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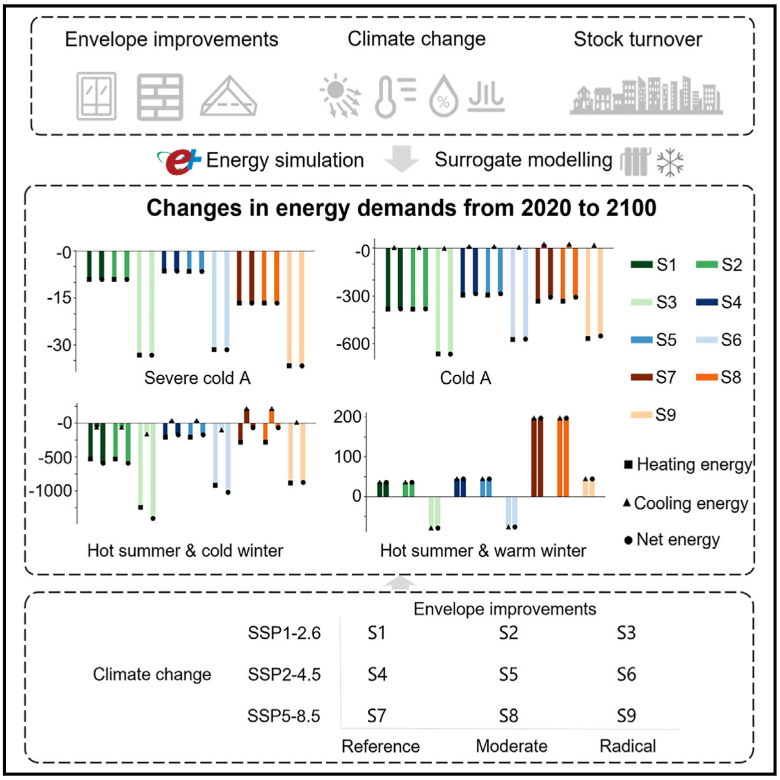
The climate opportunities and risks of improving building envelopes across 1,677 Chinese cities

Graphical abstract



Highlights

- Diagnose effects of building stock, envelope, and climate on housing energy demand
- Use a physics-based building energy model with fine spatiotemporal granularity
- Cover residential building stock of 1,677 sub-province-level cities across China
- Variable impacts of envelope upgrades on housing energy use amid climate change

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In brief

In their study, Zhang and Dang et al. explore how upgrades to building envelopes affect China's future housing energy demand amid climate change. Covering 1,677 sub-province-level cities, their physics-based model reveals that the effectiveness of these upgrades varies significantly across regions, underscoring the importance of tailored approaches to energy efficiency and climate resilience. This work highlights critical pathways for enhancing building energy performance, vital for mitigating building energy consumption and advancing climate adaptation strategies.

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The climate opportunities and risks of improving building envelopes across 1,677 Chinese cities

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SCIENCE FOR SOCIETY Buildings are essential for providing safe, reliable, and comfortable spaces for people and goods, and they account for approximately one-third of global final energy consumption, with residential buildings alone consuming 70% of this share. Consequently, residential buildings are pivotal in efforts to mitigate and adapt to climate change. However, comprehensive data on the combined effects of building envelope upgrades, building stock characteristics, and climate change on residential energy demand remain scarce. This study examines the residential building stock in 1,677 sub-province-level cities across China through a physics-based energy model, which provides a detailed analysis of heating and cooling demands with high spatiotemporal resolution. The findings underscore that the impact of envelope improvements on mitigating climate change effects on residential energy use varies across China. These results highlight the critical need for developing climate-resilient energy infrastructures and exploring alternative energy efficiency strategies, particularly in regions with limited climate adaptability.

SUMMARY

The global building sector consumes approximately 30% of final energy, making it crucial for climate change mitigation and adaptation. International calls for enhancing building energy efficiencies are growing, focusing on strategies such as energy-efficient building envelopes through renovation and replacement of older structures, along with electrification and fuel switching. However, the energy-saving potential of these improvements remains uncertain due to the complex interplay of building stock characteristics and climatic conditions. Here, we diagnose the compound effects of envelope improvements and climate change on China's housing energy demand using a physics-based building energy model with fine spatial and temporal granularity, covering 1,677 sub-province-level cities. Our model shows that envelope improvements play very different roles in ameliorating climate change impacts on housing energy use across the country, highlighting the need for building climate-resilient energy supply and pursuing alternative energy efficiency strategies in less climate-resilient regions.

INTRODUCTION

Buildings provide safe, secure, and comfortable spaces for occupants and goods. As a result, the building sector was responsible for about one-third (128.8 EJ) of the global final energy demand in 2019 of which 70% was consumed by residential buildings.[1] Moreover, as affluence and population increase, the demand for more floor area and building energy use will increase if significant energy-saving measures are not taken.[2]

In response to rising demand for space heating and cooling, scientific and policy communities have called for rapid deployment of efficient building envelopes, further electrification, and fuel switching to decarbonize the building sector.[2] Among these approaches, renovating the envelopes of existing buildings and replacing older buildings with new energy-efficient buildings can decouple energy demand and related emissions from floor area growth, easing challenges with both building decarbonization and building energy supply systems,[3] as long as new buildings are not larger than older ones and built with low-carbon materials. However, the deployment speed of energy-efficient envelopes is dependent on a complicated interaction of building stock evolution, building stock characteristics, and the ambition level of building stock renovation efforts.[4–8] Another key factor influencing building energy use is climate change because buildings are the interface between the outdoor environment and the indoor environment.[9]

Recent studies corroborate that rising average temperatures will unquestionably impact building energy use, though at various rates across locations, countries, and continents (see Table S1). While numerous studies have utilized simulation tools to measure the effects of climate change on building energy use across diverse geographic areas, they often exhibit limitations concerning geographic coverage, the trade-off between modeling accuracy and computational speed, variability in climate conditions, and differences in building codes.

Here, we develop a building-physics-based model with spatial and temporal granularity by comprehensively considering new construction, building renovation, and building longevity to identify spatiotemporal patterns of housing energy use in China between 2020 and 2100 under climate change and envelope improvement scenarios, aiming to address the limitations described above (see experimental procedures). We include three climate change scenarios (i.e., SSP1-2.6, SSP2-4.5, and SSP5-8.5) to represent lower, medium, and higher emission trajectories resulting from various socio-economic developments,[10] respectively. While the emissions projected in the SSP5-8.5 scenario are highly improbable,[11] it is deemed a reasonable proxy for the case where climatic sensitivity is higher than previously thought.[12] In addition, we develop three pathways that reflect various levels of improvements in building envelopes (i.e., reference, moderate, and radical). These three climate scenarios and three envelope scenarios result in nine scenarios (3 × 3) for assessing overall interactions between building envelope improvements and climate change (see Table 1; Figure 6).

We develop a large dataset for 1,677 sub-province-level cities in China, covering China's entire residential building stock. We apply our model to all residential building stocks in the administrative boundaries of 1,677 sub-province-level cities in China, and each city is represented by multiple building vintages. Using a machine-learning-enabled surrogate model to expedite computationally expensive building energy simulations, we model the impacts of temperature changes and envelope improvements on the hourly cooling and heating demands of China's residential building stock.

As expected, we find that heating energy intensity (energy used for heating per square meter of floor area) increases with latitude in China while cooling energy intensity decreases. Although warmer temperatures mean lower heating requirements at higher latitudes and more cooling requirements at lower latitudes, the expected improvements in building envelopes are mixed. We find that improved building envelopes reduce heating energy intensity much more than cooling intensity. In short, climate change and improved envelopes benefit cooler regions more than warmer ones. This highlights the need for building climate-resilient energy supply and pursuing alternative energy efficiency strategies in cooling-dominated regions.

RESULTS

Residential building stock characteristics exhibit significant variations across China

We observe four important characteristics of China's residential building stocks related to total floor area, per-capita floor area, building height, and climate zone. First, we find varying trends in total floor area across Chinese cities (Figure 1A), and we also select six typical cities (see details in Figure S9; Table S10) to describe the evolution of their total floor area (Figures S11, S14, S17, S20, S23, and S26). Due to a lack of county-level data for 11 provinces in North and Southwest China, aggregated data at the prefecture level were used for building stock estimation in these provinces. Therefore, sub-province-level cities in North and Southwest China are notable for having a large floor area. Higher-income cities in East and Central China see slight decreases in total floor area during 2020–2060; meanwhile, cities in North and West China see substantial increases in total floor area. This spatial variation in changes in total floor area is the combined effect of converging per-capita floor area and declining populations in such regions.

Second, most cities in East and Central China have a per-capita floor area of more than 40 m^2 or even 50 m^2 in 2020 (Figure 1B), due to their high living standard. Third, residential high-rise buildings are concentrated in cities acting as economic or administrative hubs (Figure 1C), having a significant impact on per-capita floor areas in such cities (Figure 1B). Fourth and last, climate zone-level results demonstrate that the total floor area of residential buildings in three moderate climate zones (cold A, cold B, and hot summer and cold winter) accounts for 72% in 2020 and 74% in 2100 (Figure 1D), respectively, because more than 70% of the Chinese population is concentrated in these climate zones.

Table 1. Description of nine scenarios designed in a three-by-three factorial manner

Scenario	Envelope improvement	Climate change	Description
S1	reference	SSP1-2.6	No envelope improvements will take place for existing building stocks and newly constructed buildings. The lower emission trajectory is derived from a sustainable socio-economic path.
S2	reference	SSP2-4.5	No envelope improvements will take place for existing building stocks and newly constructed buildings. The medium emission trajectory is derived from a middle-of-the-road path.
S3	reference	SSP5-8.5	No envelope improvements will take place for existing building stocks and newly constructed buildings. The higher emission trajectory is derived from a fossil-fueled path.
S4	moderate	SSP1-2.6	Envelope upgrades will take place for existing building stocks to catch up with China's present-day envelope technologies by 2060. Newly constructed buildings will adopt China's present-day envelope technologies, and no further improvements will occur. Meanwhile, the lower emission trajectory is derived from a sustainable socio-economic path.
S5	moderate	SSP2-4.5	Envelope upgrades will take place for existing building stocks to catch up with China's present-day envelope technologies by 2060. Newly constructed buildings will adopt China's present-day envelope technologies, and no further improvements will occur. Meanwhile, the medium emission trajectory is derived from a middle-of-the-road path.
S6	moderate	SSP5-8.5	Envelope upgrades will take place for existing building stocks to catch up with China's present-day envelope technologies by 2060. Newly constructed buildings will adopt China's present-day envelope technologies, and no further improvements will occur. Meanwhile, the higher emission trajectory is derived from a fossil-fueled path.
S7	radical	SSP1-2.6	Ambitious envelope improvements will take place in existing and newly constructed building stocks to catch up with the nearly zero-emission building (NZEB) standards by 2060. At the same time, a lower emission trajectory is derived from a sustainable socio-economic path.
S8	radical	SSP2-4.5	Ambitious envelope improvements will take place in existing and newly constructed building stocks to catch up with the nearly zero-emission building (NZEB) standards by 2060. At the same time, a medium emission trajectory is derived from a middle-of-the-road path.
S9	radical	SSP5-8.5	Ambitious envelope improvements will take place in existing and newly constructed building stocks to catch up with the nearly zero-emission building (NZEB) standards by 2060. At the same time, a higher emission trajectory is derived from a fossil-fueled path.

Note: China's present-day envelope technologies and the NZEB standards are detailed in Table S6.

Climate change induces location-dependent temperature increases

China has a highly diverse climate (Figure 2), with Northeast China and Tibet experiencing a subarctic climate with long, severe winters and short, warm summers and South China seeing a near-tropical climate with hot temperatures all year round. Central and East China see more variation and distinct seasonal changes. Although various climate factors can influence building energy use, our sensitivity analyses on all climate factors across eight locations indicate that dry bulb temperature is the most significant factor (see experimental procedures; Table S9). Annual average dry bulb temperature is projected to rise over the next decades with substantial spatial variation. Under SSP1-2.6 and SSP2-4.5 scenarios, increases in annual average temperature do not exceed 4°C (compared with 2020), with Northeast and East China seeing the most significant increases. Under the SSP5-8.5 scenario, increases in annual average temperature exceed 6°C, with Northeast China, Central China, Northwest China, and South China seeing significant temperature rises.

Warming future climate results in less residential heating demand

Residential heating demand exhibits a high degree of variation over time and across climate scenarios (Figure 3A). Residential buildings in Northeast, North, and West China generally require more heating compared with residential buildings in Central, East, and South China for the same indoor temperature (even when accounting for different building types and standards). However, the spatial heterogeneity in residential heating demand will narrow with radical envelope improvements in the future. The latitudinal gradient of heating demand per unit area in 2100—calculated by averaging heating demand per unit area across cities on the same latitude—shows that residential heating demand per unit area in 2,100 increases with increasing latitude across nine scenarios (Figure 3B).

A warming climate, envelope upgrades in existing and new buildings, and replacing older buildings with new buildings all result in an overall decrease in national average residential heating demand (Figure 3C). However, as demonstrated in

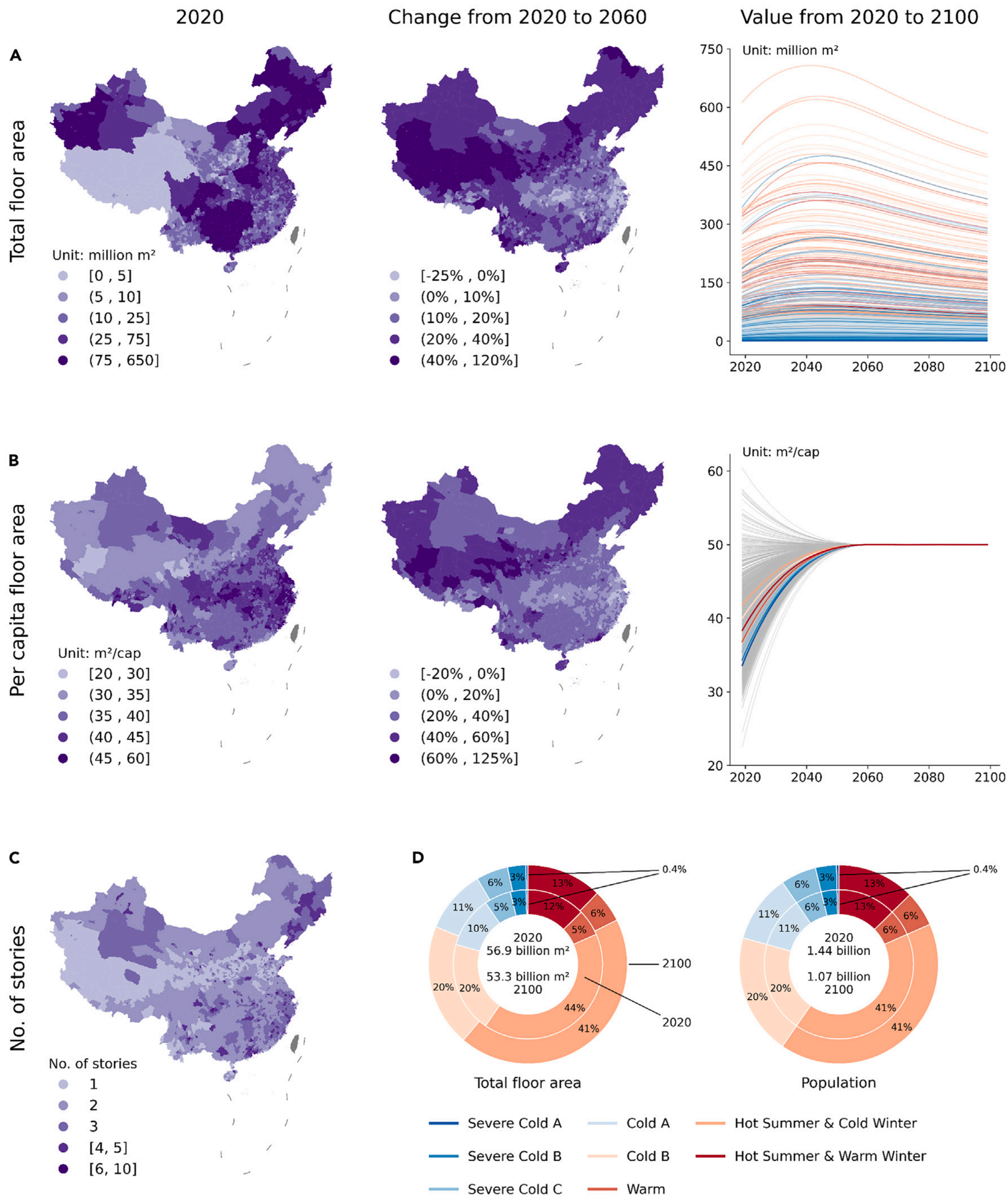

Figure 1. Residential building stock characteristics across time and space

(A) Total residential floor area across sub-province-level cities in 2020, percentage changes between 2020 and 2060, and absolute values between 2020 and 2100.

(B) Per-capita residential floor area across sub-province-level cities in 2020, percentage changes between 2020 and 2060, and absolute values between 2020 and 2100.

(C) Average number of stories of residential building stock across sub-province-level cities.

(D) Breakdown of total residential floor area and population by climate zone in 2020 and 2100. Areas colored in gray have no data.

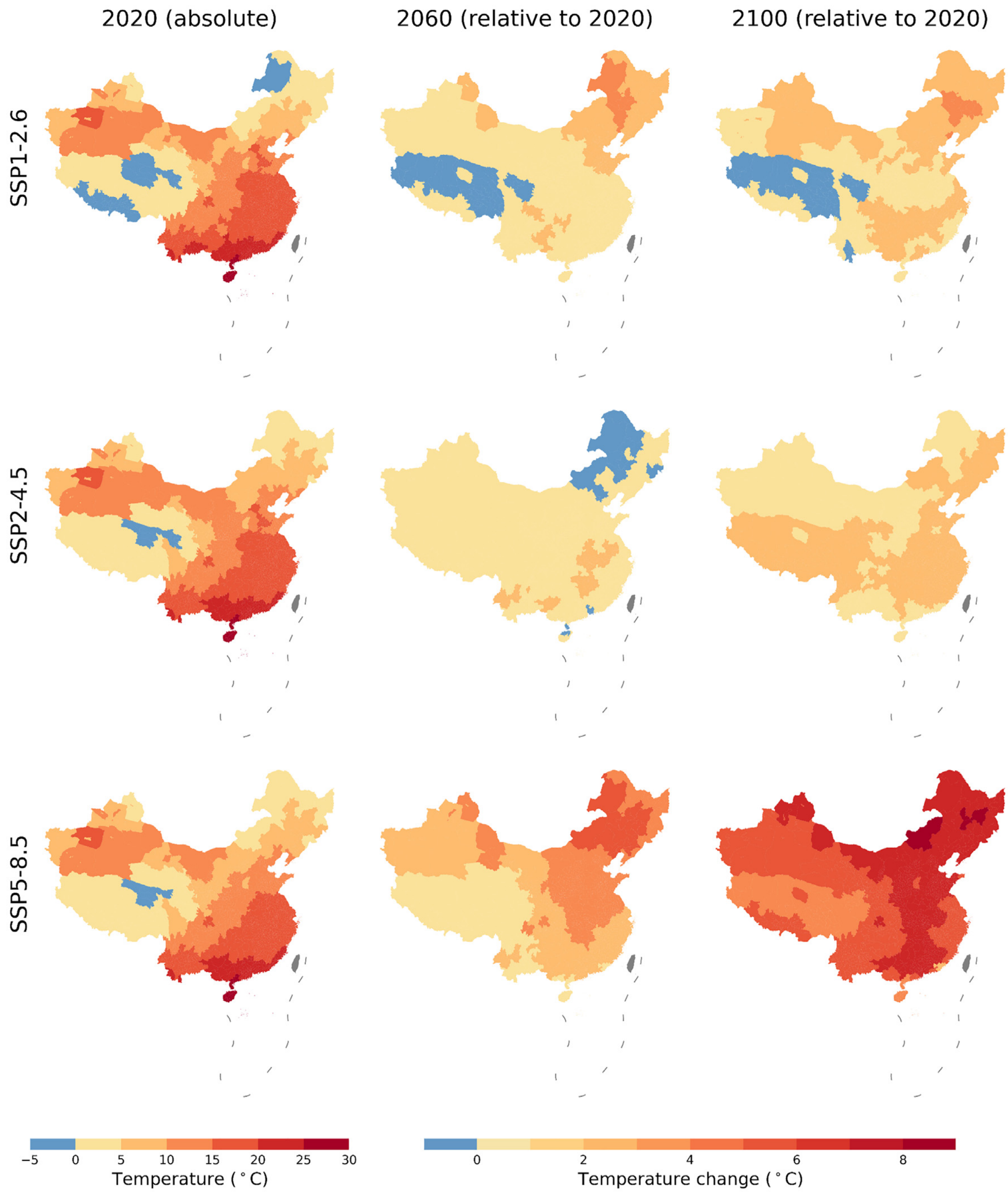

Figure 2. Spatial distribution of annual average dry bulb temperature in 2020, 2060, and 2100 under three SSP scenarios

Values for 2060 and 2100 are temperature changes relative to the 2020 average. Areas colored in gray have no data. The annual average dry bulb temperature in 2020 is generated from CMIP6 and typical meteorological year data using the morphing method (Note S2.7.3).

the moderate scenarios, retrofitting existing building stocks to catch up with China's present-day envelope technologies does not result in significant energy savings. Overall, the national average residential heating demand due to envelope improvements is expected to decline faster during 2020–2060 than 2060–2100 across nine scenarios, because the implementation of envelope improvements ceases by 2060. Notably, the national average residential heating demand is expected to converge around 2060, when old buildings are almost completely replaced by new buildings with the most energy-efficient envelopes (Figure S6). After 2060, as the implementation of envelope improvements comes to a halt and the

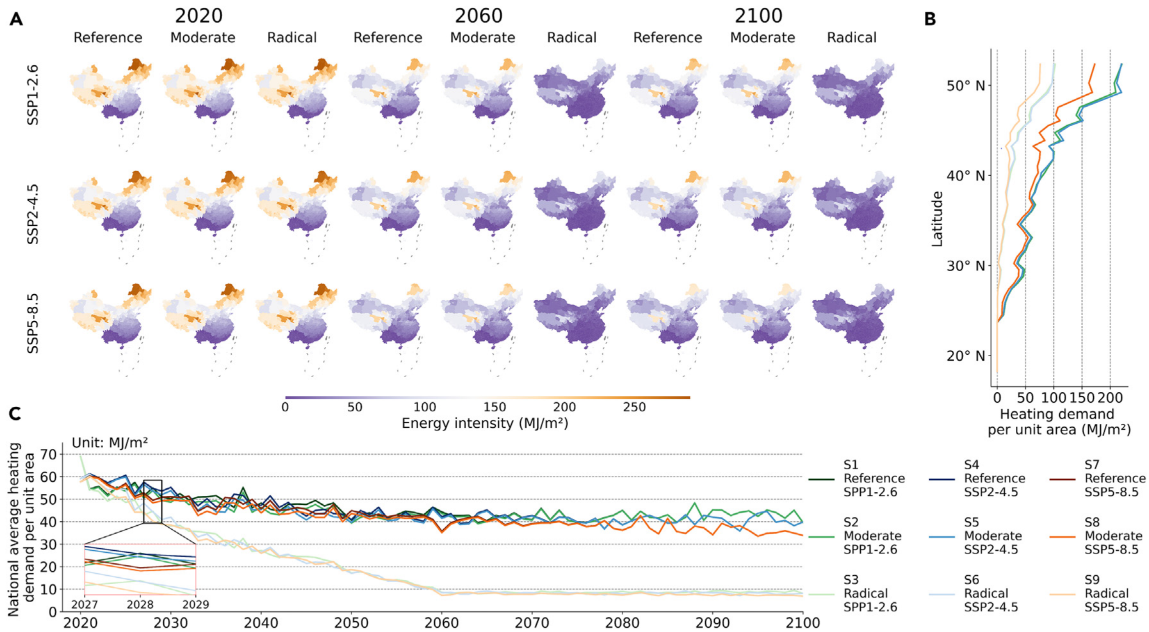

Figure 3. Heating demand per unit area of residential buildings across time and space under nine scenarios

(A) Spatial distribution of heating demand per unit area in 2020, 2060, and 2100 under nine scenarios.

(B) Latitudinal gradient of heating demand per unit area in 2100 under nine scenarios.

(C) Temporal trends of national average heating demand per unit area from 2020 to 2100 under nine scenarios. Areas colored in gray have no data, and lines representing S1, S4, and S7 are overlaid by lines representing S2, S5, and S7 because old buildings are almost completely replaced by new buildings with the most energy-efficient envelopes by 2060.

turnover of building stocks slows down, decreases in national average residential heating demand will become less significant.

Upon closer examination, the reference scenarios (S1, S4, and S7), which do not include any envelope improvements, demonstrate substantial reductions in national average residential heating demand, particularly in the SSP5-8.5 scenario (S7), compared with the SSP1-2.6 (S1) and SSP2-4.5 (S4) scenarios. This suggests that residential heating savings will overall benefit from a warming future. This is true even for moderate envelope improvement scenarios (S2, S5, and S8), in which existing building stocks undergo envelope upgrades to match China's present-day envelope technologies by 2060. However, as indicated in the radical envelope improvement scenarios (S3, S6, and S9), differences among climate scenarios in national average residential heating demand are negligible, revealing that the impact of climate change on national average residential heating demand is less evident if radical envelope improvements materialize.

Residential cooling varies significantly across space regardless of envelope improvements

Residential cooling demand also exhibits large heterogeneity over time and across climate scenarios (Figure 4A). Due to temperature increases, residential buildings in Central, East, and South China require more energy to keep the interior space cool. While the heterogeneity in residential cooling demand is substantial across scenarios, radical envelope improvements do not significantly diminish this variation, as residential cooling demand in South China grows at a faster rate. Also contrasting with residential heating demand, cooling demand per unit floor area in 2100 decreases with increasing latitude across nine scenarios (Figure 4B). Meanwhile, radical envelope improvements are expected to bring considerable cooling energy savings in low-latitude areas but do not deliver observable cooling energy savings in other latitudes, as residential buildings in higher-latitude areas require less cooling.

Rising temperatures will continue to drive up national average residential cooling demand if no envelope improvements take place for decades to come (Figure 4C). However, national average residential cooling demand is projected to remain stable or slightly decline if improved standards for building envelopes are met for both moderate (S2, S5, and S8) and radical (S3, S6, and S9) envelope improvement scenarios. Despite the positive impact of envelope improvements on reducing residential cooling demand, national average residential cooling demand remains highly variable across different climate scenarios, particularly for S3, S6, and S9. This suggests that cooling demand in residential buildings with more energy-efficient envelopes is still susceptible to rising temperatures due to the significant amount of heat generated within the building itself, such as metabolic heat generated by occupants, the energy consumption of electrical devices, and the thermal emissions from artificial lighting.

Residential energy demands will shift from heating to cooling across climate zones

As demonstrated in Figure 5, if no envelope improvements (S1, S4, and S7) or only moderate envelope improvements

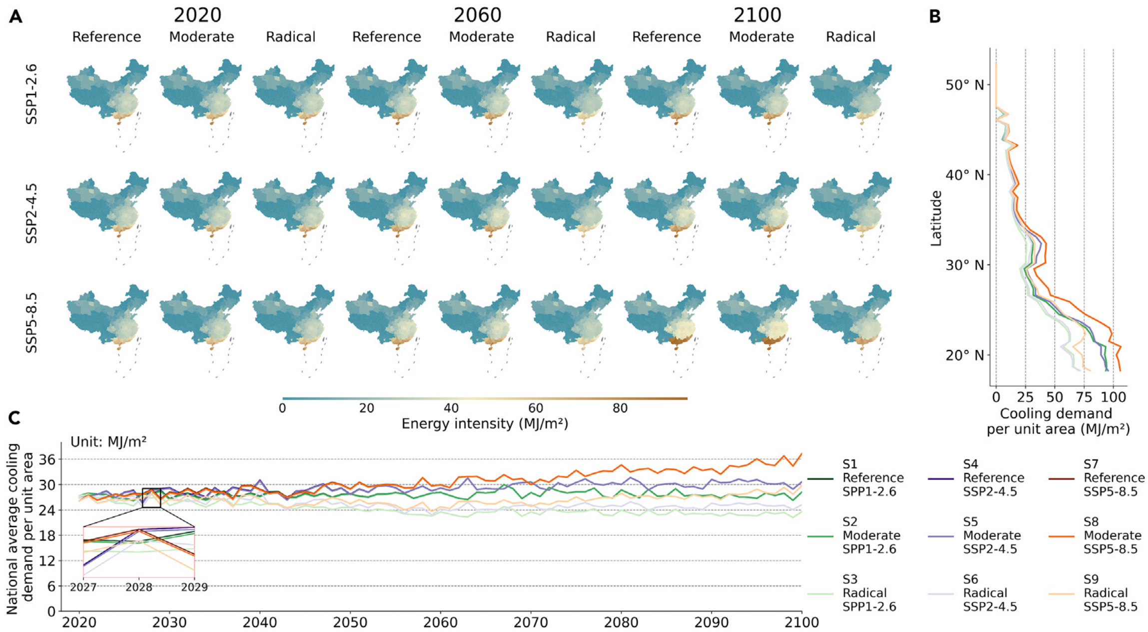

Figure 4. Cooling demand per unit area of residential buildings across time and space under nine scenarios
(A) Spatial distribution of cooling demand per unit area in 2020, 2060, and 2100 under nine scenarios.
(B) Latitudinal gradient of cooling demand per unit area in 2100 under nine scenarios.
(C) Temporal trends of national average cooling demand per unit area from 2020 to 2100 under nine scenarios. Areas colored in gray have no data, and lines representing S1, S4, and S7 are overlaid by lines representing S2, S5, and S7 because old buildings are almost completely replaced by new buildings with the most energy-efficient envelopes by 2060.

(S2, S5, and S8) take place, significant declines in energy demand for space heating in 2100 can be achieved across climate zones, except for the warm climate zone where no heating or cooling is needed and the hot summer and cold winter climate zone where heating is not needed. However, energy demand for space cooling in 2100 will considerably increase in two relatively warmer climate zones (cold and hot summer and cold winter) and more significantly in the hot summer and warm winter climate zone, particularly under the SSP5-8.5 scenarios (S7 and S8). Additionally, we select six case cities to demonstrate the city-level details about space heating demand (Figures S12, S15, S18, S21, S24, and S27).

On the other hand, if radical envelope improvements are implemented (S3, S6, and S9), energy demand for space heating in 2100 will significantly decrease across climate zones, except for the hot summer and cold winter climate zone where no heating is required. However, energy demand for space cooling in 2100 will show negligible increases in two relatively colder climate zones (severe cold and cold) but substantial changes in two relatively warmer climate zones (hot summer and cold winter and hot summer and warm winter). At the national level (see Figure S30), radical envelope improvements yield significant net reductions in energy demand, with space conditioning requiring 1,840–1,980 PJ less energy in S3, S6, and S9 compared with the corresponding reference scenarios (S1, S4, and S7). Similarly, city-level details for space cooling demand are available from Figures S12, S15, S18, S21, S24, and S27.

Warming future climate exacerbates the fluctuations in hourly heating and cooling demands

While average temperatures are important, the hourly residential heating and cooling demands per area across China can show differences compared with the annual average (Figures S13, S16, S19, S22, S25, and S28). In this case, these variations are largely consistent with the distribution of annual totals, as are the impacts of climate change and envelope improvements on hourly heating and cooling demands (Figure S31). Despite these similarities, relatively higher standard deviations of hourly heating and cooling demands per unit area are observed in Northwest China, comparable to Central, East, and South China. This may indicate more extreme hot- and cold-weather events (e.g., heat waves and cold spells) in these regions, posing challenges to energy and shelter security.

DISCUSSION

Our results have broad implications for our understanding of the location-dependent impacts of climate change on the residential energy demand for space conditioning. First, as depicted in the moderate envelope improvement scenarios, the adoption of China's present-day envelope technologies in existing and new buildings cannot deliver substantial energy savings. Therefore, further deep cuts in residential energy demand for space conditioning will require more radical envelope improvements. The short average lifespan of China's residential buildings presents an opportunity for designers, code authorities, and governments to take full advantage of the

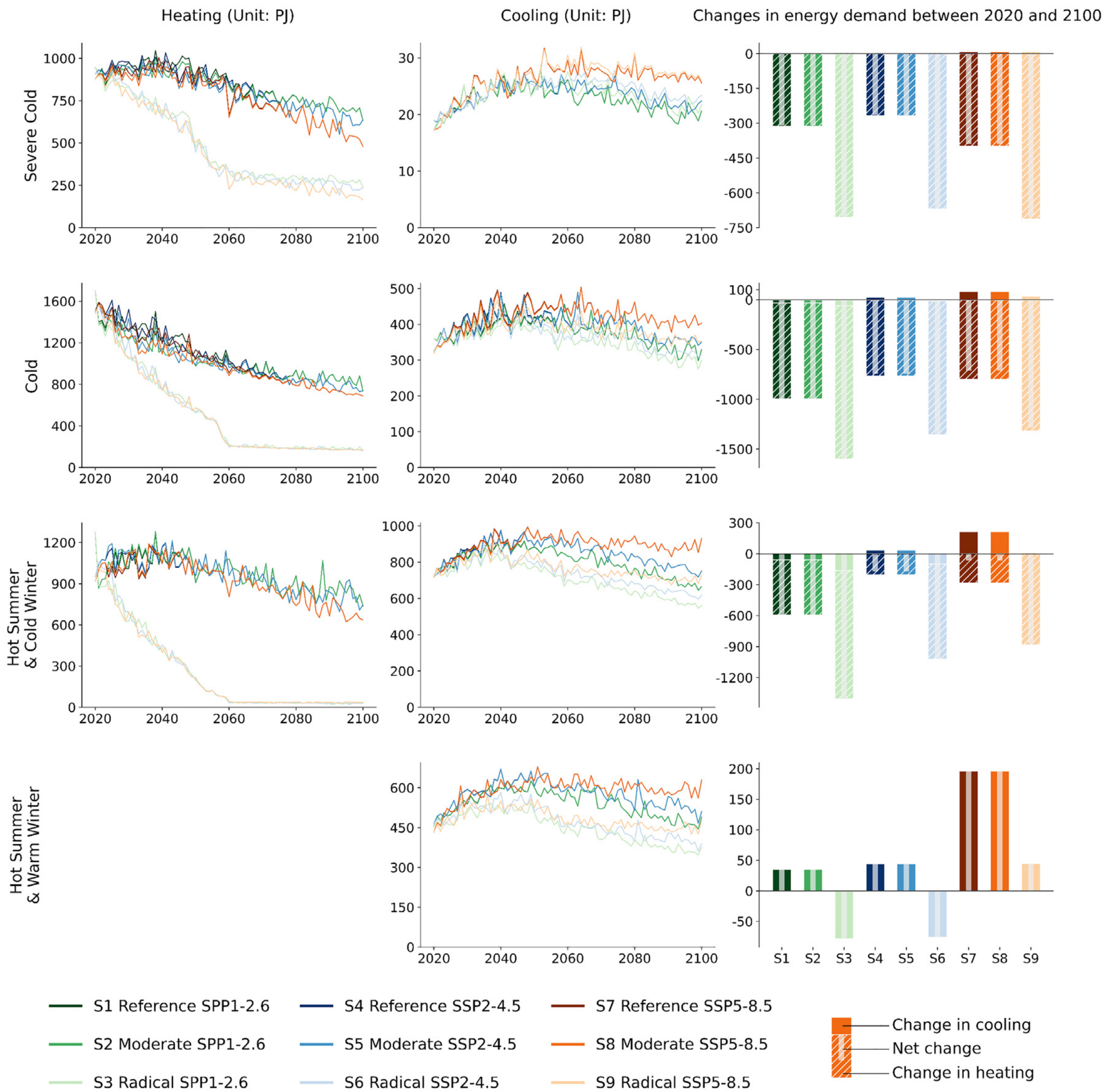

Figure 5. Temporal trends of aggregated heating and cooling demands by residential buildings across climate zones

Change = 2100 value − 2020 value; net change = change in heating + change in cooling; lines representing S1, S4, and S7 are overlaid by lines representing S2, S5, and S7 because old buildings are almost completely replaced by new buildings with the most energy-efficient envelopes by 2060, and more disaggregated results are presented in Figure S29.

window of opportunity for rolling out more ambitious plans to improve building envelopes. In addition, to delineate a more detailed path for envelope renovation, we perform a sensitivity analysis on cooling and heating demands, assuming a 5% increase in the U-value of each envelope component, as detailed in Note S2.4.3. Our analysis indicates that the U-value of the roof significantly affects heating and cooling demands in low-rise buildings, particularly in single-story structures. As building height increases, the U-value of the exterior walls predominantly influences cooling demands, whereas the U-value of windows has a more pronounced impact on heating demands. Moreover, potential increases in embodied energy and emissions associated with energy-efficient envelope designs should be carefully factored in to prevent problem shifting.[3,13–15]

Second, using fine-scale data on building stock characteristics and climate change, we can better understand the spatial disparity in residential heating and cooling performance and inform spatial prioritization for implementing climate change adaptation/mitigation policies. Simulation results with spatial and temporal granularity reveal that improving envelope technologies is less effective in areas where space cooling is more dominant than space heating. Moving forward, building codes in these areas may need more rigorous requirements for cooling-saving technologies (e.g., improved ventilation, solar shading, and fault detection and diagnostics) to address space

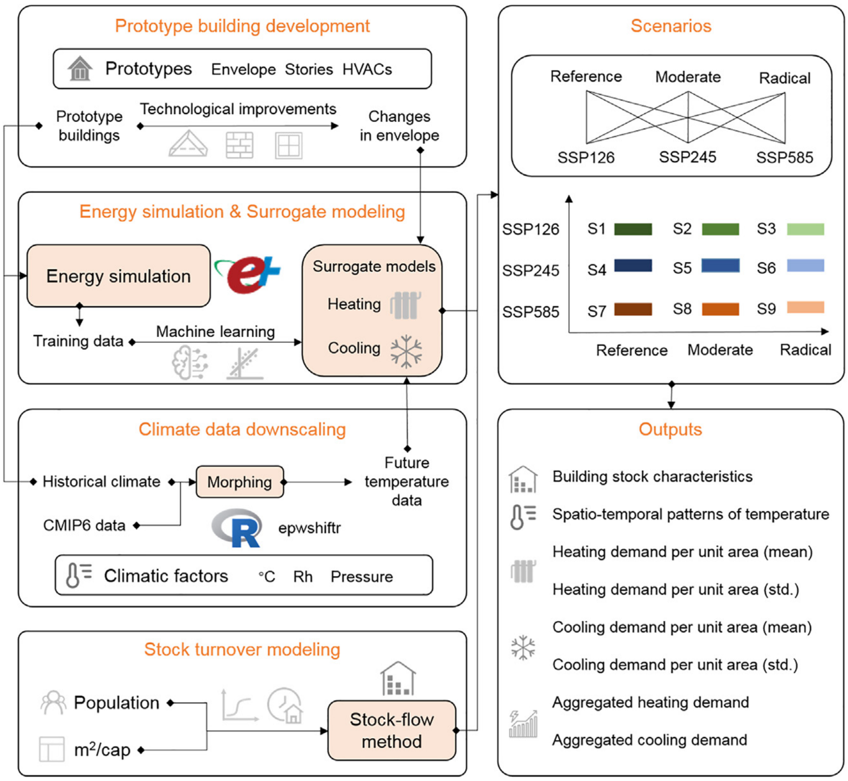

Figure 6. Spatially refined modeling framework for building energy simulation under climate change and envelope improvement scenarios

cooling. To mitigate greenhouse gas (GHG) emissions in such areas, rapid decarbonization of residential energy supply should be prioritized.

Third, there is a growing need to prioritize meeting cooling demands as opposed to current heating needs in temperate climate zones, which calls for a paradigm shift in residential energy supply in these regions. Should radical envelope improvements take place in a warming climate, residential energy demand in temperate climate zones (where both heating and cooling are required) will shift from coal-, oil-, or gas-based space heating to electricity-based space cooling, though the overall residential energy savings will greatly benefit from temperature increases and envelope improvements. The increase in electricity demand for cooling also presents an opportunity to expedite the efficient electrification of space heating, as heat pumps can cater to both cooling demands in summer and heating demands in winter. However, in such circumstances, electrical power demand will remain high and could rise considerably, putting additional strain on the power grids of these areas if an adequate (clean) electricity supply is not added to the grid.

Last, we address the key data and computational challenges faced in assessing the impacts of climate change and envelope improvements on building energy use across time and space. This is accomplished by pooling together a large dataset from various sources and leveraging surrogate modeling techniques. Moreover, our modeling framework is potentially translatable to other countries or building types to understand the locational impacts of climate change and climate change or adaptation strategies on building thermal performance. The physics-based, spatially refined nature of our modeling framework will enable analysts to explore the efficacy of a wide range of climate mitigation or adaptation strategies other than envelope improvements, including solar shading, night ventilation, adaptive setpoint temperatures, and energy-efficient lighting and appliances.

EXPERIMENTAL PROCEDURES

Modeling framework

We develop a bottom-up model (Figure 6) to predict energy demand for cooling and heating by residential buildings (including all residential building stocks within a city's administrative boundary) across 1,677 sub-province-level cities in 31 Chinese provinces (excluding Hong Kong, Macao, and Taiwan) from 2020 to 2100. Due to data paucity, aggregated data at the prefecture level were used for building stock estimation in 11 provinces (see Table S3), mainly in North and Southwest China. With this bottom-up model, we predict residential cooling and heating demands across 1,677 sub-province-level cities (including prefectures and counties). Our model consists of 4 modules: prototype building development, energy simulation and surrogate modeling, stock turnover modeling, and climate data downscaling.

Prototype building development

As buildings vary widely in their physical characteristics (size, geometry, construction, etc.) and operational characteristics (function, occupancy, schedule, etc.), prototype buildings (also referred to as archetypes[16]) are usually employed to classify the residential building stock into groups with similar building characteristics, such as building type, construction year, and climate zone.[17] Each prototype building is approximated by a simulation-ready model that includes parameters characterizing the shape, structure, function, and envelopes of the building.

We divide the residential building stock in China into distinct segments covering a realistic diversity of building characteristics (e.g., climate zone and vintage). Given geographical variations in climate across China and temporal changes in construction methods, we determine the U-values of three important envelope components (i.e., exterior walls, windows, and roof) based on climate zone and vintage. Within China, we defined eight climate zones: (1) severe cold A, (2) severe cold B, (3) severe cold C, (4) cold A, (5) cold B, (6) hot summer and cold winter, (7) hot summer and warm winter, and (8) warm (see Table S4; Figure S1). China's building standards[18–25] have stipulated U-values and other design parameters for buildings across different climate zones (see Table S2). Accordingly, we assume that cities within the same climate zone use identical prototype buildings to determine the thermal performance of buildings built before 2020. Additionally, we consider heterogeneity in the average number of stories across cities. We also draw data from the TABULA project,[26,27] based on which we define two prototype buildings for each year and each of the eight climate zones to envision future envelope improvements in both existing building stocks and newly constructed buildings. These two prototype buildings represent future envelope improvements. One prototype building is derived from the advanced refurbishment specifications, and the other is derived from the nearly zero-energy building (NZEB) standards proposed by the TABULA project. More details about prototype buildings are available in Table S6.

Due to data availability, we assume that all prototype buildings are adapted from a benchmark building (see Table S5; Figure S2), which is a cuboid with an orientation of 0° and glazed in all four directions. The benchmark building has a window-to-wall ratio of 0.3 and is divided into four conditioned spaces without considering internal structures such as corridors. The benchmark building is comprised of internal walls with a U-value of 2.511 W/m^2*K, foundations with a U-value of 1 W/m^2*K, and floors with a U-value of 1.887 W/m^2*K. Consistent with the building codes in China,[18–25] we assume that the thermostat setpoint is 18°C for heating and 26°C for cooling. Heating is only available during the heating period, and cooling is only available during the cooling period. The cooling period first starts on April 1 and ends on September 30 at the latest. The heating period first starts on September 20 and ends on May 10 at the latest (see details in Table S5).

Energy simulation and surrogate modeling

We develop surrogate models to emulate physics-based and high-fidelity building energy simulation, as building energy simulation relying on physical laws is computationally expensive.[28] The basic tenet of surrogate modeling is that machine-learning models trained on a small set of simulation input and output data can approximate physics-based simulation and instantly predict building energy performance, such as cooling and heating demands. Deriving a surrogate model consists of three steps: (1) selection of simulation inputs and outputs, (2) database generation and preprocessing, and (3) model fitting and validation.

Selection of simulation inputs and outputs

The first step of surrogate modeling is to define model inputs (i.e., design parameters) and outputs (i.e., design objectives) for generating samples. Owing to data availability, we carefully choose 23 critical design parameters as model inputs, consisting of three envelope-related parameters (i.e., U-values of exterior walls, windows, and roof), 12 climate-related parameters (i.e., dry bulb temperature, dew point temperature, relative humidity, atmospheric station pressure, horizontal infrared radiation intensity, global horizontal radiation, direct normal radiation, diffuse horizontal radiation, wind direction, wind speed, total sky cover, and opaque sky cover), four location-related parameters (i.e., weather station number, longitude, latitude, and altitude), three time-related parameters (i.e., month, day, and hour), and one parameter representing the average number of stories. Consequently, we obtain hourly heating and cooling demands per square meter as model outputs to capture changes in heating and cooling demands throughout the day.

Database generation and preprocessing

After simulation inputs and outputs are determined, we sample the design space using the Latin hypercube sampling method,[29] through which 10,000 parameter combinations are picked for building energy simulation in EnergyPlus.[30] The upper and lower bounds for climate-, location-, and time-related parameters are derived from 270 typical meteorological year (TMY) files obtained from the EnergyPlus Weather Data repository.[31] The upper and lower bounds for envelope-related parameters and the average number of stories are derived from the prototype buildings defined in Note S2.4.2. In sampling, we eliminate illogical parameter combinations (e.g., non-zero global horizontal radiation during the night). With the sampled 10,000 parameter combinations, we perform 10,000 EnergyPlus runs, each of which generates 8,760 hourly data points for heating and cooling demands per square meter. From each EnergyPlus run, 5 hourly data points are randomly sampled, resulting in a dataset of 50,000 data points. This practice ensures that we take full account of hourly data when predicting future energy demands. We standardize model inputs and outputs to ensure variables are equally weighted during model training. In doing so, we employ a robust scaling method to map the data to a uniform distribution.[32] After data preprocessing, we split the formatted dataset into a training dataset and a testing dataset for 5-fold cross-validation.

Model fitting and validation

With the prepared datasets, we employ gradient boosting regressor (GBR) to predict heating and cooling demands. GBR is a powerful ensemble-based machine-learning technique that can be used in various practical tasks, such as prediction. We select the sklearn.ensemble module because it is a well-established library providing a wide range of ensemble-based methods for classification, regression, and anomaly detection. We optimize the hyperparameters of the GBR models using a random search method, which implements a randomized search over a bounded domain of hyperparameter values. We evaluate the accuracy of the trained models by the coefficient of determination (R^2), which quantifies how much of the variance in the data is explained by the model (see details in Figures S3 and S4).

Stock turnover modeling

In this study, we develop a stock turnover model[33] to project the stock dynamics (including construction, demolition, and retrofitting) of residential building stock at the city level. Mathematically, the floor area of newly constructed buildings is the sum of the floor area of demolished buildings and net stock changes.

$$N_{t_n} = SP_{t_n} \times P_{t_n} - SP_{t_{n-1}} \times P_{t_{n-1}} + D_{t_n}$$

$$D_{t_n} = \int_{t_0}^{t_{n-1}} (S(t_{n-1} - t) - S(t_n - t)) \times N_t dt$$

N_{t_n} denotes the newly constructed floor area in the year t_n; SP_{t_n} denotes the per-capita floor area of building stock in the year t_n; P_{t_n} denotes the population in the year t_n; D_{t_n} denotes the demolished floor area in the year t_n; and $S(t_n - t)$ denotes the survival function, which describes the survival rate after a specific period $t_n - t$.

The floor area of residential building stocks at the city level is driven by changes in population and per-capita floor area (see Figure S5). The residential building stocks at the city level in 2020 are shown in Table S12. We assume that per-capita floor area follows an S-shaped curve or an inverted S-shaped curve that moves all cities toward a national convergence of per-capita floor area of 50 m^2, emulating the convergence patterns and stock-driven modeling used in previous studies.[34,35] National-level population projection during 2019–2100 is derived from the medium scenario of United Nations World Population Prospects 2019[36] in which demographic characteristics (including sex, age, and educational attainment categories) and national policies regarding fertility and population ceiling are explicitly considered. The medium scenario depicts a "middle-of-the-road" future where demographic characteristics broadly follow their historical patterns. We break down national-level population projection into cities, assuming that no inter-city population migration will take place and the population growth or decline rate is identical across China. As the survival rate of buildings is determined by building lifetime, we employ a two-parameter Weibull function to determine the survival rate of building stocks over time.[35,37] The shape and scale parameters of the Weibull function are taken from a China-specific study[5] (see Table S8).

Future climate data and downscaling

While many climate factors may affect building energy use, we deem dry bulb temperature as the more prominent climate factor for building energy use, as suggested by sensitivity analyses on all climate factors in 8 locations (i.e., Hailar, Harbin, Hohhot, Taiyuan, Tianjin, Wuhan, Guangzhou, and Kunming), each representing a climate zone in China (see details in Table S9). Therefore, we assume that other climate factors remain unchanged for energy simulations. We coordinate each of the 1,677 sub-province cities to the nearest corresponding weather station (see details about assigning weather stations to counties in Figure S7; Table S11). To project future dry bulb temperatures across counties, we draw climate outcomes from AWI-CM-1-1-MR, one of the global climate models in Coupled Model Intercomparison Project Phase 6 (CMIP6). Three climate scenarios are considered to represent lower (SSP1-2.6), medium (SSP2-4.5), and higher (SSP5-8.5) emission scenarios. To generate simulation-ready hourly climate data from 2020 to 2100, we leverage an R package named epwshiftr.[38] This R package adopts a morphing method widely used by building modelers.[39] The morphing method considers monthly trends and variations in the climate outcomes of CMIP6 while preserving the hourly patterns of historical climate data.[40] The temporal trends of outdoor dry bulb temperature from 2020 to 2100 (see Figures S8 and S10).

Scenarios

We conceive nine scenarios (3 × 3) based on three climate change scenarios (i.e., SSP1-2.6, SSP2-4.5, and SSP5-8.5) and three envelope improvement scenarios (i.e., reference, moderate, and radical), aiming to assess the combined effects of building envelope improvements and climate change. The reference scenario assumes that no envelope improvements will occur for existing building stocks and newly constructed buildings. The moderate scenario depicts a future where envelope upgrades will take place for existing building stocks to catch up with China's present-day envelope technologies by 2060, and by contrast, newly constructed buildings will adopt China's present-day envelope technologies, and no further improvements will take place. The radical scenario envisages a future with ambitious envelope improvements in existing building stocks and the NZEB standards to be gradually adopted by newly constructed buildings between 2020 and 2060. We assume that new envelope technologies will be linearly deployed (see details in Table S13).

RESOURCE AVAILABILITY

Lead contact

Any requests for further information should be directed to Zhi Cao (zhicao@nankai.edu.cn).

Materials availability

The materials that support the findings of this study are available from the supplemental information and supplemental data.

Data and code availability

Source data for plotting figures are provided along with this study. Codes used for surrogate modeling are available via GitHub (https://github.com/ZhiCaoIE/China_Housing_Energy). Stock turnover modeling is implemented using the ODYM framework (https://github.com/IndEcol/ODYM). Climate data downscaling is implemented using an R package named epwshiftr (https://github.com/ideas-lab-nus/epwshiftr).

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AUTHOR CONTRIBUTIONS

C.C. and Z.C. conceived and designed the research. Y.Z. and M.D. collected the data and performed the simulations. Y.Z., M.D., C.C., and Z.C. produced the figures. P. Behrens, P. Berrill, and X.Z. contributed to the result interpretation. Y.Z., M.D., C.C., and Z.C. prepared the first draft. All authors reviewed and edited the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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