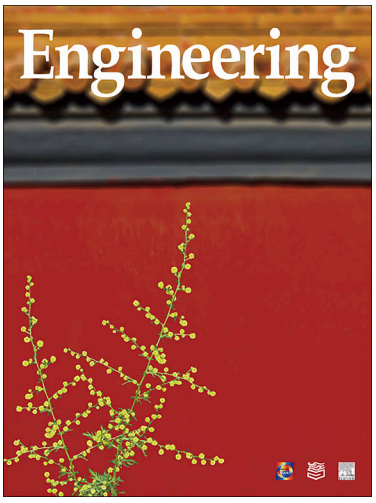
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Article

Sectoral Coordination to Maximize China's National and Provincial Building Carbon Emissions Mitigation

Qiance Liu, Kairui You, Xin Ouyang, Wei Feng, Kun Sun, Menglin Dai, Wu Chen, Weiguang Cai, Gang Liu

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Carbon Neutrality Pathways for Building Operation—Article

Sectoral Coordination to Maximize China's National and Provincial Building Carbon Emissions Mitigation

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ABSTRACT

The building sector is central to achieving China's carbon peak and neutrality targets, yet existing assessments seldom integrate full life cycle emissions into subnational policy design. Here we develop a building material – energy – emission (BMEE) model to quantify direct, indirect, and embodied CO_2 emissions from all building types across 31 Chinese mainland provinces from 2000 to 2060 and to evaluate 50 policy scenarios that combine five strategies: urban renewal, green buildings, low-carbon construction, circular economy, and energy transition. The model links dynamic material flow analysis with energy balance sheet splitting, supported by newly compiled national databases on building material and operational energy intensities, and incorporates a renovation module that prioritizes renovation over demolition. We find that China's building emissions have peaked around 2017 and can decline to between 0.69 and 2.48 Gt (10^9 tonnes) CO_2 by 2060. Under the lowest-emission pathway, cumulative emissions are reduced by 39.5% relative to business-as-usual, with urban renewal providing the largest contribution to total mitigation, followed by green buildings and energy transition. Public buildings, the material sector, and northern provinces exhibit the largest mitigation potentials, while provincial results highlight distinct strategy priorities. Monte Carlo analysis confirms that these conclusions are robust despite widening parametric uncertainty. Our findings underscore the importance of sectoral coordination and regionally tailored policy packages to maximize building decarbonization in China and provide a scalable framework for other large countries facing concurrent new construction and stock-renewal challenges.

Keywords: Building decarbonization, Building-Material-Energy-Emission (BMEE) model, Urban renewal, Sectoral coordination, Provincial disparities

1. Introduction

Buildings are key to climate change mitigation as they produce large amounts of greenhouse gas (GHG) emissions in operation [1], in the construction and production of embodied materials [2], and in the future due to lock-in effects from long lifetimes [3]. According to the Intergovernmental Panel on Climate Change (IPCC) [4], in 2019, buildings were responsible for 21% of global GHG emissions, including 57% of indirect emissions from offsite electricity and heat generation, 24% of direct emissions from building operational use, and 18% of embodied emissions from construction and materials production [5]. Consequently, buildings have become a focus of the global (e.g., the Paris Agreement) and national (e.g., Nationally Determined Contributions, NDCs) climate policy. As of 2025, over 60 countries, over 700 cities, and nearly 10 000 companies and organizations have established climate targets, pledges, or action plans that include or are relevant to building-related mitigation measures [6,7].

The multi-sectoral involvement in the life cycle of buildings (i.e., construction, operation, and demolition), however, creates complexity in accounting for and managing building carbon emissions. A few recent efforts, based on the International Energy

Agency (IEA) [1,5], the International Institute for Applied Systems Analysis (IIASA) [8] and the Resource Efficiency and Clim[illegible] and embodied building GHG emissions with integrated modelling and a stocks and flows based analytical framework at global, continental, or national levels [9,12–14]. These frameworks typically integrate material cycles, energy use and emissions within unified accounting systems [15], and further extend to demand-side mitigation modeling linked with building stock evolution [16] and to vacant [17,18] or unfinished [19] buildings. However, such integrated assessment and mitigation strategy discussions on reducing building GHG emissions remain insufficient at the subnational level, with limited resolution for capturing intra-country heterogeneity [20]. In contrast, subnational analyses often remain fragmented in terms of life cycle coverage or system boundary definition [21]. This gap is particularly important for large countries such as China (with 34 provincial-level administrative divisions) and the United States [22] (with 51 states/districts), where substantial disparities in material intensity, energy structure, and building stock dynamics exist. A higher-resolution, life cycle and integrated accounting framework that consistently links building stock dynamics with material and energy flows is therefore urgently needed to support localized and differentiated building decarbonization strategies.

China is an interesting case not only because it is the largest emitter of building GHG emissions [1,23], but also because it stands at a crucial juncture as the construction boom calms [24] and large-scale renovation begins. From a system perspective, this transition implies a shift from construction-dominated emissions to increasingly complex interactions among construction, operation, and renovation processes [15]. Although the past decade has already seen an increase in studies on quantifying and mitigating Chinese building GHG emissions, covering topics such as urban emissions [25,26], embodied emissions [12,27], and overall building sector analyses [23,28–32], existing studies still tend to focus on partial processes or single dimensions of the system. For example, demand-side mitigation studies are often constrained to operational energy use without fully linking to material cycles [16,33]. At the same time, circularity-oriented analyses emphasize material loops but may not be fully coupled with dynamic building stock evolution or regional heterogeneity [15]. Although renovation has been considered in several building decarbonization studies [22,34,35], its integration into province-level [36] and full-life-cycle modeling [37] that couples building stock turnover, material flows, operational energy use, and coordinated mitigation strategies remains limited in China. In light of China's "peak by 2030 and neutrality by 2060" climate ambition and its window of opportunity for "new construction and urban renewal" at the same time [38,39], we conduct a full life cycle, system analysis on quantifying and mitigating China's building emissions with explicit consideration of regional disparities, which is crucial for both China and the world on the path to a net-zero future.

Given the existing building emission models operate within narrower process boundaries or limited spatial scales, and therefore do not provide a province-level, full-life-cycle framework for China, we develop a building material – energy – emission (BMEE) model to simulate the trajectories of both national and provincial building CO_2 emissions and mitigation potentials from 2000 to 2060 for China (the largest contributor to GHG emissions in the world). We compile two primary databases on material intensity and operational energy intensity to support more accurate, region-specific province-level modeling. We further incorporate a renovation module to simulate the effects of five major building decarbonization strategies (i.e., urban renewal, green buildings, low-carbon construction, circular economy, and energy transition) for China and its provinces through policy-driven scenarios [40]. Our study provides a guide to subnational building emissions mitigation for other major countries or regions facing similar challenges, whether related to renovating existing buildings, accelerating new construction, or both.

2. Material and methods

2.1 Model framework

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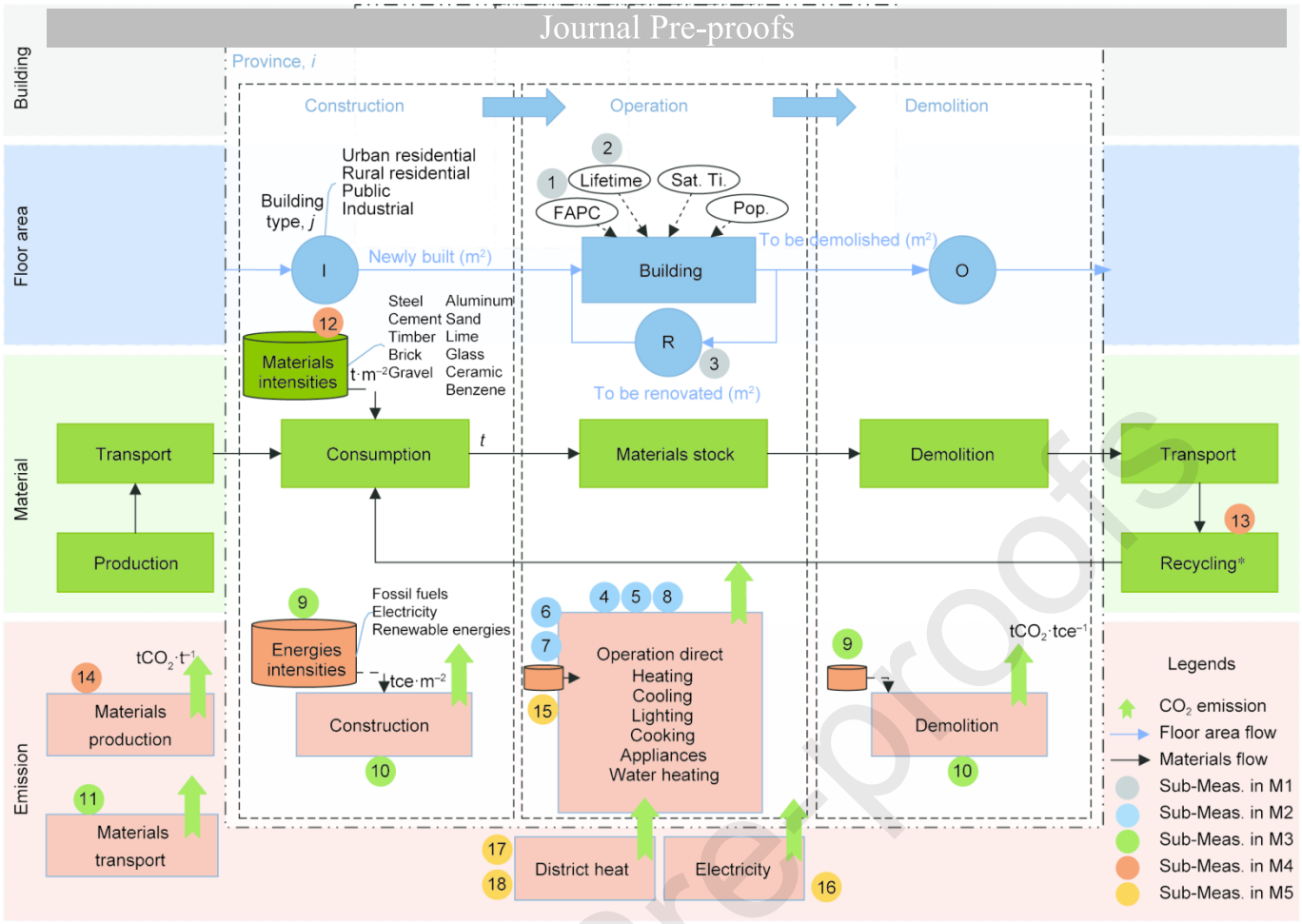


Fig. 1. Framework of building material − energy − emission (BMEE) model. This model runs with three layers: floor area, construction materials, and energy-emission. The fundamental driver of the BMEE model is the floor area flow or stock of a specific building type in a province. Material and energy consumption were then transferred by floor area, with material or energy intensities. Finally, CO_2 emissions were calculated by multiplying energy or material consumption by the corresponding emission factors. Materials Transport emissions include both transport of construction materials and demolition-related transport. Recycling is represented by substituting secondary steel and aluminum production for primary production, while emissions from collection and preprocessing are excluded due to limited data availability. Sat. Ti.: saturation time, Pop.: population, FAPC: Floor area per capita, I: inflow, R: renovation, O: outflow. Numbers represent measures in Table 1.

We implement the BMEE model by coupling dynamic material flow analysis (MFA) with energy balance sheet splitting, systematically calculating building CO_2 emissions (as shown in Fig. 1). Such a model facilitates the simulation of floor area change, material and energy consumption, and associated carbon emissions within an integrated framework primarily driven by building (i.e., floor area) stock dynamics. We explicitly consider 31 provincial-level regions (municipalities/autonomous regions) in Chinese mainland and aggregate them into three regions according to climate zones and heating practices: the north, the north − south transition region (hereafter, the Transition region), and the south (Fig. S1 in Appendix A). More details on the model framework are provided in Fig. S2 in Appendix A.

The BMEE model operates at multiple resolutions, covering the period from 2000 to 2060, 31 provincial-level administrative regions, four building types, 11 construction materials, six operational end uses, and eight emission processes. Four building types are included: urban residential, rural residential, public and commercial, and industrial buildings. The national results are derived by aggregating the corresponding outcomes from each province. Construction materials include steel, aluminum, cement, timber, brick, gravel, sand, pitch, glass, ceramics, and expanded polystyrene (EPS) board. Direct (onsite fossil fuel) and indirect (offsite electricity and district heat) emissions are classified into six operational uses: heating, cooling, appliances, lighting, cooking, and water heating. In addition, we distinguish between onsite and district heating and classify them as direct and indirect emissions, respectively. Notably, district heat is only applicable to urban residential and public buildings in the North region. For industrial buildings, we include lighting energy for operational use, using public buildings as a proxy, while industrial production energy is excluded, as it falls under industrial sector energy consumption. The complete temporal, spatial, building-type, material, energy, and process resolutions are summarized in Table S1 in Appendix A.

The BMEE model advances existing building-sector models (e.g., renovation treatment in ODYM-RECC [9–11]) in three main aspects. First, it provides a province-level full-life-cycle accounting framework for China, addressing the limited subnational resolution of many integrated building decarbonization models, which are often developed at global, regional,

national, city, or residential-sector scales. Second, it explicitly links building stock dynamics, material flows, operational ener[illegible]tion involves interactions among multiple sectors: stock renewal changes material demand, energy retrofits affect operational energy use, electrification shifts emissions from buildings to the power sector, and recycling connects building outflows with material production. Third, the model incorporates coordinated policy scenarios covering urban renewal, green buildings, low-carbon construction, circular economy, and energy transition, enabling a systematic assessment of multi-sector mitigation interactions at the provincial level.

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Within this integrated framework, the BMEE model introduces an explicit renovation module that reflects China's ongoing transition from construction-dominated to renovation-driven building emissions. In general, we prioritize renovation over new construction. Some buildings planned for demolition are renovated to keep the building stock constant. Three critical assumptions are made for renovation as follows, ① for non-energy renovation, the building lifetimes of renovated buildings will be extended to the same as those newly built buildings in the same year; ② for energy renovation, renovated buildings are assumed to comply with the mandatory building energy-efficiency standard applicable in the retrofit year, so the energy-saving effect varies with building vintage, retrofit year, and regional stock composition; and ③ renovated floor areas are selected from outflow before renovation to ensure buildings can only be renovated once. Further details are provided in Appendix A Section S3.1.2 and Fig. S3.

The BMEE model is a province-level integrated accounting framework that links building stock dynamics with material demand, operational energy use, and process-based CO_2 emissions. Specifically, the model first simulates historical and future floor area inflow, stock, and outflow using dynamic material flow analysis, with a flow-driven approach for the historical period and a stock-driven approach for the future period based on floor area per capita, population, lifetime, and saturation dynamics. Material inflow, stock, and outflow are then derived from floor area using material intensity parameters, while operational energy use is estimated from the building stock using province-specific energy intensity data obtained from energy balance sheet splitting. CO_2 emissions are finally calculated for construction, operation, demolition, materials production, materials transportation, district heat, and electricity generation using process-specific emission factors. To reflect China's transition from construction-led growth to stock renewal, we further incorporate a renovation module that redirects part of the outflow into renovated stock, with extended lifespans and improved energy performance. All calculations are conducted for 31 provinces and four building types, with climate-related heterogeneity represented through differentiated provincial inputs and regional grouping into North, Transition, and South. Details of the modelling process are provided in Section S3 of Appendix A.

2.2 Methods

The dynamics of floor area are simulated using dynamic material flow analysis (dMFA) methods [9,41] and are divided into two parts: a historical estimation and a future simulation. Generally, historical (1950–2024) and future (2025–2060) flows and stocks (F&S) of floor area are calculated using the inflow- and stock-driven models. Please see details of dMFA models in the Appendix A Section S3.1.1.

Energy consumption and carbon emissions for operational building end-use are obtained using a combination of "top-down" and "bottom-up" methods in our previous study [42]. Energy consumption is distinguished by building type, energy type, and operational end-uses. Based on the specific scope of the Ministry of Ecology and Environment of the People's Republic of China [43], operational emissions include direct emissions (i.e., emissions from direct fossil fuel combustion) and indirect emissions (i.e., emissions from heating and power generation).

2.3 Uncertainty analysis

We conducted a comprehensive uncertainty assessment for all 20 groups of modeling parameters using a Monte Carlo simulation. Each simulation was performed 1000 times. The parameters were assumed to follow a normal distribution, where the mean (μ) was set as the parameter's baseline value, and the standard deviation (σ) was designed to increase linearly from 0 in 2020 to 10% in 2060, reflecting the fact that uncertainties tend to accumulate over time. We applied this uncertainty analysis to both the business-as-usual (BAU) and Best scenarios (i.e., S1 and S32).

2.4 Data sources

To derive more accurate region-specific material intensities, we compile a building material intensity database comprising material intensity data for 3051 individual buildings from our previous study [44]. The key attributes of this material intensity database include location, urban/rural classification, structure, function, building name, completed year, and intensities of 11 construction materials. To balance region consideration and data representativeness, we aggregate provincial data into three regions (i.e., North, Transition, and South), completion years into three periods (1940–1979, 1980–1999, and 2000–2024), and building functions into four types (urban residential, rural residential, public, and industrial building). We calculate the average values for individual buildings for each region and completion period, then allocate them to their corresponding provinces and years.

To derive more accurate region-specific operational energy consumption intensities, we compile a building energy intensity database based on a survey of 1 128 residential buildings and 7 320 public buildings from 4 911 households across 31

provinces of China. This database includes key attributes such as location, urban/rural classification, building function, floor area [illegible] heat) energy consumption. By integrating city statistics, we obtain energy consumption intensities for six operational uses (i.e., heating, cooling, cooking, water heating, lighting, and appliances) across 321 cities in China [42]. The city-level data are further aggregated to the provincial/region level by dividing total direct or indirect energy consumption by the total floor area. Please see details of data source in the Table S2 in Appendix A.

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3. Results

3.1 Historical building emissions from 2000 to 2024

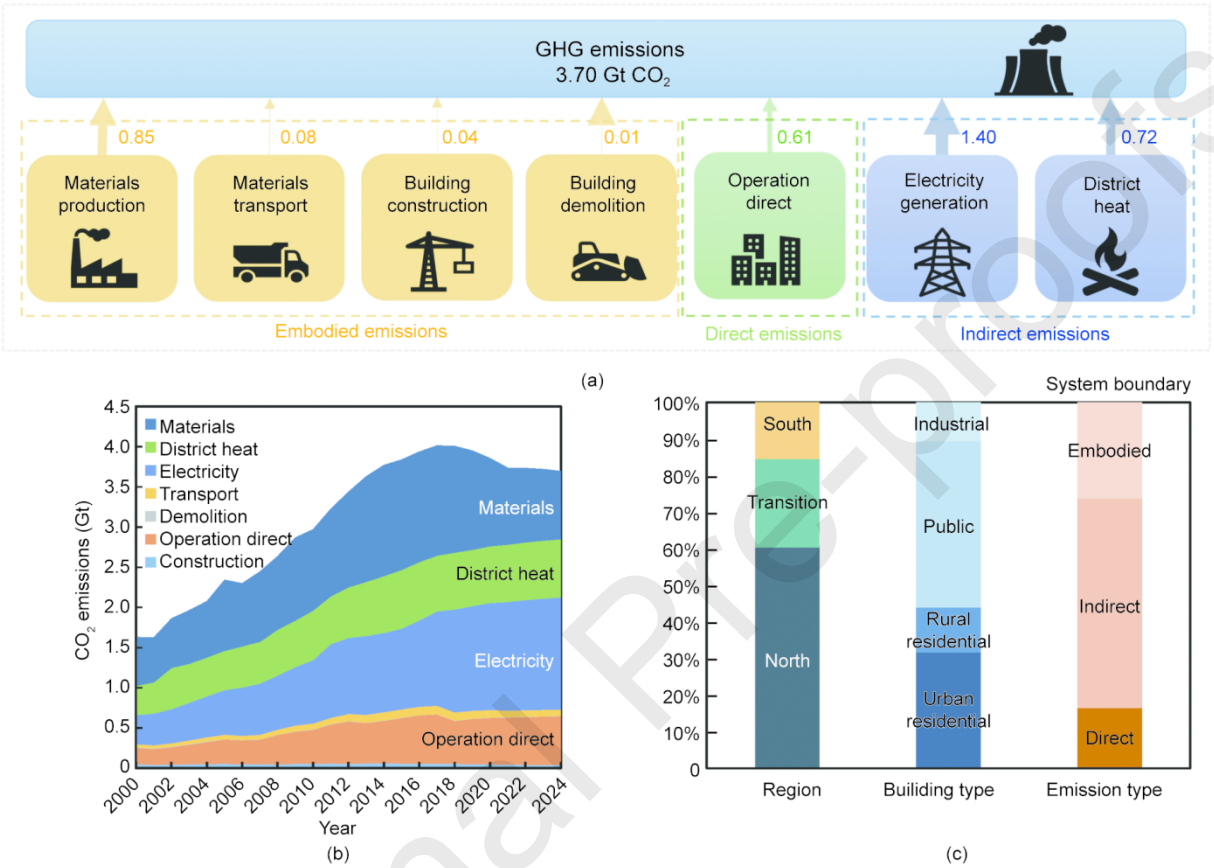


Fig. 2. Historical CO_2 emissions from buildings in China from 2000 to 2024. (a) 2024 emission composition for each emission type. **(b)** Historical emission trajectory from 2000 to 2024. **(c)** 2024 emission composition by region, building, and emission types. For industrial buildings, we considered only embodied emissions and lighting-related emissions (see Section 2.2 (Methods)). Regions (North, Transition, and South) are defined based on China climate zone classification (Fig. S1).

Over the past 25 years, China's building and construction industry has experienced rapid expansion, resulting in substantial increases in material and energy consumption and, consequently, CO_2 emissions. The "Four-trillion-yuan Stimulus Plan" implemented by China's central government [45] for post-financial-crisis economic recovery in 2008 further accelerated this growth. Consequently, total CO_2 emissions from buildings reached 3.70 Gt (1 Gt = 10^9 tonnes) in 2024 (Fig. 2(a)), following an increase from 1.63 Gt in 2000 to a peak of 4.02 Gt in 2017, and a subsequent gradual decline (Fig. 2(b)). When breaking down these 3.70 Gt CO_2 emissions in 2024 (Fig. 2(a)), we find that 0.61 Gt (16.5%) arise from direct emissions linked to the fossil fuel combustion in building operations, 2.12 Gt (57.4%) are attributed to indirect emissions originating from electricity and central heating generation, and the remaining 0.97 Gt (26.2%) stem from embodied emissions, primarily associated with construction materials production.

The regional composition analysis (Fig. 2(c)) reveals that buildings in the North region accounted for the largest share of emissions, contributing over half (60.4%) of the total in 2024. This was followed by the Transition area, which contributed 24.2%, and the South region, responsible for 15.4% of the total emissions. The North region's dominance reflects several factors, including its substantial operational floor area, higher material and energy intensities, and the use of central heating in urban residential and public buildings to combat cold weather. In terms of building type, public buildings contribute the largest share (45.5%), followed by urban residential buildings (31.7%), rural residential buildings (12.3%), and industrial buildings (10.6%) in 2024.

3.2 Building decarbonization strategies and scenario narratives

Table 1

Decarbonization strategies, measures, and parameter descriptions.

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Strategy	Measures	Parameter description
ST1:Urban Renewal	M1: Intensive use	The floor area per capita (FAPC) saturation level decreased by 10%
	M2: Lifetime extension	For new buildings, lifetimes increase to 50 years from 2020 to 2035 and to 80 years from 2036 to 2060 [46]
	M3: Extensive renovation area	Renovation rates increase linearly to 3% in 2035 and remain unchanged until 2060 [47]. After renovation, buildings will have lifespans equal to those of new buildings built in the same year
	M4: Behavior changes for energy saving	The operational demand for central heating, heating, cooling, lighting, and home appliances decreases by 15%, 30%, 25%, and 10%, respectively [31,48,49]
	M5: Building energy renovation	All renovated buildings undergo building energy renovation and comply with the mandatory building energy efficiency standard at the time of renovation [50]
ST2: Green Building	M6: Energy efficiency improvement for new buildings	Energy intensities for heating and cooling in new buildings decrease [51].
	M7: Energy efficiency improvement of operational equipment	Energy efficiency of cooking, water heating, lighting, and appliances increases by 20% [16].
	M8: Building electrification	Electrification rates of operational equipment increase to 95% [52]
ST3: Low-carbon Construction	M9: C&D energy intensity reduction	Energy intensities of construction and demolition decrease by 15% [53]
	M10: C&D machinery electrification	Electrification rates of construction and demolition machinery increase to 70%
	M11: Transport electrification	Material transportation achieves 100% electrification.
ST4: Circular economy	M12: Material substitution & Light-weight design	Steel intensities linearly decrease by 19%; Cement, brick, gravel, and sand linearly decrease by 10%; Timber linearly increases by 10% [8]
	M13: Material recycling	Recycling rates of steel and aluminum increase to 90% and 95%, respectively [8]
	M14: Materials cleaner production	Emission intensities of primary steel and cement production decrease by 52% and 42% [41,54] due to circularity measures
ST5: Energy Transition	M15: Renewable operational energy	Renewable energy shares in energy supply for operational uses increase to 13% [51]
	M16: Renewable electricity	Renewable energy's share of electricity generation in north, transition, and south China increases to 80%, 85%, and 90%, respectively [55].
	M17: District heating energy efficiency improvement	Energy efficiencies of boilers increase to 90% in 2060 [48]
	M18: Renewable district heating	Renewable energy shares in district heating generation increase to 30% [52,56]

Detailed descriptions of model parameters are available in Appendix A Section S3.

In light of China's climate commitments (i.e., reaching a carbon peak by 2030 and achieving carbon neutrality by 2060) and to project the future trajectories of its building emissions, we compile a comprehensive collection of Chinese policies related to building decarbonization (Table S3 in Appendix A). Subsequently, we identify five widely adopted strategies (ST1 – ST5) corresponding to 18 representative measures (M1–M18) in Table 1 [8,16,31,41,45–56]. These strategies and measures were distilled from major policy packages, regulations, and technical guidelines issued by key Chinese ministries, ensuring consistency with national priorities for building sector decarbonization. Given the multitude of highly specific actions in practice (e.g., rooftop photovoltaic system, insulation retrofitting), we aggregate them into an intermediate set of measures that capture the essential technological and operational dimensions of mitigation while remaining suitable for quantitative modeling. The correspondence of these measures with the SER framework, target emission processes, and IPCC emission scopes is summarized in Table S4 in Appendix A. Detailed assumptions regarding floor area per capita, building lifetimes, renovation rates, energy-efficiency improvements, electrification, material intensities, and emission factors are presented in Figs. S4-S11 in Appendix A Section S3.

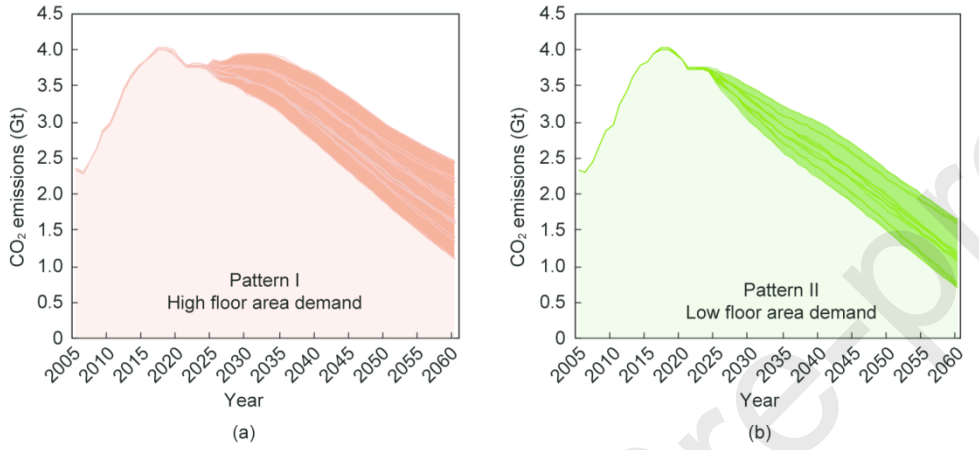
A total of 50 scenarios (S1–S50) were developed to capture both synergistic and individual effects of decarbonization actions. Scenarios S1–S32 represent all possible combinations of the five strategies (ST1–ST5), while S33–S50 assess the impacts of individual measures (M1–M18). Each strategy comprises 2–4 measures that are implemented jointly, allowing the scenario design to reflect both integrated and isolated mitigation pathways. The controlling parameters and their correspondence with scenarios S1-S50 are provided in Table S5 in Appendix A.

In particular, to simulate the impact of renovation on building decarbonization in China, we developed a novel renovation module (Fig. S3). Previous renovation models, such as the one developed by Norwegian University of Science and Technology (NTNU) and widely applied in studies of Norway and the Netherlands [57–60], were designed primarily for long-lived building stocks (typically > 100 years). However, this approach is not directly applicable to China, where historical

floor-area flow and stock (F&S) data are available only since 1949, and the average building lifetime has been around 35 yearJournal Pre-proofsgs in China are expected to increase. To account for this transition, we incorporated the new renovation module into our model to better simulate future renovation dynamics.

The renovation module is grounded in the principle of "renovation instead of demolition," consistent with the policy direction of China's Ministry of Housing and Urban–Rural Development (MOHURD) [61]. Under this principle, a proportion of the building stock originally slated for demolition is instead renovated, thereby reducing the need for new construction while maintaining the total in-use stock. Renovated buildings achieve improved operational energy efficiency through energy retrofits, and extended service lives through structural reinforcement and functional upgrades. The impact of renovation is ultimately reflected in the implementation of lifetime extension (M2) and extensive renovation (M3) in the urban renewal strategy (ST1), as well as deep energy renovation (M5), operational energy efficiency improvement (M7), and building electrification (M8) in the green building strategy (ST2). Detailed assumptions and model set-up are available in Appendix A Section S3.1.2.

3.3 Future trajectory of building CO_2 emissions



	Construction	Operation direct	Demolition	Material	Electricity	Heating	Transport
ST1	0.44	1.69	0.03	12.71	4.18	1.50	1.20
M1	0.21	1.87	0.01	5.92	4.54	2.02	0.53
M2	0.09	–0.01	0.03	2.81	–0.02	–0.01	0.31
M3	0.17	–0.16		5.22	–0.33	–0.48	0.47
ST2		4.85			2.03	6.24	
M4		0.80			2.28	3.24	
M5		0.12			0.24	0.35	
M6		0.50			1.16	2.91	
M7		0.48			1.68		
M8		3.44			–3.79		
ST3	0.07		0.03				0.45
M9	0.10		0.03				
M10	–0.03		–0.01				
M11							0.45
ST4				7.83			0.24
M12				2.29			0.24
M13				1.91			
M14				4.92			
ST5	0.08		0.03		8.84	4.06	
M15					1.47		
M16	0.08		0.03		7.68		
M17						1.78	
M18						2.57	

(c)

Fig. 3. Pathways of future building CO_2 emissions in China. (a) CO_2 emission trajectory from 2025 to 2060 in high floor area demand. **(b)** CO_2 emission trajectory from 2025 to 2060 in low FAPC demand. The solid lines represent scenarios S1–S32. The dark shaded area reflects the range between the highest emission (i.e., the S1 baseline) and the lowest across the scenarios for the two demand patterns. **(c)** Contribution of individual strategies (S2 – S6) and measures (S33 – S50) to cumulative mitigation (Gt CO_2) from 2025 to 2060 relative to S1. Contributions of individual measures were estimated using Shapley value decomposition to avoid order-dependent attribution bias when combining mitigation measures

(Section S3.4 in Appendix A). Blank cells indicate zero contribution, meaning that the corresponding strategy or measure does not affect that emis

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Our analysis indicates that building emissions in China may follow diverse trajectories in the future under the first 32 scenarios, depending on the demand for gross FAPC. Under Pattern I (high floor area demand; Fig. 3(a)), building CO_2 emissions remain at a relatively high level in the early transition period and then gradually decline, reaching 1.15–2.48 Gt CO_2 by 2060 across scenarios. Under Pattern II (low floor area demand; Fig. 3(b)), emissions decline more rapidly and fall further to 0.69–1.61 Gt CO_2 by 2060. Combined with the historical trend, these results suggest that China's building emissions reached a peak around 2017 and may either remain on a slow decline trajectory or enter a faster decline pathway depending on the future floor area demand. This also highlights the critical role of intensive use (M1) in shaping long-term emissions trajectories.

Fig. 3(c) elucidates how strategies and measures contribute to mitigating building emissions. Among all strategies, urban renewal (ST1) provides the largest cumulative mitigation potential, reducing emissions by 21.75 Gt CO_2 over 2025–2060. Its effect is broad-based, with the largest contribution coming from the materials sector (12.71 Gt), followed by electricity (4.18 Gt), operation (1.69 Gt), heating (1.50 Gt), and transport (1.20 Gt). Green building (ST2) and energy transition (ST5) also contribute substantially, with cumulative reductions of 13.12 Gt and 13.01 Gt CO_2, respectively. ST2 mainly reduces emissions through operations (4.85 Gt), heating (6.24 Gt), and electricity-related emissions (2.03 Gt), whereas ST5 primarily reduces emissions through decarbonizing electricity (8.84 Gt) and district heating (4.06 Gt). By contrast, circular economy (ST4) contributes 8.07 Gt CO_2, largely through the materials sector (7.83 Gt), while low-carbon construction (ST3) has a much smaller overall contribution of 0.55 Gt, mainly from transport (0.45 Gt).

At the measure level, the results further reveal important interactions across sectors. In particular, M1 (intensive use) is the most influential individual measure, with especially strong mitigation effects in materials (5.92 Gt) and electricity (4.54 Gt). By contrast, M8 (building electrification), when implemented alone, increases electricity-related emissions by 3.79 Gt, indicating that electrification without simultaneous power-sector decarbonization may lead to higher emissions under the current electricity mix.

3.4 National characteristics in building decarbonization

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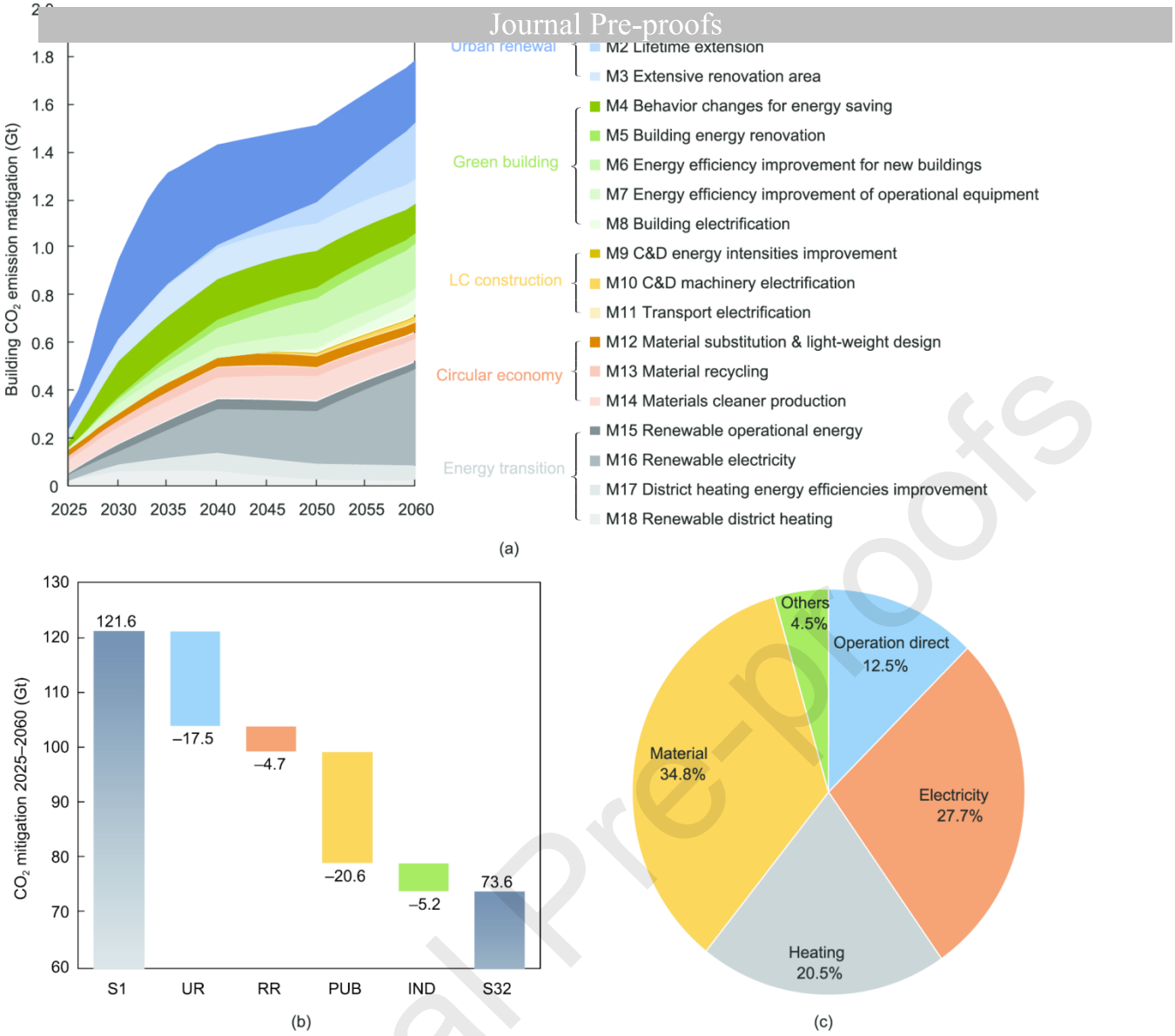


Fig. 4. Building CO_2 emissions mitigation potentials in China from S1 to S32. (a) Annual mitigation potentials by strategy and measure for all types of buildings. **(b)** Mitigation decomposition by building types. Values above S1 and S32 represent accumulated CO_2 emissions from 2025 to 2060. UR: urban residential buildings. RR: rural residential buildings. PUB: public buildings. IND: industrial buildings. S1 is the Business-as-usual (BAU) scenario. S32 is the lowest emission scenario (LES). **(c)** Mitigation composition by sectors. Contributions of individual measures were estimated using Shapley value decomposition to avoid order-dependent attribution bias when combining mitigation measures (Section S3.4 in Appendix A).

Scenario S32 emerges as the lowest emission scenario (LES) by implementing all strategies and measures. Under this scenario, the annual mitigation potential increases from 0.33 Gt in 2025 to 1.78 Gt by 2060 (Fig. 4(a)). Accordingly, cumulative CO_2 emissions over 2025–2060 are reduced to 73.6 Gt, compared with 121.6 Gt in the baseline scenario S1 (Fig. 4(b)), corresponding to a total mitigation of 48.0 Gt (~39.5%). Among all strategies, urban renewal (ST1) contributes the largest share of mitigation, accounting for about 38.0% of the total reduction. Green building (ST2) and energy transition (ST5) follow closely, contributing 24.3% and 24.0%, respectively. The remaining 13.7% is achieved through circular economy (ST4) and low-carbon construction (ST3).

At the building type level, public buildings exhibit the highest mitigation potential, contributing 20.6 Gt, followed by urban residential buildings (17.5 Gt) (Fig. 4(b)). By contrast, industrial and rural residential buildings contribute relatively smaller but still non-negligible reductions of 5.2 Gt and 4.7 Gt, respectively. Notably, the mitigation potential of industrial buildings still exceeds that of rural residential buildings, despite often receiving less attention in previous studies [22,36,62]. From a sectoral perspective, the materials sector accounts for the largest share of total mitigation (34.8%), followed by electricity (27.7%) and district heating (20.5%) (Fig. 4(c)). Direct operational emissions contribute 12.5%, while the remaining 4.5% comes from construction, demolition, and transport. Overall, these results indicate that deep decarbonization of China's building sector relies primarily on reducing material demand and accelerating the decarbonization of electricity and heat supply systems.

Beyond steel and aluminum, we further assessed the recycling potential of major non-metallic construction and demolition waste, including waste concrete, brick, and timber, by combining BMEE-derived material outflows with scenario-based

recycling rates and literature-based unit carbon reduction factors. Their cumulative mitigation potential over 2025–2060 is estim[Journal Pre-proofs]f its dominant waste volume, whereas timber achieves 93–109 Mt CO_2 despite much smaller outflows due to its higher per-unit mitigation benefit. This suggests that the carbon benefit of non-metallic material recycling is jointly determined by waste volume and substitution effect. More details are provided in Appendix A Note S1.

3.5 Provincial disparities in building decarbonization

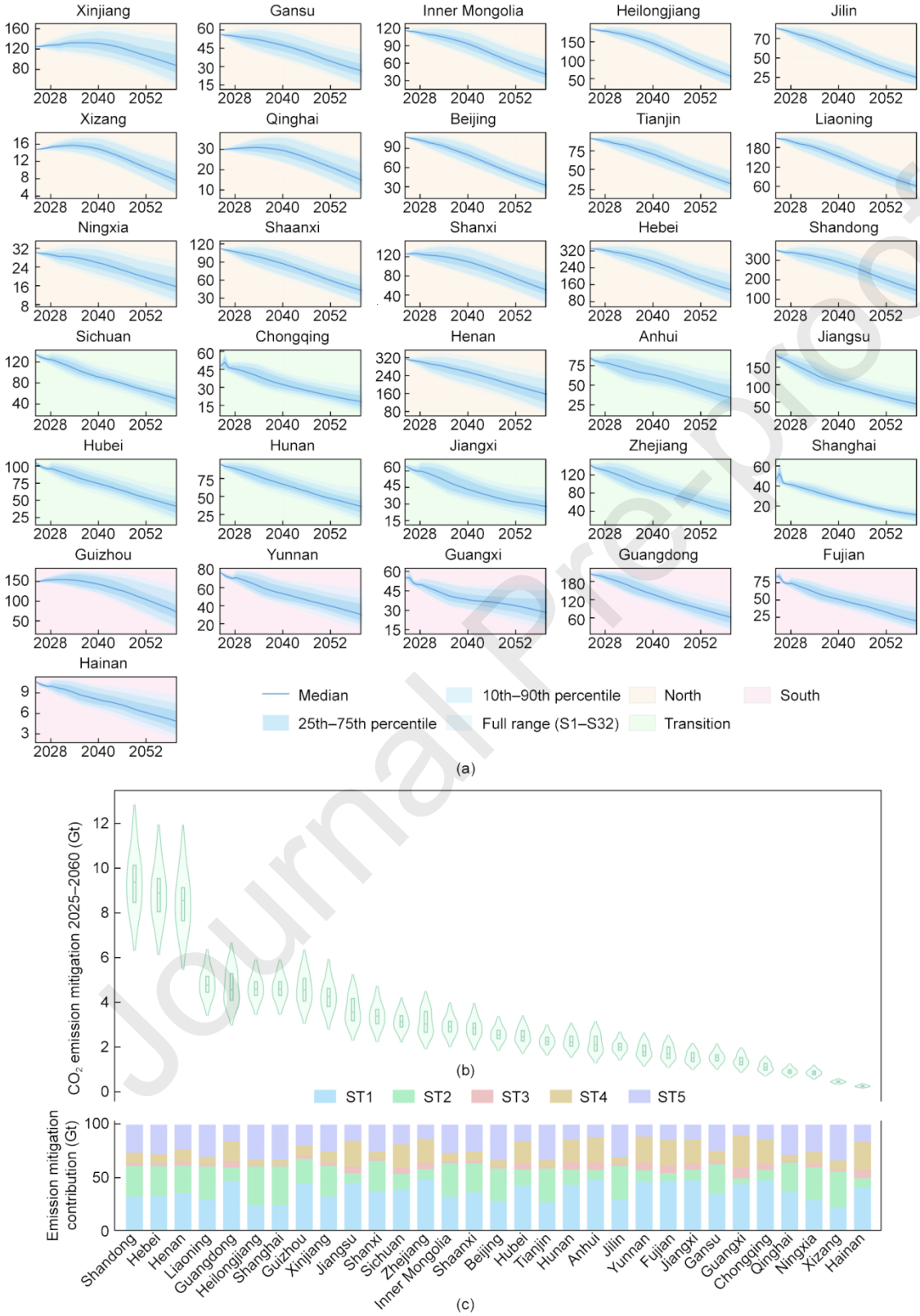


Fig. 5. Provincial disparities of building CO_2 emission mitigation. (a) Provincial CO_2 emission trajectories under scenario uncertainty (S1–S32). Median projections are shown with shaded uncertainty bands (25th–75th percentile and full range). Provinces are grouped into North, Transition, and South regions. (**b)** Distribution of cumulative emission reduction potential across provinces (2025–2060). Violin plots represent the distribution of cumulative reductions across all scenarios (S1–S32), with median and interquartile range indicated. (c) Contribution of

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mitigation strategies to total emission reductions by province. Stacked bars show the relative contribution of five strategies (ST1–ST5) to cumu

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Comparing provincial emission pathways reveals pronounced spatial heterogeneity in both emission levels and long-term mitigation space (Fig. 5(a)). Across all scenarios, most provinces exhibit persistent declines after the historical peak, but absolute levels remain highly uneven. Provinces with the largest pathway envelopes are concentrated in major building-demand regions, especially Shandong, Hebei, and Henan, which also remain the largest emitters across the scenario ensemble. By contrast, provinces such as Hainan, Xizang, Qinghai, and Ningxia maintain much lower absolute emission levels throughout the projection period. The spread of scenario ranges is also much wider in provinces such as Shandong, Henan, Hebei, Guangdong, Guizhou, and Xinjiang, indicating that long-term provincial outcomes are highly sensitive to strategy combinations in these regions.

The cumulative mitigation potential over 2025–2060 shows strong interprovincial disparity (Fig. 5b). The largest total reduction potentials are found in Shandong (4639.9 Mt CO_2), Henan (4603.7 Mt), and Hebei (4143.1 Mt), followed by Guangdong (2623.9 Mt), Guizhou (2347.0 Mt), Xinjiang (2230.5 Mt), Liaoning (2107.1 Mt), and Jiangsu (2098.6 Mt). These provinces combine large building stocks with substantial mitigation space and therefore dominate national reductions. In contrast, Hainan (148.3 Mt) and Xizang (188.4 Mt) exhibit much lower cumulative mitigation potentials due to their relatively low baseline emissions. Provinces with greater mitigation potential also tend to exhibit wider scenario distributions, yet their relative rankings remain broadly stable, suggesting robust identification of key mitigation regions.

Decomposition of mitigation contributions further highlights strong regional differences in strategy effectiveness (Fig. 5(c)). Urban renewal (ST1) is the dominant strategy in most provinces, and is particularly important in Zhejiang (50.7%), Anhui (50.6%), Jiangxi (49.2%), Chongqing (49.2%), Fujian (48.8%), Guangdong (48.2%), Yunnan (47.9%), and Jiangsu (47.0%). By contrast, green building (ST2) plays a larger role in several northern provinces, especially Heilongjiang (36.9%), Xizang (34.3%), Jilin (32.7%), Tianjin (32.3%), Liaoning (32.3%), Inner Mongolia (31.9%), and Ningxia (31.8%), underscoring the importance of operational efficiency improvement in colder or energy-intensive regions. Energy transition (ST5) becomes the leading contributor in Beijing (34.0%) and Tianjin (33.8%), and remains highly important in Xizang (34.6%) and Heilongjiang (33.6%). Meanwhile, circular economy (ST4) contributes more strongly in several eastern provinces, such as Jiangsu (25.4%), Fujian (25.6%), Yunnan (25.5%), and Anhui (25.2%), whereas low-carbon construction (ST3) remains comparatively small across all provinces. These results indicate that provincial decarbonization cannot rely on a one-size-fits-all pathway, and instead requires region-specific mitigation portfolios aligned with local building stocks, energy systems, and development conditions.

4. Discussion

4.1 Implications for national building decarbonization

Our results identify three priority domains for China's building decarbonization: material-related emissions, public buildings, and northern provinces. Among the mitigation measures, intensive floor-area use and urban renewal play a pivotal role because they reduce the demand for new construction while also lowering associated material, transport, and operational energy needs.

Our results also underscore the need to consider potential trade-offs among measures and sectors. Electrification measures should be coordinated with power-sector decarbonization. When implemented alone, building electrification (M8), construction and demolition machinery electrification (M10), and material transport electrification (M11) can show negative mitigation effects in the short term because additional electricity demand is supplied by a still carbon-intensive power system (Fig. 3(c)). The net effect depends on both equipment efficiency and the electricity emission factor. For building operations, high-efficiency heat pumps, which are about 2–3 times as efficient as combustion boilers, can already provide mitigation benefits in regions with relatively low electricity emission factors. Given that the coal emission factor is about 2.66 tCO_2 per tonne of coal equivalent (tce), heat pumps are currently more suitable for wider deployment in the Transition region, where the electricity emission factor is about 4.3 $tCO_2 \cdot tce^{-1}$. They can be more broadly promoted in northern China after 2030 as the power system decarbonizes. By contrast, direct electric heating and electric cooking offer smaller efficiency gains and are better suited to large-scale deployment after 2040. For construction machinery and material transport, electric equipment is generally about twice as efficient as fossil-fuel-based alternatives. Given the emission factors of gasoline and diesel, nationwide electrification of these applications becomes more favorable after 2030, provided that renewable electricity deployment continues. Thus, electrification should be phased in at the same pace as power-sector decarbonization.

Synergy between building and materials sectors also matters, even though they are regulated by different ministries in China. For example, the building sector can drive mitigation in both sectors through intensive use (M1) to reduce material consumption, or through green construction materials to promote cleaner production (M14). This shows that emissions reduction can be maximized only through effective coordination among sectors and ministries.

To achieve "carbon neutrality by 2060," in addition to carbon capture, utilization, and storage (CCUS) [23], it is imperative to deploy advanced technologies such as renewable energy sources (e.g., solar, geothermal, and bioenergy) for heating and prioritize waste heat recovery, particularly to replace coal-fired power for central heating in the North.

4.2 Implications for provincial building decarbonization

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The pronounced interprovincial heterogeneity reflects structural differences in building stocks, energy systems, and development [illegible] current emissions and cumulative mitigation potential, indicating a strong scale effect. Meanwhile, wider scenario ranges in several eastern and southern provinces suggest that mitigation outcomes are more sensitive to strategy combinations, implying both greater flexibility and higher uncertainty. Importantly, the contributions of mitigation strategies vary systematically across regions. Urban renewal plays a central role in rapidly developing provinces, whereas operational efficiency improvements and energy transition are more critical in northern and resource-dependent regions. These differences indicate that building-sector decarbonization is driven by multiple pathways rather than a single dominant strategy. Therefore, effective mitigation requires region-specific policy portfolios aligned with local conditions, rather than uniform approaches.

Our simulations indicate that China's "carbon peak by 2030" target is achievable for the building sector (Fig. 3). Depending on per capita floor area patterns, the peak in building emissions is expected to occur as early as 2017. However, our results also reveal potential disparities across provinces in peak times. Provincial peak timings show substantial heterogeneity (Fig. S12 in Appendix A). Most provinces are projected to peak between the late 2010s and the 2020s, indicating that building emissions in many regions have already peaked or are close to peaking. By contrast, several western and resource-intensive provinces, such as Xinjiang, Qinghai, and Inner Mongolia, exhibit later and more uncertain peak windows extending into the 2030s or beyond. Eastern municipalities and coastal provinces generally peak earlier and within narrower ranges, consistent with earlier urbanization saturation and faster low-carbon transition. These results suggest that national peaking masks important subnational divergence and require differentiated provincial pathways.

4.3 Uncertainty and limitations

The uncertainty analysis was applied to both the BAU and Best scenarios (S1 and S32). Results show that uncertainty ranges gradually widen over time, increasing from about ±(5%–8%) in the near term (around 2030) to approximately ±(20%–25%) under the BAU scenario and ±(25%–30%) under the Best scenario by 2060 based on the 10th–90th percentile range from Monte Carlo simulations (see Fig. S13 in Appendix A). Despite the increasing uncertainty, the divergence between scenarios remains substantial throughout the projection period. By 2060, the difference in mean emissions between the BAU and Best scenarios remains about 1.78 Gt CO_2. In absolute terms, the uncertainty band under the Best scenario is still much narrower than that under BAU in 2060 (0.53–0.90 Gt CO_2 versus 1.93–3.09 Gt CO_2), indicating that coordinated mitigation actions not only deliver deeper emission cuts but also improve the stability of long-term outcomes.

For sensitivity analysis, a population sensitivity analysis indicates that demographic uncertainty mainly affects the magnitude of building CO_2 emissions rather than the overall mitigation trajectory. Although the population-adjusted scenario reduces cumulative emissions by 4.24 Gt CO_2 over 2025–2060, it does not alter the timing of the peak or the declining trend driven by mitigation measures (Fig. S14 in Appendix A). To further clarify the source of provincial differentiation, we conducted a province-level sensitivity analysis for all individual measures (Fig. S15 in Appendix A). The results show that the same mitigation measure can generate markedly different responses across provinces. Stock-related measures, especially intensive use and lifetime extension, show the largest average effects, while renewable electricity also provides substantial reductions through lower indirect emissions. In contrast, construction- and transportation-related measures have smaller and more consistent effects across provinces. These results indicate that provincial pathways are shaped by the interaction between mitigation measures and province-specific building stock dynamics, energy intensity, heating demand, electrification levels, and electricity emission factors, rather than by baseline emission differences alone. Overall, the main conclusions are statistically robust, with uncertainties primarily influencing the rate of decline rather than the magnitude of mitigation.

Cross-study differences are primarily attributable to variations in system boundary, building-type coverage, and material scope (Fig. S16 in Appendix A). For direct and indirect emissions excluding industrial buildings, our estimate (2.1 Gt CO_2 in 2020) is close to IEA's estimate (2.2 Gt CO_2) [23]. Our estimate for 2023 total emissions (3.80 Gt CO_2) is also broadly consistent with the Tsinghua Report (3.6 Gt CO_2) [30] and the CABEE Report (3.99 Gt CO_2) [31], indicating good agreement with existing national assessments. More noticeable differences arise in specific categories. Our estimate for 2022 (2.41 Gt CO_2) is higher than that of Hu et al. (2.16 Gt CO_2) [63], while our residential estimate for 2020 (1.7 Gt CO_2) is lower than that of You et al. (2.0 Gt CO_2) [16], reflecting differences in system boundary and material intensities. For material-related emissions, our estimate (1.15 Gt CO_2 in 2019) is lower than that of Zhong et al. (1.4 Gt CO_2) [8], mainly because their study included a broader range of materials. Overall, our results are consistent with previous studies, with remaining differences primarily driven by methodological scope. A detailed comparison of the BMEE model with representative recent building-decarbonization models is provided in Table S6 in Appendix A.

This study has several limitations that should be acknowledged, as certain assumptions and data constraints may affect the comprehensiveness of our findings. First, although the model incorporates renovation-induced stock changes, energy-performance improvements, and material recycling benefits, it does not explicitly account for the additional material and energy inputs required during renovation activities, nor the collection, sorting, preprocessing, and transport processes associated with recycling. These processes may become increasingly important as renovation and recycling activities expand in future China. Future work should therefore improve the process-level representation of renovation and recycling activities when more consistent data become available. Second, although aluminum has been added to the revised material module and the secondary utilization of major non-metallic construction and demolition waste is assessed in Note S1, other materials such as copper and plastics remain outside the current accounting boundary due to limited province-level intensity data. Their inclusion would further improve the completeness of embodied-emission accounting.

5. Conclusions

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In this study, we developed a province-level Building-Material-Energy-Emission (BMEE) model to quantify China's building CO_2 emissions and mitigation potentials from 2000 to 2060 under integrated policy scenarios. Our results show that China's building emissions peaked around 2017 and may decline to 0.69–2.48 Gt CO_2 by 2060 depending on future floor area demand and mitigation efforts. Under the lowest-emission scenario (S32), cumulative emissions over 2025–2060 can be reduced by 48.0 Gt CO_2 (39.5%) relative to the baseline, with urban renewal providing the largest contribution, followed by green building and energy transition. Public buildings, the materials sector, and several high-emission provinces exhibit the greatest mitigation potential, while provincial results reveal substantial heterogeneity in both emission pathways and differentiated strategy priorities. Uncertainty and sensitivity analyses further confirm that these conclusions are robust.

Overall, our findings highlight that deep building decarbonization in China depends on coordinated action across building stocks, materials, and energy systems, and requires region-specific policy packages rather than one-size-fits-all approaches. To move toward carbon neutrality by 2060, future efforts should further strengthen low-carbon heating, expand renewable electricity, expand waste heat recovery, and coordinate electrification across building operation, construction, and transport. At the same time, future research should improve the representation of renovation- and recycling-stage processes, expand the coverage of additional materials and secondary utilization pathways, and further refine province-specific parameterization. More broadly, our study provides a scalable framework for other large countries facing the dual challenge of accelerating new construction while renovating aging building stocks.

Author contributions

Qiance Liu: Conceptualization, Methodology, Investigation, Data Curation, Software, Formal Analysis, Visualization, Writing – Original Draft, Writing – Review & Editing. Kairui You: Conceptualization, Methodology, Investigation, Data Curation, Software, Formal Analysis, Visualization, Writing – Original Draft, Writing – Review & Editing. Xin Ouyang: Software, Formal Analysis, Visualization, Writing – Review & Editing. Kun Sun: Software, Formal Analysis, Visualization, Writing – Review & Editing. Wei Feng, Menglin Dai, and Wu Chen: Writing – Review & Editing. Weiguang Cai: Conceptualization, Methodology, Supervision. Gang Liu: Conceptualization, Methodology, Supervision, Resources, Funding acquisition, Project administration, Writing – Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declaration of Generative AI Use

Generative AI tools were used only to assist with language polishing and editing, and all scientific content, analyses, and interpretations were conducted and verified by the authors.

Appendix A. Supplementary Information

The following are the Supplementary Information to this article:

Supplementary figures, tables, notes and descriptions.

Data availability

All data inputs and results of all scenarios in this study are available at https://github.com/BMEE-MODEL/BMEE-MODEL.

Code availability

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All calculations in this study were performed in Python. The codes are available at https://github.com/BMEE-MODEL/BMEE-MODEL.

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Declaration of Interest Statement

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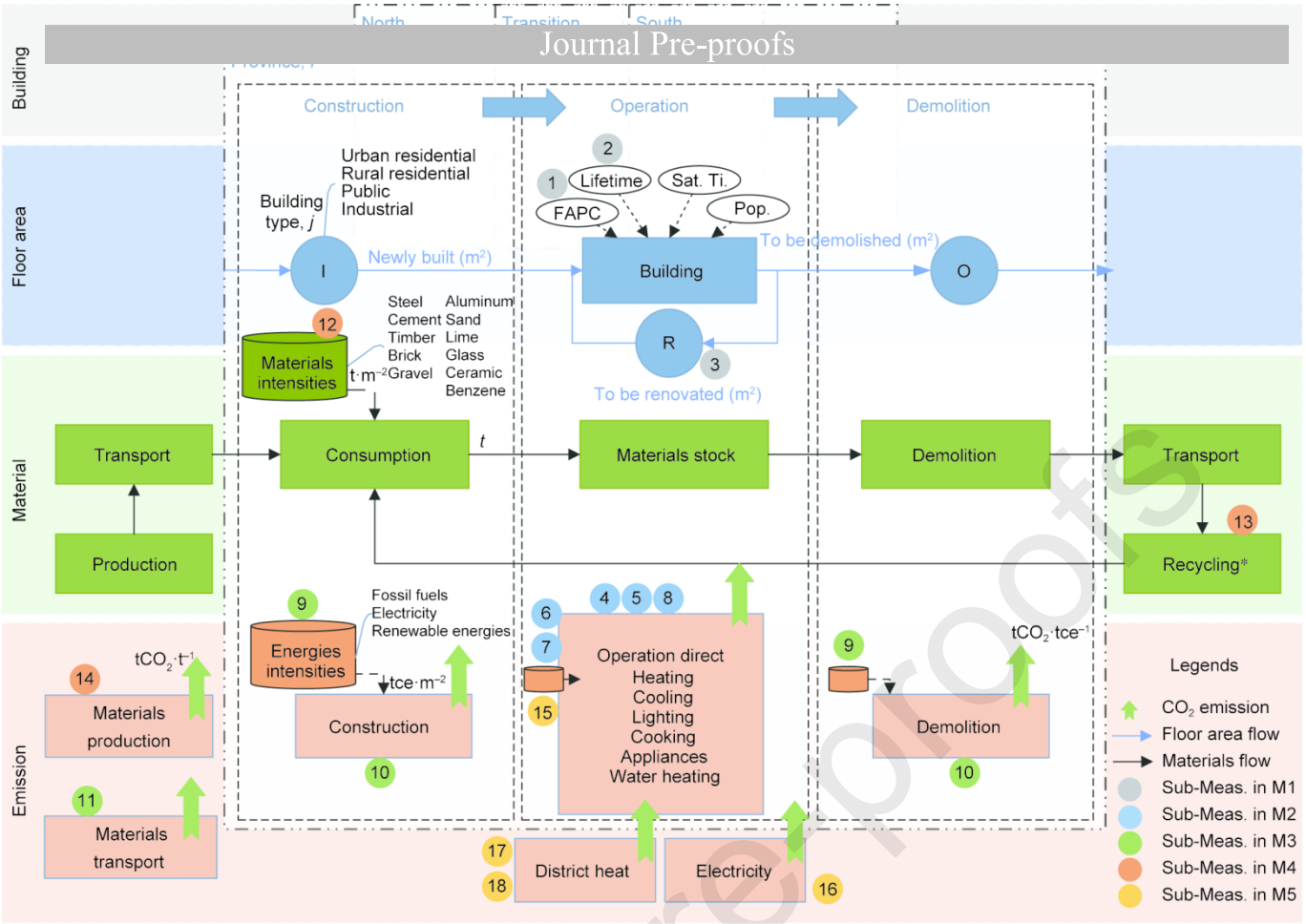
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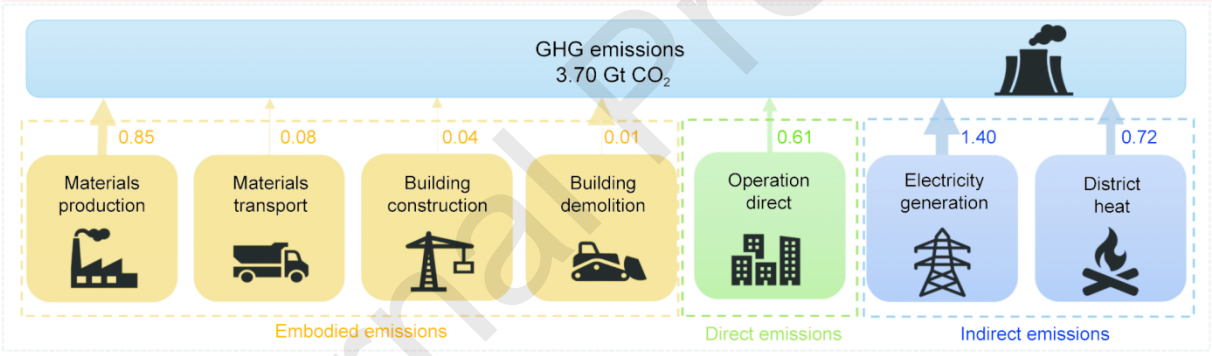
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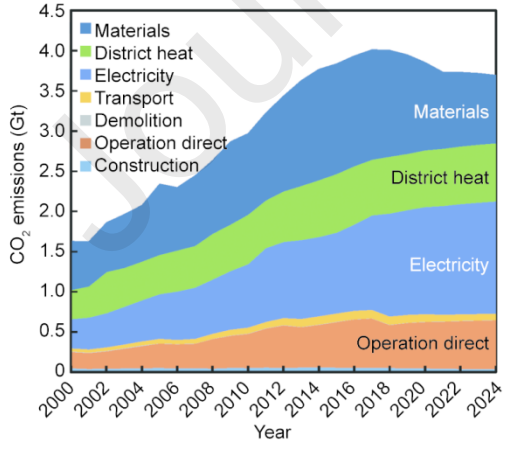
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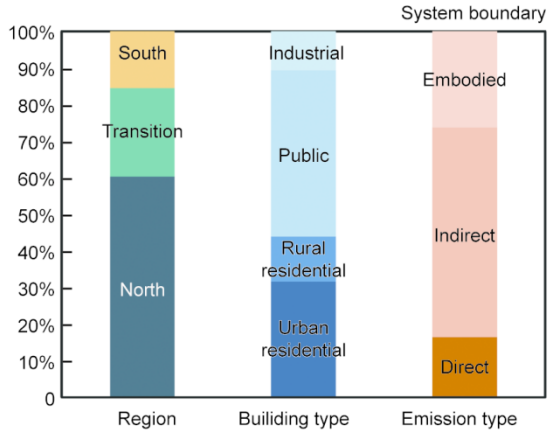




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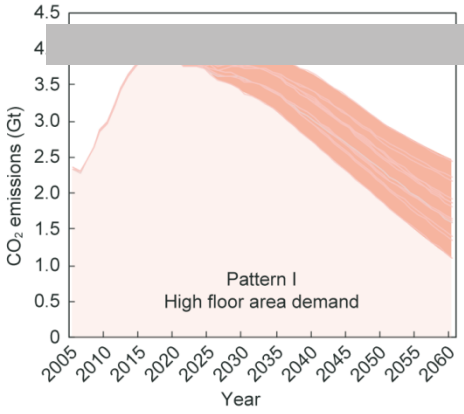


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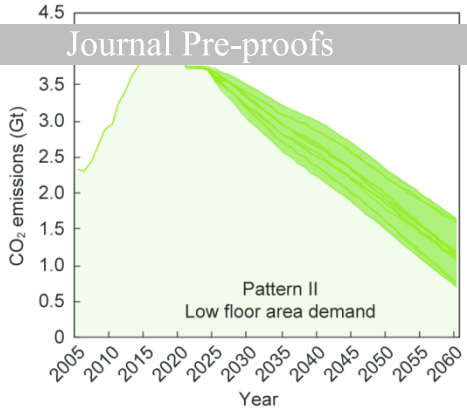


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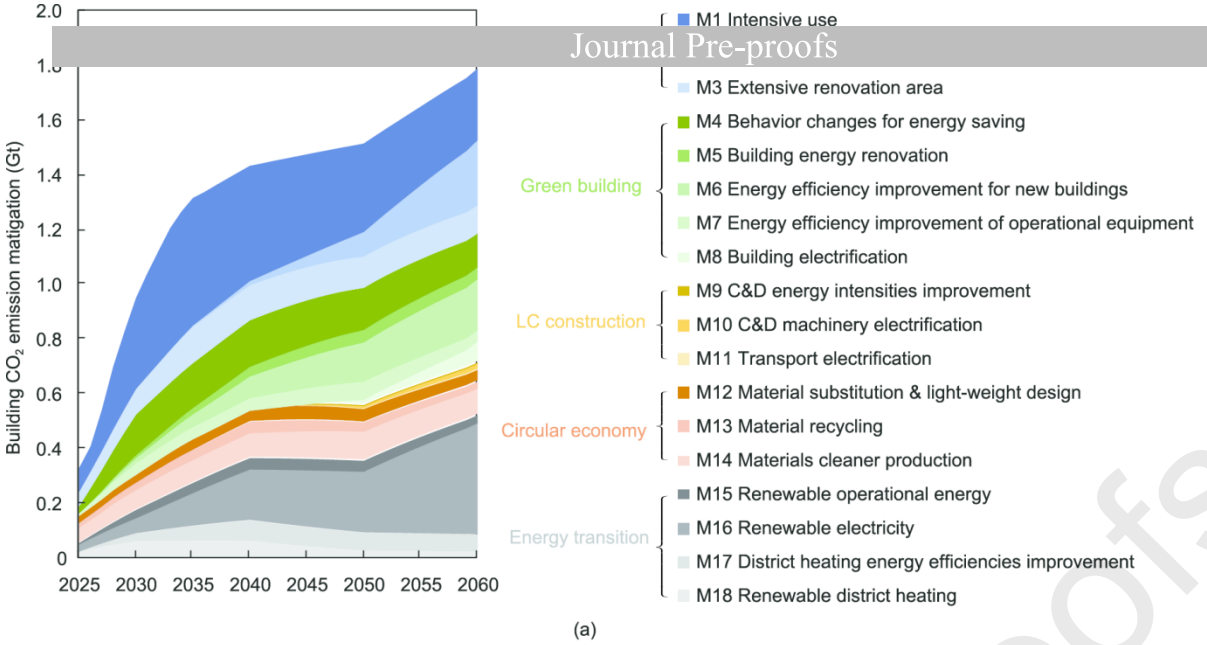
(b)

	Construction	Operation direct	Demolition	Material	Electricity	Heating	Transport
ST1	0.44	1.69	0.03	12.71	4.18	1.50	1.20
M1	0.21	1.87	0.01	5.92	4.54	2.02	0.53
M2	0.09	–0.01	0.03	2.81	–0.02	–0.01	0.31
M3	0.17	–0.16		5.22	–0.33	–0.48	0.47
ST2		4.85			2.03	6.24	
M4		0.80			2.28	3.24	
M5		0.12			0.24	0.35	
M6		0.50			1.16	2.91	
M7		0.48			1.68		
M8		3.44			–3.79		
ST3	0.07		0.03				0.45
M9	0.10		0.03				
M10	–0.03		–0.01				
M11							0.45
ST4				7.83			0.24
M12				2.29			0.24
M13				1.91			
M14				4.92			
ST5	0.08		0.03		8.84	4.06	
M15					1.47		
M16	0.08		0.03		7.68		
M17						1.78	
M18						2.57	

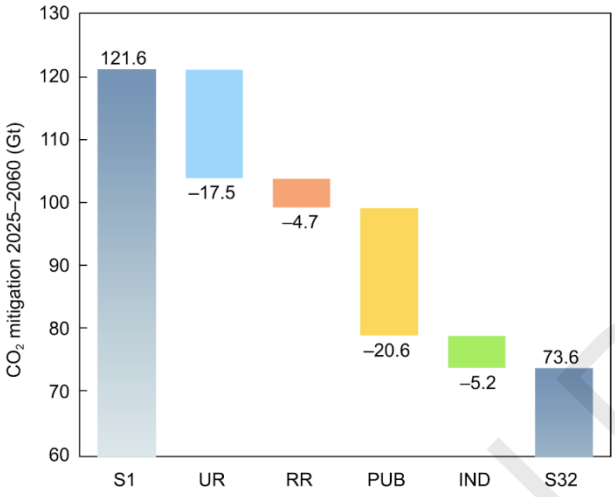
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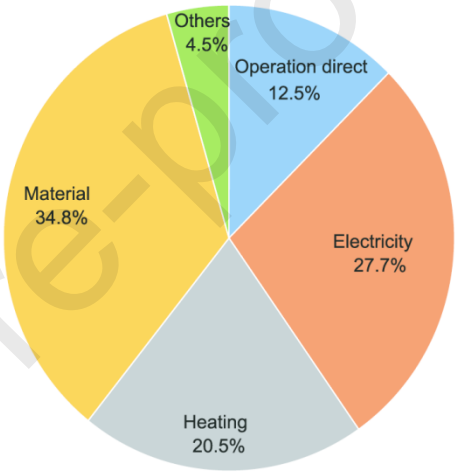
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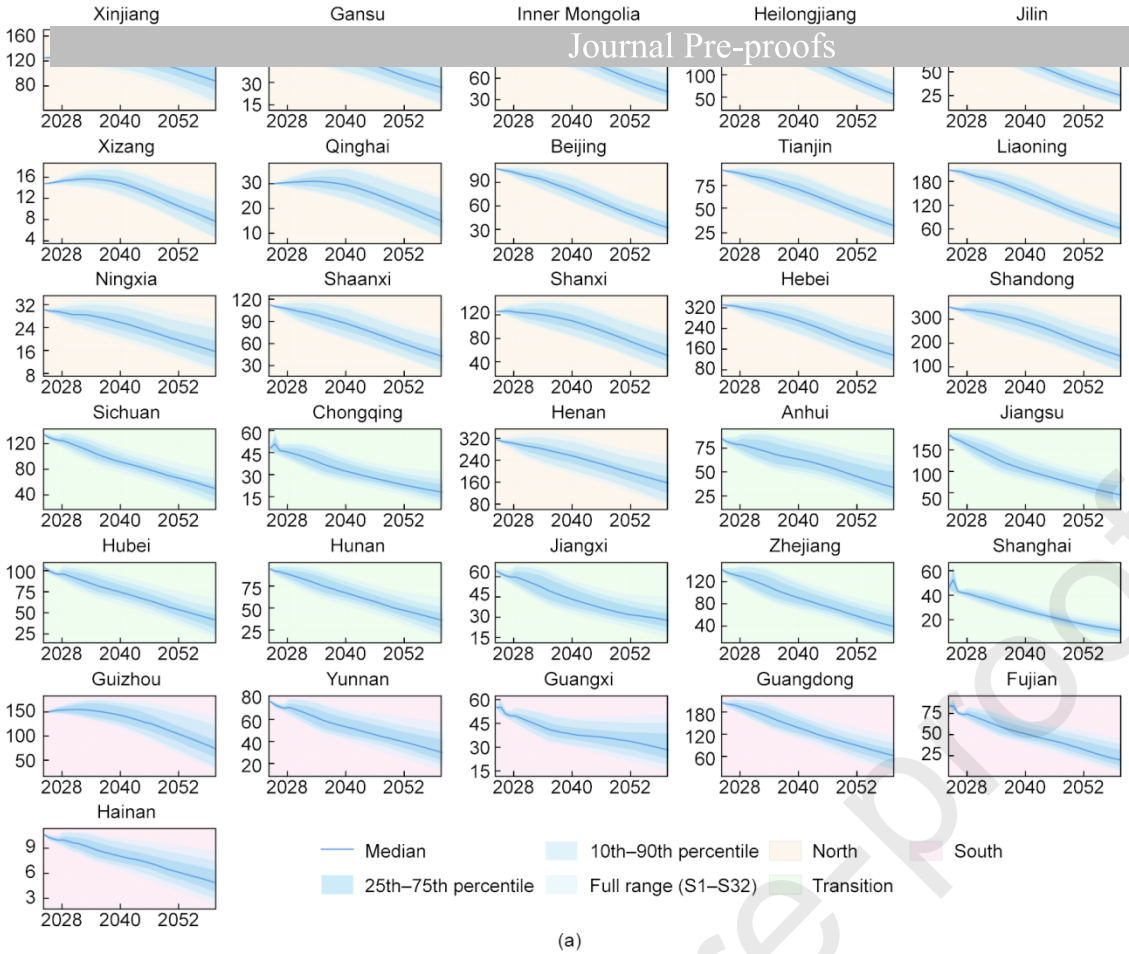
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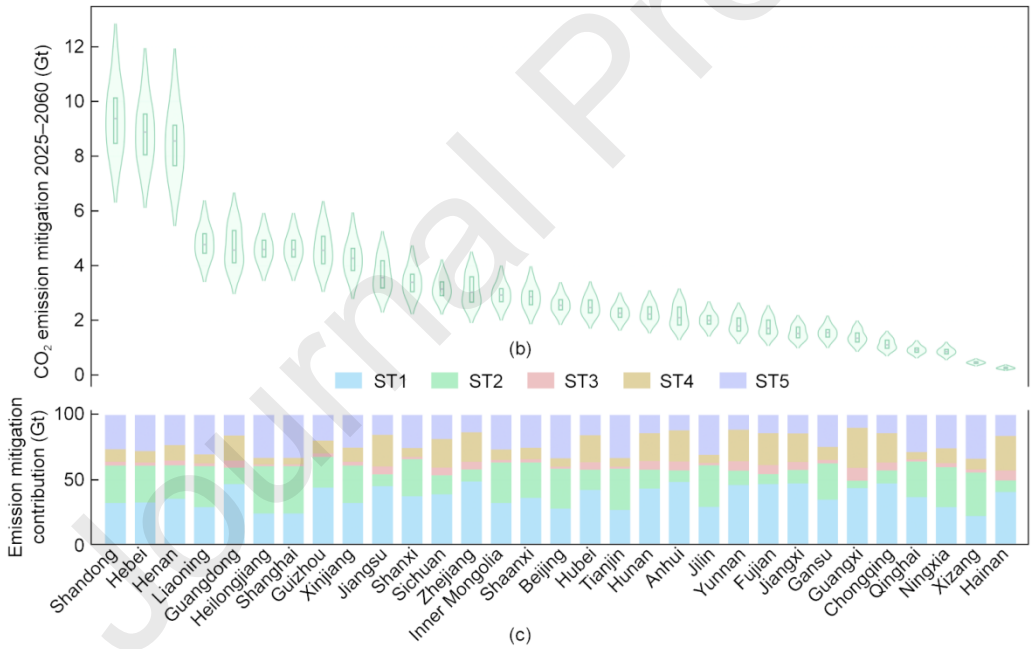
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(a)



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