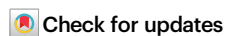


Mitigating emissions and costs through demand-side solutions in Chinese residential buildings

Received: 20 November 2024

Accepted: 29 July 2025

Published online: 09 August 2025

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The building sector plays a pivotal role in climate change mitigation. By regulating the demand for services and products from supply sectors, building sector can contribute to decarbonization. To assess the decarbonization and cost-saving potential of demand-side solutions for China's residential building sector, this study develops a demand-side solution framework and an end-use technology model. The model covers the building sector and major supply sectors, considering the heterogeneous impacts of demand-side solution measures on different supply sectors. Here we show that the most optimistic cost-effective demand-side solution can reduce cumulative CO₂ emissions by 47% (42.21 Gt CO₂-eq), while achieving a 16% saving in the net present value of costs over the period 2020–2060. Additionally, results indicate that the demand-side solution enable China's rural residential buildings to achieve carbon neutrality without carbon dioxide remove options, while simultaneously mitigating uncertainties in reaching carbon neutrality targets.

The demands of buildings for services and products from upstream supply sectors (e.g., material production, transportation, construction, and energy generation) generate significant CO₂ emissions, accounting for nearly 40% of global CO₂ emissions¹. However, this demand continues to exhibit a rapid growth trend, particularly in developing countries, particularly in emerging and developing economies^{1,2}. Although supply sectors have significantly reduced the carbon intensity of their products by adjusting energy structures and improving production efficiency, their decarbonization efforts may be offset by increasing demand^{3–5}. This highlights the critical importance of building demand-side solutions (DSS) as a pivotal strategy to mitigate global climate change.

An increasing number of scholars and policymakers have focused on the role of DSS in climate mitigation, highlighting that DSS can effectively reduce CO₂ emissions while generating cost savings for

both supply and demand sectors^{6–10}. Based on technology-oriented or behavior-based DSS measures, several studies have forecasted future CO₂ emissions and proposed decarbonization pathways for different sectors^{9,11,12}. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) dedicated a separate chapter to DSS for the first time, introducing the Avoid-Shift-Improve (ASI) framework to review DSS measures and their decarbonization potential across transportation, agriculture, buildings, and manufacturing sectors⁸. Avoid refers to reducing unnecessary demand, such as curbing unsustainable behaviors in household appliance utilization or lowering building vacancy rates; Shift refers to shifting to more sustainable technique modes, replacing fired boilers with heat pumps or adopting wood structures over concrete-steel; Improve denotes improving the efficiency of existing techniques, such as deploying high-energy-label household appliances and lightweight building structural designs^{8,13,14}.

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Several studies have developed an ASI framework for buildings, yet they primarily focus on the interaction between the energy generation and the building sector^{4,15–17}. Other building supply sectors contribute significant embodied CO₂ emissions, accounting for nearly half of building-related CO₂, particularly in emerging and developing economies, such as China and India^{1,2}. Meanwhile, DSS measures may exert heterogeneous impacts on different supply sectors. For instance, extending building lifespan reduces the need for new buildings, thereby decreasing demand for raw materials and construction services². However, this practice also locks in the update of building energy efficiency techniques, potentially increasing operational energy demands^{18,19}. Methodologically, existing models typically focus on interactions between a single supply sector and the building sector, hindering comprehensive analysis of DSS measures' heterogeneous impacts across multiple supply sectors^{15,20,21}. Life Cycle Assessment (LCA) provides a from cradle to grave perspective for buildings, enabling analysis of critical parameters in energy use and material efficiency for DSS measures²². Notably, most building LCA studies remain static and unit-based. Therefore, to achieve wider decarbonization through building DSS, it is essential to examine DSS measures from a building life cycle perspective and integrate them and their cost into the next generation model^{15,19,23}.

Against this background, we propose an DSS framework titled LCA-ASI. The DSS measures within LCA-ASI are characterized by two attributes: targeted supply sectors and action modes (i.e. avoid, shift, and improve). Concurrently, we developed an end-use technology model to assess the CO₂ emissions and cost investments under different DSS scenarios. The model extends building LCA studies from static and on a unit basis to dynamic and on a system basis, dynamically linking demand for products across different supply sectors. We apply the model to the case of Chinese residential buildings (CRB), which is responsible for 2 GtCO₂-eq, equaling nearly 30% of Chinese CO₂ emissions and the entire European Union CO₂ emissions²⁴. The results show that the most optimistic cost-effectiveness scenario can reduce cumulative CO₂ emissions by 47% and achieve a 16% saving in net present value (NPV) from 2020 to 2060. Additionally, our model indicates that the carbon neutrality of CRB requires synergistic efforts from both DSS and supply sectors.

Results

LCA-ASI demand-side solution framework of buildings

To analyze the decarbonization potential and cost investments of building DSS, this study proposes an ASI framework encompassing the main upstream supply sectors of buildings (Fig. 1). Figure 1a illustrates the pathway from building occupants' demand for building functions to the demand for supply sector products. The pathway comprises three subprocesses: building function demand, technique mode, and appliance efficiency—matched with avoid, shift, and improve, respectively. In this study, buildings provide seven functions for residents: space heating, space cooling, lighting, water heating, cooking, other appliances, and activity space. The LCA-ASI framework concludes 11 demand-side solution measures (seven avoid measures, two Shift measures, and two Improve measures), and emphasizes that a single DSS measure can influence demand for products and services across multiple supply sectors.

End-use technique model is grounded in multiple stock-driven-flow (SDF) models of physical units (e.g., buildings and household appliances). We coupled technique flow with SDF to examine changes in technique efficiency and mode (see Supplementary Fig. 9). The three components of building SDF depict the number of buildings in different life cycle stages. Inflow buildings are in the production and construction stage, stock buildings are in the use stage, and outflow buildings are in the end-of-life stage. Leveraging these components, we

dynamically quantify demand for supply sector products (Supplementary Fig. 1), allowing the end-use technology model to establish dynamic linkages between demands across different supply sectors. Detailed calculation is shown in Method and Supplementary Note 1. Furthermore, referencing China's current policies and relevant literature, we defined low, medium, and high levels for each DSS measure (Fig. 1b). Measure-specific parameters and their values are listed in Supplementary Table 1. Additionally, the model incorporates uncertainties for 16 key supply sector parameters (Fig. 1c & Supplementary Table 2) to assess the distribution of future CO₂ emission trends under various DSS scenarios.

Cost-effectiveness of scenarios and scenario selection

All combinations of the 11 DSS measures were simulated. Cost-effectiveness was defined as the sum of each scenario's decarbonization rate and NPV-saving rate, with values below the Base scenario serving as the benchmark. We selected 11 single-DSS-measure scenarios and 9 typical combinations (Fig. 2b), including: Low (Base), medium (ASII), and high levels (ASI2) of all measures; high level of only avoid (A2), shift (S2) or improve (I2) measures; scenario with most optimistic decarbonization (PD), NPV-saving (PNS), and cost-effectiveness (PCE);

Figure 2a illustrates the long-term (up to 2060) impact of all combinations of low and high levels of 11 DSS measures. Overall, scenarios with higher decarbonization rates generally exhibit higher NPV-saving rates. Based on similar cost-effectiveness, scenarios cluster into two distinct groups: economy-oriented and decarbonization-oriented. Most of avoid measures are related to utilization behaviors, which generally incur few additional costs. S2 and I2 fall into the decarbonization-oriented groups, suggesting that accelerating the promotion of shift and improve measures requires government subsidies and techno-economic efficiency gains^{7,25}.

Due to its limited decarbonization effect, the cost-effectiveness of PNS is lower than that of PD. The PCE scenario can reduce cumulative CO₂ emissions by 47% and achieve a 16% saving in NPV. The difference between three scenarios lies in the adoption of M4, M5, M7, and M11. PCE contains M4 and M7, and excludes M5 and M11, indicating that adopting building envelope retrofit and high-efficiency appliances has negative cost-effectiveness. For one thing, China's latest Building Energy Efficiency Standards (BEES) achieve nearly 30% energy savings compared to the previous generation²⁶. The exponential function relationship indicates that the energy-saving margin between successive BEES is gradually diminishing. As a result, increasing reinvestment cost for a better building envelope and decreasing energy-saving will erode the cost-effectiveness of building energy retrofits. For other things, energy-saving benefits from advanced building envelopes and high-efficiency heating/cooling appliances can partially offset each other²⁵. Therefore, our study suggests finding a suitable implementation object to improve cost-effectiveness. Such as old buildings in colder areas (e.g. Heilongjiang, Jinlin, Inner Mongolia, and Liaoning provinces) for M11.

Notably, when considering time scales, most DSS combinations demonstrate significant improvements in decarbonization rate, NPV-saving rate, and cost-effectiveness over the long term (up to 2060) compared with the short-term (up to 2030, Supplementary Fig. 2), particularly those containing M2, M4, and M9. The continuously declining emission factor of electricity enables electric appliances to achieve greater annual emission reductions in the future. New buildings with long lifetimes will reduce material demand in the future. Notably, It is noteworthy that the short-term most optimistic cost-effectiveness combination excludes DSS measures to enhance new building envelopes (M4) compared with PCE, which is caused by that building envelopes have long lifetimes²⁷ and incremental costs require long cycle times for recovery²⁸.

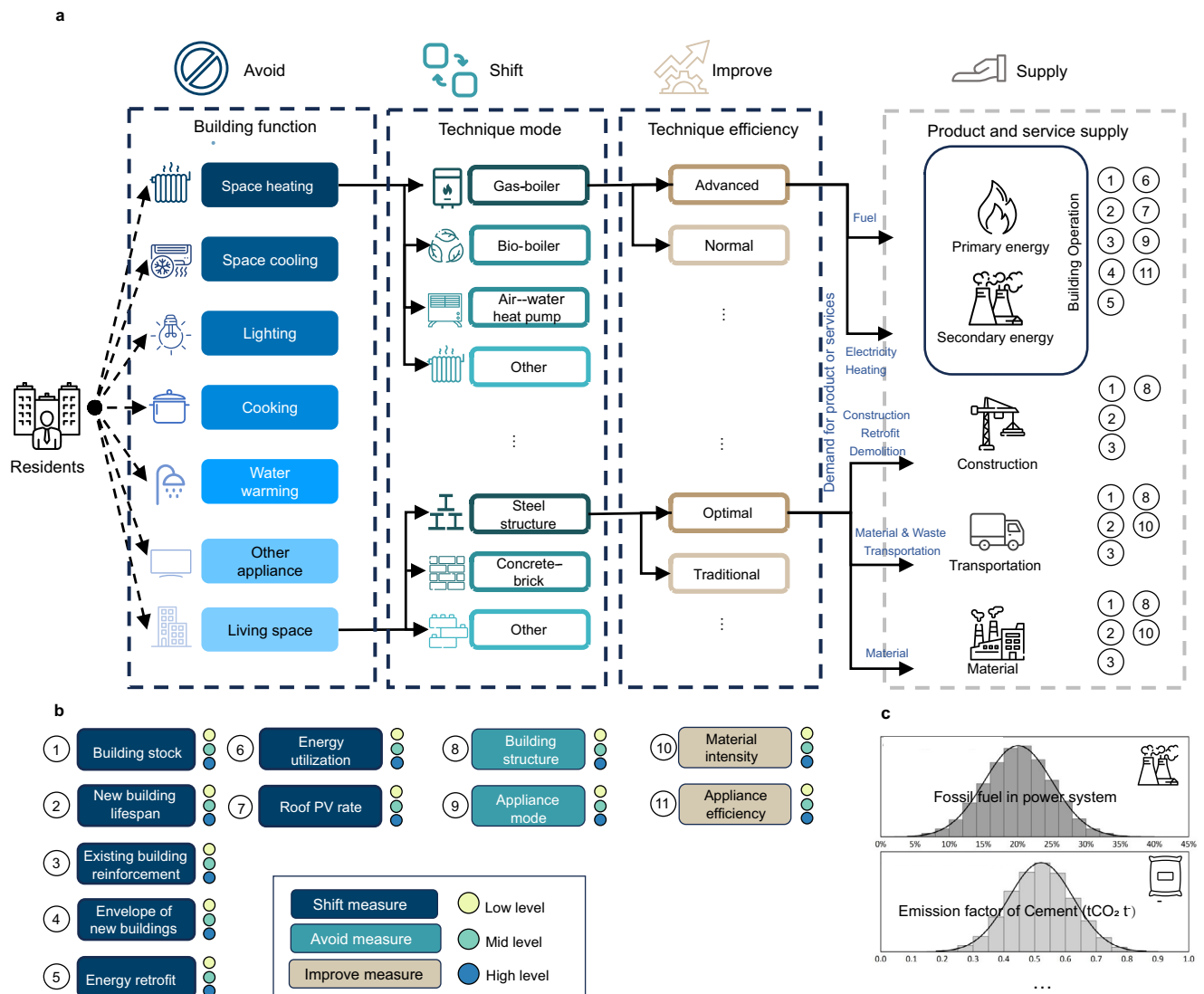


Fig. 1 | LCA-ASI framework of buildings. **a** LCA-ASI (Life Cycle Assessment – Avoid-Shift-Improve) analysis framework, translating residents' demands for building functions into demands for products and services from the building's upstream supply sectors. **b** Key parameters matched with 11 demand-side solution (DSS)

measures. Full measure names are provided in Supplementary Table 1. **c** Uncertainties in supply sectors. 16 parameters and their uncertainties for supply sectors are detailed in Supplementary Table 2.

CO₂ emissions of demand-side solution scenarios

Figure 3 depicts future CO₂ trends under different DSS scenarios. In 2020, CRB emitted 2.08 GtCO₂ -eq, accounting for nearly 30% of China's energy-related CO₂ emissions²⁴. Building operation contributed the largest share (57.01%), primarily from space heating and cooling (Supplementary Fig. 3). Cement carbonization of CRB contribute 123.18 MtCO₂ -eq of carbon sink, nearly half of cement processing emissions²⁹. Following the current techniques utilization pattern (Base scenario in Fig. 3a), CRB CO₂ emissions will peak in 2036 (2.42 Gt CO₂-eq) and decline by 24.36% by 2060 relative to 2020. Rural residential buildings have lower emissions and have already reached a carbon peak. Due to the Chinese rapid urbanization process, the carbon peak time of urban residential buildings exhibit a later peak timing.

DSS significantly reduces CRB CO₂ emissions. Implementing all DSS measures at high level (ASI2) achieves cumulative reductions of 43.62 Gt CO₂-eq. The decarbonization effect of PCE is slightly lower than PD, which achieves cumulative cuts of 45.57 Gt CO₂-eq. Building operation achieve a largest mitigation potential, with 56.11% reduction on cumulative emissions under PD. Meanwhile, cumulative CO₂

emissions in material production, construction, and transportation decrease by 40.59%, 37.63%, and 24.40%, respectively. Although DSS substantially advances CRB toward carbon neutrality, PD still leaves a last-mile gap (0.26 GtCO₂ -eq), with building operation and material production contributing 0.19 and 0.14 Gt CO₂-eq, respectively. That highlights the decarbonization coordination of the electricity sector and the material sector.

Among three categories of demand-side measures, avoid achieves the highest level of decarbonization potential. In contrast, Shift exhibits the lowest decarbonization potential, primarily because the positive decarbonization effect of adopting low-carbon appliances (M9) is offset by the negative effect of changing building structures (M8). Shift involves altering technical modes, which in turn changes energy types and building materials, highlighting the need for "Shift" to align with the decarbonization progress of supply sectors. Shift requires the operation stage shift to a higher electrification. However, as China's electricity emission factors are higher than those of coal and natural gas in the short and medium terms, the emission factors of building operation will increase with the rise in building electrification rates (Fig. 4a). Specifically, the operational emission factors in S1 and S2

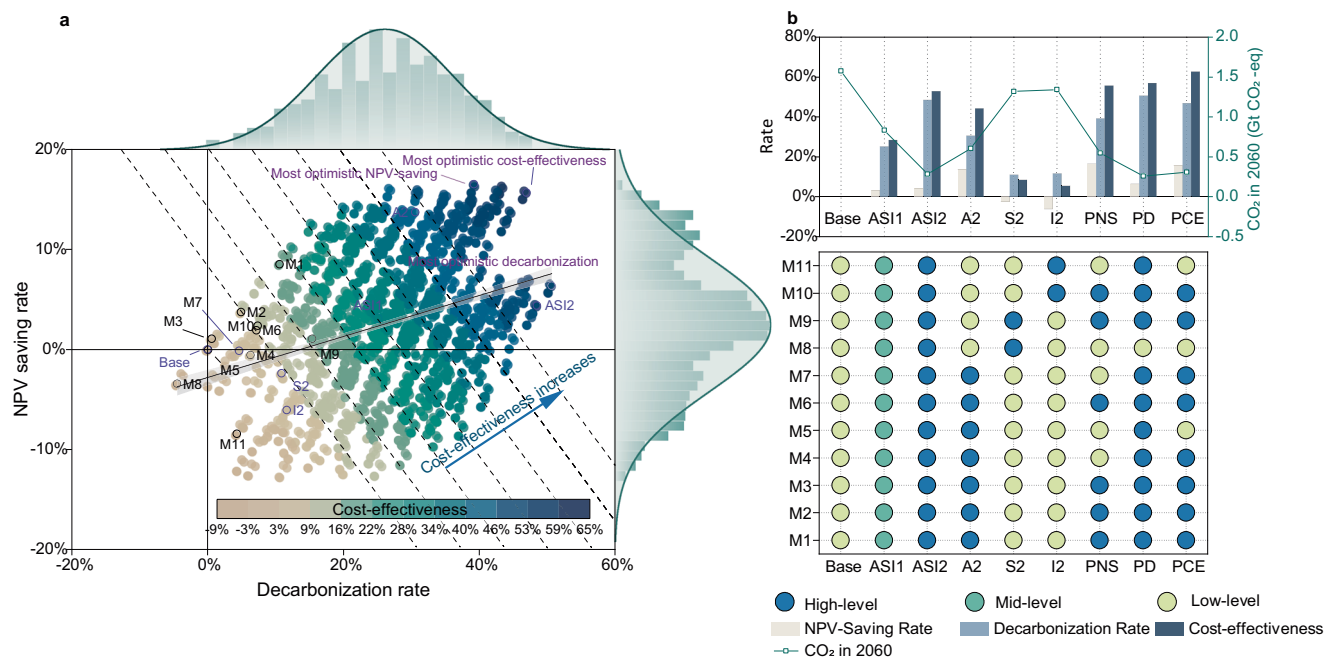


Fig. 2 | Cost-effectiveness of different demand-side scenarios. **a** Decarbonization rate of cumulative CO₂ emissions and NPV-saving rate (IRR = 0.06). M1, limited building stock; M2, improving lifespan of new buildings; M3, reinforcing existing buildings; M4, improving envelope performance of new buildings; M5, energy retrofitting for existing buildings; M6, green energy utilization behaviors; M7, Utilization of building PV; M8, optimal building structure; M9, technique modes of

household appliances; M10, Light building structure; M11, Improving efficiency of household appliances; **b** 9 typical combinations of DSS measures, ASI1, middle level of all ASI measures; ASI2, high level of all ASI measures; A2, high level of all avoid measures; S2, high level of all shift measures; I2, high level of all improve measures; PNS, most optimistic NPV-saving scenario; PD, most optimistic decarbonization scenario; PCE, most optimistic cost-effectiveness scenario.

scenarios exceed those of the Base scenario before 2051 and 2037, respectively. Therefore, it is necessary that building electrification process balances emission factors of electricity and energy efficiency of electric appliances³⁰. For example, the current emission factor of electricity is nearly 2 times that of coal and 3 times that of gas. Promoting coal-fired boilers (energy efficiency < 1) shifts to gas- or ground-water heat pumps (energy efficiency > 3), and delaying gas-cookers to electricity-cookers since their energy efficiency is similar. For building material production, China's preference for high-rise buildings and resource endowment may drive the adoption of steel structures as the primary alternative to traditional brick-concrete and steel-concrete structures. However, steel currently has a higher emission factor, and steel will be locked in system by the building's long lifespan and won't be recycled in the short- or mid-term. The Shift measure will increase the embodied emission intensity of new buildings before 2060 (Fig. 4b), contributing cumulatively to 3.94 Gt CO₂-eq (Fig. 3b). Additionally, the Shift measure widens the gap between steel demand and recycled steel from building demolition. Under the S2 scenario, recycled steel covers only 31.07% of steel demand by 2060, which is lower than Base scenario (44.68%), thereby driving up primary steel production (Fig. 4b).

Figure 3b shows the decarbonization potential of each DSS measure. Only shifting to low-carbon household mode (M9, 2021) will accelerate the carbon peak of CRB to before 2030 (Supplementary Fig. 4). M9 achieves the highest level of decarbonization, with cumulative reductions reaching 13.86 Gt CO₂-eq. This is particularly driven by heating, cooling, and lighting systems, where adopting high-performance heat pumps and LEDs significantly enhances energy efficiency in the short term.

Additionally, the results highlight that early actions can significantly reduce future CO₂ emissions. Extending building lifespan (M2) and better envelope (M4) for new buildings exhibit high but lagging decarbonization effects. Their cumulative decarbonization effects rank 9th and 11th before 2040, respectively, but rise to 3rd

and 4th during 2050–2060. Notably, increasing building lifespan presents a double-edged sword effect: M2 and M3 slow building turnover rates, cutting material-related CO₂ emissions by 4.32 and 1.05 Gt CO₂-eq, yet they hinder envelope technology updates and increase operational emissions by 39.85 and 245.91 Mt CO₂-eq. That suggests that governments need to develop optimized building metabolism or retrofit plan to balance the impacts of lifetime on building embodied and operational emissions. Compared with China, developed countries usually have a larger lock-in effect in building operations from longer building lifespans and higher stocks of old buildings. Take space heating as an example, in 2015, the average heating intensity of existing buildings in China's cold and severe cold areas was 1.21 times that of new buildings constructed after 2010, while the figures were 1.72 times in the United States, 1.84 times in the United Kingdom, 2.37 times in Germany, and 2.23 times in Denmark (Supplementary Fig. 5)^{31–33}. More new buildings and short-lifetime old buildings (nearly 35 years) mean that Chinese building energy efficiency can be easily improved in the future by building metabolism. Developed countries need a larger-scale building energy retrofit to break lock-in effect.

Under all scenarios, Chinese residents' demand for building functions will continue to grow. Beyond technical solutions, enhancing energy-utilization behaviors (M6) significantly mitigates this trend and rapidly reduces operational CO₂ in the short term. 6 has demonstrated extraordinary energy-saving potential across different building functions. For example, district heating saving of 15% (e.g. by replacing area-based charge to meter-based charge)³⁴, individual heating and cooling saving of 10–30% (e.g. by revising temperature setting)⁴, lighting saving of 10–70% (e.g. by timely turn-off light and smart system control)^{4,35}, water heating saving of 10–50% (e.g. by adjusting the temperature setting of water and shorter showers)^{4,36,37}, and other appliance saving 3–12% (e.g. by reducing the standby power use)³⁸. These measures entail minimal additional costs and barely impact residents' quality of life^{4,36}.

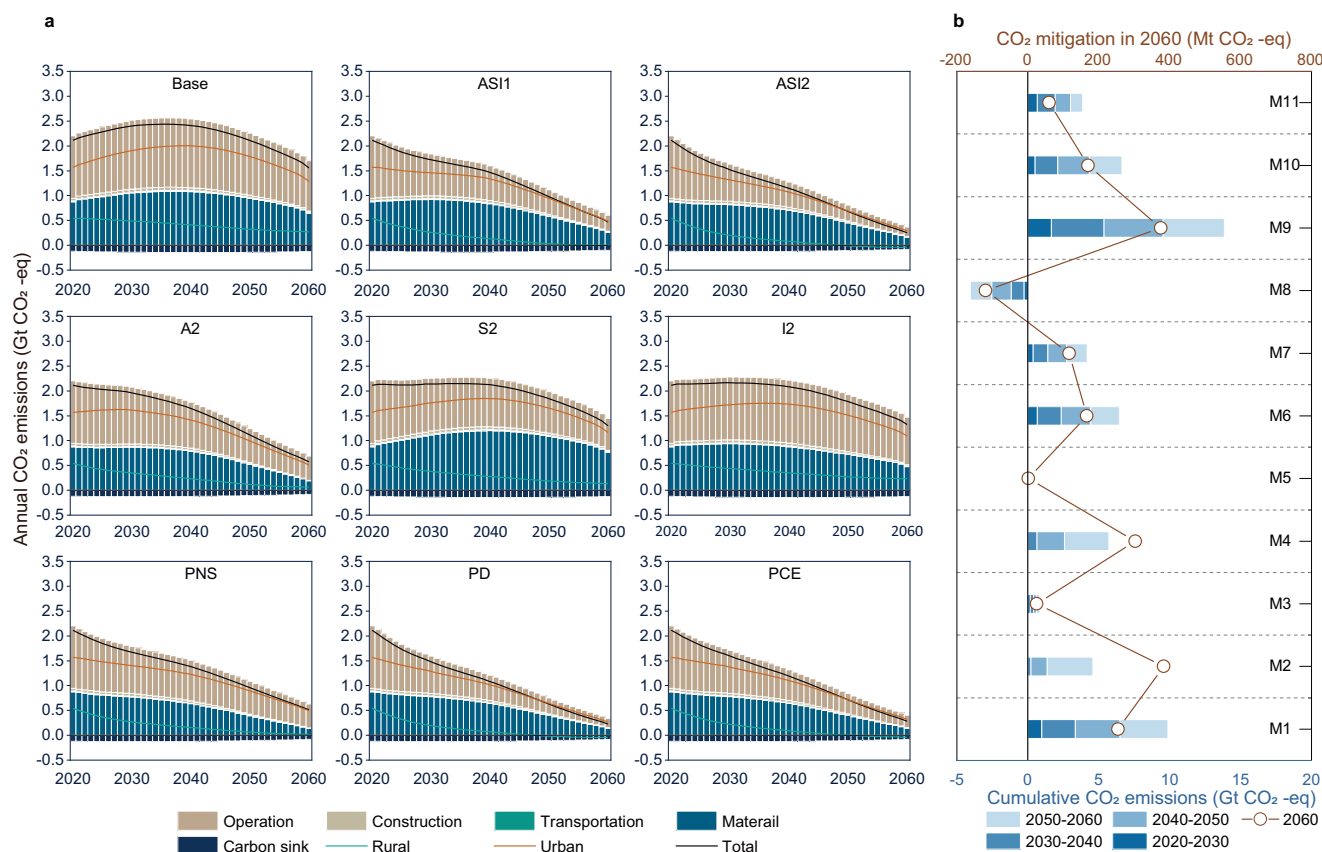


Fig. 3 | CO₂ emissions of different demand-side scenarios. **a** CO₂ emissions of 9 combined scenarios from 2020–2060. Base, low level of all ASI measures; ASI1, middle level of all ASI measures; ASI2, high level of all ASI measures; A2, high level of all avoid measures; S2, high level of all shift measures; I2, high level of all improve measures; PNS, most optimistic NPV-saving scenario; PD, most optimistic decarbonization scenario; PCE, most optimistic cost-effectiveness scenario.

b Cumulative decarbonization of 11 single measure scenarios (high level of each

measure) during the period of 2020–2060. M1, limited building stock; M2, improving lifespan of new buildings; M3, reinforcing existing buildings; M4, improving envelope performance of new buildings; M5, energy retrofitting for existing buildings; M6, green energy utilization behaviors; M7, Utilization of building PV; M8, optimal building structure; M9, technique modes of household appliances; M10, Light building structure; M11, Improving efficiency of household appliances.

Cost investment of demand-side solution scenarios

Figure 5 shows the annual investment of CRB. Under the Base scenario, CRB's actual cost investment reached 6.05 trillion Chinese Yuan (CNY) in 2021 and is projected to increase by nearly 50% by 2060. In 2021, costs from building materials (including materials and envelopes), building construction, household appliances, and energy consumption accounted for 30.26%, 25.62%, 24.69%, and 17.87% of the total, respectively. As per capita building area demand approaches saturation, the share of costs for building materials and construction will gradually decline.

DSS can achieve emission mitigation while saving costs. Compared with the Base scenario, the PNS scenario is expected to save over 16.52% of NPV and reduce annual investment by 3.72 trillion CNY by 2060. The PCE scenario saves 15.67% of NPV and demonstrates the lowest annual costs after 2046. Among the three DSS categories, avoid achieves the highest level of NPV savings (13.72%), primarily derived from reduced material, construction, and energy consumption costs. In contrast, shift and improve increase costs. The S2 and I2 scenarios raise NPV by 2.39% and 6.08%, respectively. The cost increase in S2 stems mainly from expenditures on building materials and household appliances, while all incremental costs in I2 are attributed to household appliance purchases.

For DSS measures, limiting building stock (M1) and extending lifespan for new buildings (M2) yield the top two cost savings. Both measures reduce unnecessary costs in building materials and construction by addressing building vacancy rates and rapid stock

turnover, enabled by improved building structure design and surrounding infrastructure services. Notably, M4 and M7 will decrease annual costs after ~2040 (Supplementary Fig. 4), indicating strong techno-economic viability and long-term NPV savings. For household appliance selection (Supplementary Fig. 6), shifting appliance modes (M9) proves more economical and low-carbon than purchasing higher-efficiency models (M11) for space heating, lighting, and cooking, particularly changing to high-efficiency heat pumps (e.g. sewage- or ground- sources), electric cookers, and LEDs. For household cooling, advanced appliances or air-to-water heat pumps are recommended. Solar water heaters are suitable for areas with optimal lighting and climate, reducing the experience of residents due to unstable weather and long preparation time. Joint utilization of air/ground-source heat pumps for heating, cooling, and water heating or multi-family shared systems in high-rises—is also advocated. Other appliances (e.g., TVs, refrigerators) drive M8 to incur higher appliance costs than the Base scenario. In the appliance market, energy label upgrades often bundle additional service functions, inflating premiums; this highlights the need for subsidies to target energy-saving-oriented products. Figures 2, 3, and 5 show that large-scale building envelope retrofitting (M5) is not suitable for China. M5 only benefits buildings without insulation or with low-level insulation (i.e. building energy efficiency standard with a 30% or 50% energy-saving rate). Buildings adhering to the latest BEES are unsuitable for future retrofitting and struggle to recover retrofit costs.

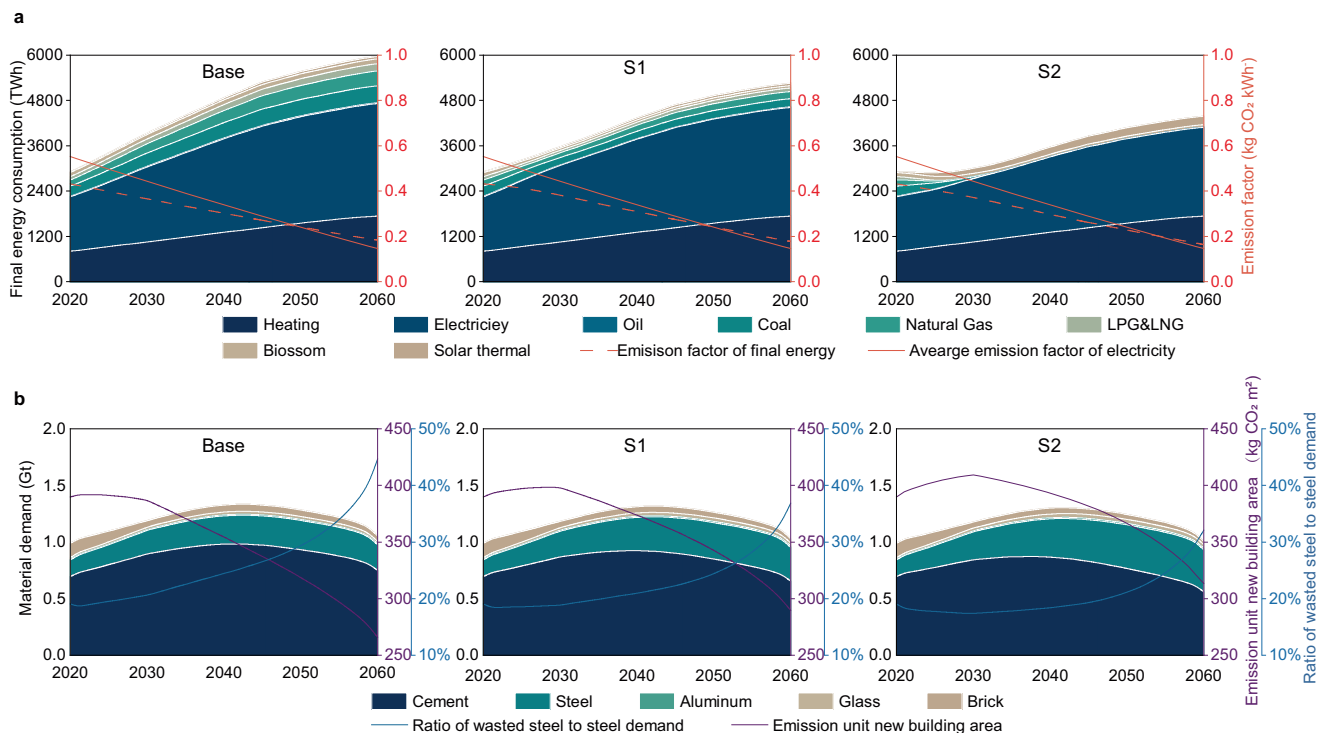


Fig. 4 | Shift in final energy and building material consumption. a Final energy demand and comprehensive emission factor in building operation. S1, middle level of all shift measures; S2, high level of all shift measures. **b** Material demand and

material CO₂ emissions unit new building area (consider recycling material from demolition buildings) under Base, S1, and S2 scenarios.

Uncertainty of achieving carbon neutrality of demand-side solution scenarios

By accounting for parameter uncertainties in supply sectors (Supplementary Table 2), we evaluated the uncertainty of achieving carbon neutrality for CRB under the Base and most optimistic-decarbonization (PD) scenarios. Results in Fig. 6 show that implementing DSS reduces the uncertainty of CRB CO₂ emissions. Specifically, at the 95% ($\pm 2\sigma$) confidence level, the CO₂ emission errors under the Base and PD scenarios are ± 346 and ± 96 Mt CO₂-eq in 2060, respectively. In other words, DSS mitigates decarbonization pressure on supply sectors by adjusting demands for upstream services and products, effectively decoupling CRB carbon neutrality from supply-sector decarbonization processes. Sensitivity analysis (Supplementary Fig. 7) reveals that the share of fossil energy in power and heating generation has the greatest impact on uncertainty. Under coal reduction policies and a new power system dominated by renewables, heat sources from coal-fired and cogeneration boilers are expected to decline, presenting significant challenges for heat source acquisition. Policy frameworks and studies advocate shifting from district heating to individual heating. Such as China's Carbon Peak Plan for urban-rural construction promotes ultra-low-energy buildings without central heating in severe cold and cold region.

Although DSS can significantly reduce CRB's CO₂ emissions, Carbon Dioxide Removal (CDR) options are essential for completing the last mile of CRB's carbon neutrality. Under the PD scenario, CRB will have 299 Mt CO₂-eq (± 96.00) remaining by 2060. The carbon sink from cement carbonization (85.31 Mt CO₂-eq) nearly matches the CO₂ emissions from cement production by 2060. From a whole industry chain perspective, cement carbonization can offset part of the decarbonization responsibility for cement production, relieving the cement sector from high-cost CDR pressure in the short to mid-term. Additionally, without CDR, urban residential buildings cannot achieve carbon neutrality (projected to have 334 ± 102 MtCO₂-eq in 2060). In

contrast, rural residential buildings under the PD scenario are 99.97% likely to achieve carbon neutrality before 2060, with the neutrality year estimated to be around 2050. For one thing, population urbanization and stability have led to a decline in rural populations and residential buildings, reducing demand for building materials and construction. Given that existing rural residential buildings are not bound by mandatory BEES and usually have poor envelope performance, they should become the primary target for future building energy retrofits to reduce lock-in risks. For other things, the lower roof area-to-floor area ratio in rural residential buildings means that rooftop photovoltaic (PV) has more mitigation potential in rural residential buildings, which usually have 1-2 floors. This highlights the need for new urban residential buildings to rationally plan floor counts and limit approvals for supertall buildings, which can also reduce energy consumption from auxiliary systems like elevators and water supply.

Discussion

In this study, we discuss the decarbonization potential and cost investment of the DSS of buildings. It is different from most building DSS studies that only focus on the interaction between the building sector and the energy sector^{8,39-41}. The DSS framework of this study covers multiple building supply sectors, considering heterogeneous impact of single DSS measure on supply sectors. We further assess the decarbonization potential and cost savings of DSS scenarios. Notably, our scenarios explicitly integrate a series of techniques packaged for buildings and building appliances, rather than general policies such as improving energy efficiency or promoting electrification^{19,42}. These contributions enable more detailed policy formulation and full exploitation of building mitigation potential.

DSS can significantly mitigate cumulative CO₂ emissions of Chinese residential buildings by up to 51%. A similarly substantial decarbonization effect of building DSS has also been observed in European⁴¹, the United state⁴² and global⁷ cases. Compared with cleaner techniques of supply sectors, DSS can also save costs^{3,41}. The most

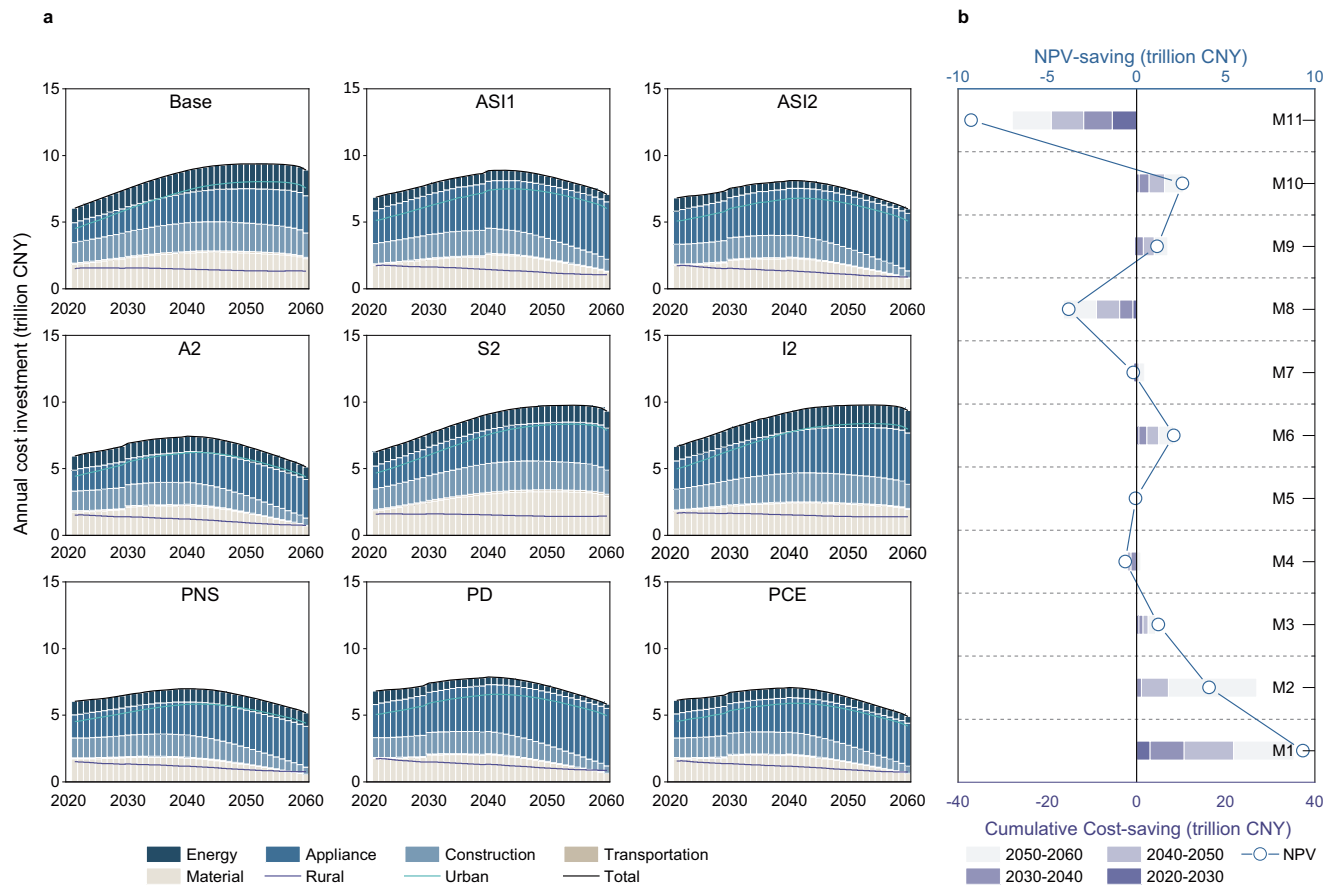


Fig. 5 | Annual cost investment of different demand-side scenarios. a Annual cost investment of 9 combined scenarios from 2020 to 2060. Base, low level of all ASI measures; ASI1, middle level of all ASI measures; ASI2, high level of all ASI measures; A2, high level of all avoid measures; S2, high level of all shift measures; I2, high level of all improve measures; PNS, most optimistic NPV-saving scenario; PD, most optimistic decarbonization scenario; PCE, most optimistic cost-effectiveness scenario. **b** NPV (IRR = 6%) and actual value of cumulative cost-saving of 11 single

measure scenarios during the period of 2020–2060. M1, limited building stock; M2, improving lifespan of new buildings; M3, reinforcing existing buildings; M4, improving envelope performance of new buildings; M5, energy retrofitting for existing buildings; M6, green energy utilization behaviors; M7, Utilization of building PV; M8, optimal building structure; M9, technique modes of household appliances; M10, Light building structure; M11, Improving efficiency of household appliances.

optimistic cost-effectiveness scenario cuts 47% of cumulative CO₂ emissions while saving 16% of NPV during 2020–2060. By reducing and shifting product demand, DSS decreases reliance on reliance on high-cost techniques (e.g. CDR) in hard-to-abate supply sectors (e.g., cement/steel production, heavy-truck material transportation, heavy-machine construction)⁴³. Excessively high premiums on clean products in the supply sector may render them unacceptable to the building sector. For instance, green hydrogen and CDR techniques increase costs in the building materials sector by 70–80% and 20–80%, respectively⁴⁴.

Avoid measures achieve the highest level of mitigation, particularly in the short to mid-term. However, their implementation faces significant challenges. For example, the long lifespan of buildings and attached infrastructures hinders technological updates and service improvements^{45,46}. Low-efficiency buildings and infrastructures will be used long term, especially for high-rise buildings, which are the majority of Chinese urban buildings. Retrofitting high-rises is inherently difficult, often requiring group decisions from over 30 households. Moreover, our results and European case⁴¹ collectively indicate that large-scale building energy retrofitting is not technically economical. Inadequate infrastructure services may prompt occupants to purchase new buildings, thereby boosting demand for construction materials. These encourages the government to enhance the operational efficiency of buildings and infrastructures by strengthening design approval mechanisms for new constructions,

optimizing urban planning frameworks, formulating evidence-based subsidy policies, and promoting energy performance contracting management^{45,46}. Regarding resident behaviors, several studies show that the plasticity of part low-carbon behavior is low under current policies^{36,47}, requiring to quickly deploy packages of interventions including monetary incentives, information, social comparison and motivation, especially for monetary incentives⁴⁸. Furthermore, long-term interventions are also necessary for the formation of habit and environment, leading to a long-lasting energy conservation impact⁴⁹.

Shifting to low-carbon household appliance modes (M9) yields the highest decarbonization potential. Shift measures lead to a change in technology modes, altering the types of services and products from supply sectors. Consequently, shift measures must coordinate with supply-sector decarbonization, such as aligning building electrification with the decarbonization process of the power sector³⁰. This transcends the limitation of previous studies, which primarily emphasized the critical role of building electrification alone.

Considering that the life cycle perspective has proven extraordinarily useful for tapping the decarbonization potential of DSS at a larger scale. The most optimistic decarbonization scenario shows that material production, construction, and transportation sectors collectively contribute 36% of cumulative emission mitigation. Meanwhile, LCA-ASI requires balancing the impacts of DSS measures across different supply sectors to maximize overall decarbonization. to balance the double-edged sword impact of

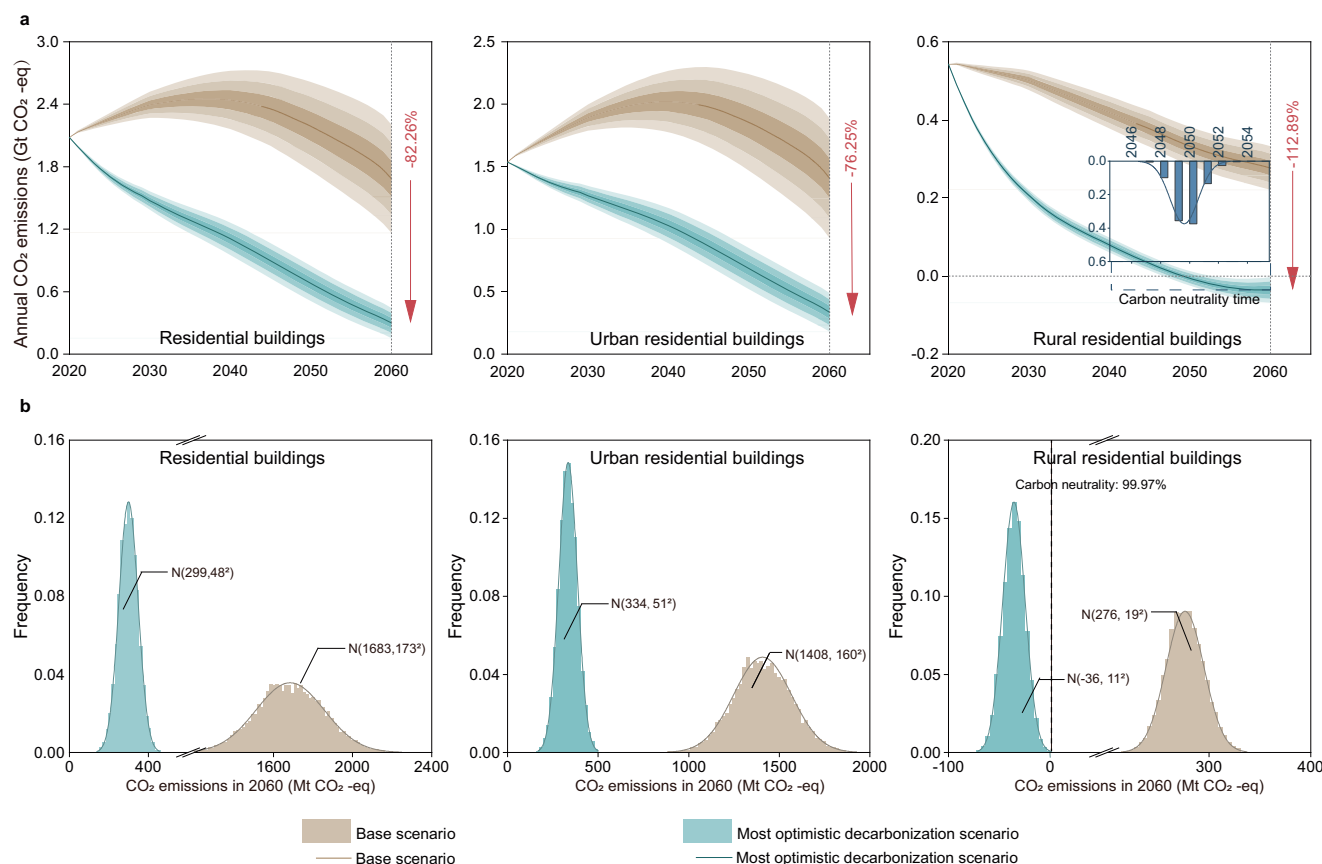


Fig. 6 | Uncertainty of achieving carbon neutrality of CRB. a CO₂ emission trend considering the uncertainty of supply sectors during 2020–2060 under base and most optimistic decarbonization scenario. The uncertainties of 16 parameters are shown in Supplementary Table 2. The solid lines are the median value of simulated

outcomes, and the shaded areas represent the 68%, 95% and 99.7% uncertainty range of simulated outcomes. The number of simulation runs is 10000.

b Uncertainty of CO₂ emission in 2060 under base and most optimistic decarbonization scenario.

extending building lifespans, policymakers are advised to consider regional attributes (e.g. climate conditions and occupants' behaviors) and establish reasonable building turnover and retrofit strategies⁵⁰. Additionally, LCA-ASI encourages policymakers to seek cross-sectoral solutions, fully account for the differing economic dynamics of demand- and supply-side technologies, and realign the focus of financial incentives.

This study has several limitations that require acknowledgment and addressing in future research. Firstly, we only assessed the decarbonization and cost-saving of DSS measures, without integrating the impact of residential interventions on DSS implementation and building decarbonization. Several studies have observed the impact of resident's characteristics, product prices and economic incentives on cleaner technique selection⁵¹. Notably, our model incorporates parameters for utilization behaviors (e.g., M1, M2, M3, M6) and technology penetration rates in annual building inflows (e.g., M4, M5, M8, M10) or household appliances (e.g., M7, M9, M11). Once the micro-mechanisms between interventions and resident behaviors are better understood, our model can be updated and provide suggestions for government policies. Additionally, demand adjustment is related to residents' well-being and social equity. For instance, building electrification and improved airtightness of building envelopes can reduce indoor pollution exposure, thereby decreasing residents' health losses^{52,53}. Thus, future research should establish quantitative links between DSS measures and indicators of well-being/social equity (e.g., UN's 17 Sustainable Development Goals) to enable comprehensive effectiveness assessments of DSS.

Methods

Building the end-use techniques model

Building demand for services and products from upstream supply sectors is linked to activities across the building life cycle (Supplementary Fig. 1). The three main components of SDF (i.e. inflow, stock, and outflow) are matched with the stages in the building life cycle. Inflow buildings are in the production and construction stage, stock buildings are in the use stage, and outflow buildings are in the end-of-life stage. We calculated building demand based on the quantity of these three components (Supplementary Note 1). The SDF of buildings (matching M1 and M2) is added to building retrofit mode (matching M3) and coupled stock dynamics of building envelop techniques (aligning with M6 and M7) (Supplementary Fig. 10). The SDF of buildings can be calculated by Eq. 1.

$$SB_t = SB_{t-1} + NB_t - DB_t + RB_t - DRB_t \quad (1)$$

where SB_t , NB_t , DB_t , RB_t and DRB_t represent stock, new, demolition, reinforcement buildings, and demolition buildings after reinforcing in year t . The normal distribution (μ, σ^2) is adopted as the survival function for buildings to calculate the number of demolitions. Based on the sectoral attribution of products and services generating CO₂ emissions, this study divides all CO₂ emissions (C) into five sections: building operation (C_1), material production (C_2), building construction (C_3), material and waste transportation (C_4), and carbon sink (C_5). The overall emissions and those of the five sections can be calculated by Eqs. 2–7, respectively. The detailed calculation process is shown in

Supplementary Note 1.

$$C = C_1 + C_2 + C_3 + C_4 - C_5 \quad (2)$$

$$C_1 = \sum_i \sum_j N_{1,i} \times r_{1,i,j} \times e_{1,i,j} \times t_{1,i,j} \times ef_{1,i,j} \quad (3)$$

$$C_2 = \sum_k (N_k^{demand} - N_k^{waste} \times \theta_k) \times ef_{2,k} \quad (4)$$

$$C_3 = (NB \times ef_{3,new} + RB \times ef_{3,reinforce} + (DB + DRB) \times ef_{3,demolition}) \quad (5)$$

$$C_4 = \sum_k (N_k^{demand} \times ef_{4,k}^{new} - N_k^{waste} \times ef_{4,k}^{waste}) \quad (6)$$

$$C_5 = C_{cement} \quad (7)$$

For building operation, heating, cooling, and lighting are analyzed based on stock buildings. From the perspective of physical units as technology carriers, the conservation of both material and technique exists in the SDF. We integrate the techniques flow in SDF and depict the dynamic changes in efficiency and mode of techniques (Supplementary Fig. 9). For buildings, we mainly consider the envelope performance mandated by BEES, meaning heating and cooling demand is also determined by historical annual building inflows. We develop SDF models of household appliances to translate end-use service demand into final energy demand (Supplementary Fig. 11), aligning with M8, M9, and M11. These SDF models account for changes in technology mode and energy efficiency and feature three layers (Supplementary Fig. 12): end-user services (i.e. space cooling, space heating, water warming, lighting, cooking, other, and roof PV), functions (*i*) and appliances (*j*). $N_{1,i}$ represents the total number of appliances for function *i*; $r_{1,i,j}$ is the share of appliances *j* in function *i*; $e_{1,i,j}$, $t_{1,i,j}$ represent average efficiency and annual utilization frequency (matching M6) of appliances *j*, respectively. $ef_{1,i,j}$ is the emission factor of the energy used by appliance *j*. Based on the historical China energy label, we assumed a 5%–10% increase in energy efficiency for most electricity appliances (Supplementary Note 1).

For material production, the model includes cement, steel, brick, aluminum, and glass. We consider variations in material intensity across building structures (matching M8 and M10) and the offset effect of waste material recycling. Raw material demand (N_k^{demand}) is calculated from inflow and reinforce buildings, and waste material (N_k^{waste}) is calculated from the outflow buildings. $ef_{2,k}$ represent the emission factor of building material *k*.

For building construction, $ef_{3,new}$, $ef_{3,reinforce}$ and $ef_{3,demolition}$ represents represent emission factor ($\text{kgCO}_2 \text{ m}^{-2}$) of building construction, reinforce, and demolition, respectively. For material and waste transportation, $ef_{4,k}^{new}$ and $ef_{4,k}^{waste}$ represent the transportation emission factor ($\text{kgCO}_2\text{-eq}$ of per ton material) of new and waste building material *k*, respectively; For building carbon sink, the model considers carbon sink from cement carbonization ($C_{5,cement}$). The cement carbonization is that cement hydration products gradually reabsorb atmospheric CO_2 through a physicochemical process. The study of Xi et al. provided a calculation model of cement carbonization²⁹.

We only focus on the cost incurred by the building sector for products and services from upstream supply sectors. Based on the sectoral attribution of these products and services, we divided all costs into five parts: raw material (i.e. building materials and building envelop), energy (i.e. first and secondary energy), construction, transportation, and household appliance cost. Cost calculation is based on the number of products and services of supply sectors, with detailed procedures provided in the Supplementary Note 2.

Coupling with the model of supply sectors

We establish a simplified supply-sector model comprising 16 parameters across four main sectors: energy generation, material production, transportation, and construction sector (Table S2). The model of supply sectors can output emission factors ($ef_{1,j}$, $ef_{2,k}$, $ef_{3,new}$, $ef_{3,retrofit}$, $ef_{3,demolition}$, $ef_{4,k}^{new}$ and $ef_{4,k}^{waste}$) of products and services from the supply sector. The parameters of supply sectors have two conditions: freeze and dynamic conditions. The freeze condition means that parameters keep the same levels in different DSS scenarios to compare DSS scenarios' decarbonization potential and cost-saving effect. Dynamic condition integrates the uncertainties of 16 supply-sectors parameters by Monte Carlo simulation (Eq. 8) to assess the distribution of CO_2 emissions and the probability of achieving carbon neutrality under each DSS scenario. The freeze condition represents the mean of the dynamic condition's distribution.

$$P_t^{Dynamic} = P_t^{Freeze} + \omega_p \cdot \frac{t - 2020}{2060 - 2020}, \omega_p \sim N(0, \sigma_p) \quad (8)$$

$P_t^{Dynamic}$ and P_t^{Freeze} represent the value of parameter *P* in year *t* under dynamic and freeze conditions, respectively. ω_p is the uncertainty of parameter *P* and follows the normal distribution $N(0, \sigma_p)$.

Study area and data

We set 2020 as the base year and conducted a scenario analysis toward China's carbon neutrality target by 2060. Given the substantial influence of climatic and rural-urban disparities on building operation energy consumption, we develop 6 model cases (urban and rural buildings in three climate zones). Based on the characteristics of space heating and cooling, the five climate zones in Chinese Building Energy Efficiency Standard are integrated into three climate zones (Supplementary Table 3) including Northern area (Severe Cold area, and Cold area), Transition area (Hot Summer and Cold Winter area), and Southern area (Hot Summer and Warm Winter area, and Moderate area).

For historical modeling data, socioeconomic data (e.g. including population and family size) is sourced from the China Statistical Yearbook. Building-related data, including building stock, distribution of built years, and building structure, were collected from the China Census Data and the China Association of Building Energy Efficiency⁵⁴. Household appliance data (e.g. number, proportion, energy efficiency, and lifespan) and residents' behaviors are derived from the China Statistical Yearbook, the Chinese Residential Energy Consumption Survey of Renmin University⁵⁵, and related standards and literature^{15,56–58}. The performance of building envelopes is simulated by EnergyPlus. Cost-related data are compiled from literature, policy documents, practical cases, and data Grabbing on main China E-commerce platforms (e.g. JD.com, Tmall, and Taobao). The data on supply sectors were obtained from the Chinese Urban and Rural Construction Statistical Yearbook, Energy Balance Sheet, and literature (Supplementary Table 2).

Scenario settings

According to a wide review of government documents, reports, and literature, we define the low, medium, and high levels for each DSS measure (Fig. 1 and Supplementary Table 1), with measure-specific parameters and values detailed in Supplementary Table 1. Furthermore, we select 20 main scenarios to analyze the impact of DSS on the long-term trend of demand, CO_2 emissions, and cost investment. 20 main scenarios include 11 single-measure scenarios (i.e. high-level in all DSS measures) and 9 combined-measure scenarios (Fig. 2).

For supply-sector parameters, establishing their distribution follows the principle that the optimal and worst values match the upper and lower bounds of 95% confidence level ($\pm 2\sigma$), respectively. The optimal and worst values of each parameter are obtained from

literature and reports and are listed in Supplementary Table 2. Besides, forecasting the future value of socioeconomic parameters is beyond the boundary of this study. They are collected from the Shared Socioeconomic Pathways 2 of the studies of Chen, et al.⁵⁹.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The data generated and used in this study can be found in the Supplementary Table 1–14. Source data underlying is provided in Source Data. Data and parameter to calculate carbon sink of cement is available from two global cement carbonation model^{29,60}. Source data are provided with this paper.

Code availability

The codes to calculate and analyze decarbonization and cost-saving of demand-side solution of buildings can be accessed at Zenodo (<https://zenodo.org/records/15805277>). The codes to calculate carbon sink of cement is available from two global cement carbonation model^{29,60}.

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Acknowledgements

The study was supported by the National Natural Science Foundation of China (no. 72488101 and 72293605, Y.-M.W.), the Postdoctoral Fellowship Program of CPSF (no.GZB20240939, K.Y.), the Beijing Natural Science Foundation (no. 9254035, K.Y.), and the China Postdoctoral Science Foundation (no.2024M754102, K.Y.).

Author contributions

K.Y., W.F., W.C., and Y.-M.W. conceived of and led the project. K.Y. and L.Z. conducted literature analysis and developed the demand-side solution framework of buildings. K.Y., Y.L., and Z.L. conducted the development of the model and scenario. K.Y. and Y.L. complete result analysis, original draft preparation and visualization. W.F., W.C., and Y.-M.W. contributed to manuscript review and editing.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41467-025-62675-0>.

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Peer review information *Nature Communications* thanks Xiaoxiao Xu, and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. A peer review file is available.

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