future time interval during which the annual carbon budget and embodied carbon limits are identical
j	Counter for regions divided for analysis of differentiated embodied carbon limits
k	The specific year corresponding to the embodied carbon limit under analysis
q	Year of completion for the buildings analyzed for renovation
$I(k)$	Counter for the time interval corresponding to the year k

1. Introduction

The imperative to mitigate carbon emissions has emerged as a cornerstone of global sustainable development efforts. In 2023, the building and construction sector was responsible for 39% of global energy-related carbon emissions [1], while in China, this proportion reached 48.3% in 2022 [2]. Though operational carbon currently dominates the carbon footprint of buildings, embodied carbon—associated with material production, construction, and maintenance—presents a more formidable challenge for reduction due to the relatively slow pace of technological advancements in these areas [3]. Moreover, the embodied carbon inherently from chemical reactions during material production further complicates efforts to achieve carbon neutrality in the construction sector [4]. Early-stage interventions, particularly through structural design optimization with low carbon as an objective, have been identified as a critical

lever for regulating embodied carbon [5]. However, the absence of scientifically grounded quantitative embodied carbon limit, especially in China, poses a significant barrier to aligning structural design practices with overarching carbon neutrality objectives.

Existing research attempted to derive carbon emission limit of buildings through top-down and bottom-up approaches. Top-down approaches typically decompose global carbon budget first to nation-specific budget, then to construction sector, and ultimately to individual buildings, where the grandfathering principle that bases budget allocations on current sectoral shares is mostly adopted [6, 7]. Bottom-up approaches, on the other hand, derive the limit based on benchmark values of existing construction cases and carbon intensity reduction targets [8, 9] or best low-carbon practices [10]. Additionally, Hollberg et al. [10] have combined top-down and bottom-up information to plan a dual verification, where the former defines carbon reduction targets and the latter focuses on the feasibility of carbon reduction.

While these existing methods provide foundational insights, they often rely on static assumptions, such as fixed sectoral shares in national carbon budgets and a uniform carbon limit for the same building type nationwide [6]. However, these assumptions are ill-suited to the dynamic and heterogeneous context of construction sector in developing countries with large territories, represented by China, which present temporal and spatial complexities that necessitate a more nuanced approach to embodied carbon regulation. Temporally, China's construction boom over the past two decades has resulted in a disproportionately high share of carbon emissions [2]. As construction demand declines with the population decrease and urbanization plateau [11, 12], budget allocation based on such a high share may undermine the construction sector's responsibility in carbon reduction. Furthermore, the transition of China's construction sector from large-scale construction to urban renewal requires distinct embodied carbon limits for new construction and renovation to balance their emissions. Spatially, China's vast geographic and developmental disparities contrast sharply with those of other countries focused on by relevant studies, such as Switzerland [10] and New Zealand [6], and regional variations in construction technology, energy dependency, and manufacturing carbon intensity render nationwide uniform carbon limit impractical and inequitable for China. Additionally, considering uneven decarbonization rates of embodied and operational carbon of buildings, Hollberg et al. [10] have set separate limits for embodied

and operational carbon with a fixed budget allocation, where a larger allowable proportion was specified for embodied carbon, reflecting its greater reduction difficulty. However, emerging low-carbon building technologies may achieve operational carbon reduction at the expense of increased embodied carbon during initial construction [13], which makes it necessary to establish a flexible trade-off relationship between embodied and operational carbon specific to the designed building lifecycle to provide a more adaptive approach for carbon emission management.

To address the above issues, this paper proposes a multi-factor dynamic approach for deriving embodied carbon limit of building structures focusing on two key points: (1) integrating top-down decomposition and bottom-up benchmarking to project the dynamic upper and lower bounds of embodied carbon limit based on the national carbon mitigation roadmap and building stock dynamics (**Section 2**); (2) incorporating adjustment factors of embodied carbon limit accounting for building type, carbon regulation level, regional disparities, and tradeoffs within the life cycle of a designed individual structure (**Section 3**). Then, the feasibility of the proposed approach will be demonstrated through an illustrative analysis in the context of China (**Section 4**), which aims to provide scientifically robust, regionally sensitive, and dynamically adaptable embodied carbon limit, thereby enabling low-carbon structural design and advancing China's carbon neutrality goals (**Fig. 1**).

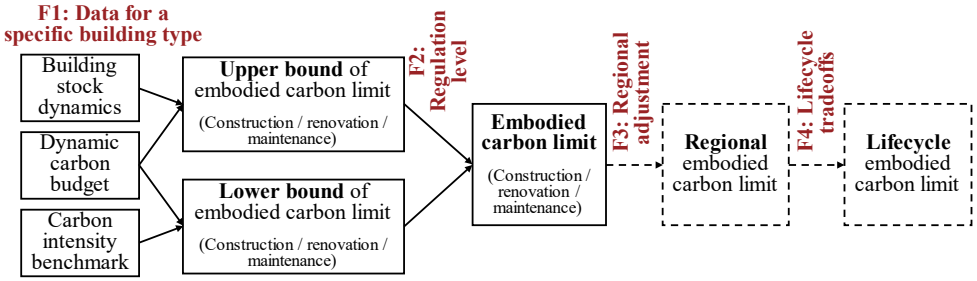


Fig. 1. Framework of dynamic multi-factor approach for deriving embodied carbon limit of building structures. **Note:** F1–F4 denote the four adjustment factors to be proposed; the dashed lines and boxes imply the optional steps according to the data availability or design requirement.

2 Dynamic bounds for embodied carbon limit

2.1 Scope of embodied carbon limit

The embodied carbon limit serves as a verification criterion for low-carbon structural design, indicating the extent to which structural embodied carbon needs to be reduced to qualify as low-carbon. Specifically, it defines the maximum allowable embodied carbon for building structures to meet both

usage demands and carbon reduction targets from a macro perspective. In standard practice of low-carbon structural design, the embodied carbon (E) of a proposed design is assessed and compared against the predetermined embodied carbon limit (L), with the objective of ensuring that $E \leq L$, or that the probability of $E \leq L$ is sufficiently high, thereby ensuring that structural designs align with macro-level carbon reduction targets. This study is exclusively concerned with the determination of embodied carbon limits, which is based on unit building floor space (BFS), in line with the approach adopted by most existing studies [6, 7, 14, 15]. The assessment or optimization of specific low-carbon structural designs falls outside the scope of this study.

Ensuring the safe service of building structures requires coordinated efforts across multiple sectors, e.g., the production of building materials in the manufacturing sector, the transportation of materials and products in the transportation sector, the construction activities in the construction sector, etc. [16] The embodied carbon associated with structural lifecycles, although originating from various sectors, can be collectively regulated through changes in design parameters in structural design. Since the embodied carbon limit is intended to guide carbon regulation in structural design, at the sector level, we define the collective carbon budget, which is an intermediate variable for deriving the embodied carbon limit, specifically as the holistic limit for embodied carbon linked to the lifecycle processes of overall building demands, rather than adopting a definition based on economic sectors.

Meanwhile, for an individual building structure, its lifecycle carbon budget is shared by various stages, which can be categorized by purpose into initial construction and subsequent maintenance activities. Additionally, with the promotion of the circular economy and sustainable technologies, the renovation of existing buildings is expected to become an increasingly significant means of meeting new building demand, replacing new construction [17]. Therefore, we distinguish embodied carbon limits for construction, renovation, and maintenance, given the substantial differences in their conditions, objectives, and embodied carbon characteristics. The combination of limits for construction/renovation and maintenance can then be applied to structural lifecycle design (see **Section 3.4**).

Unlike conventional cradle-to-gate life cycle assessments, which separately analyze end-of-life and recycling processes (e.g., EN 15804 [18]), we propose integrating the embodied carbon from demolition

and recycling into their subsequent construction, renovation, or maintenance stages for calculation and verification. This approach is justified by:

(1) In urbanized areas, especially where low-carbon design is prioritized, construction often involves demolishing existing structures rather than developing greenfield sites. Since most demolished old structures were built without carbon management, attributing real-world demolition emissions to current projects ensures these emissions are properly accounted for and regulated.

(2) Isolating end-of-life embodied carbon disrupts integrated decision-making between demolition and reconstruction, particularly regarding recycled materials [19].

(3) Conventional life cycle assessments project demolition far into the future, making accurate estimation difficult due to evolving technologies and management. Adjusting the structural lifecycle to span from prior demolition to the end of service of the designed structure enables more effective carbon management under current regulations.

(4) End-of-life embodied carbon represents a small fraction of total lifecycle emissions [20], and the end-of-life processes of existing structures required for renovation differ markedly from those for traditional construction. Establishing separate limits for the end-of-life stage could unnecessarily complicate low-carbon design verification.

The decomposition of global/national decarbonization targets into structural embodied carbon limits is critically contingent upon effort-sharing principles [14, 21]. To establish scientifically robust thresholds, we first evaluate their theoretical upper and lower bounds through top-down and bottom-up analytical frameworks. These bounds subsequently inform the determination of context-specific embodied carbon limit for low-carbon structural design, calibrated to the construction sector's carbon regulation stringency (**Section 3.1**).

2.2 Embodied carbon limits for renovation and maintenance

To ensure scenario consistency in the generation and application of embodied carbon limits across different activities, this study formulates the limits for renovation and maintenance activities using conversion parameters relative to the limit for new construction.

The ratio of carbon intensities of renovation to new construction during the time interval i ($\alpha_{r,i}$) is

defined to characterize the typical carbon emission level of renovation. Due to the limited carbon emission data for emerging building renovation practices, setting this ratio based on benchmarks is challenging. According to Gao et al. [22], based on a review of carbon emissions from building refurbishment, the expected ratio of carbon emissions from refurbishment to those from material production, transportation and construction was assumed to be proportional to the designed service life of the building, with a coefficient of 0.5% per year. This study adopts this assumption and uses the average age of renovated buildings as a proxy to replace the aforementioned designed service life. In this way, the coefficient $\alpha_{r,i}$ is calculated by,

$$\alpha_{r,i} = \frac{\sum_{k=Y_i^s}^{Y_i^e} \alpha_{r,k} R_k}{\sum_{k=Y_i^s}^{Y_i^e} R_k}; \quad \alpha_{r,k} = 0.5\% \cdot T_{r,k}; \quad T_{r,k} = \frac{\sum_{q=Y_0}^{k-1} (k-q) \cdot R_{k,q}}{R_k} \tag{1}$$

where $\alpha_{r,k}$ is the ratio of carbon intensities of renovation to new construction in the year k, and R_k is the estimated total BFS of buildings renovated in the year k; Y_i^s and Y_i^e are the start and end year of the time interval i, respectively; $T_{r,k}$ is the average age of buildings renovated in the year k; $R_{k,q}$ is the estimated BFS of buildings completed in the year q and renovated in the year k; Y_0 is the year since which buildings completed are available for renovation. The coefficient $\alpha_{r,i}$ enables the derivation of the embodied carbon limit for renovation per unit BFS ($L_{r,i}$) from that for new construction per unit BFS ($L_{c,i}$), i.e.,

$$L_{r,i} = \alpha_{r,i} L_{c,i} \tag{2}$$

Our previous study [17] has justified that such estimations tend to overestimate the carbon emissions of renovation projects, which may further lead to relatively high embodied carbon limit for renovation. Nevertheless, this could make the design of renovation projects more feasible, encouraging greater adoption of this resource-efficient, low-carbon way of supplying new buildings.

Regarding maintenance activities, there are significant individual differences among occupied building structures, such as variations in completion years and material types. Consequently, the timing and frequency of maintenance—which involves interventions with various materials and equipment—can be intricate [23]. Even for the same structural design, different design schemes may result in different maintenance schedules. Determining embodied carbon limit based on the specific maintenance

schedules would require iterative updates between the design scheme and the embodied carbon limit, unnecessarily complicating the low-carbon structural design process. This is especially true given that the timing of maintenance is inherently uncertain and may be performed as needed rather than strictly following a predetermined schedule.

The embodied carbon limit is intended to be applied at a broad scale, where a large number of different building structures undergo various maintenance activities each year, and the annual maintenance-related carbon emissions of the building stock do not exhibit the pronounced fluctuations seen in single-building analyses. Therefore, from the perspective of fairness in carbon reduction among structures, we propose specifying the same maintenance carbon emission limit for all occupied structures each year. This establishes the average annual embodied carbon limit for maintenance (i.e., $L_{\mathrm{m0},i}$ for occupied building structures within time interval i; unit: kg $CO_2/(m^2 \cdot year)$] as a characteristic value for constraining maintenance emissions, as defined by:

$$L_{\mathrm{m0},i} = \frac{L_{\mathrm{m},i}}{T_{\mathrm{m},i}} = \frac{L_{\mathrm{m},i}}{L_{\mathrm{c},i} T_{\mathrm{m},i}} \cdot L_{\mathrm{c},i} = \alpha_{\mathrm{m},i} \cdot L_{\mathrm{c},i} \tag{3}$$

where $L_{\mathrm{m},i}$ is the embodied carbon limit (unit: kg CO_2/m^2) for a single maintenance action during the time interval i; $T_{\mathrm{m},i}$ is the average maintenance cycle (unit: year) during the time interval i; $\alpha_{\mathrm{m},i}$ is the ratio of the average annual carbon intensity of maintenance to the carbon intensity of construction (unit: $year^{-1}$) during the time interval i, which can be estimated as:

$$\alpha_{\mathrm{m},i} \approx \frac{\overline{B}_{\mathrm{m},i}}{\overline{B}_{\mathrm{c},i} T_{\mathrm{m},i}} \tag{4}$$

where $\overline{B}_{\mathrm{m},i}$ and $\overline{B}_{\mathrm{c},i}$ represent the mean carbon intensity benchmarks for maintenance and construction, respectively (unit: kg CO_2/m^2), which are referenced in determining embodied carbon limits during time interval i. This defined limit $L_{\mathrm{m0},i}$ facilitates top-down decomposition of carbon budget (**Section 2.3**) and can be conveniently used to generate the lifecycle embodied carbon limit for individual structures based on the specified design service life (**Section 3.4**), as well as the maintenance embodied carbon limit when the actual maintenance cycle is known (**Section 5.1**).

2.3 Top-down decomposition – upper bound

To translate the macro-level carbon budget into regulatory limit in low-carbon structural design, we propose a two-level top-down decomposition approach, which accounts for disparities across different sectors or activities.

The first level decomposes the national carbon budget into the collective budget of building structures defined in **Section 2.1**. In the absence of officially released, sector-specific carbon budgets for construction in many countries/regions, the grandfathering principle, which is commonly used in developed countries to allocate carbon budgets based on historical/current shares [6, 7], is adopted for reference. The collective carbon budget is subsequently calculated by,

$$C_{\mathrm{C},i} = \beta_{\mathrm{b}} \cdot C_{\mathrm{N},i} \tag{5}$$

where $C_{\mathrm{N},i}$ and $C_{\mathrm{C},i}$ are respectively the national carbon budget and the collective carbon budget for building structures during the same time interval i; β_{b} represents the status-quo share of embodied carbon from building structures in national annual carbon emissions. Against the backdrop of shrinking construction demands, e.g. the transitioning construction sector in China [24], the grandfathering principle would provide an upper bound, rather than an appropriate value, for the collective carbon budget of building structures.

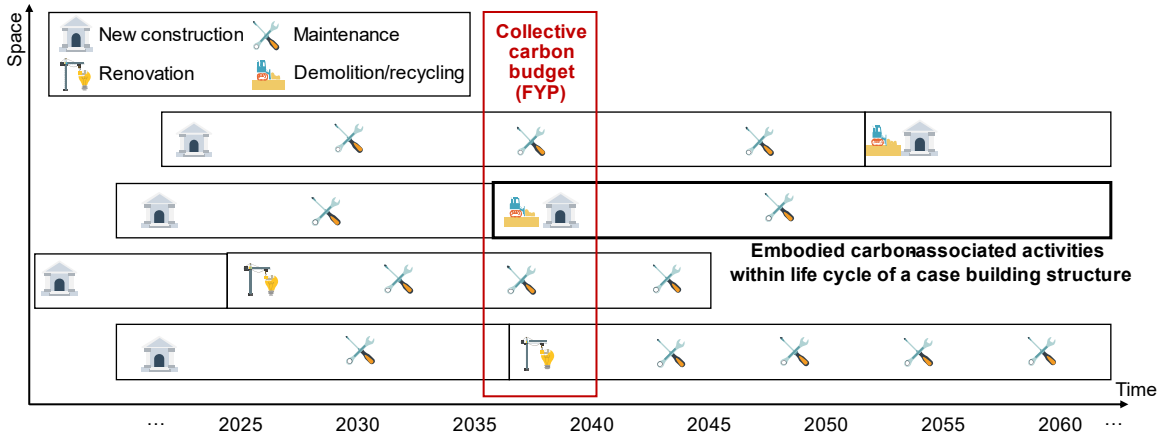


Fig. 2. Temporal and spatial mismatch between the collective carbon budget and the lifecycle embodied carbon of different case building structures (adapted from Habert et al. [14]). **Note:** FYP denotes a Five-Year Plan; when urban renewal becomes the dominant paradigm of construction sector, the beginning of a building life cycle can be considered as the demolition/recycling of old buildings, as per our previous study [19].

The second level breaks down the collective carbon budget at the sector level into embodied carbon limits for individual structures. Embodied carbon from construction or renovation are typically

concentrated within a few years and usually occur immediately after design (**Fig. 2**). Therefore, the embodied carbon limit of construction/renovation for low-carbon structural design can be directly derived from the collective carbon budget corresponding to the time interval in which construction or renovation takes place. Within the time interval i, the ratio of the share of the collective carbon budget allocated to renovation versus the share allocated to new construction is:

$$\frac{L_{\mathrm{r},i}\cdot\Delta A_{\mathrm{r},i}}{L_{\mathrm{c},i}\cdot\left(\Delta A_i-\Delta A_{\mathrm{r},i}\right)}=\frac{L_{\mathrm{r},i}\cdot r_{\mathrm{r},i}\Delta A_i}{L_{\mathrm{c},i}\cdot\left(1-r_{\mathrm{r},i}\right)\Delta A_i}=\frac{\alpha_{\mathrm{r},i}r_{\mathrm{r},i}}{1-r_{\mathrm{r},i}} \tag{6}$$

where $r_{\mathrm{r},i}$ is the proportion of planned BFS of renovation ($\Delta A_{\mathrm{r},i}$) in the incremental BFS demand for occupied buildings (ΔA_i) during the time interval i, i.e., $r_{\mathrm{r},i} = \Delta A_{\mathrm{r},i} / \Delta A_i$.

In contrast, maintenance emissions may occur at multiple time points across extended periods, creating a challenge in estimating the quantity of maintenance activities that fall within a specific time interval of collective carbon budget. Since collective carbon budgets focus on the spatial aggregation of allowable emissions across multiple structures over short-term periods (e.g., annually or every five years), whereas embodied carbon limits address the temporal accumulation of emissions over a decade-long structural lifecycle (as illustrated in **Fig. 2**), it is difficult to determine how much of the collective carbon budget should be allocated to the embodied carbon limit for maintenance. To address this issue, we introduce the following assumption: the proportion of occupied building structures requiring maintenance each year is considered equivalent to the average annual structural maintenance frequency. Accordingly, within the time interval i, the ratio of the share of the collective carbon budget allocated to maintenance versus the share allocated to new construction is:

$$\frac{L_{\mathrm{m},i}\cdot\sum_{k=Y_i^{\mathrm{s}}}^{Y_i^{\mathrm{e}}}\left(A_{0,k}\cdot\frac{1}{T_{\mathrm{m},i}}\right)}{L_{\mathrm{c},i}\cdot\left(1-r_{\mathrm{r},i}\right)\Delta A_i}=\frac{L_{\mathrm{m},i}}{L_{\mathrm{c},i}T_{\mathrm{m},i}}\cdot\frac{A_i}{\Delta A_i}\cdot\frac{1}{\left(1-r_{\mathrm{r},i}\right)}=\alpha_{\mathrm{m},i}\cdot\frac{1}{r_{\mathrm{n},i}}\cdot\frac{1}{\left(1-r_{\mathrm{r},i}\right)}=\frac{\alpha_{\mathrm{m},i}}{r_{\mathrm{n},i}\left(1-r_{\mathrm{r},i}\right)} \tag{7}$$

where $A_{0,k}$ is the annual BFS of occupied buildings in year k within the time interval i, estimated based on building stock dynamics; A_i is the cumulative BFS of occupied buildings within the time interval i; $r_{\mathrm{n},i}$ is the ratio of incremental BFS demand (ΔA_i) to the cumulative BFS of occupied buildings (A_i) within the time interval i, calculated as $r_{\mathrm{n},i} = \Delta A_i / A_i$.

Then, the annual collective carbon budget can be decomposed into the three primary activities in

261 construction sector, i.e., new construction, renovation and maintenance, expressed by,

262 $$C_{\mathrm{C},i} = L^{\mathrm{U}}_{\mathrm{c},i} \cdot \left(1 - r_{\mathrm{r},i}\right) \Delta A_i \cdot \left[1 + \frac{\alpha_{\mathrm{r},i} r_{\mathrm{r},i}}{1 - r_{\mathrm{r},i}} + \frac{\alpha_{\mathrm{m},i}}{r_{\mathrm{n},i}\left(1 - r_{\mathrm{r},i}\right)}\right] = \left[\left(1 - r_{\mathrm{r},i}\right) r_{\mathrm{n},i} + r_{\mathrm{r},i} r_{\mathrm{n},i} \alpha_{\mathrm{r},i} + \alpha_{\mathrm{m},i}\right] \cdot A_i \cdot L^{\mathrm{U}}_{\mathrm{c},i} \quad (8)$$

263 where $L^{\mathrm{U}}{}_{\mathrm{c},i}$ represents the upper bound of embodied carbon limit for new construction per unit BFS
264 during the time interval *i*, calculated by,

265 $$L^{\mathrm{U}}_{\mathrm{c},i} = \frac{C_{\mathrm{C},i}}{\left[\left(1 - r_{\mathrm{r},i}\right) r_{\mathrm{n},i} + r_{\mathrm{r},i} r_{\mathrm{n},i} \alpha_{\mathrm{r},i} + \alpha_{\mathrm{m},i}\right] \cdot A_i} \quad (9)$$

266 Based on the value of $L^{\mathrm{U}}{}_{\mathrm{c},i}$, the upper bounds of embodied carbon limits for renovation ($L^{\mathrm{U}}{}_{\mathrm{r},i}$) and
267 maintenance ($L^{\mathrm{U}}{}_{\mathrm{m0},i}$) can be derived using **Eqs. (2)&(3)**.

268 It should be noted that although the global carbon budget until carbon neutrality is achieved is widely
269 referenced in research [25], setting a uniform embodied carbon limit for structural design over such a
270 long period would make the short-term limit control hard to achieve while potentially leaving
271 excessively loose limits for future reductions, given the anticipated technological advancements. The
272 practice in the UK, and likely in China, of setting national carbon budgets on a five-year cycle alleviates
273 this issue [26, 27]. By focusing on short time intervals, the derived embodied carbon limit becomes
274 more representative, owing to smaller technological fluctuations, ensuring that embodied carbon limits
275 remain aligned with evolving policies and societal transformation pathways.

276

277 **2.4 Bottom-up benchmarking – lower bound**

278 The bottom-up approach derives embodied carbon limits by discounting current carbon intensity
279 benchmarks according to targeted carbon intensity reduction ratios [9]. However, sector-specific carbon
280 reduction targets for building structures remain absent in most regions. Building construction is
281 inherently carbon-intensive—in China, for example, carbon emissions from building construction
282 accounted for 26.6% of the country's total carbon emissions in 2022 [2], significantly exceeding the
283 combined value-added contribution of the construction and real estate sectors to GDP (12.8% [24]).
284 Moreover, the decarbonization rate of building construction is generally expected to be slower than the
285 societal average [28]. Therefore, aligning the reduction rate of embodied carbon intensity (using mean

carbon intensity benchmarks as the average-level regulatory reference [29]) with the targeted national carbon budget reduction rate provides a lower bound for embodied carbon limits, with the value for new construction given by:

$$L^{\mathrm{L}}_{\mathrm{c},i} = \overline{B}_{\mathrm{c},i} \cdot \frac{C_{\mathrm{N},i} / N_{\mathrm{y},i}}{C_{\mathrm{NB},i}} \tag{10}$$

where $L^{\mathrm{L}}{}_{\mathrm{c},i}$ is the lower bound of embodied carbon limit for new construction per unit BFS during the time interval i; N_i is the number of years for the time interval i; $C_{\mathrm{NB},i}$ represents the national carbon emissions in the year of carbon intensity benchmarking for $\overline{B}_{\mathrm{c},i}$.

Based on the value of $L^{\mathrm{L}}{}_{\mathrm{c},i}$, the lower bounds of embodied carbon limits for renovation ($L^{\mathrm{L}}{}_{\mathrm{r},i}$) and maintenance ($L^{\mathrm{L}}{}_{\mathrm{m0},i}$) can be derived using **Eqs. (2)&(3)**. The lower bound of the embodied carbon limits presented here reflects the minimum estimate of allowable average carbon intensity for structures within a group, but not the minimum achievable carbon intensity for any individual low-carbon structural design case.

3 Multi-factor adjustments for embodied carbon limit

3.1 Building type-specific embodied carbon limit

Disparities in socioeconomic development can lead to varying demands for different building types, such as urban residential, rural residential, and public buildings, as noted in [28, 30, 31]. Additionally, the carbon intensities associated with the construction/maintenance of these building types also vary significantly [2, 28]. Given these differences, instead of applying a uniform embodied carbon limit across all building types, it is advisable to incorporate building type-specific parameters or benchmarks when determining embodied carbon limit, based on the approach we proposed earlier.

It should be noted that the classification of building types concerned here corresponds to different usage needs and is demand-driven. Differentiated embodied carbon limits across structural types (such as concrete, steel, or hybrid structures) are not imperative, as optimal structural types can be adaptively selected through low-carbon structural design to comply with the embodied carbon limit for the specified building type of demand.

3.2 Carbon regulation level for construction sector

As illustrated by **Eq. (5)**, given the national carbon budget, modifying β_b allows for adjusting the regulation level of embodied carbon of buildings relative to other sectors/activities. In **Section 2**, the upper bound is derived under the assumption that β_b remains unchanged at its current/historical value, while for the lower bound, the construction sector's share in the carbon budget inherently decreases in proportion to the changes in demands of construction or maintenance activities. Thereby, by allowing β_b to vary between these two assumptions, the embodied carbon limit can be adjusted between its upper and lower bounds. For simplified tuning, a regulation-level factor (γ_L) is proposed to derive embodied carbon limit that interpolates between its upper and lower bounds, i.e.,

$$L_{c,i} = \gamma_L L^U_{c,i} + (1-\gamma_L) L^L_{c,i} \tag{11}$$

Then, the embodied carbon limits for renovation ($L_{r,i}$) and maintenance ($L_{m0,i}$) can also be derived using **Eqs. (2)&(3)**. This flexible adjustment ensures that the carbon emission targets for the construction sector remain adaptable to both national carbon mitigation goals and the specific regulation level of the construction sector. A special case arises when the value of $L^U_{c,i}$ obtained from **Eq. (9)** is lower than $L^L_{c,i}$ from **Eq. (10)**, indicating a growing demand for new construction. In such cases, β_b should be redetermined with a comprehensive assessment of local development needs rather than following the grandfathering-based approach.

3.3 Adjustments accounting for regional disparities

Due to uneven regional development, significant disparities exist in construction technology levels, energy dependency, and carbon intensity in manufacturing supply chains [14, 32, 33]. These disparities result in varying carbon intensity benchmarks and divergent feasibility in achieving carbon reduction targets. While setting region-specific limits based on localized data (as outlined in **Section 3.1**) remains a viable approach, it is critical to recognize that spatial and typological variations in embodied carbon intensity distributions—modeled here as probabilistic variables—may lead to disparate feasibility in achieving the same carbon emission level. By using benchmark percentiles representing optimal low-carbon practices, feasibility-related information can be integrated into analysis to address this

heterogeneity [10].

Thereby, we propose the following regional adjustment approach to derive region-specific embodied carbon limits based on the national average limit. Firstly, a uniform probability of keeping structural embodied carbon below the limit is assumed for each region. Then, the average carbon intensity derived from the combination of all analyzed regions is calibrated to align with the national average embodied carbon limit. Taking the embodied carbon limit for new construction as an example, the mentioned uniform probability (p) is determined by solving the following equation,

$$L_{c,i} = \sum_{j=1}^{N_r} r_{i,j} F_{B_{c,j}}^{-1}(p) \tag{12}$$

where N_r represents the number of regions divided for analysis of differentiated embodied carbon limits; $r_{i,j}$ denotes the share of planned new construction in the j^{th} region relative to the total planned construction across all analyzed regions during the time interval i; $B_{c,j}$ is the random variable representing the carbon intensity benchmark for new construction in the j^{th} region, and $F_{B_{c,j}}^{-1}(p)$ is its inverse cumulative probability function. The solved value of p also represents the percentage of construction practices that satisfy the embodied carbon limit. Then, the regional adjustment factor for the j^{th} region during the time interval i ($\gamma_{R,i,j}$) is evaluated by,

$$\gamma_{R,i,j} = F_{B_{c,j}}^{-1}(p) / L_{c,i} \tag{13}$$

while the corresponding embodied carbon limit for new construction in the j^{th} region during the time interval i ($L_{c,i,j}$) is calculated by,

$$L_{c,i,j} = \gamma_{R,i,j} L_{c,i} \tag{14}$$

The above approach also applies to the adjustment of regional embodied carbon limits for renovation or maintenance (i.e., $L_{r,i,j}$ and $L_{m0,i,j}$), when the carbon intensity benchmarks in **Eqs. (12)&(13)** are changed to those for renovation or maintenance (B_r, B_{m0}).

3.4 Tradeoffs within life cycle of individual structures

The annual embodied carbon limits for new construction, renovation, and maintenance of building structures derived above can serve as benchmarks for carbon emissions in corresponding activities

within specified time intervals (typically 5-year-long). Even for activities spanning different time intervals, the average limit over the activity period or the stricter limit at the end year of the activity can be applied. However, the separate verifications of construction/renovation and maintenance for an individual structure may limit the flexibility of carbon reduction strategies across the life cycle of a structure.

Emerging integrated lifecycle design of structures renders the interactions among the embodied carbon of construction/renovation and maintenance activities, as well as the operational carbon, increasingly relevant. For instance, durability improvement designs may use high-durability but intensive-carbon-emission materials during construction/renovation to reduce future maintenance needs [34]. Besides, structure-function integrated design approaches, such as insulated structural wall panels [35], passive building systems [36], building-integrated photovoltaics (BIPV) [37], and optimized heating ventilation and air conditioning (HVAC) design [13] may increase embodied carbon during construction/renovation but significantly reduce operational energy use. Such tradeoffs are particularly relevant in the context of building renovation, where energy-efficient retrofits with additional carbon emissions play a critical role in avoiding carbon lock-in during operation [38]. These cases could reduce lifecycle carbon emissions at the expense of increased construction/renovation carbon emissions. Thereby, to promote forward-looking lifecycle carbon reduction, low-carbon structural design needs to allow flexibility in adjusting embodied carbon across multiple stages and coordinating it with operational carbon [13]. Such tradeoffs are feasible to align with the control of total carbon budget, and the lifecycle embodied carbon limit for an individual structure is determined by,

$$\begin{cases} L_{\mathrm{LC},i,j} = L_{\mathrm{c},i,j} + \sum_{k=Y_\mathrm{d}}^{Y_\mathrm{d}+T_\mathrm{d}} \left(L_{\mathrm{m0},I(k),j} + S_{\mathrm{o},k} \right) & \text{for new construction} \\ L_{\mathrm{LC},i,j} = L_{\mathrm{r},i,j} + \sum_{k=Y_\mathrm{d}}^{Y_\mathrm{d}+T_\mathrm{d}} \left(L_{\mathrm{m0},I(k),j} + S_{\mathrm{o},k} \right) & \text{for renovation} \end{cases} \tag{15}$$

where $L_{\mathrm{LC},i,j}$ is the lifecycle embodied carbon limit for the building structure in the j^{th} region designed during the time interval i; Y_d is the year of structural design, and T_d is the designed structural service life; $I(k)$ represent the time interval corresponding to the year k; $S_{\mathrm{o},k}$ is the annual saving of operational carbon compared to conventional practice in the year k.

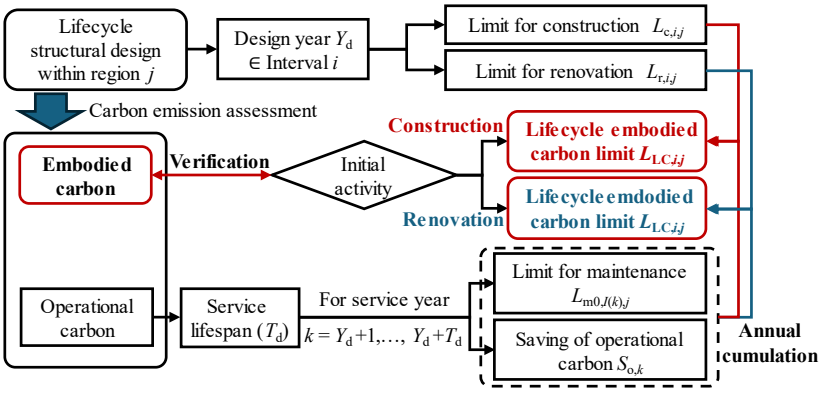


Fig. 3. Workflow for determining the lifecycle embodied carbon limit.

To verify the embodied carbon of an individual structure in lifecycle design, the corresponding lifecycle limit, $L_{LC,i,j}$, can be determined using the workflow shown in **Fig. 3**. A lifecycle design scheme can satisfy the low-carbon requirement with a temporal profile of embodied carbon that is flexibly adjusted to specific project conditions, provided that its lifecycle cumulative value remains below $L_{LC,i,j}$. The rationale for this verification, which ensures that the design scheme achieves climate change mitigation benefits comparable to those required by the embodied carbon limit, is that the overall impact of carbon emissions on climate change is determined by their cumulative total. Moreover, for CO_2 emissions (the greenhouse gas category of primary concern in this study), within a typical decade-long structural lifecycle, the differences in their long-term climate change impacts (e.g., over several centuries) resulting from variations in emission timing are minimal [39, 40]. For the implementation of structures designed with a lifecycle perspective, their carbon emissions at each stage—construction/renovation, maintenance, and operation—should be controlled based on design-phase projected carbon emissions, instead of the general limits derived in previous sections.

It should be noted that while a comprehensive low-carbon design integrating both embodied and operational carbon is ideal, practical considerations such as data quality and design feasibility may limit its application. Careful assessment and reliable justification of potential operational carbon reductions are essential before introducing $S_{o,k}$ to adjust the embodied carbon limit, as the cumulative operational carbon over multiple years of service can be substantial compared to the magnitude of embodied carbon limit. Misusing the tradeoffs could undermine the effectiveness of regulation based on the embodied carbon limit.

Moreover, the choice between using a lifecycle carbon limit or separate limits for different activities

for low-carbon verification depends on the degree of task separation in structural design. When structural designs significantly influence operational energy use or involve unconventional maintenance measures, the former choice is recommended. Otherwise, if construction/renovation and subsequent maintenance activities are independently designed, and the structure has minimal impact on operational energy use, applying separate embodied carbon limit for each activity type is more straightforward, which essentially presumes conventional carbon emission proportions among different activities.

4. Illustrative analysis for deriving embodied carbon limit

This illustrative analysis takes China as an example to demonstrate how the proposed methodology can be applied to derive embodied carbon limits that are tailored to regional characteristics, building types, and design verification requirements.

4.1 Scenarios for illustrative analysis on urban residential buildings in China

Since the Chinese government has not yet released authoritative national carbon budgets, to start top-down decomposition, this analysis temporarily allocates the remaining global carbon budget based on cumulative population, as suggested by [6], i.e.,

$$C_{\mathrm{N}} = C_{\mathrm{G}} \times \frac{\sum_{k=2023}^{2060} P_k^{\mathrm{C}}}{\sum_{k=2023}^{2060} P_k^{\mathrm{G}}} \tag{16}$$

where C_{G} and C_{N} are respectively the global and national total carbon budget until carbon neutrality is achieved; $P^{\mathrm{C}}{}_k$ and $P^{\mathrm{G}}{}_k$ represent China's population and global population in the year k, respectively. Inferring from IPCC [25], Jiang et al. [12] and Our World in Data [41], C_{N} for China that is compatible with 2°C climate target is estimated to be 165.112 billion t CO_2 (*Supplementary Data 1*).

China's construction sector, characterized by decreasing demand and an ongoing transition to low-carbon technologies, already presents significant opportunities for carbon reduction. To anticipate this decreasing trend in embodied carbon limits, we make the following assumptions regarding the temporal variation of the national carbon budget used for limit determination: (1) the budget value decreases annually from the 2023 value to zero by the target year of carbon neutrality in China (i.e., 2060); (2)

the reduction rate decreases annually to zero by 2060 due to the increasing marginal difficulty in carbon reduction as emission levels decline; (3) the sum of budget values over 2023-2060 equals the national total carbon budget derived by **Eq. (16)**. A cubic function is then used to approximate the pathway of national carbon budget. Based on the expected carbon budget and its 5-year cycle management mode, annual carbon budgets from 2026 to 2060 are generated by averaging values over each 5-year period, as shown in **Fig. 4**.

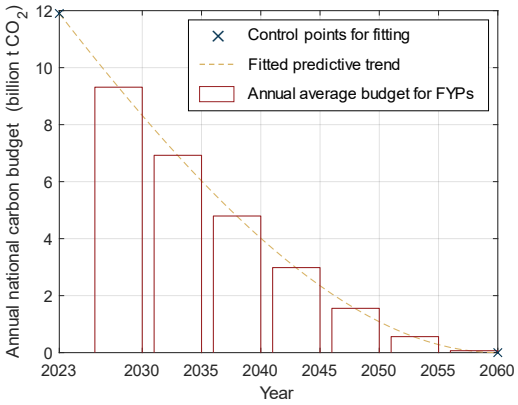


Fig. 4. Tentative national carbon budget for China used to estimate the collective carbon budget of building structures.

It should be noted that the national carbon budget (C_N) derived above is a hypothetical value intended solely for this illustrative analysis in generating the collective carbon budget for building structures. Such a global carbon budget allocation principle could otherwise be unfair to developing countries considering the regional divergence in historical carbon emissions, as well as the essential development needs for emerging countries [42, 43]. Moreover, this hypothetical temporal variation in the budget may not reflect the actual near-term trajectory of China's national emissions, which may continue rising until peaking before 2030 [27].

Leveraging available carbon emission data specific to urban residential buildings (URBs) reported in CABEE [2] and URB stock dynamics modeling results obtained in our prior study [17], we here conduct an illustrative analysis focusing on China's URBs, as explained in **Section 3.1**. According to CABEE [2], the newly completed BFS of URBs in China in 2022 reached 1,873 million m^2, with associated embodied carbon amounting to 756 million t CO_2. This yields a national average embodied carbon intensity benchmark of 403.6 kg CO_2/m^2 for 2022 construction practices (i.e., $\overline{B}_c$ = 403.6 kg CO_2/m^2).

Besides, through a review of existing case studies on carbon emissions of construction and

maintenance (*Supplementary Data 2*), the current value of $\alpha_{m,i}$ is estimated to be about 0.3% year^{-1}. Taking into account the contributions of new building construction and existing building maintenance to the collective embodied carbon of URBs, while ignoring the contribution of current limited renovation projects, the current value of β_b for URBs in China, as introduced in **Eq. (5)**, is calculated as,

$$\beta_b = \frac{\overline{B}_c \Delta A_B + \alpha_m \overline{B}_c A_B}{C_{NB}} \tag{17}$$

where ΔA_B and A_B are the BFS of newly completed URBs and occupied URBs in China for benchmarking in 2022, respectively estimated to be 1,873 million m^2 [2] and 29,790 million m^2 [17]; C_{NB} is the national carbon emissions in China in 2022, i.e., 12,527 million t CO_2 as per World Bank Group [44]. Thereby, β_b is estimated to be 6.32%.

For demonstrative purposes, we analyze four possible construction management scenarios for construction sector in China (**Table 1**), focusing on two feasible management strategies in China's construction sector, i.e., housing vacancy rate (HVR) reduction (demand-side mitigation) and renovation of existing buildings to replace new construction (supply-side mitigation). The results of URB stock dynamics from our prior study [17] are used for this analysis, which involve annual estimates of new construction, occupied RBs, and possible renovation, as well as the average age of buildings to be renovated, and the source data are presented in *Supplementary Data 3*.

Table 1
Possible construction management scenarios in China for analysis.

Scenario	Management strategy	Construction / renovation	Occupied RBs
BAU	Business as usual (no HVR change & no renovation)	**Fig. 5(a)**	**Fig. 5(e)**
VR	HVR reduction	**Fig. 5(b)**	
RN-D	Renovation and demolition restriction	**Fig. 5(c)**	
RVR-D	HVR reduction + Renovation and demolition restriction	**Fig. 5(d)**	

Note: (1) HVR represents the housing vacancy rate of URBs in China, which exceeded 30% in 2022 [17]; (2) For HVR reduction strategy, HVR is expected to be reduced to 10% by 2060; while for renovation and demolition restriction, the demolition ratio and renovation rate of reusable URBs is respectively planned to be decreased to 20% and increased to 50% by 2060. (3) Building lifespan extension is excluded from this analysis for two reasons: i) Quantifying and regulating lifespan extension is less intuitive compared to measurable interventions like HVR and renovation rate; ii) reusing existing URBs through HVR reduction, renovation and demolition restriction inherently achieves building lifespan extension synergistically.

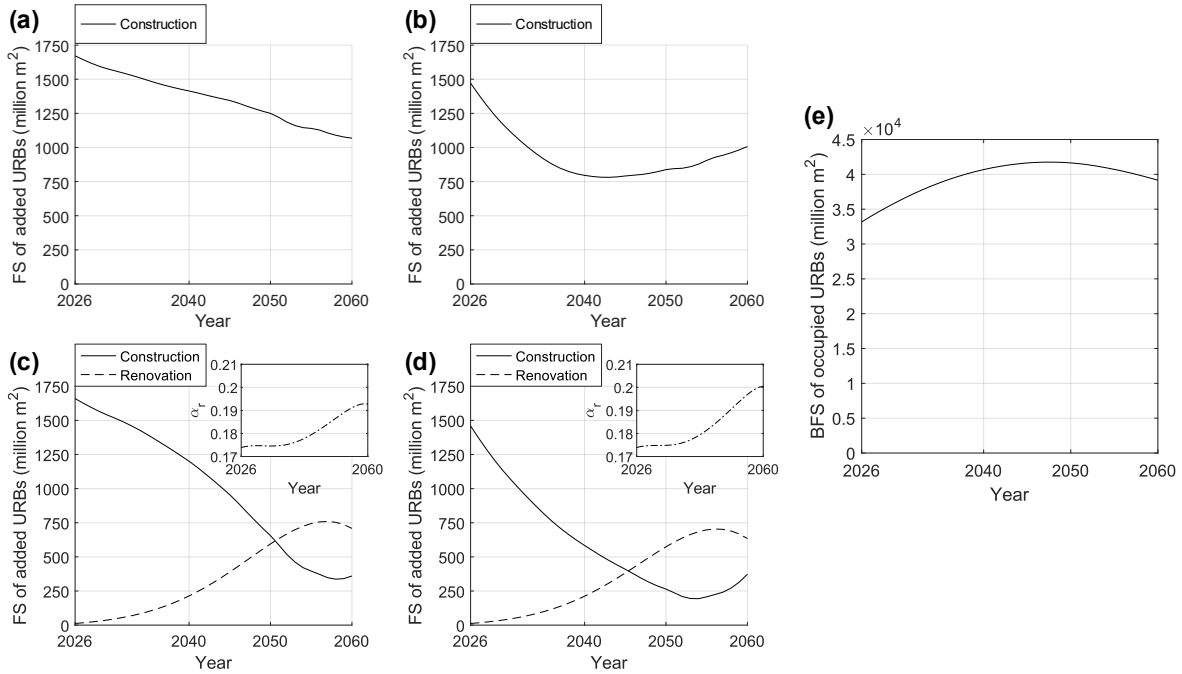


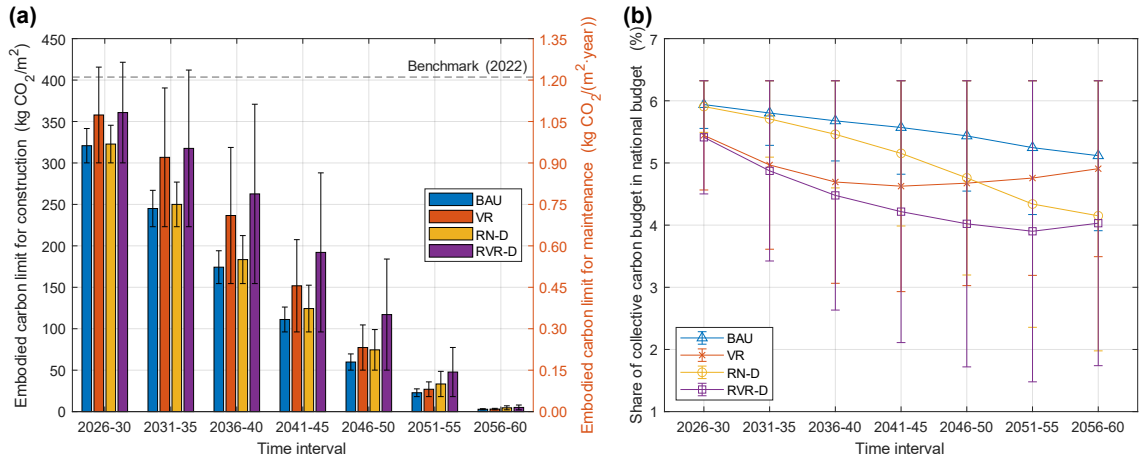
Fig. 5. Annual BFS of new construction, renovation and occupied URBs for different construction management scenarios. **(a)** BAU, **(b)** VR, **(c)** RN-D, **(d)** RVR-D, and **(e)** occupied URBs for all analyzed scenarios. **Note:** The presented results used for analysis correspond to the Shared Socioeconomic Pathway (SSP) 1 – Sustainability, which aligns with the 2°C-compatible global carbon budget underlying the embodied carbon limit derived in this illustrative analysis. Details on the stock dynamics modeling used to generate the presented data are available in our published work [17].

The above input data reflect the current status of embodied carbon in China's URBs and are suitable for deriving short-term limits (e.g., for the 2026–30 FYP). For long-term projections, updated input data for future conditions are recommended but currently unavailable. Therefore, this illustrative analysis uses existing data to demonstrate the derivation of embodied carbon limits for 2026–2060. Sensitivity analyses on the carbon budget and $\alpha_{m,i}$ are then conducted to assess the robustness of the results.

4.2 Ranges of embodied carbon limit for residential buildings

The embodied carbon limit derived by the proposed methodology maintains a downward trend, indicating increasingly stringent carbon reduction requirements, until the target of net zero carbon emissions is achieved by 2060 [**Fig. 6(a)**]. Since the bottom-up approach inherently decouples the lower bound of embodied carbon limit from building stock dynamics, the lower bounds corresponding to different construction management scenarios always remain the same, [**Fig. 6(a)**], while the share of the collective carbon budget in the national carbon budget corresponding to the lower bounds varies proportionally with the changes in construction/renovation demands [**Fig. 6(b)**]. In contrast, with a

514 constant value of β_b [**Fig. 6(b)**], the upper bound of embodied carbon limit is scenario-dependent, where
515 reductions of construction activities or their replacement with less carbon-intensive renovation activities
516 allow for increases in the embodied carbon limit for construction activities [**Fig. 6(a)**]. Specifically,
517 reducing HVR alleviates the immediate pressure to cut carbon emissions from construction activities,
518 while the limit relaxation achieved through renovation is relatively modest in the near term. When
519 approaching 2060, avoiding large-scale demolitions and promoting renovation of existing URBs can
520 effectively ease the pressure of carbon reduction efforts. Moreover, synergistic application of HVR
521 reduction, renovation and demolition restriction would more effectively enhance the embodied carbon
522 limit for new construction and maintenance [**Fig. 6(a)**].



523
524 **Fig. 6.** Embodied carbon limits for new construction and maintenance. **(a)** Upper and lower bounds, as
525 well as results for moderate level of regulation for different construction management scenarios; **(b)**
526 values of β_b. **Note:** the upper and lower limits of error bars correspond to the upper and lower bounds
527 of embodied carbon limits, while the bars in subfigure (a) and lines in subfigure (b) correspond to the
528 average values of the upper and lower bounds, representing a moderate level of regulation.
529

530 For the 2026-30 FYP, due to the notable anticipated decrease in national carbon budget (**Fig. 4**), the
531 upper bound of the embodied carbon limit for new construction could be low without effective
532 construction management. For example, the upper bound under the BAU scenario is estimated to be
533 341.6 kg CO_2/m², representing a 15.3% reduction compared to the benchmark in 2022 [**Fig. 6(a)**].
534 However, if HVR reduction, renovation and demolition restriction are implemented, the significant
535 reduction in construction activities could result in the upper bound of the embodied carbon limit for
536 new construction (i.e., 421.5 kg CO_2/m²) exceeding the benchmark value in 2022 [**Fig. 6(a)**]. This
537 implies that the macroscopic construction management could provide buffer time for the widespread

application of low-carbon technologies in structural design. Nevertheless, adopting such a high limit might squander the carbon reduction benefits achieved through stringent management of construction activities, hindering carbon reduction advocacy in structural design, which represents a major drawback of the recommended limit values in our previously published paper [45]. Therefore, this study introduces the regulation level adjustment between the upper and lower bounds of embodied carbon limit to overcome this drawback. With the lower bound estimated as 300.1 kg CO_2/m^2, the embodied carbon limit for new construction during 2026-2030 with a moderate level of regulation is evaluated to range between 320.8–360.8 kg CO_2/m^2 depending on the construction management strategy [**Fig. 6(a)**], while the corresponding reductions compared to the 2022 benchmark vary between 10.6% and 20.5%.

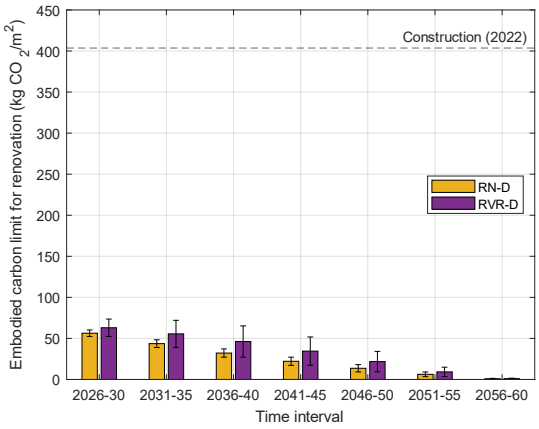


Fig. 7. Embodied carbon limit for renovation. **Note:** the upper and lower limits of error bars represent the upper and lower bounds of embodied carbon limit, while the bars represent the average values of the upper and lower bounds, corresponding to a moderate level of regulation.

According to **Eq. (3)**, the embodied carbon limit for maintenance is set to be proportional to those of construction, with values determined by the right-hand axis of **Fig. 6(a)**. For example, $L_{m0,i}$ under the BAU scenario decreases from 0.90–1.02 kg $CO_2/(m^2 \cdot year)$ for the 2026-30 FYP to nearly zero by 2060. For scenarios involving renovation activities, the embodied carbon limit for renovation (e.g., 52.4–73.6 kg CO_2/m^2 for the 2026-30 FYP) is significantly lower compared to new construction, as illustrated in **Fig. 7**. The lower bound of embodied carbon limit for renovation also remains consistent across scenarios, and the HVR reduction allows for a higher upper bound of embodied carbon limit for renovation activities.

4.3 Lifecycle embodied carbon limit

Taking the RVR-D scenario as an example, when the impact of structural design on operational carbon is not considered, the results of lifecycle embodied carbon limit for a structure with 50-year designed service life are shown in **Fig. 8**. When considering the lifecycle design, the magnitude of embodied carbon limit being lower than the 2022 benchmark will increase. This is primarily due to the tightening trend of the embodied carbon limit for maintenance, which results in much lower carbon emission allowances for subsequent maintenance activities in lifecycle design compared to the embodied carbon limit for maintenance in the year of construction/renovation. Moreover, the extension of 50-year designed service life starting from 2026 will exceed 2060, after which the embodied carbon limit for maintenance becomes zero. Consequently, the lifecycle embodied carbon limit decreases at a faster rate compared to the embodied carbon limit for merely construction or renovation activities, while the two types of limits gradually converge when approaching 2060.

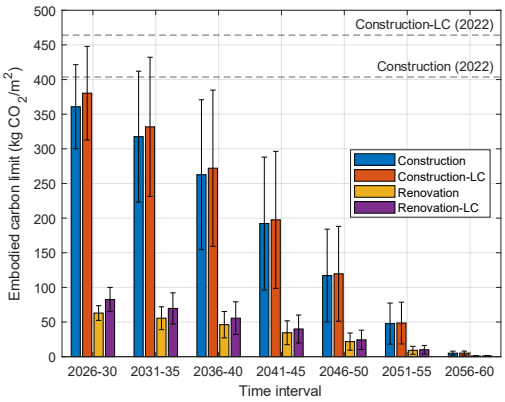
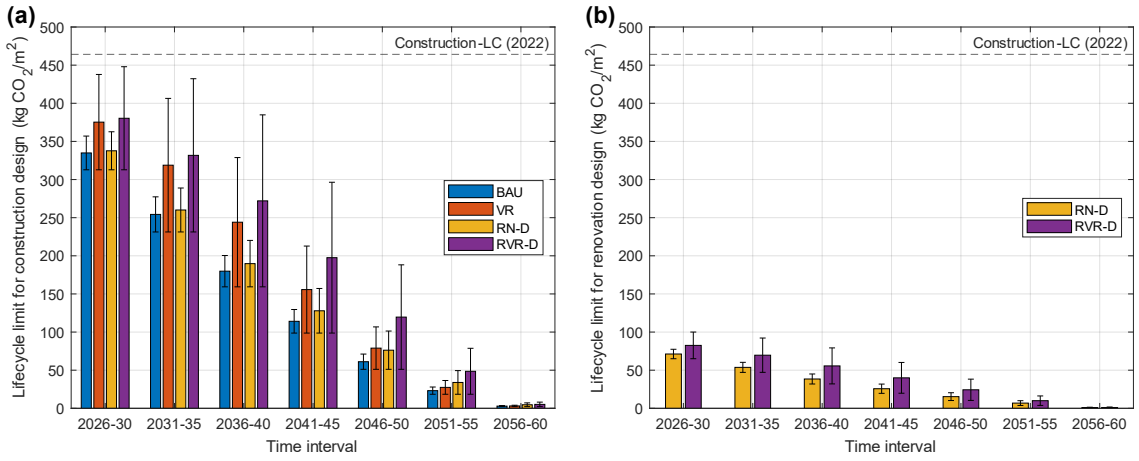


Fig. 8. Comparison of lifecycle embodied carbon limits and the limits for merely construction or renovation activities under the RVR-D scenario. **Note:** "construction-LC" and "renovation-LC" respectively represent the limits for lifecycle design with the initial activity being construction and renovation.

As per **Eq. (15)**, the contributions of embodied carbon limit for maintenance to the lifecycle embodied carbon limits are the same for construction and renovation designs in the same year. Thereby, considering lifecycle design has more pronounced impacts on the embodied carbon limit for renovation design (**Fig. 8**), offering more design flexibility. Additionally, the differentiating characteristics of lifecycle embodied carbon limits across various construction management scenarios follow similar patterns to those of the limits for merely construction or renovation activities discussed in **Section 4.2**, with the lifecycle values at a moderate regulation level decreasing from 334.9–380.3 kg CO_2/m^2 (new

586 construction design) or 71.2–82.5 kg CO_2/m^2 (renovation design) for the 2026-30 FYP to nearly zero
587 by 2060 (**Fig. 9**).



588
589 **Fig. 9.** Lifecycle embodied carbon limits for different construction management scenarios with the
590 initial activity being **(a)** new construction, and **(b)** renovation.
591

592 **4.4 Regional adjustments**

593 The regional disparities in China's construction sector are pronounced, with typical patterns as follows:
594 a high proportion of construction takes place in the eastern region with relatively advanced building
595 technologies, whereas a low proportion in the western region with higher carbon intensity of
596 construction due to delayed development [32, 46].

597 Taking the embodied carbon limit for new construction over 2026-2030 as an example, a hypothetical
598 analysis of regional adjustments is presented, distinguishing among the developed, moderately
599 developed and underdeveloped regions in the Chinese Mainland with a brief division presented in
600 *Supplementary Data 4*. Regional proportions in newly completed BFSs constructed by construction
601 enterprises in 2022 are presented in **Table 2**, according to the *China Statistical Yearbook* [46]. This
602 analysis assumes that the completed BFSs of URBs approximately follow the same proportional
603 distribution, based on which, differentiated carbon intensity benchmarks across regions are weighted to
604 calculate the national average carbon intensity benchmark, leading to the following relationships among
605 regional carbon intensity benchmarks.

606 $$a_j = \frac{\overline{B}_{c,j}}{\overline{B}_c};\ \ \sum_{j=1}^{N_r} r_{B,j} a_j = 1 \tag{18}$$

607 where a_j is the ratio of the mean carbon intensity benchmark of new construction in the j^{th} region ($\overline{B}_{c,j}$)

to the nationwide mean benchmark ($\overline{B}_{c}$); $r_{B,j}$ is the proportion of newly completed URBs in the j^{th} region to the national total in the year of benchmarking. The vector $\mathbf{a} = \{a_1, a_2, \ldots, a_{N_r}\}$ represents the regional disparities in carbon intensity level of new construction, and two hypothetical cases are used for analysis, as shown in **Table 2**.

The regional adjustment factor as introduced in **Eq. (13)** can be decomposed into two coefficients influenced by the mean ($\lambda_{m,i,j}$) and dispersion ($\lambda_{f,i,j}$) of the embodied carbon benchmark, respectively, i.e.,

$$\gamma_{R,i,j} = \lambda_{m,i,j}\lambda_{f,i,j}; \quad \lambda_{m,i,j} = \frac{\overline{B}_{c,j}}{\sum_{j=1}^{N_R} r_{i,j}\overline{B}_{c,j}} = \frac{a_j}{\sum_{j=1}^{N_R} r_{i,j}a_j} \tag{19}$$

where $\lambda_{m,i,j}$ represents the carbon intensity level in the j^{th} region relative to the national average carbon intensity level due to the changes in construction proportions across various regions during the time interval i; $\lambda_{f,i,j}$ captures feasibility disparities in reducing embodied carbon of new construction across regions.

Table 2
Cases for the hypothetical analysis of regional embodied carbon limit adjustments.

Parameter	Case for analysis	Region		
		Developed (D)	Moderately developed (M)	Underdeveloped (U)
$r_{B,j}$	—	55.1%	28.8%	16.1%
a_j	L1	0.938	1.04	1.15
	L2	0.797	1.14	1.48
$r_{2026\text{-}30,j}$	R1	55.1%	28.8%	16.1%
	R2	20.0%	30.0%	50.0%
CV of $B_{c,j}$	C1	0.15	0.25	0.35
	C2	0.35	0.25	0.15
	C3	0.25	0.25	0.25

Note: L1 assumes 10% lower and 10% higher intensity levels respectively for developed and underdeveloped regions relative to the moderately developed region; while L2 assumes 30% lower and 30% higher intensity levels for developed and underdeveloped regions.

The proportions of planned construction in different regions during the time interval i (i.e., $r_{i,j}$) determine the value of $\lambda_{m,i,j}$, with two cases analyzed for 2026-2030: maintaining the original construction proportions (R1) or primarily developing the underdeveloped region (R2) (**Table 2**). Additionally, the dispersion of carbon intensity benchmark for RB construction in China can be calibrated by a gamma distribution [47], which is used to describe regional carbon intensity benchmarks

for the three analyzed regions. Then, the distributions of regional benchmarks are characterized by their coefficients of variation (CVs), and three cases of regional disparities in CVs are compared (**Table 2**).

The region with low mean carbon intensity benchmark, due to high level of low-carbon technology application, allows for smaller embodied carbon limit, i.e., low λ_m value [**Fig. 10(a)**]. Besides, for the region with low CV of benchmark, the high technological maturity makes further carbon reduction more challenging; thus, from a feasibility standpoint, it is not favorable to set the embodied carbon limit significantly below the mean of benchmark, corresponding to a relatively high λ_f value [**Fig. 10(a)**]. A typical case (C1) is that the mean and CV of carbon intensity benchmark for construction in more developed regions may both be lower. Then, the above two types of influences could compensate for each other, allowing the regional adjustment factors to fluctuate around 1 with minimal variation [**Fig. 10(b)**]. In such a case, the national average embodied carbon limit could well apply to various regions without adjustments.

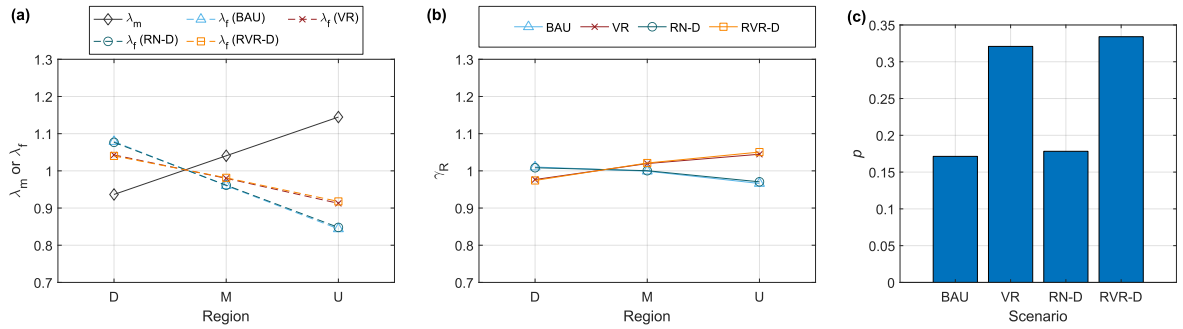


Fig. 10. Regional adjustments applied to the embodied carbon limit for new construction over 2026-2030 under different construction management scenarios. **(a)** λ_m and λ_f; **(b)** λ_R; **(c)** value of p. **Note:** D, M, and U represent the developed, moderately developed, and underdeveloped regions, respectively; the results presented correspond to the case of R1L1C1; the values of λ_m for different scenarios are the same.

Among the analyzed scenarios of building stock dynamics, HVR reduction significantly reduces the demand for new construction in the near term, thereby increasing the national average embodied carbon limit for 2026-2030 and allowing for a larger possibility (i.e., value of p) to achieve the limit [**Fig. 10(c)**]. Then, for the region with higher CV of carbon intensity benchmark (relatively low λ_f value), the increase of the quantile value corresponding to p is more significant, narrowing the gaps among the λ_f values for the three regions [**Fig. 10(a)**]. Additionally, the assumed minor impact of renovation and demolition restriction on the near-term construction results in minimal changes to regional adjustments for 2026-

2030 embodied carbon limit [**Fig. 10(b)**].

Another case (C2) is that the developed region may have greater potential for technological advancement owing to economic advantages, increasing the feasibility of carbon reduction, while the underdeveloped region may rely more on traditional technologies, making carbon reduction more challenging. Then, the differences in regional embodied carbon limits, i.e., lower limit in the developed region while higher limit in the underdeveloped region, will be exacerbated [**Figs. 11(a),(b)**]. For the combination of cases C2 and R1, the developed region with high proportion of construction activities possesses higher carbon reduction feasibility; thus, the difficulty for reaching the targeted carbon limit could be alleviated, with the value of p increased [**Fig. 11(c)**]. It is worth mentioning that given all regional embodied carbon limits follow the same type of distribution with the same CV (C3), λ_f equals 1 [**Fig. 11(a)**], and the embodied carbon limits across different regions are proportional to their mean carbon intensity levels [**Eq. (19)**].

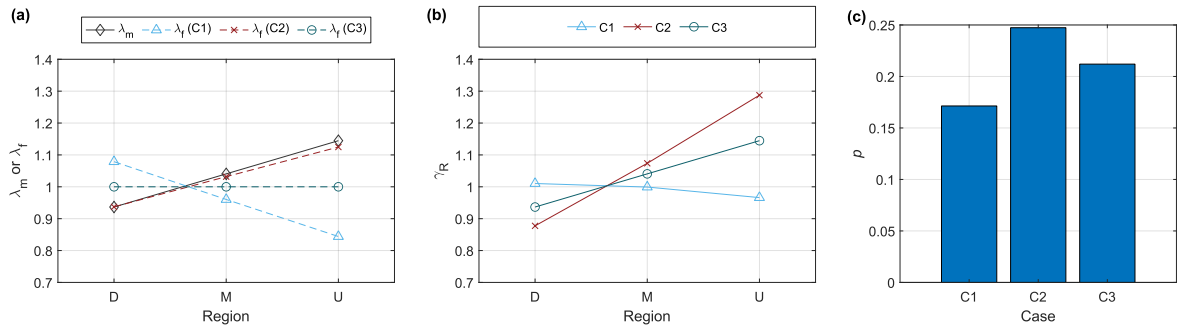


Fig. 11. Regional adjustments applied to the embodied carbon limit for new construction over 2026-2030 under different regional disparities in CV of carbon intensity benchmarks. **(a)** λ_m and λ_f; **(b)** λ_R; **(c)** value of p. **Note:** the results presented correspond to the cases of R1L1 and the BAU scenario; the values of λ_m for the cases analyzed are the same.

When the differences in mean carbon intensity benchmarks among regions are more pronounced (L2 vs. L1), the gaps among the λ_m values for different regions will become greater [**Fig. 12(a)**]. If construction is shifted to primarily focus on the underdeveloped region where the carbon emission level is higher (R2 vs R1), the increased proportion of construction activities with higher carbon emission level makes the required reduction compared to the national average carbon intensity benchmark larger, employing lower λ_m values [**Fig. 12(a)**]. In this case, the contribution of the underdeveloped region to reducing the national average carbon emissions is also greater. When the underdeveloped region

exhibits greater decarbonization potential (C1), where the reduction of the quantile value relative to the mean is more significant under the same value of p, R2 tends to increase the value of p compared to R1 [**Fig. 12(c)**] to achieve the same national average embodied carbon limit, leading to increases in λ_f values [**Fig. 12(a)**]. Overall, the impacts of the changes in regional construction proportions on the values of p and γ_R depend on the levels of disparities in mean and CV of carbon intensity benchmarks. For example, for the cases of L1C1, the influence of disparity in CV of benchmarks prevails, adjusting R1 to R2 increases both values of γ_R and p [**Figs. 12(b),(c)**]. Conversely, for the cases of L2C1, the influence of the disparity in the mean of benchmarks prevails; thus, R2 compared to R1 significantly reduces the value of p, necessitating stricter embodied carbon limit adjustments with lower γ_R [**Figs. 12(b),(c)**].

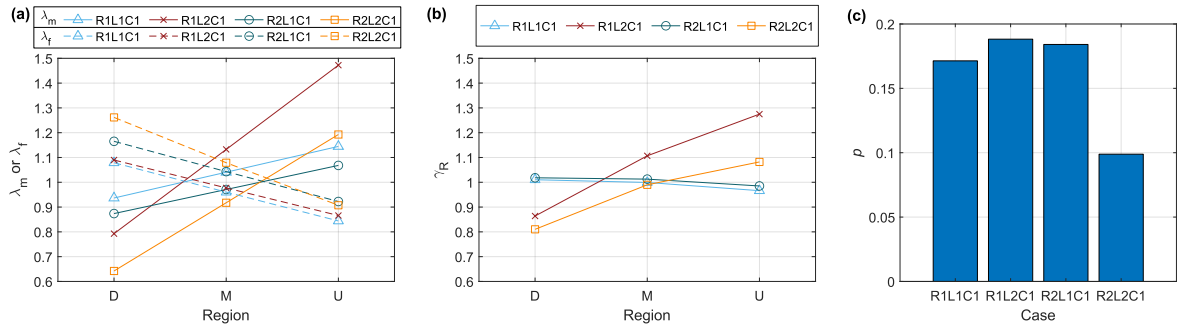


Fig. 12. Regional adjustments applied to the embodied carbon limit for new construction over 2026-2030 under different regional disparities in construction proportions and mean carbon intensity benchmarks. **(a)** λ_m and λ_f; **(b)** λ_R; **(c)** value of p. **Note:** the results presented correspond to the BAU scenario.

4.5 Sensitivity analysis

The following analysis examines how fluctuations in the values of national carbon budget and $\alpha_{m,i}$ affect the results of national average embodied carbon limits derived using our proposed methodology.

According to **Eqs. (9)&(10)**, both the upper and lower bounds of the embodied carbon limits vary proportionally with changes in the annual national carbon budget for the same time interval (**Fig. 13**). Based on the assumptions regarding the temporal variation of the national carbon budget in **Section 4.1**, changes in the national total carbon budget until carbon neutrality have a relatively minor impact on near-term national carbon budget estimates [**Fig. 13(a)**] and, consequently, on near-term embodied carbon limits [**Fig. 13(b)**]. However, this impact increases significantly over time. For example, a 20%

change in the national total carbon budget leads to an 11.4% change in the embodied carbon limits for the 2026–2030 FYP, but results in a 62.7% change for the 2056–2060 FYP (**Fig. 13**). Therefore, utilizing interval-specific updated information enables more accurate determination of embodied carbon limits, further underscoring the importance of dynamic limit derivation proposed in this study. Moreover, the results from the above illustrative analysis can be adjusted by multiplying them by the ratio of the actual carbon budget to the estimated national carbon budget shown in **Fig. 4**.

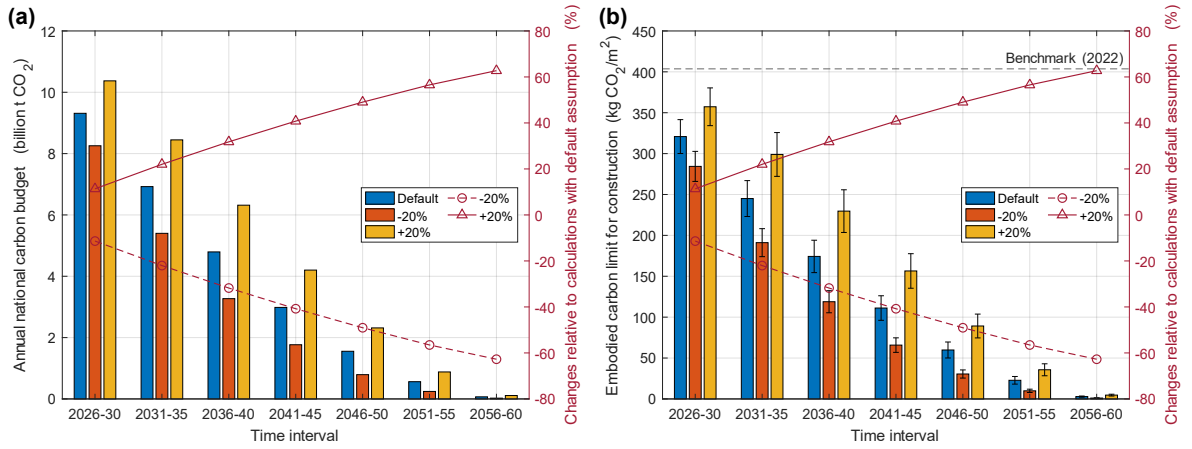


Fig. 13. Changes in **(a)** annual national carbon budget and **(b)** embodied carbon limit for construction under different national total carbon budget assumptions for China. **Note:** Bars show results for the default budget [165.112 billion tons for China until carbon neutrality (see *Supplementary Data 1* for details)] and for its 20% decrease or increase. Lines indicate the relative changes due to 20% decrease or increase in national total carbon budget compared to calculations with the default assumption. Proportional changes in embodied carbon limits for renovation or maintenance match those for construction, as their coefficients remain constant with budget variations [**Eqs. (2)&(3)**].

Changes in $\alpha_{m,i}$ do not affect the lower bounds of the embodied carbon limits for construction or renovation [**Eq. (10)**], while that for maintenance varies proportionally with $\alpha_{m,i}$ [**Eq. (3)**]. Regarding the upper bounds, an increase in $\alpha_{m,i}$ results in a greater share of the carbon budget being allocated to maintenance, thereby raising the upper bound of the embodied carbon limit for maintenance. Conversely, the shares for construction and renovation decrease, decreasing the upper bounds of their embodied carbon limits.

Within the same interval, construction management scenarios with higher embodied carbon limits for construction (see **Fig. 6**) reflect lower demand for construction and renovation activities. As time progresses, the demand for construction and renovation of URBs in China also declines. In both cases, larger portions of national carbon budget are allocated to maintenance, making changes in $\alpha_{m,i}$ more impactful on the embodied carbon limits for construction or renovation (**Fig. 14**). Nevertheless, even if

$\alpha_{m,i}$ doubles from 2% to 4%, the magnitude of this influence may still be limited, especially for the 2026–2050 FYP, the reductions in the carbon budget for construction or renovation across analyzed scenarios does not exceed 2% (**Fig. 14**). Therefore, the embodied carbon limits for construction and renovation derived in this study remain robust to changes in $\alpha_{m,i}$.

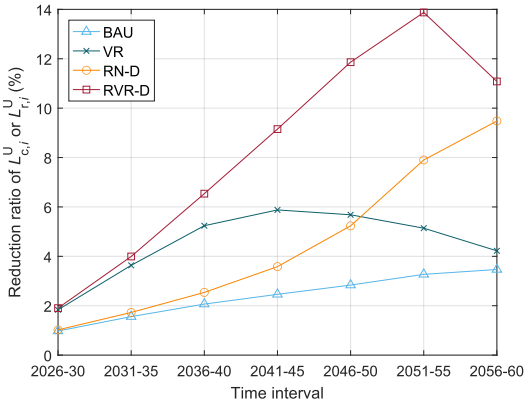


Fig. 14. Reduction ratios of the upper bounds of embodied carbon limits when $\alpha_{m,i}$ = 0.4% compared to those when $\alpha_{m,i}$ = 0.2%.

5. Discussions

5.1 Verification against embodied carbon limit in structural design

The methodology proposed in this paper derives the embodied carbon limit per unit BFS, while the embodied carbon allowance for the design of a specific building structure can be generated by multiplying the derived embodied carbon limit by its BFS, which is a primary design parameter typically defined at the early design stage. Exceptionally, for the separate low-carbon verification of maintenance activities, the embodied carbon limit needs to be generated by multiplying $L_{m0,i}$ by both the BFS and maintenance cycle. Given the significant variability in carbon reduction feasibility across structural components and systems—particularly since early-stage design choices at the structure level (e.g., layout optimization) may yield notable decarbonization potential [5]—this study advises against decomposing the structural embodied carbon limit further to the component level. Such granularity may constrain the flexibility of low-carbon technology adoption and compromise safety design. Component-specific guidance, if needed, may be explored in future research through performance-based benchmarks rather than prescriptive limits.

With the proposed methodology, the embodied carbon limit for renovation specifically applies to

policy-driven, planned renovation activities. For the voluntarily adopted renovations in place of new constructions, the embodied carbon limit for construction is still used for low-carbon design verification. As demonstrated by the values of $\alpha_{r,i}$ (around 20%, as per *Supplementary Data 3*), renovations typically entail significantly lower emissions for supplying equivalent BFS, creating a compliance buffer that incentivizes renovation over demolition and reconstruction.

Furthermore, the successful application of lifecycle embodied carbon limit in low-carbon design verification requires two critical points: (1) science-based projections of future maintenance work and/or operational energy, and (2) incorporation of time-varying carbon intensity reduction trends into emission forecasts. The latter aligns with decarbonization trajectories assumed in national or collective carbon budgets, ensuring scenario consistency between the evaluation of structural embodied carbon and the determination of its limit. To avoid the carbon lock-in effect, where short-term carbon reduction masks long-term inefficiencies [39], low-carbon decisions on renovation need to be based on the verification of lifecycle embodied carbon. Although unplanned renovations are assigned no carbon allowance due to their absence in the prior derivation process of limit values, the tradeoff mechanism in **Section 3.4** rewards renovations that effectively reduce operational carbon (e.g., insulation upgrades) or future maintenance needs (e.g., corrosion-resistant coatings), fostering lifecycle-oriented decisions that align with the reduction of long-term cumulative carbon emissions to pursue climate mitigation goals. Additionally, low-carbon verification for renovation design is also recommended to be based on the lifecycle embodied carbon limit, since the prolonged service of old structures post-renovation may increase maintenance demands.

It should be noted that the derived embodied carbon limit clarifies the carbon mitigation obligation within construction sector, but the levers to keep embodied carbon of building structures below its limit may not be restricted to structural design adjustments alone. For instance, purchasing carbon allowance through carbon trading market may also compensate for excessive carbon emissions [29].

5.2 Dynamic inputs for deriving updated embodied carbon limits

Ensuring that the derived dynamic embodied carbon limits remain representative and up-to-date requires continuous updates to carbon budgets and carbon intensity benchmarks, based on real-world

evidence of carbon mitigation policies, advancements in low-carbon technologies and changes in carbon intensities owing to societal decarbonization efforts, such as energy transition.

Particularly, outdated benchmarks pose a significant risk of distorting feasibility assessments in the regional adjustments proposed in Section 3.3. For example, for the regional adjustment of 2031-35 embodied carbon limit for new construction under the R1L1C1 case and the BAU scenario, if the 2022 benchmarks are adopted, the achievement probability of limit regulation (p) would be extremely low [less than 2%, as **Fig. 15(a)**], implying unrealistically high difficulties for achieving the limit requirement compared to reality. On one hand, the 2022 benchmark distributions fail to account for new lower-carbon technologies that may emerge and the phasing out of old higher-carbon technologies by 2031-2035, and thereby cannot accurately reflect the typical low-carbon technological status for the 2031-35 FYP. On the other hand, due to the idealized nature of probability models, there are inherent assumptions that may not align with real-world conditions, making the tail information less accurate. Using outdated benchmarks that are too low relative to the embodied carbon limit may cause over-reliance on tail information for regional adjustments, potentially leading to impractically large differences in regional adjustments [**Fig. 15(b)**] and hindering fair distribution of carbon mitigation obligations among regions.

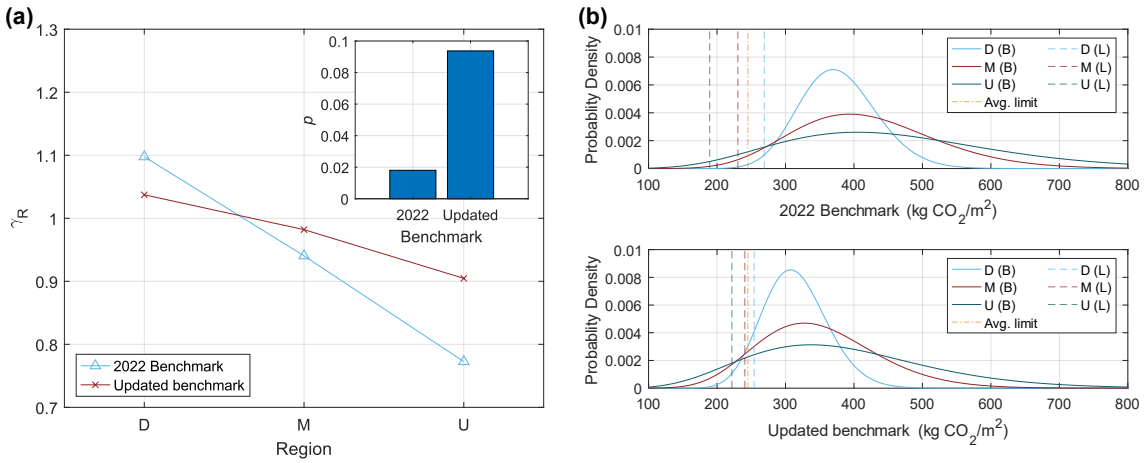


Fig. 15. Regional adjustments applied to embodied carbon limits for new construction over 2031-2035 based on different carbon intensity benchmarks. **(a)** Results of γ_R and p; **(b)** Distribution of assumed regional benchmarks. **Note:** the results presented correspond to the R1L1C1 case and the BAU scenario; in the legends of subfigure (b), (B) denotes the benchmark distribution, while (L) represents the regional limit.

If an updated benchmark is adopted, assuming the mean of the benchmark changes according to predictions disclosed in our previous study [17]—specifically, that the mean for 2031-35 is approximately 83.2% of the 2022 benchmark—the above issues can be mitigated. By reflecting the incorporation of new low-carbon technologies and the elimination of outdated high-carbon technologies, the probability of achieving limit requirement can be enhanced to nearly 10%, while the differences in adjustment across regions would be reduced (**Fig. 15**). Additionally, the achievement feasibility remaining low after updating benchmarks highlights that relying solely on low-carbon construction technologies without integrating construction management may significantly limit future low-carbon structural design options.

5.3 Use of time-dependent embodied carbon limit

A defining feature of the embodied carbon limit derived in this study is its time-dependent variations, which could dynamically trace the carbon mitigation obligation required by real-world decarbonization pathways, contrasting with existing studies typically providing a constant limit over decades [6, 10]. By assigning higher embodied carbon limit in the near term (e.g., 2025–2040) and lower limit approaching 2060, this dynamic approach accommodates transitional challenges in low-carbon technology adoption and aligns with the progressive decline in carbon intensities, balancing feasibility for current projects while preserving future decarbonization opportunities.

The time-dependent embodied carbon limit is intended to pave the way for construction sector toward carbon neutrality. As approaching 2060 (the target year of carbon neutrality in China), the embodied carbon limit—both upper and lower bounds—will approach zero. Since achieving zero embodied carbon of building structures is generally considered challenging, our previous paper proposed additional allowances for embodied carbon by introducing external carbon sinks [45]. However, during this study, we have noticed that buildings themselves hold the potential to storage or offset carbon. For example, concrete and wood structures have the ability to absorb or store carbon [48, 49], while BIPV [37] and vertical greening systems [50] offer opportunities for negative carbon emissions during building operation. Therefore, when calculating the collective carbon budget for building structures, this study excludes external carbon offsets, and encourages the construction sector to internalize its

837 slower decarbonization progress with strategies such as reducing building demands, substituting new
838 construction with renovation, and leveraging the carbon offset potential of buildings. Especially, for the
839 post-carbon neutrality era, the carbon storage and offset measures would be essential for achieving net
840 zero carbon of building structures, while the trade-off mechanism in **Section 3.4** may still provide a
841 positive lifecycle embodied carbon limit for feasible low-carbon structural design.
842
843 **5.4 Limitations and prospects**
844 The illustrative analysis in **Section 4** is primarily for demonstration purposes and based on predictive
845 modeling. Direct use of the currently derived regional embodied carbon limit values requires careful
846 consideration, as their accuracy is currently constrained by the lack of robust, region-specific carbon
847 intensity benchmarks. According to our proposed regional adjustment approach, refining these regional
848 limits critically depends on obtaining reliable and comparable regional benchmarks. Therefore, it is
849 essential to further establish standardized, formalized carbon emission measurement protocols and data
850 quality frameworks. This would enable the development of regional benchmarks with consistent
851 statistical boundaries and data quality, accurately reflecting the distinct carbon emission characteristics
852 of regional construction practices. Additionally, the embodied carbon benchmark for construction used
853 in illustrative analysis does not yet account for emissions from demolition, which may result in
854 relatively stringent limits for low-carbon verification of construction and renovation designs.
855 Furthermore, this study offers policymakers insights into the necessity of specifying context-robust
856 metrics, including carbon budgets, low-carbon regulation-level factor and planned
857 construction/renovation schemes, to facilitate the carbon regulation in construction sector. The
858 embodied carbon limits derived in this study pertain to CO_2 emissions and do not explicitly account for
859 non-CO_2 greenhouse gases, given that CO_2 is the predominant greenhouse gas in building material
860 production and construction processes [39, 40]. While this paper is mostly contextualized within China,
861 the methodological framework provides transferable insights for other rapidly developing and
862 transforming regions.
863

6. Conclusions

This paper has introduced a novel methodology for deriving dynamic embodied carbon limit of building structures within the context of a transitioning construction sector. By examining reasonable changes in the allocation of the national carbon budget to the collective embodied carbon of building structures, we have proposed methods for determining the upper and lower bounds of limits respectively for new construction, renovation and maintenance. The upper bound is derived using a top-down approach based on the grandfathering principle, which involves decomposing the carbon budget according to building stock dynamics. Conversely, the lower bound is determined using a bottom-up approach, estimating the reduction in carbon intensity of embodied carbon-related activities in line with the societal average decarbonization rate.

Moreover, building on this derived range, we have developed multi-factor adjustments to establish flexible embodied carbon limit tailored to building types, sectoral carbon regulation levels, regional characteristics, and lifecycle design. These adjustments include: (1) the use of building type-specific data to generate pertinent limit; (2) a regulation-level factor to avoid excessively high limit resulting from strict construction management or excessively low limit that is challenging for the conservative construction sector to achieve; (3) accounting for regional disparities by adjusting for the feasibility of carbon reduction based on the mean and dispersion of regional carbon intensity benchmarks; (4) setting lifecycle embodied carbon limit based on scientifically predicted future maintenance and operational energy savings, thereby promoting trade-offs in carbon allowance over the service life of building structures. This methodology is particularly applicable to countries with vast territories undergoing social or construction industry transitions, facilitating macro-control and top-level design for sectoral carbon emissions.

Subsequently, we provide an illustrative analysis demonstrating the operability and application characteristics of the proposed methodology. This analysis generates the embodied carbon limit for urban residential building structures in China over the period 2026-2060, encompassing new construction, maintenance, renovation, and lifecycle considerations. Key findings include:

(1) The dynamic embodied carbon limit exhibits a notable decreasing trend until the target of net zero

carbon emissions is achieved by 2060. Both demand-side and supply-side mitigation strategies in construction management help raise the upper limit of embodied carbon, providing a buffer period for the widespread adoption of low-carbon technologies in structural design.

(2) For the 2026-30 Five-Year Plan (FYP) of China with a moderate carbon regulation level for construction sector, reasonable embodied carbon limits for new construction, maintenance and renovation (if available) activities are 320.8–360.8 kg CO_2/m^2, 0.90–1.02 kg $CO_2/(m^2 \cdot year)$ and 56.3–63.0 kg CO_2/m^2, respectively, while for 50-year lifecycle design of new construction and renovation (if available), the ranges are respectively 334.9–380.3 kg CO_2/m^2 and 71.2–82.5 kg CO_2/m^2, depending on the construction management strategy.

(3) Regions with lower mean or higher coefficient of variation (CV) in carbon intensity benchmark tend to adopt lower embodied carbon limit from a feasibility perspective. Changes in the proportion of construction activities across different regions can lead to simultaneous increases or decreases in regional adjustment factors, depending on the relative impact of regional disparities in the mean and CV of carbon intensity benchmarks. Construction management strategies that raise national average embodied carbon limit mitigate the impact of regional differences in CV of benchmarks.

(4) Ensuring that the derived dynamic embodied carbon limit remains representative and up-to-date requires continuous real-world updates to carbon budgets and carbon intensity benchmarks. For decision-making of renovation projects, low-carbon verification based on lifecycle embodied carbon limit is recommended to provide greater design flexibility. If renovation is voluntarily chosen over new construction, the embodied carbon limit for new construction should still be applied. For unplanned additional renovations, future changes in operational carbon or maintenance demands need to be considered to create compliant carbon allowances.

Declaration of Competing Interests

The authors declare no competing interests.

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