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Exploiting vacant urban residential buildings to promote carbon neutrality in China

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Urban construction has been a major contributor to carbon emissions. As China's housing demands decelerates, addressing the vacancy of residential buildings has become essential for revitalizing the real estate sector and promoting low-carbon and circular urban development. Here we show that China's housing vacancy rate within the available residential building stock may have exceeded 30% since 2021. We assess three strategies to transform excessive vacancy into an opportunity for carbon neutrality: (i) demand-side mitigation by housing vacancy rate reduction to slow down near-term carbon emissions, (ii) supply-side mitigation through the renovation of old residential buildings, and (iii) restricting demolition for sustained carbon reduction. These three strategies collectively yield superimposed carbon mitigation benefits: moderate implementation could reduce China's urban residential construction emissions by more than 43% over 2023–2060, meeting a 2 °C-compatible carbon budget under the Sustainability Shared Socioeconomic Pathways and offering a transferable framework for low-carbon, resource-efficient urban construction.

Large-scale urban construction, which initiated in the early 21st century, has been a major contributor to carbon emissions in China[1]. Since 2005, China has emerged as the world's largest annual emitter of greenhouse gases (GHGs), predominantly carbon dioxide (CO_2)[2]. The 2020 announcement of China's ambition to achieve carbon neutrality by 2060 marked the beginning of intensified efforts to reduce carbon emissions, directly positioning decarbonization as the construction sector's foremost priority[3]. While the development and adoption of low-carbon construction materials and technologies are indispensable[4,5], their widespread implementation to achieve the desired benefits requires an incremental approach over an extended period[6–10]. Consequently, reducing the carbon-intensive construction by fully utilizing existing residential buildings is imperative to meet the imminent and challenging carbon neutrality target[6,7,10–13].

Previous studies have evaluated several different strategies to decarbonize the existing residential buildings, focusing, for example, on building lifetime extension[7,10,14,15], space sharing[16], and spatial planning[17]. However, systematic discussion on dealing with the large vacancy of existing building stock is insufficient. Over the past four decades, China's booming construction and real estate sectors have increased the floor space per capita (FSPC) of residential buildings from 6.7 m^2 in 1978 to over 40 m^2 in 2023[18,19]. Nevertheless, speculative investment in real estate during this period, especially over the past two decades, has led to excessive construction and a surplus of residential buildings[20–22]. Such a critical issue has long been concealed by the past rapid population growth and urbanization, which facilitated the swift absorption of excessively constructed residential buildings into active use. However, with these growth rates now slowing, the surplus of residential buildings has become a heavy burden on urban

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socio-economic and green development. Recent notable increases in housing turnover periods and the subsequent crisis in the real estate sector[23] confirm this concern. Since 2015, the combined value-added contributions of the construction and real estate sectors have accounted for more than 13% of China's gross domestic product (GDP) annually[18]. Thus, addressing the surplus of residential buildings is not only critical to China's decarbonization efforts but also essential for revitalizing national economy[24,25].

In 2024, Chinese government announced a set of policies to promote destocking of newly built vacant residential buildings, primarily including government purchases of unsold homes (Supplementary Table 12), the easing of mortgage rules[25–27], the assurance of unfinished residential building deliveries[26,28], and the relaxation of housing purchase restrictions[25]. Additionally, initiatives for renovation of aging urban communities were announced in 2020 and 2023[29,30], alongside directives issued in 2021 and 2023 to restrict large-scale or unplanned demolition (Supplementary Table 13)[31,32], facilitating the repurposing and utilization of old vacant residential buildings. The intensification of such measures indicates the growing inevitability and urgency of addressing vacant residential buildings as a critical step in reviving China's real estate sector while transitioning the construction sector towards low-carbon and circular urban renewal.

A more systematic approach is required to develop an integrated national policy and action plan to fully realize the potential of vacant residential building utilization. However, the absence of reliable data remains a key barrier. In China, the National Bureau of Statistics has yet to release official statistics on vacant residential buildings, and the total quantity of the existing building stock has not been updated since 2007[18,33]. Additionally, discrepancies between top-down data, such as annually completed floor space (FS) and demolished FS, and bottom-up data, including FSPC and population, pose challenges in accurately estimating the existing residential building stock[34–36]. The lack of consideration for building vacancy, coupled with inconsistencies in statistical methods over time, may lead to misjudgments regarding residential building stock levels and service lifespans (Supplementary Note 1 and 6). Although some recent studies based on remote sensing and social media data have provided indications of high housing vacancy rate (HVR) in China[21,37–40], these sources are limited in distinguishing the causes or completion years of vacant residential buildings, which hinders detailed assessment of their potential contributions to future housing demands. Other studies based on household surveys and electricity consumption data, though useful for identifying occupancy in resident-owned residential buildings, often overlook the vacancy of newly completed but unsold residential buildings[41–43]. Moreover, institution-level surveys and remote sensing analyses are inherently restricted in their regional coverage (Supplementary Data 18). Therefore, conducting a comprehensive national-scale analysis on HVR status and related regulations remains essential to evaluate the effectiveness and climate implications of vacant residential building utilization across China.

Here, we address the abovementioned knowledge and data gaps by employing a dynamic housing stock model that incorporates housing vacancy (see "Methods"). Using this model, we evaluate the effectiveness of vacant residential building utilization for reducing embodied carbon emissions from material production and construction processes associated with residential buildings. Firstly, the FSs and service lifespans of annually completed residential buildings in urban and rural areas are calibrated based on available authoritative data from the National Bureau of Statistics of China, which support the inflow-driven analysis to infer the historical changes in HVR. Subsequently, we characterize three mitigation strategies for vacant residential building utilization—HVR reduction, renovation, as well as demolition restriction—and use a stock-driven approach to compare their carbon emission reduction effects up to 2100 under different scenarios. Then, we analyze the impacts of building service lifespan extension and different levels of regulation targets on the achievable benefits of vacant residential building utilization. Finally, we demonstrate the contributions of these carbon mitigation efforts to China's pathway towards carbon neutrality. Our findings reveal optimal strategies for both near-term and long-term decarbonization in urban construction by leveraging existing vacant residential buildings in China, facilitating the formulation of a statistics-based, coordinated, and systematic national policy and action plan.

Results

Problems and opportunities in the existing residential building stock in China

Figure 1a presents the FSs and service lifespans (L_s) of annually completed residential buildings in China up to 2022, calibrated using data from China Statistical Yearbooks[18] and China Population Censuses[44,45] or Micro Censuses[46,47] ("Methods" and Supplementary Note 2). The data indicate a growing disparity between urban and rural residential building construction since the early 21st century, alongside significantly shorter service lifespans of residential buildings in China (mostly under 50 years) compared to those reported in many industrialized countries (predominantly exceeding 50 years by a significant margin)[15]. Unless otherwise specified, this study will focus on urban residential buildings due to their large numbers and concentration.

Figure 1b presents the classification of existing residential buildings in China based on their usage status. According to the National Bureau of Statistics of China, the FS of in-service residential buildings held by residents can be calculated by multiplying the FSPC value obtained from household surveys and the total population for the same year. However, in 2020, over 44% of urban in-service residential buildings were held by approximately 25% of the urban population[45] (Fig. 1c). This inequality in FSPC distribution suggests the potential existence of underused residential buildings, which surpass essential demands for regular, long-term residence and could be infrequently inhabited (e.g., seasonal dwellings and fixed asset investments)[48], as distinct from occupied residential buildings (Fig. 1b). If the FSPC distribution were to return to a rational pattern, the FSs of in-service residential buildings could decrease by approximately 10% (Supplementary Note 4), indicating underused proportions of around 10% (Fig. 1c). Furthermore, by examining discrepancies between the FSs of in-service residential buildings and completed ones[18,45] (Supplementary Note 1), a substantial number of newly completed residential buildings that have not yet been put into use can be identified, referred to as new vacant residential buildings.

Moreover, within the out-of-service residential buildings, we define those no longer utilized due to their unsuitability for habitation as retired ones, while obsolete residential buildings are those rendered unusable due to inadequate structures involving safety concerns. Correspondingly, the time interval between the completion and retirement of residential buildings is defined as their service lifespan, whereas the interval between the completion and obsolescence is defined as their maximum lifespan (see "Methods"). The quantity of demolished residential buildings typically exceeds that of obsolete ones (Supplementary Fig. 15), indicating the existence of over-demolished residential buildings. Meanwhile, the quantity of retired residential buildings generally surpasses that of demolished ones[34,49], leading to the classification of retired residential buildings that have not been demolished or become obsolete as reusable ones.

The identified underused, new vacant, and reusable residential buildings represent three major categories of vacant residential buildings in China (Fig. 1b). The first two types can be directly utilized to satisfy the housing demands, while the reusable ones typically need renovation before being reintroduced into service. Consequently, in addition to occupied residential buildings, underused, new vacant and renovated reusable ones are considered as available residential buildings, with renovated reusable residential buildings possibly

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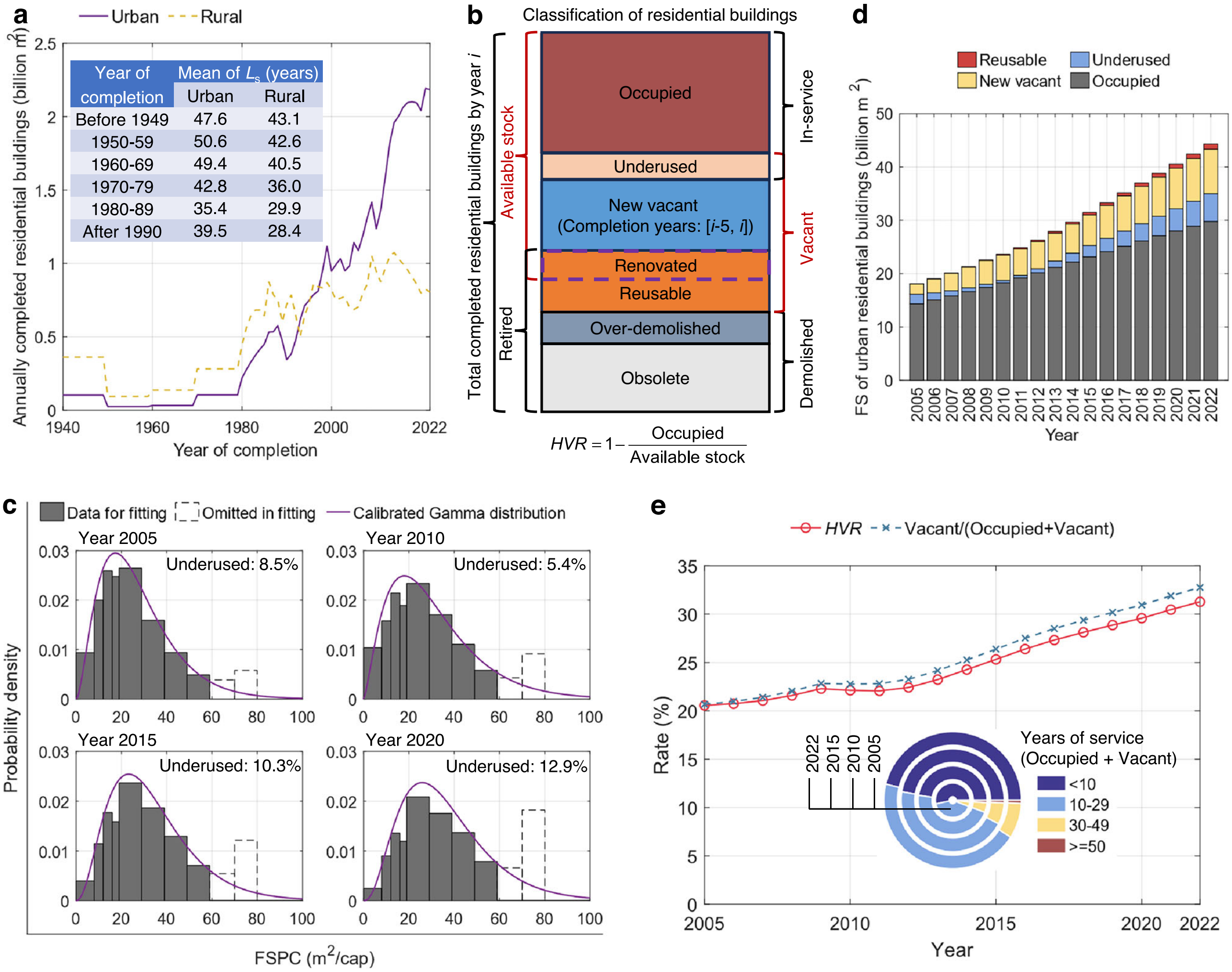

Fig. 1 | The status of existing residential building stock in China. a Calibrated floor spaces (FSs) of annually completed residential buildings. Due to the absence of data on annually completed residential buildings before 1980, an equal annual FS is assumed for each 10-year interval prior to 1980, and the residential buildings completed before 1949 are categorized as those completed between 1940 and 1949. The calibrated mean values of service lifespan (L_s) align with existing knowledge (Supplementary Note 7). **b** Classification of existing residential buildings in China. **c** Fitting floor space per capita (FSPC) distributions from census data using gamma distributions and the estimated proportions of underused residential buildings within in-service ones. **d** Dynamic changes in urban residential buildings from 2005 to 2022, including consideration of the reusable residential buildings retired since 2005. **e** Proportions of vacant residential buildings and the housing vacancy rate (HVR); the pie chart illustrates the years of service for occupied and vacant residential buildings in 2005, 2010, 2015 and 2022. HVR represents the vacancy rate of available residential buildings, consistent with Fig. 1b, i.e., the proportion of vacant residential buildings within the available residential building stock, without considering unrenovated retired buildings with reusable potential. In contrast, Vacant represents total vacant residential buildings, including unrenovated reusable ones. **Note:** The sporadic residential building renovation practices before 2022 are neglected in historical statistics.

also being occupied, and the proportion of vacant residential buildings within the available residential building stock is quantified as the HVR (see Fig. 1b).

Despite a doubling in the demand of occupied residential buildings between 2005 and 2022, rapid construction has led to a notable increase in new vacant residential buildings (Fig. 1d), which is a primary driver of the increasing HVR. The HVR has remained above 20% since 2005 and exceeded 30% since 2021 (Fig. 1e), representing a relatively high HVR level compared to existing estimates[38,39] (Supplementary Note 7). Moreover, the existence of reusable residential buildings indicates an even larger quantity of vacant residential buildings with potential for utilization (Fig. 1e). Over the past two decades, new residential buildings have dominated the Chinese residential building stock, with their years of service falling significantly below their maximum lifespans (Fig. 1e). The remainder of this paper will present a detailed quantitative evaluation to demonstrate how vacant residential buildings can be utilized to achieve the dual objectives of satisfying housing demands and decarbonizing the construction industry. This approach aims to transform the legacy of excessive residential building construction into opportunities for carbon mitigation.

Background scenarios and mitigation strategies

The internationally accepted Shared Socioeconomic Pathways (SSPs) serve as the foundation for the forecasts, which provide the projections of (1) housing demands, (2) carbon intensity of residential building construction, and (3) maximum lifespans of residential buildings for analysis ("Methods" and Supplementary Note 4). SSP5 (Fossil-fueled Development) and SSP3 (Regional Rivalry) are excluded from the analysis of vacant residential building utilization, as both scenarios assume high material consumption patterns[50]. Instead, three background scenarios have been developed based on SSP4–6.0, SSP2–4.5, and SSP1–2.6, hereafter referred to as SSP4, SSP2, and SSP1, which respectively represent Inequality, Middle of the road (i.e., historical patterns), and Sustainability, with social carbon emission levels decreasing in this order[50,51].

Table 1 | Mitigation strategies of vacant residential building utilization and their default values in model implementation

Strategy type	Strategy code	Description	Model implementation (default values)			
			HVR_t	$r_{R,t}$	$r_{D,t}$	$Year_a$
None	BAU	Business as usual	—	—	—	N/A
Supply side	RN	Renovation	—	60%	—	2060
	RN-D	Demolition restriction + Renovation	—	60%	20%	2060
Demand side	VR	HVR reduction	10%	—	—	2060
Supply and demand sides	RVR	Renovation + HVR reduction	10%	60%	—	2060
	RVR-D	Demolition restriction + Renovation + HVR reduction	10%	60%	20%	2060

Note: (1) HVR_t, $r_{R,t}$, $r_{D,t}$ respectively represent the target values of housing vacancy rate *HVR*, renovation rate r_R and over-demolition ratio r_D that are expected to be achieved by $Year_a$. After $Year_a$, these parameter values are assumed to be kept as their target values (see Supplementary Fig. 16 for the assumed variations of *HVR*, r_R and r_D over 2023-2100); (2) The symbols — in the table cells denote that the values in 2022 are followed, that is, HVR_t = 31.3%, $r_{R,t}$ = 0%, or $r_{D,t}$ = 69.6%–69.7% (Supplementary Note 5); (3) The period between 2023 and $Year_a$ is referred to as the transition period, while the period after $Year_a$ is termed the stable period; (4) The determination of default regulation targets for multiple mitigation strategies is elaborated in Methods.

Aligned with the existing policies in China mentioned above, we analyze the low-carbon benefits of three mitigation strategies for vacant residential building utilization: (1) reducing HVR in available residential building stock (referred to as HVR reduction); (2) renovating reusable residential buildings (Renovation); (3) restricting the demolition of reusable residential buildings (Demolition restriction). HVR reduction represents a demand-side strategy aimed at diminishing redundant housing demands while promoting the optimized utilization of existing available residential buildings. Conversely, renovation addresses the issue from the supply side by exploiting the service potential of reusable residential buildings, thereby substituting for conventional resource-intensive construction to meet housing demands.

Estimates from 1997 to 2011 indicate that approximately 70% of non-obsoleted residential buildings were demolished following their retirement (Supplementary Note 5). This demonstrates how China's traditional paradigm of large-scale demolition and construction in China, combined with the short service lifespan of residential buildings, has inevitably caused massive premature demolition and substantial resource waste. Demolition restriction can increase the quantity of reusable residential buildings, which serves as a supplementary strategy for renovation, as the increased stock of reusable residential buildings cannot be effectively utilized to satisfy housing demands without renovation. Furthermore, a business-as-usual (BAU) condition, assuming no change in HVR and no renovation of reusable residential buildings, is incorporated for comparative analysis. Table 1 outlines the various mitigation strategies and their combinations considered in this research.

Carbon mitigation benefits from vacant residential building utilization

All analyzed background scenarios indicate slowing growths in housing demand across urban China, with demand projected to peak around 2050 and then continuously decline (Fig. 2a). Demand-side mitigation through HVR reduction will cause demand for available residential buildings to peak earlier. Due to the anticipated decrease in demand increments, the FS of annually completed residential buildings shows a downward trend across all pathways, while the Sustainability pathway (SSP1) is expected to require a smaller quantity of residential buildings to be completed (Fig. 2b) due to lower demands of available residential buildings compared to the development with historical patterns (SSP2) (Fig. 2a).

When exploiting the potential of vacant residential buildings, HVR reduction is projected to continuously decrease the annually completed residential buildings over 2023–2100 (Fig. 2b). This effect is particularly pronounced during the transition period, as year-by-year reductions in HVR lead to the occupation of previously vacant available residential buildings. Due to the dominance of new residential buildings within the existing stock (Fig. 1e), the accumulation of reusable residential buildings is likely to be slow in the near term. Additionally, with the anticipated gradual promotion of renovation, the FS of renovated residential buildings replacing new construction is expected to increase over time, with more significant effects becoming apparent in the middle to long term (Fig. 2b). Given certain renovation rates, demolition restriction can further increase the quantity of renovated residential buildings while reducing annual construction. Although this effect may remain modest in the near term, it is anticipated to become more pronounced in the middle to long term (e.g., around 2060 and beyond), potentially leading to the FS of annual renovation surpassing that of new construction (Fig. 2b). This transition would signify a paradigm shift in China's construction sector—from conventional large-scale demolition and construction to a sustainable mode where renovation serves as the primary method for satisfying urban housing demands (Supplementary Fig. 18), similarly as seen currently in many industrialized countries. Overall, the combination of imminent HVR reduction, renovation and demolition restriction will effectively reduce new construction in the near, middle, and long term, paving the way for a more sustainable construction sector.

A conservative estimate suggests that renovation, as a substitute for new construction, could reduce approximately 80% of carbon emissions per unit of FS supplied for residential buildings (Supplementary Fig. 8), while the carbon emissions associated with reduced housing demands by HVR reduction can be directly avoided. Furthermore, the autonomous decrease in the carbon intensity of construction, driven by societal carbon mitigation actions (Supplementary Note 4), suggests that earlier reductions in construction activities may yield greater carbon emission reductions. Consequently, the annual carbon emission reductions across all analyzed mitigation strategies are projected to peak before 2060 (Fig. 2c), with the near-term demand-side mitigation through HVR reduction contributing more significantly to cumulative carbon emission reductions compared to renovation or demolition restriction (Fig. 2d).

For each analyzed period, the preset demolition restriction strategy can double the carbon mitigation effectiveness achieved by renovation (Fig. 2d). When HVR reduction is incorporated, the carbon mitigation contributions from renovation and demolition restriction would merely be decreased with minimal variations, especially in the near term (2023–2060) (Fig. 2d). This indicates that HVR reduction and renovation/demolition restriction, addressing demand and supply sides respectively, can generate superimposed carbon mitigation benefits.

Renovation and its combination with demolition restriction yield substantially higher cumulative carbon emission reduction ratios over 2023–2100 than those over 2023–2060 (Fig. 2e). On the contrary, the benefits of HVR reduction are most impactful in the near term, with carbon emission reduction ratios over 2023–2060 higher than those achieved through the combined effects of renovation and demolition restriction (Fig. 2e). Thereby, to ensure that China's 2060 carbon neutrality goal remains achievable, we strongly advocate for

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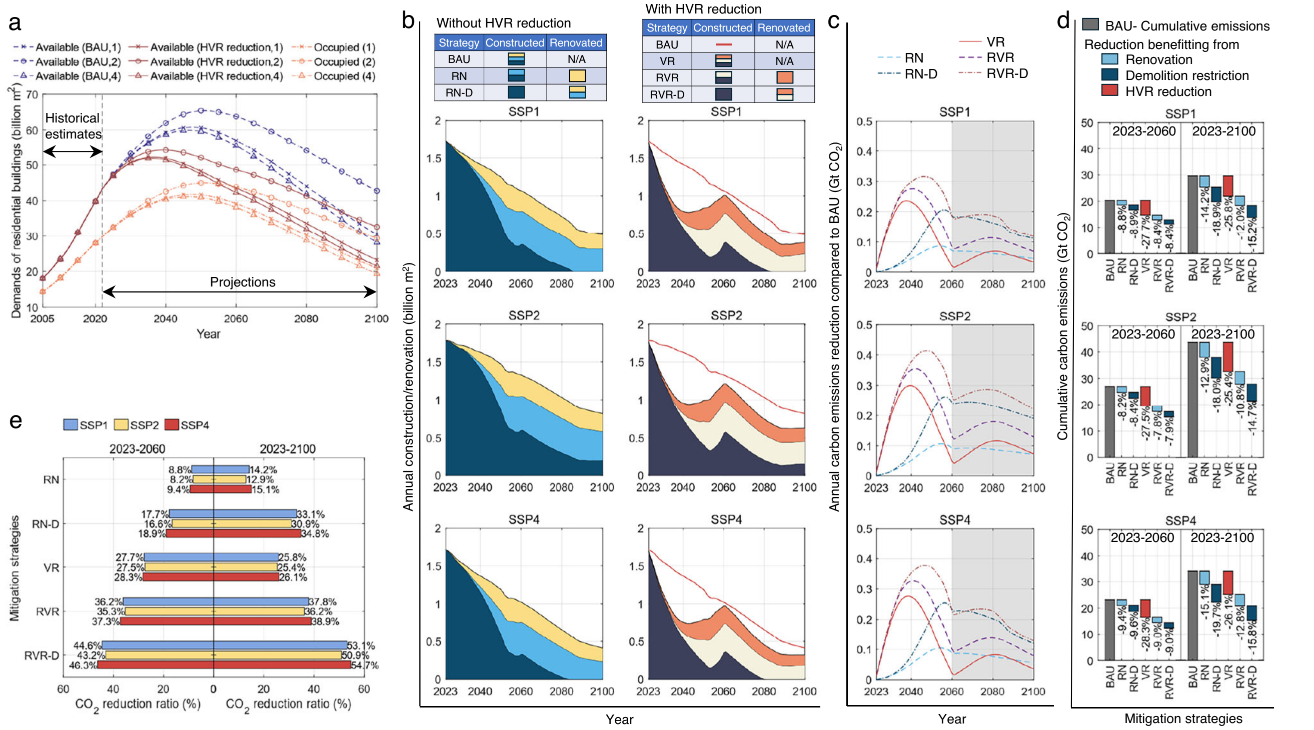

Fig. 2 | Projections of residential building construction, renovation, and carbon emission reduction effects with mitigation strategies for vacant residential building utilization under various background scenarios. a Demands of occupied and available residential buildings; the number in the bracket denotes the SSP. **b** Pathways for annual construction and renovation; under each SSP, the annual floor spaces (FSs) of residential buildings required to be completed, which can be met through new construction and/or renovation, are identical across the analyzed strategies without housing vacancy rate (HVR) reduction, i,e., BAU (business as usual), RN (renovation), and RN-D (demolition restriction + renovation); such consistency also holds for the strategies with HVR reduction, i.e., VR (HVR reduction), RVR (renovation + HVR reduction), and RVR-D (demolition restriction + renovation + HVR reduction). **c** Reductions of annual carbon emissions from residential building construction and renovation compared to BAU by adopting different mitigation strategies. **d** Contributions of different mitigation strategies to the reduction of cumulative carbon emissions from residential building construction and renovation over 2023–2060 or 2100. **e** Reduction ratios of cumulative carbon emissions from residential building construction and renovation compared to BAU by adopting different mitigation strategies over 2023–2060 or 2100. **Note:** Since this study focuses on analyzing mid- to long-term variation trends in residential building stock and cumulative carbon mitigation over decades, the annual changes in construction, renovation and carbon emissions shown here reflect general trends. However, actual yearly fluctuations of residential building construction or renovation may also be influenced by other factors not considered in this study, such as prices and market conditions.

heightened attention and imminent actions to prioritize HVR reduction in residential building management.

As shown in Fig. 2e, for a specific combination of mitigation strategies, the differences in cumulative carbon emission reduction ratios under different background scenarios are relatively minor. The reduction ratios under SSP2 are slightly lower in most cases, attributed to its comparatively higher demands for occupied residential buildings (Fig. 2a). This indicates that the context of slowdown or decline in China's population and housing demands could amplify the carbon mitigation contribution of vacant residential building utilization. Due to the superimposed benefits of the proposed mitigation strategies, multi-strategy combinations (e.g., RVR-D) can achieve the most significant reductions in cumulative carbon emissions across all analyzed background scenarios, estimated to range from 43.2% to 46.3% over 2023–2060, and from 50.9% to 54.7% over 2023–2100 (Fig. 2e).

Influence of service lifespan and regulation targets

The above analyses are predicted on the assumption that the service lifespan of urban residential buildings in China will maintain consistent with the current status. However, this assumption may be subject to change in future development due to the possible implementation of the widely advocated building service lifespan extension (SLE)[7,10,14,15,52]. SLE has the potential to facilitate demand-side mitigation of residential building construction (Fig. 3a), though its carbon mitigation mechanism is different from that of HVR reduction. Specifically, SLE delays the retirement of available residential buildings, whereas HVR reduction maximizes the actual utilization of available residential buildings to meet housing demands. Consequently, the carbon mitigation contributions of HVR reduction are only marginally influenced by the incorporation of SLE (Fig. 3b). However, due to the reduced generation of reusable residential buildings under SLE, the carbon mitigation benefits of renovation and demolition restriction will be notably diminished (Fig. 3b). Despite this, SLE could increase the maximum reductions of cumulative carbon emissions over 2023–2060 and 2023–2100 to 61.0% and 63.7%, respectively, under the Sustainability pathway (SSP1) (Fig. 3c).

While SLE represents a promising approach to reducing embodied carbon emissions, it is important to recognize that the continued use of old buildings without renovation may lead to carbon lock-in[16,53] during their service. This phenomenon occurs when outdated building functionalities lead to elevated operational carbon emissions. Therefore, the practical decision between renovation and SLE must be informed by a comprehensive assessment based on the lifecycle carbon emissions, especially in an era characterized by rapid advancements in low-carbon building technologies. In this context, extending the average service lifespan beyond 50 years was not analyzed in this study. For the current status of existing residential building stock in China, the utilization of vacant residential buildings could be a more effective carbon mitigation solution than the widely advocated SLE (Fig. 3c). Even when SLE has already been adopted, vacant residential building utilization can still more than double the carbon mitigation benefits (Fig. 3c), warranting special attention at this timing.

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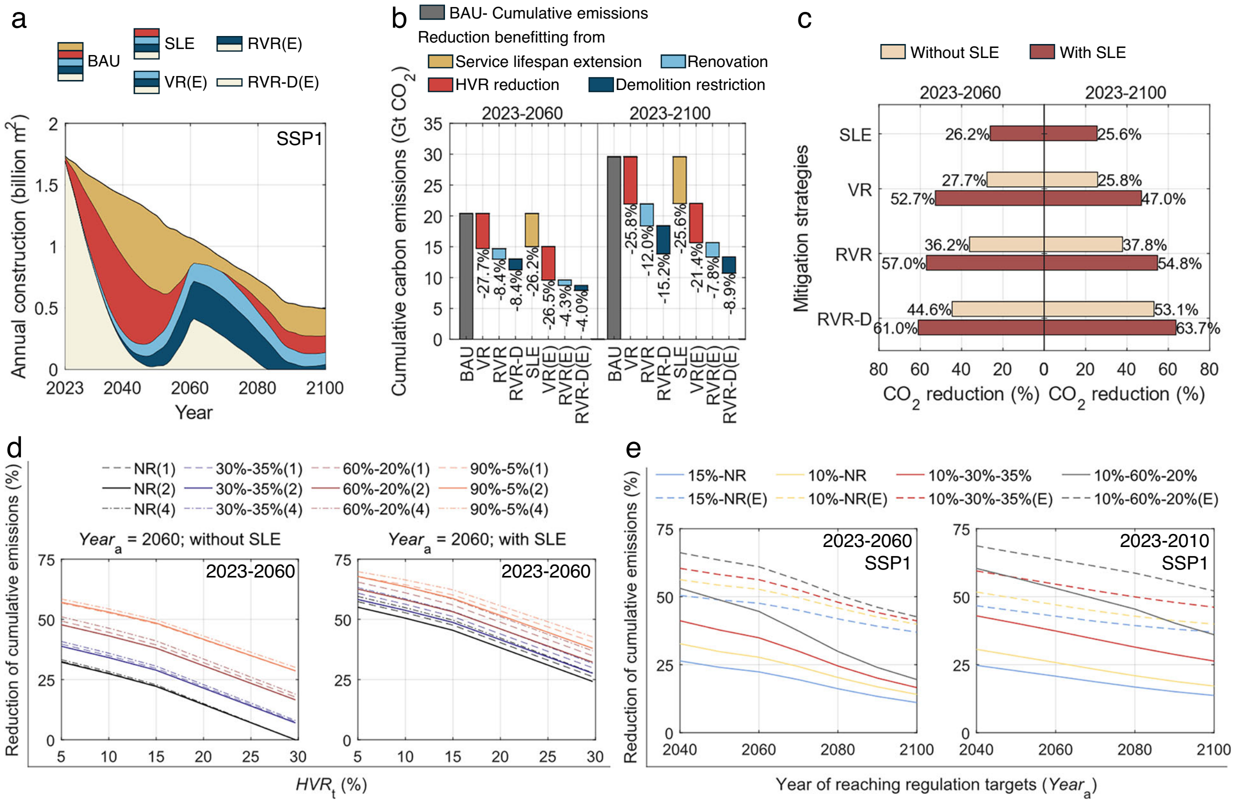

Fig. 3 | Variations of service lifespan and regulation targets on carbon mitigation effects of vacant residential building utilization. **a** Projections of annual construction with different mitigation strategies under SSP1; BAU denotes business as usual, SLE denotes service lifespan extension, VR denotes housing vacancy rate (HVR) reduction, RVR denotes renovation + HVR reduction, RVR-D denotes demolition restriction + renovation + HVR reduction, and (E) denotes the combined implementation of SLE. **b** Contributions of different mitigation strategies to the reduction of cumulative carbon emissions from residential building construction and renovation (2023–2060/2100) in the context with and without SLE under SSP1. **c** Reduction ratios of cumulative carbon emissions from residential building construction and renovation (2023–2060/2100) compared to BAU by adopting different mitigation strategies with and without SLE under SSP1. **d** Variations of the cumulative carbon emission reduction ratio over 2023–2060 with respect to the target value of housing vacancy rate (HVR_t); legend numbers denote the target value of renovation rate ($r_{R,t}$)-the target value of over-demolition ratio ($r_{D,t}$), while NR denotes no renovation, and the number within the bracket denotes SSP scenario; $Year_a$ denotes the year of reaching the regulation targets. **e** Variations of cumulative carbon emission reduction ratio over 2023–2060 or 2100 with respect to $Year_a$ under SSP1; legend numbers denote the value of HVR_t-NR or the values of HVR_t-$r_{R,t}$-$r_{D,t}$. **Note:** For SLE, the service lifespan of urban residential buildings is extended to the code-specified 50 years by the year of 2060, with expected changes as shown in Supplementary Fig. 14.

The default parameter values provided in Table 1 and the carbon mitigation effects obtained above correspond to a modest level of regulation through vacant residential building utilization (see "Methods"). Targeted carbon mitigation levels can be achieved by adjusting the regulation targets or timeline for achieving regulation targets ($Year_a$). As illustrated in Fig. 3d, when $Year_a$ is fixed at 2060, the cumulative emission reduction ratio increases approximately linearly as the HVR target decreases. Stricter renovation and demolition restriction targets also enhance the carbon reduction ratio, with more significant effects observed in scenarios without SLE. The trends and levels of cumulative emission reduction ratios are consistent across the three background scenarios analyzed.

Figure 3e indicates that achieving the HVR target earlier may reduce cumulative emissions more effectively than specifying a more stringent target. For example, achieving and maintaining a HVR of 15% by 2040 may result in reduction ratios that rivals achieving and maintaining an HVR of 10% by 2060. Consequently, failing to utilize existing vacant residential buildings promptly will cause a significant loss of carbon emission reduction potential. Regarding renovation and demolition restriction strategies, prompt action is critical for achieving efficient short-term carbon mitigation, while achieving higher cumulative emission reduction ratios over a long-term period relies more on sustained efforts of tightening regulation targets (Fig. 3e). A similar conclusion can be drawn in the context of SLE, although the reduction ratios are less sensitive to changes in $Year_a$.

Implications for China's carbon mitigation

While the anticipated slowing growth or decline in housing demand may reduce the share of residential building construction in China's carbon emissions, the expected slower decarbonization of construction compared to the social average level under the SSP1 (Supplementary Fig. 19) tends to increase this share (Fig. 4a). Under SSP1 without mitigation strategies, the share of residential building construction in China's cumulative emissions over 2023–2060 is close to the historical value observed for 2011–2022 (Fig. 4b). This finding implies that the embodied carbon emissions of buildings could remain as a bottleneck for achieving carbon neutrality.

Meanwhile, the proportion of carbon emission reduction achieved by multiple vacant residential building utilization strategies (RVR-D) in China's annual carbon emissions is expected to rise over the years and then maintain at a high level (Fig. 4a). Overall, RVR-D has the potential to reduce China's carbon emissions by 2.4%–3.7% during 2023–2060, with the contribution of vacant residential building utilization to societal decarbonization being especially prominent for the SSP1 (Fig. 4b).

The cumulative carbon emissions from conventional urban residential building construction (i.e., BAU) under SSP1, although lower

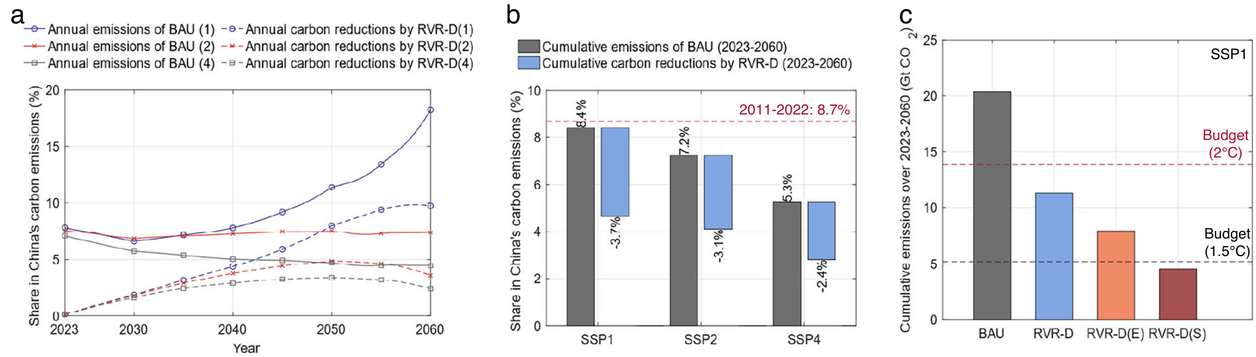

Fig. 4 | Implications of carbon mitigation by vacant residential building utilization for societal decarbonization in China. a Shares of annual carbon emissions from residential building construction with BAU (business as usual) and annual carbon reductions by RVR-D [demolition restriction + renovation + housing vacancy rate (HVR) reduction] in China's annual carbon emissions; the number within the bracket in legend denotes SSP scenario. **b** Shares of cumulative carbon emissions from residential building construction with BAU and cumulative carbon reductions by RVR-D in China's cumulative carbon emissions over 2023–2060. **c** Comparisons of cumulative carbon emissions by adopting different mitigation strategies with the 2 °C- and 1.5 °C-compatible carbon budgets for urban residential building construction in China over 2023–2060; (E) denotes the combined implementation of service lifespan extension (SLE, as shown in Supplementary Fig. 14); (S) denotes the strategy implementation with SLE and stringent regulation targets for HVR (HVR_t), renovation rate ($r_{R,t}$) and over-demolition ratio ($r_{D,t}$), specifically $HVR_t = 5\%$, $r_{R,t} = 90\%$, $r_{D,t} = 5\%$, while the year of reaching the regulation targets ($Year_a$) is set to be 2040. **Note:** See Supplementary Data 16 and Supplementary Data 17 for historical records (2011–2022) and projections (2023–2060) of China's carbon emissions used for calculations.

than those under other background scenarios (Fig. 2d), are still projected to notably exceed the 2 °C-compatible carbon budget (Fig. 4c), which is allocated from the global carbon budget (see "Methods"). A modest level of regulation through multiple vacant residential building utilization strategies (RVR-D) could reduce emissions to levels below the 2 °C-compatible budget. Further tightening the targets and extending the residential building service lifespan [RVR-D(S)] can bring the cumulative carbon emissions from urban residential building construction and renovation over 2023–2060 within the 1.5 °C-compatible budget (Fig. 4c). Therefore, vacant residential building utilization emerges as a key strategy for effectively managing carbon budgets in China's future urban construction.

Discussion

As of 2024, several policies facilitating vacant residential building utilization have been promptly implemented in China. For example, local government of multiple cities have initiated the purchasing of unsold residential buildings (Supplementary Table 12), and over 258,800 old urban communities have been updated nationwide since 2019[54]. However, the lack of sufficient identification and quantification regarding housing vacancy has rendered current policies inadequate for promoting effective vacant residential building utilization. For instance, the government purchasing primarily addresses the temporary economic crisis in the real estate sector, lacking clear targets for assuring long-term implementation. Additionally, other types of vacancies, such as excessive housing held by residents, remain unaddressed. Past renovation efforts for old communities have mostly focused on updating facilities in occupied communities, with insufficient attention to the renovation of vacant, reusable residential buildings. Moreover, the absence of quantitative metrics and regulatory tools hinders the tracking of policy implementation progress, creating uncertainties about their effectiveness and timeliness.

Therefore, to fully realize the potential benefits from vacant residential building utilization, it is imperative to elevate current fragmented policies into an evidence-based, coordinated, and systematic national policy and action plan. This need is especially pressing given China's enormous urban residential building stock and regional disparities in policy acceptance. The quantitative methods developed in this study for identifying various categories of vacant residential buildings and regulating their interrelated utilization benefits through three vacant residential building utilization strategies could facilitate such improvements. Decarbonization is a core priority in China's forthcoming 15th Five-Year Plan commencing in 2026, which is about to initiate carbon reduction control based on sectoral and regional carbon budgets[55]. Therefore, by quantitatively linking macro-strategy parameters for vacant residential building utilization with carbon mitigation benefits and carbon budgets, this study not only identifies the low-hanging yet underexploited opportunities vacant residential building utilization offers for China's carbon mitigation efforts, but also provides a scientific foundation for setting quantitative regulation targets. Such targets would support the formulation of long-term macro-control policies for vacant residential building utilization, coordinating sustainable urban development with climate goals.

The issue of high HVR may also be observed in other countries or regions, such as Japan[56]. Additionally, the contradiction between rapid urbanization and insufficient regional governance in developing countries/regions may pose similar risks of excessive housing vacancy. The mitigation strategies and the decision-making model we proposed for addressing the severe vacancy situation in China could shed light for policy-making in those regions as well. This approach could help formulate shared strategic targets and systematic policy plans aimed at carbon mitigation goals, considering the specific characteristics of housing stock and demand evolution across various regions. Such strategies may help pave the way for resource-efficient construction of sustainable cities and communities, thereby advancing global climate actions. Moreover, our data calibration method offers insights for analysis in other regions with incomplete housing vacancy statistics. Last, we call for clarifying the statistical definitions and improving the survey methods for new vacant, underused, and reusable residential buildings. Strengthening these efforts will enhance our understanding of building stock status and enable the setting of more reliable quantitative targets.

Methods

Historical estimates of urban residential buildings in China

This study encompasses 31 provinces, municipalities, and autonomous regions in the Chinese Mainland. Given the limited mobility of residential buildings between urban and rural areas (except for conversions resulting from urban expansion[18]), a distinction is made between urban and rural areas to accurately capture the dynamic changes in FS of residential buildings. A comprehensive analysis has been made on available authoritative records regarding residential buildings, including data from China Statistical Yearbooks, China Population Censuses, and 1% Population Sample Surveys (commonly referred to as

Micro Censuses) released by the National Bureau of Statistics of China, as well as China Urban and Rural Construction Statistical Yearbooks published by Ministry of Housing and Urban-Rural Development of China (Supplementary Note 1). From these sources, annual records of completed residential buildings from China Statistical Yearbooks and surveys of existing in-service residential buildings from censuses (including China Population Censuses and Micro Censuses) were selected for estimating historical residential building stock.

Due to the incomplete statistical calibers of residential buildings in China Statistical Yearbooks (e.g., limited to sampling household surveys, fixed-asset investments, construction enterprise projects, or real estate development projects), amplification factors are applied to adjust the annual records of completed urban residential buildings [Supplementary Equation (4)]. Besides, census surveys underrepresent the newly completed but unsold residential buildings, leading to discrepancies with data from China Statistical Yearbooks (Supplementary Note 1). To address these discrepancies, we propose the following calibration method, which allows for the identification of new vacant residential buildings while avoiding underestimation of completed residential buildings (see Supplementary Note 2 for more details).

For calibration based on the available data from censuses, we exclude the residential buildings that have not been put into service within five years of completion from the estimated completed ones (Fig. 1b), and assume that the service lifespans (L_s) of residential buildings follow normal distributions with the coefficient of variance (CV) being 1/3[35,57]. Then, the following quantitative relationship is constructed to calibrate α^k and $\mu_{L_s}^k$ (i.e., the amplification factor and mean service lifespan for the k^{th} residential building group with completion years between s_k and e_k):

$$I_{Y_c,k} = \sum_{j=s_k}^{e_k} \alpha^k N_j \left[1 - \Phi\left(\frac{Y_c - j - \mu_{L_s}^k}{\mu_{L_s}^k/3}\right)\right], \quad Y_c = 2005, 2010, 2015, 2020\,;\ s_k < e_k < Y_c - 5 \tag{1}$$

where $I_{Y_c,k}$ is the FS of in-service residential buildings within the k^{th} group from the census in year Y_c; N_j is the recorded FS of completed residential buildings in year j from China Statistical Yearbooks; $\Phi(\cdot)$ is the cumulative distribution function (CDF) of standard normal distribution. The calibrated FS of residential buildings completed in year j (C_j) is then estimated by:

$$C_j = \alpha^k N_j,\ \ s_k \le j \le e_k \tag{2}$$

Furthermore, census FSPC distributions (i.e., the proportion of households classified by FSPC) show a bimodal pattern, where the high frequencies at high FSPC intervals may not represent the essential demands for occupied residential buildings (Fig. 1c). Thereby, we fit a rational distribution pattern (assuming a gamma distribution[58,59]) to the FSPC data after excluding two bins for high FSPC intervals (Fig. 1c). Then, the reduction in the mean of the fitted gamma distribution compared to the mean FSPC of the original data estimates the underused proportion. These estimates align reasonably with results from online-listed unit investigations[48] (Supplementary Note 4) and a report by China International Capital Corporation (CICC)[36] (Supplementary Note 6).

Dynamic housing stock model incorporating housing vacancy

We propose a dynamic housing stock model incorporating housing vacancy to estimate the development pathways of residential building construction and associated carbon emissions, with its workflow presented in Supplementary Fig. 7. A brief introduction of the model is provided below, with detailed explanations elaborated in Supplementary Note 3.

The calibrated FSs and the service lifespans of annually completed residential buildings are used as inputs to estimate the composition of available residential building stock by completion years for each analyzed year:

$$A_i = \sum_{j=Y_0}^{i} C_j \left[1 - F_{L_{s,j}}(i-j)\right] \tag{3}$$

where A_i is the FS of available residential building stock in year i; $F_{L_{s,j}}(\cdot)$ is the CDF for the service lifespan of residential buildings completed in year j ($L_{s,j}$); Y_0 is the start year from which the completed residential buildings are considered (e.g., 1940 in this study). Correspondingly, the FS of residential buildings retiring in year i (R_i) is calculated using the following equation:

$$R_i = C_i F_{L_{s,i}}(0) + \sum_{j=Y_0}^{i-1} C_j \left[F_{L_{s,j}}(i-j) - F_{L_{s,j}}(i-j-1)\right] \tag{4}$$

Similarly, the FS of the available residential buildings that become obsolete in year i (O_i) can be calculated using the following equation:

$$O_i = C_i F_{L_{M,i}}(0) + \sum_{j=Y_0}^{i-1} C_j \left[1 - F_{L_{s,j}}(i-1-j)\right] P(L_{M,j} \le i-j \mid L_{M,j} > i-1-j) \tag{5}$$

where $F_{L_{M,j}}(\cdot)$ is the CDF of maximum lifespan for the residential buildings completed in year j ($L_{M,j}$), determined based on the historical development of structural design codes in China and potential impact of climate change, as elaborated on in Supplementary Note 4.

Subsequently, the cumulative FS of reusable residential buildings in year i (U_i) can be estimated by:

$$U_i = (1 - r_{D,i}) \cdot (R_i - O_i) + \hat{U}_i \tag{6}$$

where $r_{D,i}$ is the over-demolition ratio of newly added reusable residential buildings in year i; and $\hat{U}_i$ is the remaining FS of the reusable residential buildings that have retired before year i (see Supplementary Note 3 for details). Conservatively, the accumulation of reusable residential buildings has been quantified starting from 2005, i.e., $\hat{U}_{2005} = 0$.

Additionally, the housing vacancy rate within available residential building stock in year i (HVR_i) is calculated as:

$$HVR_i = 1 - \frac{D_i^{\text{u}}}{A_i} \tag{7}$$

where D_i^{u} is the historical or anticipated demand of urban occupied residential buildings in year i, see Supplementary Note 4.

For historical estimates, an inflow-driven analysis using Eqs. (3)–(7) is employed. The FS of underused residential buildings is calculated as the difference between the FS of in-service residential buildings [Hermite interpolation based on results via Supplementary Equation (2)] and the estimated D_i^{u}. The excess of the available residential building stock [Eq. (3)] over in-service residential buildings is considered as new vacant ones. Meanwhile, the dynamic changes of reusable residential buildings [Eq. (6)] are estimated in parallel with the available residential building stock and can be regulated by the over-demolition ratio. Since residential building renovation practices before 2022 are sporadic, renovated reusable residential buildings are not included in the historical estimates of available residential building stock and HVR.

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For future projections of residential building construction, a stock-driven analysis is conducted based on the status of residential building stock derived from historical estimates and the future demands of occupied residential buildings determined using bottom-up information from background scenarios (Supplementary Note 4). The required FS of completed residential buildings in year i (C_i) for meeting housing demands can be evaluated through incremental calculations, as expressed by the following equation:

$$C_i = \frac{D_i^{\mathrm{u}} \cdot (1 + HVR_i) - \sum_{j=Y_0}^{i-1} C_j \left[1 - F_{L_{s,j}}(i-j)\right]}{1 - F_{L_{s,i}}(0)} \tag{8}$$

Since all three categories of vacant residential buildings within the available residential building stock—underused, new vacant and renovated reusable ones—are considered capable of meeting housing demands, future projections do not distinguish among these categories, but instead estimate and regulate their total amount using the HVR_i parameter. It should be noted that reusable residential buildings are included in the available residential building stock after renovation, while their inclusion is regulated by the renovation rate. Correspondingly, the required FS of renovated reusable residential buildings (RN_i) and newly constructed residential buildings (CS_i) in year i are respectively evaluated as:

$$\begin{cases} RN_i = r_{\mathrm{R},i} U_i - r_{\mathrm{R},i-1} \hat{U}_i \\ CS_i = C_i - RN_i \end{cases} \tag{9}$$

where $r_{\mathrm{R},\ i}$ is the renovation rate of reusable residential buildings in year i.

Since data on the completion years of urban residential buildings used for data calibration are only available from censuses beginning in 2005 (Supplementary Note 1), the time interval of historical estimates is defined as 2005–2022 (Supplementary Note 2). Additionally, as the SSPs, which form the basis for background scenario development, provide forecasts extending to year 2100[50], the future projection period is set from 2023 to 2100.

This updated dynamic model incorporates three major categories of vacant residential buildings identified in China, enabling quantitative analysis of dynamic changes in vacant residential buildings with varying utilization potential. Furthermore, by introducing three time-dependent strategy parameters—HVR, renovation rate, and over-demolition ratio—this model allows for the assessment of decarbonization opportunities from vacant residential building utilization, based on the dynamic balance between supply and demand.

Carbon emissions of construction and renovation

This study examines the embodied carbon emissions caused by the material production and construction processes associated with the construction and renovation of residential buildings. The carbon intensity of renovation is inferred based on the ratio of carbon emissions from renovation or refurbishment to those from new construction, by reviewing relevant data in existing studies[60–62] (see Supplementary Note 3 for details). By integrating the FS of annual construction and renovation derived from the dynamic housing stock model and their corresponding carbon intensities, the annual carbon emissions from construction and renovation of residential buildings in year i (E_i) can be calculated as follows,

$$E_i = \beta_{\mathrm{C},i}(CS_i + \gamma_{\mathrm{R},i} RN_i) \tag{10}$$

where $\beta_{\mathrm{C},i}$ represents the carbon intensity of construction in year i; $\gamma_{\mathrm{R},i}$ is the ratio of the carbon intensity of renovation to that of construction for the residential buildings renovated in year i. It is important to note that the emissions of various GHGs associated with residential building construction have been converted to carbon dioxide equivalents based on global warming potential.

Development of background scenarios

The scenarios for future pathway projections are developed based on SSPs, each involving calibrations and/or projections of the following three datasets for the period 2005–2100 (Supplementary Note 4):

(1) Housing demands: Projections of urban housing demands are determined using SSP-based population trends for China as provided by Jiang et al.[63], as well as the temporal variations in urbanization rate and the changes in urban FSPC relative to per capita cumulative GDP calibrated by logistic functions. Historical urbanization rates derived from census data are utilized for calibration, and the saturation values of urbanization rate under different SSPs are determined following Chen et al.[64]. Besides, the urban FSPC is calibrated using China's GDP data from the World Bank World Bank Group[65] and historical urban FSPC inferred from census records, with saturation values determined with reference to IRP[66] and Hu et al.[67]. Future variations in FSPC of occupied residential buildings are forecasted based on SSP-based GDP predictions from Jiang et al.[63].

(2) Carbon intensity of construction: The carbon intensity of construction is determined by cumulating the carbon emissions from material production and construction-related energy consumption per unit FS of residential buildings. Based on material and energy consumption data for constructing different types of residential buildings[4,68,69] and the proportions of multiple types of residential buildings reported in the 2020 China Population Census[45], the average consumptions of materials and energy for constructing unit FS of residential buildings are estimated. These estimates, combined with the anticipated carbon emission factors of major building materials[70] and final energy consumption[50] under each analyzed background scenario, are used to determine the temporal variations in carbon intensity of construction. The analysis of time variations in material or energy intensities for construction lies beyond the scope of this study.

(3) Maximum lifespan of residential buildings: The maximum lifespan of residential buildings is determined based on the structural durability for safety considerations. Default maximum lifespan values are initially established without accounting for climate change, based on the historical development of China's building structure design codes. Climate change-induced accelerated structural degradation may reduce structural durability[71–74], thereby shortening the maximum lifespan of residential buildings. To address climate change adaptation[71,73,74], default values are adjusted to account for temperature-related impacts. The adjusted values for urban residential buildings (Supplementary Fig. 13) fall within the range of currently reported service lifespans of residential buildings in developed countries, such as 44 years in the USA and 132.6 years in the UK[15].

Overall, during the period 2005–2100, housing demands are ranked as SSP2 > SSP1 > SSP4 (Fig. 2a), while the carbon intensity of construction as SSP4 > SSP2 > SSP1 (Supplementary Fig. 11), and the maximum lifespan of residential buildings as SSP1 > SSP2 > SSP4 (Supplementary Fig. 13).

Default regulation targets for mitigation strategies

Since 2060 is the target year for carbon neutrality pledged by the Chinese government, it is expected that China's carbon mitigation policies will continue to intensify until then. Thereby, the default transition period is set as 2023–2060, during which the strategy parameters are assumed to become increasingly stringent each year.

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Stricter or more lenient policy implementation could lead to the regulation targets being achieved earlier or later, respectively, corresponding to higher or lower reduction of cumulative carbon reductions (Fig. 3d, e). The variations in strategy parameters between 2022 and 2060 are interpolated using Hermite functions with zero slopes at both ends, representing an initial period of slow change, followed by a phase of rapid change, and finally a gradual transition towards a stable trend (Supplementary Fig. 16).

The default HVR target for the HVR reduction strategy is set at 10%. This ratio aligns with the upper limit of the widely recognized healthy HVR range (5%–10%[38]) and slightly exceeds the natural HVR (reasonable housing vacancy accommodating population mobility) for 2017, which was 9.8% as inferred by Gan[43]. With the optimized management of existing residential buildings through HVR reduction, the natural HVR is expected to decrease further, potentially to around 5%[40]. Therefore, the default HVR target set for the HVR reduction strategy represents a modest level of regulation.

In addition, the notice issued by the Chinese government in 2021 regarding the prevention of large-scale demolition and construction stipulates that, in principle, the demolished floor space within an urban renewal area or project should not exceed 20% of the total existing floor space[31]. The default target of over-demolition ratio ($r_{D,t}$) set in this study matches this requirement, and is anticipated to be achieved nationwide after sustained efforts to promote this policy. With the progress of urban renewal actions in China, there may be potential to tighten this ratio further. As such, the default target for $r_{D,\,t}$ represents a modest level of regulation.

With the default value of $r_{D,t}$ set as described above, achieving the target renovation rate ($r_{R,t}$) of 60% can maintain the FS of unrenovated reusable residential buildings at a level similar to that without demolition restriction and renovation (Supplementary Fig. 20). This suggests that the existing residential buildings preserved by the default demolition restriction strategy can largely be renovated. Consequently, 60% is set as the default value of $r_{R,t}$, which is compatible with the modest demolition restriction for carbon mitigation. Even without demolition restriction, this $r_{R,t}$ value still corresponds to year-by-year increases in the FS of unrenovated reusable residential buildings (Supplementary Fig. 20), indicating room for further increases in the $r_{R,t}$, i.e., the default renovation rate target represents a modest level of regulation.

Overall, the carbon emission reduction levels derived under the default strategy parameters values represent the effectiveness of a modest level of efforts for vacant residential building utilization. This conservative determination intentionally incorporates real-world constraints on the feasibility of vacant residential building utilization, such as spatial mismatches of vacant residential buildings and housing demands, technical and economic challenges in renovation, and insufficient performance of old residential buildings in satisfying new demands. These factors inherently limit achievable vacant residential building utilization, causing outcomes to diverge from the ideal full utilization condition even with policy interventions. Furthermore, sensitivity analysis of the regulation targets for three strategy parameters around their default values (Fig. 3d, e) accommodates a range of practical scenarios and ensures our analysis is based on realistic assumptions.

Carbon budget for urban residential building construction

The Chinese government is planning to advance its carbon neutrality efforts based on carbon budget management[55]. However, specific carbon budget values have yet to be announced. For demonstrative purposes, tentative 2 °C-compatible and 1.5 °C-compatible carbon budgets for urban residential building construction are derived by allocating the global carbon budget based on China's proportion of global population (Supplementary Table 14) and the anticipated contribution of urban residential building construction to China's carbon emissions for business as usual (BAU) under SSP1 (8.4%, as illustrated in Fig. 4b).

The global carbon budgets from the beginning of 2020 until the achievement of net-zero GHG emissions were estimated at 500 Gt CO_2 for a 50% likelihood of limiting global warming to 1.5 °C and 1150 Gt CO_2 for a 67% likelihood of limiting warming to 2 °C[51]. Considering China's target of achieving carbon neutrality by 2060, this study compares the cumulative carbon emissions from urban residential building construction during 2023–2060 to the corresponding carbon budgets for the same period. The global carbon budgets for this period are calculated by subtracting the cumulative global carbon emissions over 2020 and 2022 from the mentioned total budgets beginning in 2020 (Supplementary Table 14).

Limitations and prospects

The assumptions made in this study—such as excluding the reusable residential buildings retired before 2005, the residential buildings not in service for more than five years post-completion, unfinished residential buildings, and underreported residential buildings in statistics records—may result in conservative estimates of carbon emission reductions through vacant residential building utilization. Furthermore, supplementing this analysis with additional demographic data reported in more future years could further improve the reliability of the calibrated results.

For future research, considering land supply constraints in urban areas may improve the coordinated selection of strategy parameters for renovation and demolition restrictions. Additionally, spatial mismatches between existing vacant residential buildings and emerging housing demands present a significant barrier to effective utilization. While China's policy of coordinated regional development may help alleviate this challenge, further improvements to urban planning, transportation, and residential building management are essential to enable more effective utilization of vacant residential buildings for meeting evolving regional housing demands. Moreover, advancements in building durability, maintenance technologies, and retrofitting techniques—as well as the upskilling of industry professionals in these areas—are likely to extend the service lifespans of existing structures beyond current projections while enhancing achievable renovation rates, ultimately unlocking even greater low-carbon potential in the vacant residential building utilization.

Data availability

The data that support the findings of this study are available in the Supplementary Information and Supplementary Data. The authoritative statistical and demographic data on residential buildings are available from the National Bureau of Statistics of China (https://www.stats.gov.cn/sj/ndsj/ and https://www.stats.gov.cn/sj/pcsj/). The results generated in this study can be reproduced from our codes deposited in Code Ocean, publicly accessible at https://codeocean.com/capsule/0932821.

Code availability

Data analyses are conducted in MATLAB (version R2024b). The MATLAB codes used to generate the results presented in this paper are deposited in Code Ocean and are publicly accessible at https://codeocean.com/capsule/0932821.

References

1. Creutzig, F. et al. Urban infrastructure choices structure climate solutions. *Nat. Clim. Change* **6**, 1054–1056 (2016).
2. Climate Watch. Historical GHG emissions (1990–2021). climatewatchdata.org/ghg-emissions (2024).
3. National Development and Reform Commission. Working guidance for carbon dioxide peaking and carbon neutrality in full and faithful

implementation of the new development philosophy. https://en.ndrc.gov.cn/policies/202110/t20211024_1300725.html (2021).
4. Zhong, X. et al. Global greenhouse gas emissions from residential and commercial building materials and mitigation strategies to 2060. *Nat. Commun.* **12**, 6126 (2021).
5. Xiao, J. & Zou, S. Cement at 200: towards net-zero fully recycled concrete. *Nature* **631**, 740–740 (2024).
6. Watari, T., Cao, Z., Hata, S. & Nansai, K. Efficient use of cement and concrete to reduce reliance on supply-side technologies for net-zero emissions. *Nat. Commun.* **13**, 4158 (2022).
7. Olsson, J. A., Miller, S. A. & Alexander, M. G. Near-term pathways for decarbonizing global concrete production. *Nat. Commun.* **14**, 4574 (2023).
8. Chen, L. et al. Green construction for low-carbon cities: a review. *Environ. Chem. Lett.* **21**, 1627–1657 (2023).
9. Giesekam, J., Barrett, J. R. & Taylor, P. Construction sector views on low carbon building materials. *Build. Res. Inf.* **44**, 423–444 (2015).
10. Song, L. et al. China's bulk material loops can be closed, but deep decarbonization requires demand reduction. *Nat. Clim. Change* **13**, 1136–1143 (2023).
11. Xia, C. et al. Outsourced carbon mitigation efforts of Chinese cities from 2012 to 2017. *Nat. Cities* **1**, 480–488 (2024).
12. Creutzig, F. et al. Demand-side solutions to climate change mitigation consistent with high levels of well-being. *Nat. Clim. Change* **12**, 36–46 (2021).
13. Cao, Z. et al. The sponge effect and carbon emission mitigation potentials of the global cement cycle. *Nat. Commun.* **11**, 3777 (2020).
14. Pauliuk, S. et al. Global scenarios of resource and emission savings from material efficiency in residential buildings and cars. *Nat. Commun.* **12**, 5097 (2021).
15. Wang, J., Zhang, Y. & Wang, Y. Environmental impacts of short building lifespans in China considering time value. *J. Clean. Prod.* **203**, 696–707 (2018).
16. Berrill, P., Wilson, E. J. H., Reyna, J. L., Fontanini, A. D. & Hertwich, E. G. Decarbonization pathways for the residential sector in the United States. *Nat. Clim. Change* **12**, 712–718 (2022).
17. Weber, R. E., Mueller, C. & Reinhart, C. A hypergraph model shows the carbon reduction potential of effective space use in housing. *Nat. Commun.* **15**, 8327 (2024).
18. National Bureau of Statistics of China. China statistical yearbooks. (China Statistics Press, 1999–2023).
19. Ministry of Housing and Urban-Rural Development of China. New achievements have been made in high-quality development of housing and urban and rural construction. https://www.gov.cn/yaowen/shipin/202408/content_6970426.htm (2024).
20. Powell, B. *Inside China's runaway building boom*, https://time.com/archive/6691257/inside-chinas-runaway-building-boom/ (2010).
21. Williams, S., Xu, W., Tan, S. B., Foster, M. J. & Chen, C. Ghost cities of China: identifying urban vacancy through social media data. *Cities* **94**, 275–285 (2019).
22. He, G., Mol, A. P. J. & Lu, Y. Wasted cities in urbanizing China. *Environ. Dev.* **18**, 2–13 (2016).
23. Wakabayashi, D. & Fu, C. China's Real Estate Crisis 'Has Not Touched Bottom'. https://www.nytimes.com/2024/01/30/business/china-evergrande-real-estate.html (2024).
24. Xinhua News Agency. 20th CPC Central Committee to hold 3rd plenary session in July. https://english.www.gov.cn/news/202404/30/content_WS6630ac71c6d0868f4e8e6996.html (2024).
25. Xinhua News Agency. The Political Bureau of the CPC Central Committee held a meeting to analyze and study the current economic situation and economic work. https://www.gov.cn/yaowen/liebiao/202409/content_6976686.htm (2024).
26. Xinhua News Agency. Chinese vice premier urges efforts to ensure delivery of housing projects. https://english.news.cn/20240517/4c88e73b3d274a3f8ea1f46b176b1d18/c.html (2024).
27. The People's Bank of China. The State Council Information Office held a regular policy briefing to introduce the relevant situation about effectively implementing supporting policies for ensuring the delivery of housing. http://www.pbc.gov.cn/goutongjiaoliu/113456/113469/5356698/index.html (2024).
28. Guo, Y. China ramps up efforts to ensure delivery of housing projects. http://english.scio.gov.cn/m/pressroom/2024-08/24/content_117385665.htm (2024).
29. General Office of the State Council. Guiding opinions on comprehensive promotion of renovation work in old urban communities. https://www.gov.cn/zhengce/content/2020-07/20/content_5528320.htm (2020).
30. Ministry of Housing and Urban-Rural Development of PR China. Notice on solidly promoting the renovation of old urban communities in 2023. https://www.gov.cn/lianbo/bumen/202307/content_6892957.htm (2023).
31. Ministry of Housing and Urban-Rural Development of China. Notice on preventing large-scale demolition and construction in the implementation of urban renewal actions. https://www.gov.cn/zhengce/zhengceku/2021-08/31/content_5634560.htm (2021).
32. Ministry of Housing and Urban-Rural Development of China. Notice on steadily and orderly promoting urban renewal. https://www.gov.cn/zhengce/zhengceku/202307/content_6891045.htm (2023).
33. Wu, Y. et al. *Report on building energy consumption in China* (China Association of Building Energy Efficiency, Chongqing, 2016).
34. Cao, Z. et al. Unravelling the mystery of Chinese building lifetime: A calibration and verification based on dynamic material flow analysis. *Appl. Energy* **238**, 442–452 (2019).
35. Huo, T. et al. China's building stock estimation and energy intensity analysis. *J. Clean. Prod.* **207**, 801–813 (2019).
36. Zhang, Y. & Wang, P. *Statistics on China's housing stock* (China International Capital Corporation (CICC), 2018).
37. Shi, L., Leichtle, T., Huang, X., Wurm, M. & Taubenböck, H. The decreasing housing utilization efficiency in China's cities. *Nat. Cities* **2**, 70–80 (2025).
38. Wang, L., Fan, H. & Wang, Y. An estimation of housing vacancy rate using NPP-VIIRS night-time light data and OpenStreetMap data. *Int. J. Remote Sens.* **40**, 8566–8588 (2019).
39. Pan, J. & Dong, L. Spatial identification of housing vacancy in China. *Chin. Geogr. Sci.* **31**, 359–375 (2021).
40. Tan, Z., Wei, D. & Yin, Z. Housing vacancy rate in major cities in China: perspectives from nighttime light data. *Complexity* **2020**, 5104578 (2020).
41. Zhang, C., Jia, S. & Yang, R. Housing affordability and housing vacancy in China: The role of income inequality. *J. Hous. Econ.* **33**, 4–14 (2016).
42. Zhu, Z. The mystery of Chinese real estate vacancy. http://finance.sina.cn/zl/2018-10-26/zl-ihmxrkzw9892115.d.html?from=wap (2018).
43. Gan, L. *Analysis of urban housing vacancy in China in 2017* (China Household Finance Survey and Research Center, Chengdu, 2018).
44. National Bureau of Statistics of China. Sixth National Population Census (Beijing, 2010).
45. National Bureau of Statistics of China. Seventh National Population Census (Beijing, 2020).
46. National Bureau of Statistics of China. 1% National Population Sample Survey in 2005 (Beijing, 2005).
47. National Bureau of Statistics of China. 1% National Population Sample Survey in 2015 (Beijing, 2015).

48. Zheng, H., Zhang, R., Yin, X. & Wu, J. Unused housing in urban China and its carbon emission impact. https://cre.mit.edu/wp-content/uploads/2023/06/UHCE_main_final-hefan-Z.pdf (2024).
49. Cai, W., Wan, L., Jiang, Y., Wang, C. & Lin, L. Short-lived buildings in China: impacts on water, energy, and carbon emissions. *Environ. Sci. Technol.* **49**, 13921–13928 (2015).
50. Riahi, K. et al. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Glob. Environ. Chang* **42**, 153–168 (2017).
51. IPCC. Climate change 2023: Synthesis report. Contribution of working groups I, II and III to the sixth assessment report of the Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change, Geneva, Switzerland, 2023).
52. The State Council of PR China. Thoroughly implement the five-year action plan for people-centered new urbanization strategy. https://www.gov.cn/zhengce/content/202407/content_6965542.htm (2024).
53. Seto, K. C. et al. Carbon lock-in: Types, causes, and policy implications. *Annu. Rev. Environ. Resour.* **41**, 425–452 (2016).
54. People's Daily. Accelerate the transformation of urban development modes and build a new model for real estate development. https://www.gov.cn/lianbo/bumen/202408/content_6970343.htm (2024).
55. General Office of the State Council. Work plan to accelerate the establishment of a dual-control system for carbon emissions. https://www.gov.cn/zhengce/content/202408/content_6966079.htm (2024).
56. Kubo, T. & Yui, Y. *The rise in vacant housing in post-growth Japan* (Springer, 2020).
57. Hong, J., Shen, G. Q., Peng, Y., Feng, Y. & Mao, C. Uncertainty analysis for measuring greenhouse gas emissions in the building construction phase: a case study in China. *J. Clean. Prod.* **129**, 183–195 (2016).
58. Mori, S., Nakata, D. & Kaneda, T. An application of gamma distribution to the income distribution and the estimation of potential food demand functions. *Mod. Econ.* **6**, 1001–1017 (2015).
59. Salem, A. B. & Mount, T. D. A convenient descriptive model of income distribution: the gamma density. *Econometrica: J. Econom. Soc.* **42**, 1115–1127 (1974).
60. Gao, H., Wang, D., Du, X. & Zhao, Z. An LCA-BIM integrated model for carbon-emission calculation of prefabricated buildings. *Renew. Sust. Energ. Rev.* **203**, 114775 (2024).
61. Peng, Z. et al. The environmental impact of the entire renovation process of urban aged residential buildings in China. *Int. J. Build. Pathol. Adapt.* https://doi.org/10.1108/ijbpa-04-2024-0077 (2024).
62. García-López, J., Hernández-Valencia, M., Roa-Fernández, J., Mascort-Albea, E. J. & Herrera-Limones, R. Balancing construction and operational carbon emissions: Evaluating neighbourhood renovation strategies. *J. Build Eng.* **94**, 109993 (2024).
63. Jiang, T. et al. National and provincial population and economy projection databases under Shared Socioeconomic Pathways(SSP1-5)_v2. https://doi.org/10.57760/sciencedb.01683 (2024).
64. Chen, Y. et al. Provincial and gridded population projection for China under shared socioeconomic pathways from 2010 to 2100. *Sci. Data* **7**, 83 (2020).
65. World Bank Group. GDP (constant LCU) - China. https://data.worldbank.org/indicator/NY.GDP.MKTP.KN?locations=CN (2024).
66. IRP. Resource efficiency and climate change: material efficiency strategies for a low-carbon future. In *A report of the International Resource Panel* (eds Hertwich, E., Lifset, R., Pauliuk, S. & Heeren, N.) (United Nations Environment Programme, Nairobi, Kenya, 2020).
67. Hu, M., Bergsdal, H., van der Voet, E., Huppes, G. & Müller, D. B. Dynamics of urban and rural housing stocks in China. *Build. Res. Inf.* **38**, 301–317 (2010).
68. Marinova, S., Deetman, S., van der Voet, E. & Daioglou, V. Global construction materials database and stock analysis of residential buildings between 1970–2050. *J. Clean. Prod.* **247**, 119146 (2020).
69. You, F. et al. Carbon emissions in the life cycle of urban building system in China—a case study of residential buildings. *Ecol. Complex.* **8**, 201–212 (2011).
70. Mastrucci, A., Guo, F., Zhong, X., Maczek, F. & van Ruijven, B. Circular strategies for building sector decarbonization in China: a scenario analysis. *J. Ind. Ecol.* **28**, 1089–1102 (2024).
71. Xia, B., Xiao, J. & Li, S. Sustainability-based reliability design for reuse of concrete components. *Struct. Saf.* **98**, 102241 (2022).
72. Xia, B., Xiao, J., Ding, T. & Zhang, K. Probabilistic sustainability design of structural concrete components under climate change. *Struct. Saf.* **92**, 102103 (2021).
73. Stewart, M. G., Wang, X. & Nguyen, M. N. Climate change adaptation for corrosion control of concrete infrastructure. *Struct. Saf.* **35**, 29–39 (2012).
74. Nguyen, M. N., Wang, X. & Leicester, R. H. An assessment of climate change effects on atmospheric corrosion rates of steel structures. *Corros. Eng. Sci. Technol.* **48**, 359–369 (2013).

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Author contributions
B.X. and J.X. conceived the study and proposed the conceptual and analytical framework. B.X. designed the methods. B.X. and X.G. performed the analysis. B.X. and J.X. drafted the manuscript. G.L., X.G., Y.L., and Y.W. contributed to enhancing the conceptual design and improving the manuscript. B.X., J.X., G.L., X.G., Y.L., and Y.W. discussed the results and reviewed the manuscript.

Competing interests
The authors declare no competing interests.

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