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Modeling the Impacts of Demand Drivers on Future Building Thermal Energy Demand in Chinese Cities

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Abstract (153 words)

Future changes in climate, demographic, and socioeconomic factors will deeply influence urban building energy demand. We apply an integrated modeling approach to investigate the impacts of the above drivers on building thermal energy service demand in 336 Chinese cities in 2020-2060. We find that China's urban building floor area will not decrease significantly due to ongoing urbanization and increasing floor area per capita. However, future trajectories of building thermal energy demand vary substantially across cities due to huge heterogeneity in floor area and intensity of energy demand, suggesting the need for tailored infrastructure planning and policy interventions. Future warming greatly changes demand patterns, reducing heating demand by 24% but increasing cooling demand by 27% compared with no warming in 2060. Compact urban development and building energy efficiency improvements are key demand-side measures, potentially reducing heating (cooling) demand in 2060 by 27% (24%) and 22% (11%) relative to a scenario with limited policy interventions.

Main text (5,634/7,000 words, 6 figures/tables)

1. Introduction

Approximately 30% of global final energy consumption and CO_2 emissions come from the building sector [1]. CO_2 emissions from buildings have doubled over the past two decades and will continue to grow under current policies [2]. Therefore, future reductions in building energy use and emissions will be crucial to global decarbonization. While electrification powered by clean energy is regarded as an essential part of emission mitigation [3], measures that reduce energy demand can make substantial contributions to the low-carbon transition of buildings as well [4–9]. Many studies have indicated that to achieve deep building decarbonization consistent with the 2 °C and 1.5°C climate targets, a portfolio of ambitious policies on both energy supply and demand is necessary [10–16].

Effective reductions in energy use require a comprehensive understanding of future energy demand and policy impacts. Previous literature has demonstrated that building energy use changes as a function of various demand drivers, including climate [17–19], population size [14,18], floor area per capita [14,20], energy behaviors [21], etc. These demand drivers have large geographic variations, further complicating energy use patterns [22]. In addition, policies on building energy efficiency (e.g., building energy codes, old building retrofits) [7,11,23,24] and compact urban development [25] also have great impacts on building characteristics and energy demand. The natural, social, and policy factors collectively shape the future pathway of building energy consumption and hence should be considered in demand projections. However, existing studies rarely took these variations into account. Wang et al. (2023) [18] modelled the impacts of population and climate on US building energy use at the city level, but they assumed fixed building stock without including changes in floor area and building energy efficiency over time.

Chinese urban buildings are responsible for over 10% of China's energy use and CO_2 emissions [26], with more than half coming from space heating and cooling [27]. As a result of rapid economic development and urbanization, Chinese cities have witnessed sharp increases in building stock and energy use over the past few decades. However, future energy use patterns of Chinese urban buildings will be deeply influenced by changes such as a shrinking population [28], continued urbanization [29], increasing floor area per capita due to income growth [27], improved energy efficiency [11], and a warming climate [17]. The future pathways of energy use and carbon emissions of Chinese buildings have been extensively modelled at the national and climate zone levels [11,30–36]. Some studies provided city-level results, either using spatial downscaling [37] or with a limited scope for one or several cities [17,38]. Most studies failed to include the above demand drivers to explore a wide range of scenarios, and they overlooked the inter-city heterogeneity in these drivers. This lack of granularity limits the accuracy of energy and emission projections as well as the ability to inform policymaking in individual cities.

Table 1. Designed scenarios for this study.

Factors	Scenarios	Description
Population	HighPop	High fertility (1.8 in 2050), 1.3 billion in 2060
	MedPop	Medium fertility (1.3 in 2050), 1.2 billion in 2060
	LowPop	Low fertility (0.7 in 2050), 1.1 billion in 2060
Floor area per capita	HighArea	Uncontrolled growth, 56 m^2/cap (national urban average) in 2060
	MedArea	Medium growth, 52 m^2/cap in 2060
	LowArea	Compact growth, 41 m^2/cap in 2060
Energy efficiency improvements	LowEff	No additional building envelope energy efficiency standards through 2060;
		Retrofit 0.18 billion m^2 (0.3%) of inefficient buildings per year (current retrofit rate in China [39])
	MedEff	Starting in 2035, new buildings must meet Nearly Zero Energy Building Standards;
		Retrofit 0.39 billion m^2 (0.65%) of inefficient buildings per year (mean of the LowEff and HighEff rates)
	HighEff	Starting in 2025, new buildings must meet Nearly Zero Energy Building Standards;
		Retrofit billion 0.6 m^2 (1%) of inefficient buildings per year (rate consistent with China's carbon neutrality goal by 2060 [39])
Climate	SSP245	Shared Socioeconomic Pathway 245
	SSP585	Shared Socioeconomic Pathway 585

Note: The baseline scenario is the MedPop_MedArea_MedEff_SSP245 scenario.

To fill this research gap, here we evaluate the implications of future climate, demographic, and socioeconomic changes for building thermal (heating and cooling) energy service demand in 336 Chinese cities from 2020 to 2060. We design a series of scenarios (Table 1) of the above demand drivers and potential policies to model urban building energy demand in various possible futures. We develop a bottom-up approach that includes the inter-city heterogeneity in building stock and demand drivers for energy simulations. We estimate that China's urban building floor area will increase by 15% between 2020 and 2060 in the baseline scenario, due to continued urbanization and increasing floor area per capita. We find huge inter-city heterogeneity in both building floor area and thermal energy intensity. We find that climate, building energy efficiency, and floor area per capita are primary drivers of energy demand. Future warming (Shared Socioeconomic Pathway 245) is projected to result in changes in urban building heating, cooling, and total

thermal energy demand of -24%, +27%, and +8.5% in 2060, respectively. Ambitious policies on compact urban development and building energy efficiency improvements could reduce national urban building heating (cooling) demand by 22% (19%) and 8% (4%) from the baseline scenario and by 27% (24%) and 22% (11%) from limited policy interventions (conservative policy scenarios) in 2060, respectively. Policy impacts on building thermal demand vary substantially across cities, suggesting that tailored infrastructure planning and policy interventions are needed to effectively reduce energy use and emissions.

2. Materials and Methods

We integrate a modeling system to investigate the impacts of various energy demand drivers on building heating and cooling demand from urban population in 336 Chinese prefecture-level cities. First, we develop various scenarios of energy demand drivers by synthesizing projections of future population, floor area, climate, as well as potential building policies. Second, we utilize a building stock turnover model to project future building floor areas under these scenarios using a historical urban building stock dataset. Next, we run a building energy use model to simulate the heating and cooling energy intensities of prototype buildings in each city. Finally, we combine the results of future city-level building stock and building energy intensities to evaluate spatial and temporal variations in Chinese urban building energy demand.

2.1 Scenario design

We construct a series of scenarios to reflect the uncertainties in various drivers of urban building stock and energy demand. We choose 2020 as the base year of our simulations and model the pathways of city-level building energy demand from 2020 to 2060, when China pledges to achieve carbon neutrality.

We build three urban population scenarios (HighPop, MedPop, LowPop) based on a dataset of city-level population projections for China [28]. The three scenarios assume national fertility rates of 1.8, 1.3, and 0.7 by 2050, capturing a wide spectrum of possible population growth trajectories based on recent trends and policies. As city-level urbanization rates are missing in this dataset, we use the future provincial urbanization rates from Chen et al. (2020) [29] to estimate urban populations and calibrate them against the urban population data from the 2020 China Population Census. Figure S1 shows future changes in total and urban populations. Across the three scenarios, China's total population declines from 1.4 billion in 2020 to 1.1-1.3 billion in 2060. However, due to continued urbanization, China's urban population will not decrease until the 2040s, and the urban population in 2060 is comparable to or even higher than its 2020 value.

We develop three scenarios of building floor area per capita (HighArea, MedArea, LowArea) based on empirical relationships between floor area and GDP from IEA (2015) [27] and projected

provincial GDP under the SSP2 scenario (consistent with the baseline climate scenario of this study) from GCAM-China [40]. We determine the residential floor area per capita of the 336 cities in the base year (2020) based on the 2020 China Population Census, and we project different future changes in city-level floor area per capita across the three scenarios (Figure S2). The residential floor area per capita is averaged only over urban residents, given that urban and rural residents of a city generally have different floor area per capita. China's current floor area per capita is still lower than many developed countries and is likely to increase with growing resident income. In the MedArea and HighArea scenarios, the national average urban residential floor area increases from 39 m^2/capita in 2020 to 52 m^2/capita and 56 m^2/capita in 2060 (following historical patterns of global countries), respectively, due to economic growth and uncontrolled expansion of urban lands. The LowArea scenario characterizes the potential effect of ambitious compact urban development policy, where the national average building floor area is limited to approximately 40 m^2/capita (around base year level) through 2060.

In addition, we design three scenarios of future building energy efficiency (HighEff, MedEff, LowEff). China has been promoting energy efficiency improvements for urban buildings by upgrading the efficiency standards since 1986 [17] and retrofitting old, inefficient buildings. As of now, five generations of efficiency standards have been developed for residential buildings, and three generations for non-residential buildings (Table S1). Here we assume a different pace of efficiency improvements in the coming decades across scenarios. In the LowEff scenario, no additional efficiency improvements will be implemented through 2060, and 0.18 billion m^2 or 0.3% (current retrofit rate in China [39]) of old buildings will be retrofitted per year through 2060, representing existing policy efforts. In the MedEff and HighEff scenarios, we raise policy ambitions by assuming the implementation of more stringent efficiency standards, where all new buildings must meet the Nearly Zero Energy Building standards starting in 2035 and 2025. We also assume more ambitious retrofits of old buildings in the MedEff and HighEff scenarios, with a retrofit target of 0.39 billion m^2 or 0.65% per year and 0.6 billion m^2 or 1% per year (rate consistent with China's carbon neutrality goal by 2060 [39]) through 2060, respectively. These policy impacts will vary across cities, as cities in different climate zones comply with different standards, and cities differ in building vintage distribution as well.

Moreover, we include two climate scenarios (SSP245, SSP585) to evaluate the potential impacts of climate change on future building energy use. In our main simulations, we use the SSP245 climate to construct a scenario with moderate warming. We also conduct sensitivity tests using the SSP585 climate to assess the impacts of extreme warming on building energy demand.

We combine these four dimensions and generate 54 scenarios for building energy demand. We use the MedPop_MedArea_MedEff_SSP245 scenario as the baseline scenario in this study.

2.2 Building stock turnover modeling

Modeling urban building energy demand requires information on building stock and its temporal variations. However, no official sources in China provide consistent statistics on urban building stock (e.g., building floor areas of residential and non-residential buildings) for all cities across decades [41]. Therefore, we use a dataset of historical Chinese city-level material stock [42] to estimate the urban building floor areas of 336 cities from 1978 to 2020. We calculate the total urban residential and non-residential building floor areas in each city and year by dividing the material stock by material intensities for buildings. The building stock evolution before 1978 is not considered, as the total urban building areas before 1978 are much smaller than their base year values (and have mostly been replaced by 2020) and hence will not greatly affect our analyses. As this dataset does not include vacant buildings, we adjust the building stock data based on urban housing vacancy rates from the literature [43–45].

We use a building stock turnover model to estimate annual new building floor areas from 1978 to 2020 and project future new floor areas by 2060 in various scenarios. The turnover of urban residential building floor area is estimated as follows:

$$A_{i,t}^{tot} - A_{i,t-1}^{tot} = A_{i,t}^{new} - A_{i,t}^{dem} \quad (1)$$

Where $A_{i,t}^{tot}$ and $A_{i,t-1}^{tot}$ are the total building floor area in city i in year t and year $t-1$, respectively; $A_{i,t}^{new}$ is the new building floor area built in city i in year t; $A_{i,t}^{dem}$ is the building floor area demolished in city i in year t.

The future urban residential building floor areas are projected as follows:

$$A_{i,t}^{tot} = P_{i,t} \times A_{i,t}^{pc} \quad (2)$$

where $P_{i,t}$ is the urban population of city i in year t; $A_{i,t}^{pc}$ is the floor area per capita in city i in year t.

Historical data on China's urban building floor areas [42] suggest that the ratio of non-residential to residential building floor area increased after 2000 and has plateaued in recent years (Figure S3). Therefore, when projecting future urban non-residential building floor areas, we assume that the ratio of non-residential to residential building floor area will remain unchanged from 2020 to 2060 in each city, so that non-residential floor area will grow at the rate of residential floor area growth.

The demolished building floor areas are estimated using the probability function [46] as follows:

$$P_t^{dem} = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{t-\mu}{\sqrt{2}\sigma}\right)\right] \quad (3)$$

where P_t^{dem} is the probability of a building being demolished after being built for t years; erf is the Gauss error function; μ is the average building lifetime; σ is the standard deviation of building lifetime (one third of μ). Previous literature estimates that the average lifetime of China's urban buildings is 30 to 40 years [46]. We assume an average building lifetime of 35 years before 2020 and 50 years (designed lifetime) after 2020, consistent with the recent trend of lifetime increases [47].

In addition, we consider old building retrofits during building stock turnover. We assume that building retrofits start from the oldest, most inefficient buildings in each city, and the retrofitted buildings will upgrade their energy efficiency by up to two generations of efficiency standards (Table S1) but not more efficient than the latest standard implemented in the year of retrofits. Retrofitted buildings are assumed to have a fixed lifetime of 30 years [48] and will be demolished upon reaching the lifetime.

We evaluate the estimated historical urban building stock against data from 2020 China Population Census. We find that our data derived from Li et al. (2023) [42] underestimated the residential floor area built before 2010 while overestimating the floor area built after 2015 (Figure S4). We then calibrate the building stock data by scaling the annual new building floor area in each period (as defined in the census) by a different factor, so that both the building vintage distribution and the total building floor area in 2020 are consistent with the census data.

2.3 Future weather data

To include the effects of climate change on building energy demand, we extract future weather data for the SSP245 and SSP585 scenarios from the Coupled Model Intercomparison Project Phase 6 (CMIP6) databases. We retrieve 6-hourly dry-bulb temperature, relative humidity, air pressure, wind speed, and wind direction at the surface level of each city from a climate dataset based on an ensemble of 18 CMIP6 models [49]. Additionally, we retrieve 3-hourly global horizontal irradiance and diffusive horizontal irradiance at the surface level of each city from the Beijing Climate Center Climate System Model version 2 - Medium Resolution (BCC-CSM2-MR) dataset [50]. We calculate direct normal irradiance using global horizontal irradiance, diffuse horizontal irradiance, and solar zenith angle [51]. We use interpolation to convert these weather variables into hourly data of dry-bulb temperature, dew point temperature, relative humidity, air pressure, global horizontal radiation, direct normal radiation, diffuse horizontal radiation, wind direction, and wind speed for building energy simulations. Given the interannual climate variations in CMIP6 models, we use the 5-year average of weather variables as inputs for each year of building energy simulation.

2.4 Building heating and cooling energy demand modeling

Urban building energy use can be modelled with top-down and bottom-up approaches. While top-down models use aggregated data to characterize the relationship between building energy use and its drivers, bottom-up models use disaggregated data to quantify the energy uses of individual buildings and extrapolate them to the aggregated level [52]. Here we take a bottom-up approach, as we aim to investigate the impacts of future changes in climate and building energy efficiency.

We employ a state-of-the-art building energy simulation model, EnergyPlus (https://energyplus.net/), to simulate individual building energy intensities for heating and cooling in Chinese cities. EnergyPlus is a physical model based on energy balance equations and has been widely used for evaluating the response of building energy use to changes in climate and building characteristics [18]. As this study focuses on building energy demand drivers, we only evaluate the final energy demand without explicitly modeling how the energy demand will be met by different technologies. We design 92 prototype residential buildings (4 building types (forms) × 5 climate zones × 3 or 5 building energy efficiency standards per climate zone) and 90 prototype non-residential buildings (6 building types (2 forms × 3 operation schedules (office, mall, and hotel)) × 5 climate zones × 3 building energy efficiency standards) for Chinese cities based on previous literature [17,53]. We choose 5 years during 2020-2060 (2020, 2030, 2040, 2050, 2060) to conduct simulations. In combination, we perform a total of 127,680 EnergyPlus simulations (336 cities × 38 prototype buildings per city × 5 years × 2 climate scenarios). We assume a target temperature of 20°C for heating and 27°C for cooling for residential buildings based on a Chinese indoor thermal comfort database [54]. For non-residential buildings, we adopt the heating and cooling patterns from China's urban non-residential building energy efficiency standards (Table S1). The model outputs are annual building heating and cooling energy uses at an hourly resolution.

The city-level building energy demand is calculated as follows:

$$E_{s,i,t} = \sum_{j=1}^{N_i}(A_{s,i,j,t} \times \sum_{b=1}^{N_b}(EI_{i,j,b,t} \times w_b)) \times P_{s,i,t} \times CF_{i,t} \quad (4)$$

where $E_{s,i,t}$ is the total heating or cooling energy demand of city i in year t under scenario s; N_i is the number of building energy efficiency levels (required by energy efficiency standards in Table S1) in city i; $A_{s,i,j,t}$ is the total floor area of buildings with energy efficiency level j in city i in year t under scenario s; N_b is the number of prototype buildings; $EI_{i,j,b,t}$ is the heating or cooling energy intensity for building type b with energy efficiency level j in city i in year t under scenario s; w_b is the weight applied to building type b, based on the share of various building types estimated from data of urban building heights and types (Supplementary Note 1); $P_{s,i,t}$ is the penetration of heating or cooling appliances in households of city i in year t under

scenario s (Supplementary Note 2); $CF_{i,t}$ is the calibration factor that accounts for behavioral heterogeneity such as "part time, part space" heating and cooling behaviors of Chinese urban households (Supplementary Note 3).

2.5 Decomposition of the contributions of demand drivers to building energy demand changes

Urban building heating and cooling demand are collectively determined by urban population, floor area per capita, building energy efficiency, climate, and energy behaviors, as the following equation shows:

$$E_{s,i,t} = P_{s,i,t} \times A_{s,i,t} \times I_{s,i,t} \times C_{s,i,t} \times B_{s,i,t} \quad (5)$$

where $E_{s,i,t}$, $P_{s,i,t}$, $A_{s,i,t}$, $I_{s,i,t}$, $C_{s,i,t}$, and $B_{s,i,t}$ represent total energy demand, urban population, floor area per capita, average building energy intensity under base year climate, climate effect on building energy intensity (i.e., the ratio between average building energy intensities under the climate of base year and year t), and the effect of energy behavioral changes (as the product of heating or cooling appliance penetration and calibration factor, see Equation 4), respectively, of city i in year t under scenario s.

To decompose the contributions of various demand drivers to the simulated future changes in urban building heating and cooling demand, we apply the logarithmic mean Divisia index (LMDI) method [18] to our modelled demand. Future demand changes can be attributed as:

$$\Delta E_{t-t_0} = \Delta E_{P,t-t_0} + \Delta E_{A,t-t_0} + \Delta E_{I,t-t_0} + \Delta E_{C,t-t_0} + \Delta E_{B,t-t_0} \quad (6)$$

where

$$\Delta E_{P,t-t_0} = \frac{E_t - E_{t_0}}{\ln E_t - \ln E_{t_0}} \times \ln\left(\frac{P_t}{P_{t_0}}\right) \quad (7)$$

$$\Delta E_{A,t-t_0} = \frac{E_t - E_{t_0}}{\ln E_t - \ln E_{t_0}} \times \ln\left(\frac{A_t}{A_{t_0}}\right) \quad (8)$$

$$\Delta E_{I,t-t_0} = \frac{E_t - E_{t_0}}{\ln E_t - \ln E_{t_0}} \times \ln\left(\frac{I_t}{I_{t_0}}\right) \quad (9)$$

$$\Delta E_{C,t-t_0} = \frac{E_t - E_{t_0}}{\ln E_t - \ln E_{t_0}} \times \ln\left(\frac{C_t}{C_{t_0}}\right) \quad (10)$$

$$\Delta E_{B,t-t_0} = \frac{E_t - E_{t_0}}{\ln E_t - \ln E_{t_0}} \times \ln\left(\frac{B_t}{B_{t_0}}\right) \quad (11)$$

ΔE_{t-t_0} is the energy demand change between year t and t_0, and it can be decomposed into the contributions of the above demand drivers, as derived in Equation 7-11.

3. Results

3.1 Future urban building stock changes

We model future urban building stock changes in China at the city level based on projections of urban population and floor area per capita (Section 4.1). Figure 1A-C show the national urban building floor area changes from 1978 to 2060 in the baseline (MedPop_MedArea_MedEff_SSP245) scenario. We estimate that the total urban building floor area in 2020 (the base year of simulations) is 60 billion m^2, with residential buildings making up over 70% of the floor area. In the baseline scenario, while China's total population began to decline in 2020 (Figure S1), its urban population continues to increase until mid-century. Building floor area grows until 2047, due to ongoing urbanization with associated population increase and increasing floor area per capita. The total floor area in 2060 is 68 billion m^2, 15% higher than 2020, suggesting moderate potential for further building stock growth. New building construction decreased significantly between 2020-2024 due to the real estate crisis in China resulting from strict housing policies but is projected to recover afterwards due to recent policy shifts promoting the real estate market. However, the future scale of building construction is expected to be much lower than the peak during the 2010s (Figure 1B).

Future urban building stock varies substantially across different scenarios (Figure 1D). We find that the total urban building floor area ranges from 50 billion m^2 to 78 billion m^2 in 2060, depending on assumptions of population and floor area per capita. We note that only in scenarios with compact urban development (the LowArea scenarios) would China stabilize the urban building stock below the 2020 level in the coming decades.

In addition, in the baseline scenario, we examine changes in building vintage distribution over time. Figure 1E, F show future urban building floor area by year of construction. We find that, due to replacement of old buildings with new buildings that follow more stringent energy efficiency standards, the share of buildings with relatively efficient envelopes increases rapidly over time. In 2040, more than half of buildings will meet the energy efficiency standards in place in 2020, and this share increases to 94% by 2060. The energy efficiency of new buildings built after 2020 will largely determine the future energy demand of China's urban buildings, presenting a great opportunity to reduce future building energy demand through rapid implementation of more stringent efficiency standards (e.g., the Nearly Zero Energy Building Standard).

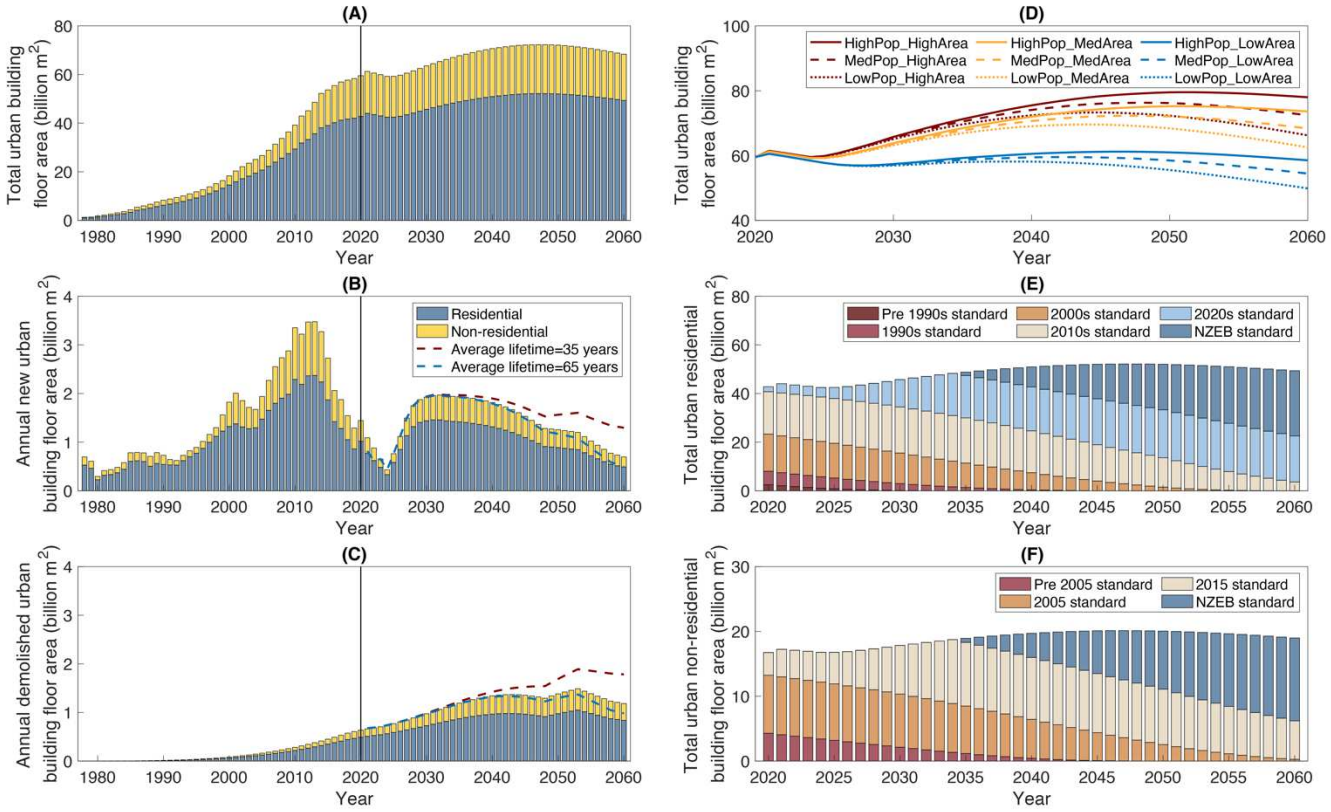


Figure 1. Historical and future urban building stock changes. (A-C) National (A) total, (B) annual new, and (C) annual demolished urban building floor areas from 1978 to 2060 in the baseline scenario. The blue and yellow bars show residential and non-residential building floor areas, respectively. The vertical black line indicates the base year (2020). We assume an average building lifetime of 50 years for buildings constructed after 2020. The red and blue dashed curves in (B) and (C) show the building floor areas with alternative lifetimes of 35 and 65 years, respectively. (D) National total urban building floor area under various scenarios from 2020 to 2060. Red, yellow, and blue curves indicate high, medium, and low population scenarios, respectively. Solid, dashed, and dotted curves indicate high, medium, and low floor area per capita scenarios, respectively. (E, F) Vintage distribution of urban (E) residential and (F) non-residential building floor areas from 2020 to 2060 in the baseline scenario. Buildings are grouped by the year of construction. Each group of buildings shares the same energy efficiency standard. NZEB: Nearly Zero Energy Building.

We find huge inter-city heterogeneity in the evolution of population and building floor area in China for cities of various sizes (Figure S5). In the baseline scenario, while some cities witness a decrease in urban population and building floor area over time, most cities (especially small cities) will have a larger building stock by 2060. The changes in building floor area between 2020 and 2060 range from -80% to 200% across different cities. We observe similar patterns in non-baseline scenarios. These huge variations in urban dynamics imply that policy priorities regarding building energy and emission reductions should be contingent on the individual city context.

3.2 Building heating and cooling energy intensities

We simulate building energy intensities for space heating and cooling services at the city level under the SSP245 and SSP585 climate scenarios.

Heating and cooling energy intensities are dependent on multiple factors, including local climate, building envelope energy efficiency, and building prototypes (e.g., height, floor plan, energy behavior). Figure S6 and S7 illustrate the 2020 heating and cooling energy intensities of various prototype residential and non-residential buildings of five representative cities in different climate zones of China. We find substantial variations not only across cities but also across different building vintages within a city. Building energy intensities are generally more sensitive to efficiency upgrades in cities with a less temperate climate. In these cities, the heating and cooling energy intensities of the most efficient buildings could be 60% lower than the least efficient buildings. Our results demonstrate huge benefits of building efficiency improvements for reducing energy demand.

In addition, we investigate the inter-city heterogeneity in building energy intensity due to different local climate conditions. Figure S8A, B show the geographic variations in annual heating and cooling intensities for the currently most efficient buildings (i.e., meeting the 2020s standards) in 2020 under the SSP245 climate scenario. We observe high heating intensities in the northeast and Tibet and high cooling intensities in southeastern cities. Warming under SSP245 results in a median reduction in heating energy intensities by 23% (25th-75th percentile: 15%-31%) and a median increase in cooling energy intensities by 37% (25th-75th percentile: 26%-51%) across different cities from 2020 to 2060. Cities with higher heating or cooling energy intensities tend to experience larger changes in energy intensities over time (Figure S8C, D), which indicates that the inter-city heterogeneity would decrease for heating while increase for cooling as climate becomes warmer. Compared to the SSP245 scenario, the SSP585 climate would further lower heating energy intensities (especially in central China) and increase cooling energy intensities (especially in southern China) (Figure S8E, F).

3.3 Urban building heating and cooling demand

On the basis of modelled urban building stock and energy intensity, we estimate the total building heating and cooling service demand for each city of China. Figure 2A, B show the geographic variations in annual building energy demand at the city level in 2060 in the baseline scenario. We find that highly populated cities are hotspots for building energy use. With inter-city heterogeneity in both building floor area and energy intensity, the building energy demand for heating and cooling could differ by over five orders of magnitude across cities.

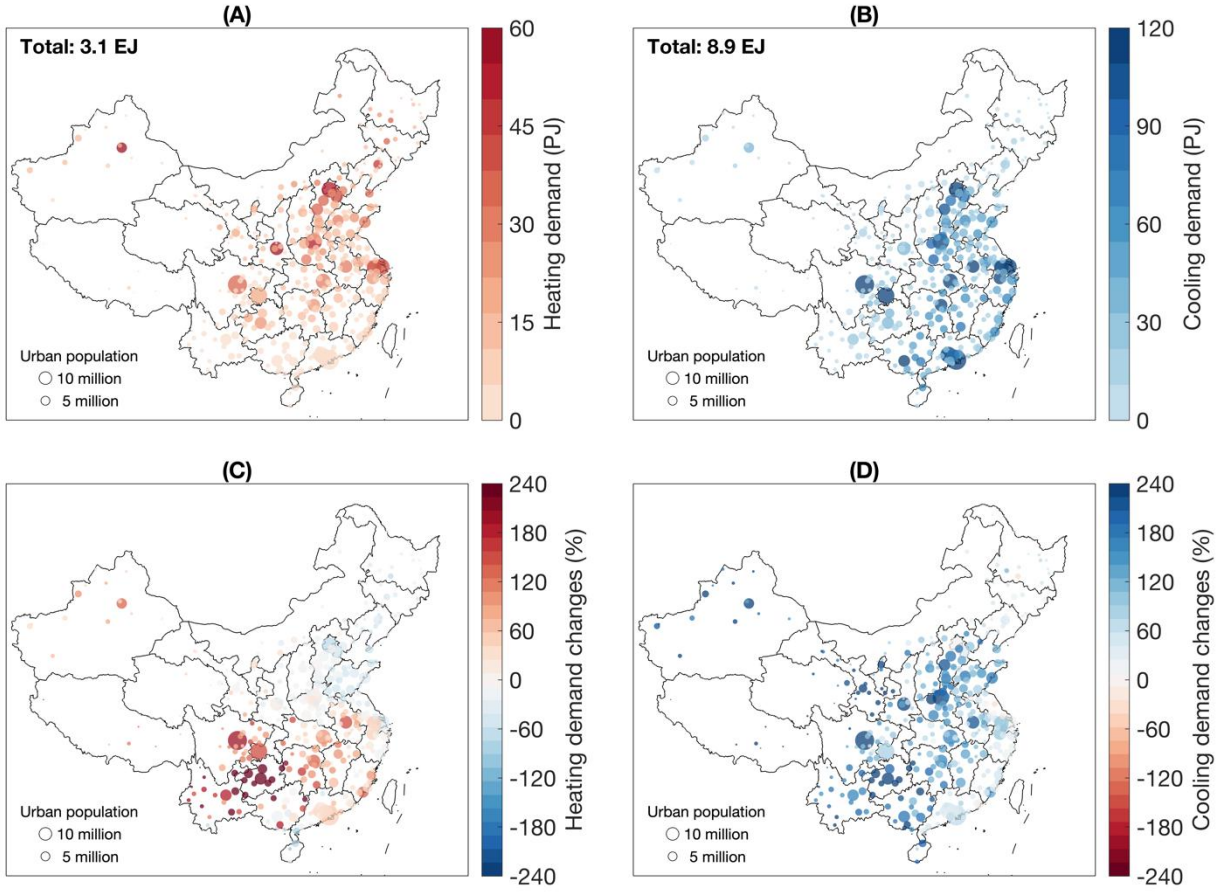


Figure 2. City-level annual building energy service demand in the baseline scenario. (A) Heating demand in 2060. (B) Cooling demand in 2060. (C) Heating demand percentage changes from 2020 to 2060. (D) Cooling demand percentage changes from 2020 to 2060. For (A) and (B), the numbers in the upper left corners indicate national total urban building energy demand. The circle size indicates the population of each city.

We also analyze the temporal changes in urban building energy demand between 2020 and 2060. We find large variations in the trajectories of heating and cooling demand across cities (Figure S9). Most cities in northern China witness significant increases in cooling demand and slight decreases in heating demand from 2020 to 2060, primarily due to a warming climate (Figure 2C). In contrast, we observe considerable increases in both heating and cooling demand in cities

in southern and northwestern China, as a result of larger urban populations and higher thermal comfort requirements (i.e., a transition from "part time, part space" towards "full time, full space" heating/cooling, see Supplementary Note 3) (Figure 2D).

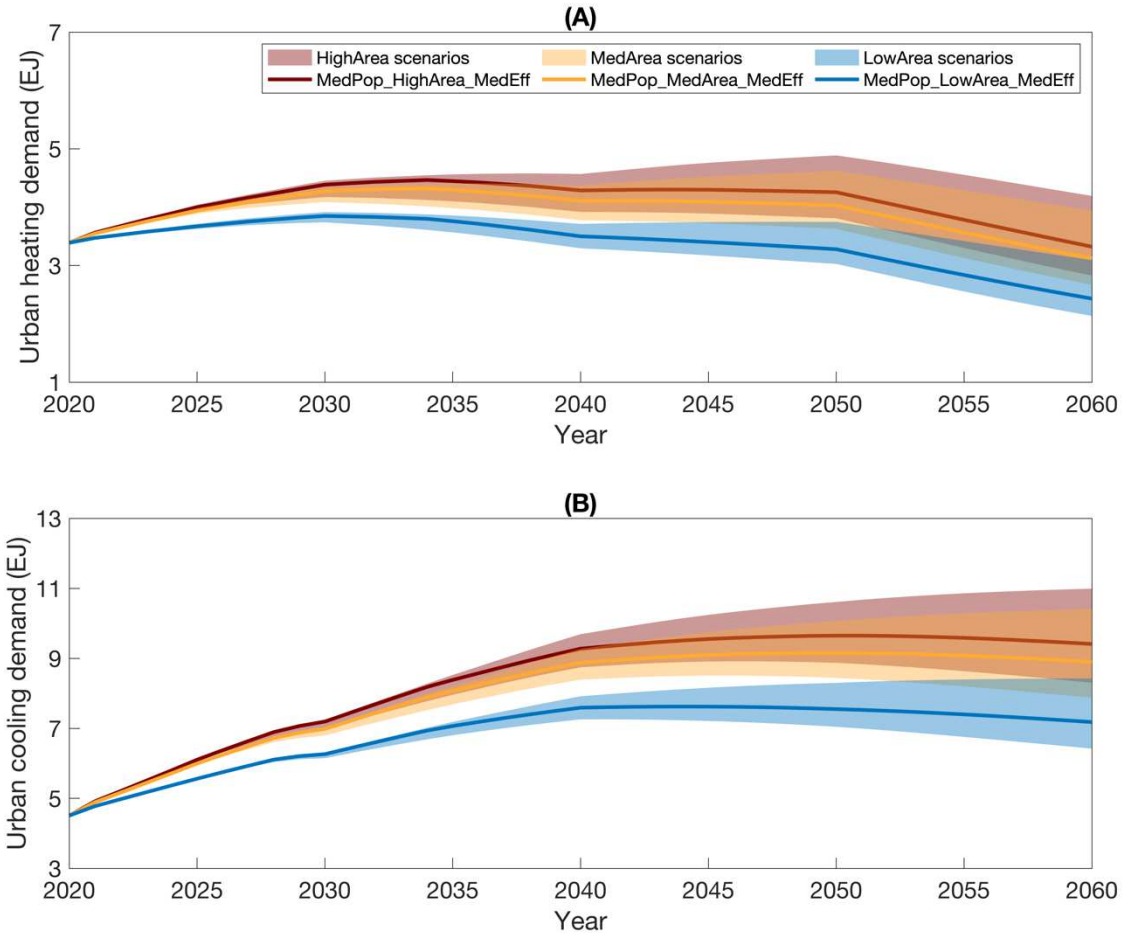


Figure 3. Changes in national urban building energy service demand from 2020 to 2060 in the SSP245 climate under various scenarios of floor area per capita. (A) Heating demand. (B) Cooling demand. The red, yellow, and blue areas show the ranges of energy demand for the HighArea, MedArea, and LowArea scenario ensembles, respectively. Colored curves indicate the trajectories of the central scenarios (scenarios where other variables are set at the baseline level) for each ensemble.

We find great impacts of demand drivers on future changes in China's urban building energy demand. Figure 3, S10, and S11 show the trajectories of national urban heating and cooling demand in the SSP245 climate for scenario ensembles grouped by floor area per capita, population, and building energy efficiency, respectively. In the baseline scenario, while national urban building heating demand slightly decreases from 3.4 EJ to 3.1 EJ between 2020 and 2060, the cooling demand increases by 98% from 4.5 EJ to 8.9 EJ in 2060. These changes result from a combination of evolving climate, building floor area, energy efficiency, energy behaviors, etc. Among various socioeconomic factors, we find that floor area per capita and building energy

efficiency are important drivers of building energy demand pathways. In 2060, compact urban development (LowArea scenario) could reduce national heating (cooling) demand by 22% (19%) compared to the baseline scenario and by 27% (24%) compared to the scenario of uncontrolled floor area growth (HighArea scenario) (Figure 3). Ambitious energy efficiency improvements (HighEff scenario) could also achieve large energy savings, lowering heating (cooling) demand by 8% (4%) from the baseline scenario and by 22% (11%) from the scenario of efficiency stagnation (LowEff scenario) in 2060 (Figure S11). Urban population has relatively smaller impacts, with heating (cooling) demand in the LowPop scenario only 7% (8%) and 12% (14%) lower than the baseline and the HighPop scenario, respectively (Figure S10).

Additionally, we find that future climate change substantially changes the building energy demand trajectories. With the baseline building stock, warming in the SSP245 climate reduces heating energy demand by 24% while increases cooling demand by 27% in 2060, resulting in a net demand increase of 0.94 EJ (8.5%) (Figure 3 and S12). The warming in the SSP585 climate leads to a similar increase in net energy demand of 1.3 EJ (12%), despite much larger changes in demand for heating (-39%) and cooling (+41%) (Figure S13). Our results show that including climate factors is necessary to accurately model future building energy demand and plan for urban energy infrastructure accordingly.

The contributions of various demand drivers to building energy demand show great variations both temporally and geographically. Figure 4 and S14 show changes in national urban residential and non-residential heating and cooling demand attributed to different drivers over time (see Section 4.5). We find that floor area per capita, building energy efficiency, and energy behaviors generally have large impacts in the short term and become relatively less important as time approaches 2060. Changes in urban population sizes lead to demand increases before 2040 and demand decreases afterwards. Climate affects demand in a more complex way, having the largest decreasing effect on heating demand in 2050-2060 and the largest increasing effect on cooling demand in 2030-2040. Moreover, the patterns of demand driver contributions also vary significantly across different cities (Figure S15 and S16), resulting from heterogeneous future changes in these drivers.

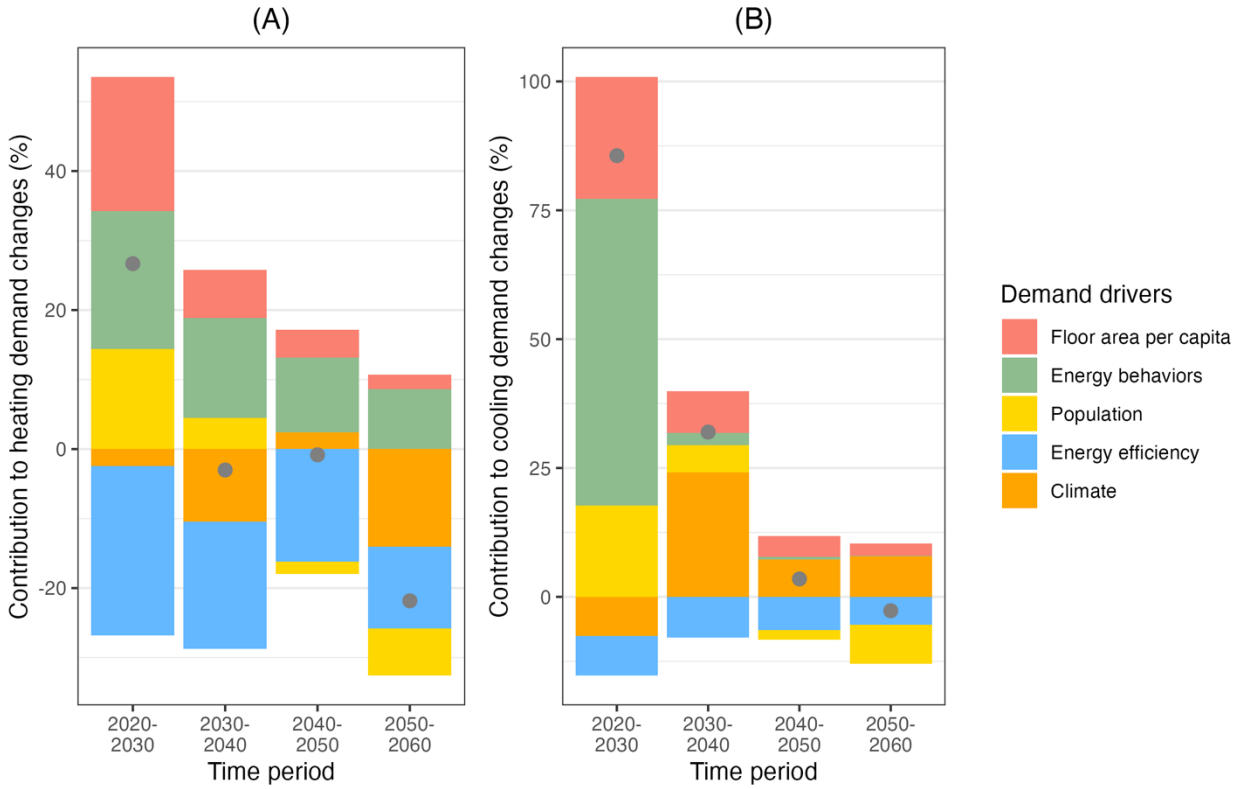


Figure 4. Contributions of various demand drivers to national urban residential building energy service demand from 2020 to 2060 in the baseline scenario. (A) Heating demand changes. (B) Cooling demand changes. The grey dots indicate net changes in energy demand.

3.4 Heterogeneous impacts of policies on cumulative urban building energy demand

We further estimate the cumulative building heating and cooling demand from 2020 to 2060 under various scenarios at the city level. We rank 336 Chinese cities by cumulative demand in the baseline scenario and find that the top 50% of cities are responsible for 83% of national urban building energy demand (Figure S17), with more than 25% of the national demand coming from the top 20 cities. This concentrated pattern of building energy demand indicates the importance of building policy implementations in these high-demand cities to overall demand control.

We evaluate the geographic distribution of cumulative heating and cooling demand reductions via increased efficiency and compact urban development (smaller floor areas). The differences between the ambitious policy and limited policy scenarios of energy efficiency and floor area per capita are shown in Figure 5. We find uneven impacts of these two policies across different cities. Containing floor area growth has a larger impact on both heating and cooling demand in most inland cities than coastal cities. This is because inland cities generally are less developed and have lower floor area per capita than coastal cities in the base year (2020) and hence have more potential for future floor area growth. In contrast, improving building envelope energy

efficiency is more effective in reducing heating demand in northern and southwestern China while more effective in reducing cooling demand in southern China. This pattern arises primarily from differences in local climate and building energy efficiency standards.

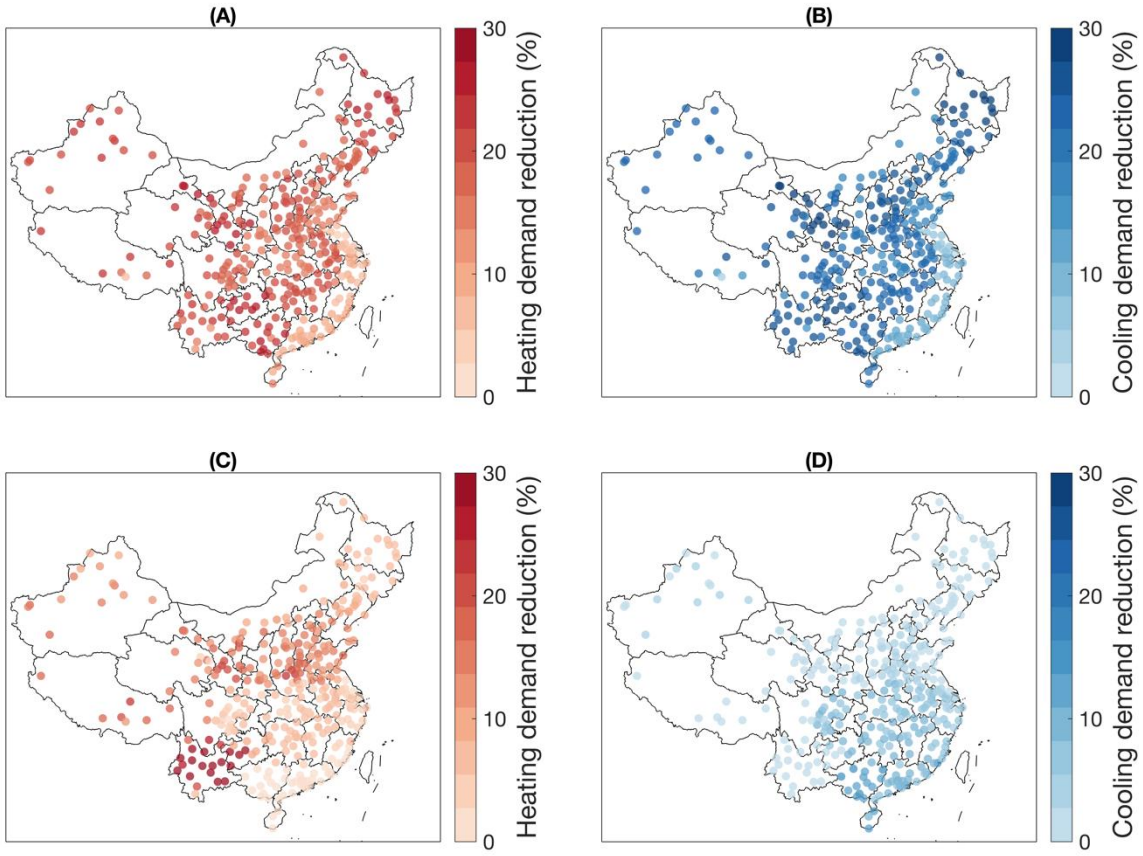


Figure 5. Impacts of (A, B) compact urban development and (C, D) building energy efficiency improvements on cumulative urban building (A, C) heating and (B, D) cooling demand from 2020 to 2060. The impact of compact urban development is defined as the percentage reduction between the MedPop_LowArea_MedEff and MedPop_HighArea_MedEff scenarios, while the impact of building energy efficiency improvements is defined as the percentage reduction between the MedPop_MedArea_HighEff and MedPop_MedArea_LowEff scenarios.

4. Discussion

This study investigates the impacts of various demand drivers on Chinese urban building thermal demand from 2020 to 2060 at the city level. We find that despite a shrinking population, continued urbanization and increasing floor area per capita in the baseline scenario will result in a 15% increase in total urban building floor area from 2020 to 2060. In addition, we find that Chinese urban buildings will have higher cooling demand, lower heating demand, and higher total energy demand (+8.5%) in 2060 due to a warming climate. China has pledged to peak carbon emissions by 2030 and achieve carbon neutrality by 2060. Growing energy demand

449 increases the decarbonization challenge for the urban building sector and jeopardizes these
450 climate goals. Early, effective actions that contain floor area increases and improve building
451 energy efficiency are needed to avoid lock-in of future emissions associated with building
452 heating and cooling, reduce the demand for alternative energy sources, and accelerate the low-
453 carbon transition [55].

454 We demonstrate that building policies have great potential to lower energy demand via reducing
455 building floor area and enhancing building envelope energy efficiency. Ambitious policies on
456 compact urban development and efficiency improvements could reduce heating (cooling)
457 demand by 27% (24%) and 22% (11%) from the conservative policy scenarios in 2060. This
458 result is consistent with the finding of Güneralp et al. (2017) that, in developing countries,
459 promoting higher urban density is generally more effective in reducing building energy
460 consumption than efficiency improvements. Built-up area per capita is widely identified as an
461 important indicator of energy use and carbon emissions at both national and city levels [56,57]. Our
462 analysis suggests that policymakers in China (particularly in fast-growing cities) should seize
463 this opportunity to contain floor area per capita by preventing excessive building construction.
464 However, we also note that the impacts of efficiency improvements may be underestimated,
465 since we only consider the building efficiency standards that are in effect or during the draft
466 stage. If China mandates more stringent efficiency standards before 2060, the resulting demand
467 reductions would be greater.

468 Our results reveal strong inter-city heterogeneity in building stock characteristics, energy
469 intensities, and energy demand, depending on the local patterns of population, floor area, and
470 climate changes. These variations imply that the portfolio of building decarbonization policies
471 should be tailored city by city to match the characteristics of future building energy demand. For
472 instance, for developed cities such as Beijing (Figure S15A, B) with decreasing population and
473 modest future floor area growth, the impacts of compact development might be limited.
474 Improving building energy efficiency could play a significant role in reducing Beijing's heating
475 demand, while policies promoting energy saving practices can be adopted to contain the cooling
476 demand growth. In contrast, for growing cities such as Chengdu (Figure S15E, F), where rising
477 population and expanding floor area continue to drive energy demand, priority should be given
478 to compact development policies (e.g., limiting the construction of large-sized apartments).
479 Meanwhile, we find a highly uneven distribution of building energy demand among cities, with
480 half of the cities responsible for over 80% of energy demand. Targeting these high-demand cities
481 would provide most reductions in energy use and emissions, although eventually buildings from
482 all cities must be addressed to achieve net zero emissions.

483 Our results are subject to the following uncertainties and limitations. First, we analyze energy
484 service demand (demand for heating and cooling) rather than actual energy consumption (use of

electricity, gas, etc.), given the lack of city-level data on heating and cooling technologies. Actual energy consumption of urban buildings will also depend on the technology mix and efficiencies and is assessed in a national-level companion study (Liu et al., manuscript submitted). Second, this study focuses on heating and cooling without accounting for other building energy uses (e.g., lighting, cooking, and appliances). Unlike heating and cooling, other energy demand will not be greatly affected by climate change but is expected to increase as the economy grows. Third, we only model four types of residential buildings and six types of non-residential buildings. In reality, there is a much higher diversity in building characteristics both within and across different cities. Other building types (e.g., data centers) would show different energy demand patterns and could be included by future studies. Fourth, as we take a bottom-up approach by aggregating energy demand of individual buildings, urban climate factors (e.g., the heat island effect) [58] are not included in the modeling. The exclusion of urban heat might result in overestimated heating demand and underestimated cooling demand.

In conclusion, this study indicates that future climate, demographic, and socioeconomic changes lead to large temporal and geographic variations in urban building thermal energy demand in China. Tailored energy infrastructure planning and building policies in individual cities are crucial to cope with this heterogeneity. Our findings suggest great opportunities for Chinese cities to reduce building heating and cooling demand through policy interventions.

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Author Contributions Statement

X.F. and D.L.M. conceived the research idea and designed the study. X.F. led the scenario design, computational experiments, and analyses. S.L. contributed to scenario design and

computational experiments. X.F. and D.L.M. wrote the manuscript with feedback from all authors.

Competing Interests Statement

The authors declare no competing interests.

Data and materials availability

All data sources of this study are listed in the Methods and Supplementary Information. Data for building energy simulations will be made available upon publication of the manuscript. EnergyPlus is an open-source building energy simulation tool available at https://energyplus.net/. The codes that support the findings of this study will be made available upon publication of the manuscript.

References

(1) IEA. *World Energy Outlook 2023*; Paris, 2023. https://www.iea.org/reports/world-energy-outlook-2023 (accessed 2024-03-11).

(2) IPCC. *Climate Change 2022: Mitigation of Climate Change*; Cambridge University Press, 2023; pp 953–1048. https://doi.org/10.1017/9781009157926.011.

(3) *Net Zero by 2050 – Analysis*. IEA. https://www.iea.org/reports/net-zero-by-2050 (accessed 2024-03-12).

(4) Barrett, J.; Pye, S.; Betts-Davies, S.; Broad, O.; Price, J.; Eyre, N.; Anable, J.; Brand, C.; Bennett, G.; Carr-Whitworth, R.; Garvey, A.; Giesekam, J.; Marsden, G.; Norman, J.; Oreszczyn, T.; Ruyssevelt, P.; Scott, K. Energy Demand Reduction Options for Meeting National Zero-Emission Targets in the United Kingdom. *Nat Energy* **2022**, *7* (8), 726–735. https://doi.org/10.1038/s41560-022-01057-y.

(5) Creutzig, F.; Niamir, L.; Bai, X.; Callaghan, M.; Cullen, J.; Díaz-José, J.; Figueroa, M.; Grubler, A.; Lamb, W. F.; Leip, A.; Masanet, E.; Mata, É.; Mattauch, L.; Minx, J. C.; Mirasgedis, S.; Mulugetta, Y.; Nugroho, S. B.; Pathak, M.; Perkins, P.; Roy, J.; de la Rue du Can, S.; Saheb, Y.; Some, S.; Steg, L.; Steinberger, J.; Ürge-Vorsatz, D. Demand-Side Solutions to Climate Change Mitigation Consistent with High Levels of Well-Being. *Nat. Clim. Chang.* **2021**, 1–11. https://doi.org/10.1038/s41558-021-01219-y.

(6) Langevin, J.; Satre-Meloy, A.; Satchwell, A. J.; Hledik, R.; Olszewski, J.; Peters, K.; Chandra-Putra, H. Demand-Side Solutions in the US Building Sector Could Achieve Deep Emissions Reductions and Avoid over $100 Billion in Power Sector Costs. *One Earth* **2023**, *6* (8), 1005–1031. https://doi.org/10.1016/j.oneear.2023.07.008.

(7) Ang, Y. Q.; Berzolla, Z. M.; Letellier-Duchesne, S.; Reinhart, C. F. Carbon Reduction Technology Pathways for Existing Buildings in Eight Cities. *Nat Commun* **2023**, *14* (1), 1689. https://doi.org/10.1038/s41467-023-37131-6.

(8) van Heerden, R.; Edelenbosch, O. Y.; Daioglou, V.; Le Gallic, T.; Baptista, L. B.; Di Bella, A.; Colelli, F. P.; Emmerling, J.; Fragkos, P.; Hasse, R.; Hoppe, J.; Kishimoto, P.; Leblanc, F.; Lefèvre, J.; Luderer, G.; Marangoni, G.; Mastrucci, A.; Pettifor, H.; Pietzcker, R.; Rochedo, P.; van Ruijven, B.; Schaeffer, R.; Wilson, C.; Yeh, S.; Zisarou, E.; van Vuuren, D. Demand-Side Strategies Enable Rapid and Deep Cuts in Buildings and Transport Emissions to 2050. *Nat Energy* **2025**, *10* (3), 380–394. https://doi.org/10.1038/s41560-025-01703-1.

(9) You, K.; Li, Y.; Cai, W.; Zhang, L.; Liu, Z.; Feng, W.; Wei, Y.-M. Mitigating Emissions and Costs through Demand-Side Solutions in Chinese Residential Buildings. *Nat Commun* **2025**, *16* (1), 7358. https://doi.org/10.1038/s41467-025-62675-0.

(10) Berrill, P.; Wilson, E. J. H.; Reyna, J. L.; Fontanini, A. D.; Hertwich, E. G. Decarbonization Pathways for the Residential Sector in the United States. *Nat. Clim. Chang.* **2022**, *12* (8), 712–718. https://doi.org/10.1038/s41558-022-01429-y.

(11) Zhou, N.; Khanna, N.; Feng, W.; Ke, J.; Levine, M. Scenarios of Energy Efficiency and CO2 Emissions Reduction Potential in the Buildings Sector in China to Year 2050. *Nat Energy* **2018**, *3* (11), 978–984. https://doi.org/10.1038/s41560-018-0253-6.

(12) Langevin, J.; Harris, C. B.; Reyna, J. L. Assessing the Potential to Reduce U.S. Building CO2 Emissions 80% by 2050. *Joule* **2019**, *3* (10), 2403–2424. https://doi.org/10.1016/j.joule.2019.07.013.

(13) Levesque, A.; Pietzcker, R.; Baumstark, L.; Luderer, G. Deep Decarbonisation of Buildings Energy Services through Demand and Supply Transformations in a 1.5°C Scenario. *Environmental Research Letters* **2021**, *16*. https://doi.org/10.1088/1748-9326/abdf07.
(14) Camarasa, C.; Mata, É.; Navarro, J. P. J.; Reyna, J.; Bezerra, P.; Angelkorte, G. B.; Feng, W.; Filippidou, F.; Forthuber, S.; Harris, C.; Sandberg, N. H.; Ignatiadou, S.; Kranzl, L.; Langevin, J.; Liu, X.; Müller, A.; Soria, R.; Villamar, D.; Dias, G. P.; Wanemark, J.; Yaramenka, K. A Global Comparison of Building Decarbonization Scenarios by 2050 towards 1.5–2 °C Targets. *Nat Commun* **2022**, *13* (1), 3077. https://doi.org/10.1038/s41467-022-29890-5.
(15) Goldstein, B.; Gounaridis, D.; Newell, J. P. The Carbon Footprint of Household Energy Use in the United States. *PNAS* **2020**, *117* (32), 19122–19130. https://doi.org/10.1073/pnas.1922205117.
(16) Garimella, S.; Lockyear, K.; Pharis, D.; El Chawa, O.; Hughes, M. T.; Kini, G. Realistic Pathways to Decarbonization of Building Energy Systems. *Joule* **2022**, *6* (5), 956–971. https://doi.org/10.1016/j.joule.2022.04.003.
(17) Xiong, J.; Guo, S.; Wu, Y.; Yan, D.; Xiao, C.; Lu, X. Predicting the Response of Heating and Cooling Demands of Residential Buildings with Various Thermal Performances in China to Climate Change. *Energy* **2023**, *269*, 126789. https://doi.org/10.1016/j.energy.2023.126789.
(18) Wang, C.; Song, J.; Shi, D.; Reyna, J. L.; Horsey, H.; Feron, S.; Zhou, Y.; Ouyang, Z.; Li, Y.; Jackson, R. B. Impacts of Climate Change, Population Growth, and Power Sector Decarbonization on Urban Building Energy Use. *Nat Commun* **2023**, *14* (1), 6434. https://doi.org/10.1038/s41467-023-41458-5.
(19) Zhou, Y.; Clarke, L.; Eom, J.; Kyle, P.; Patel, P.; Kim, S. H.; Dirks, J.; Jensen, E.; Liu, Y.; Rice, J.; Schmidt, L.; Seiple, T. Modeling the Effect of Climate Change on U.S. State-Level Buildings Energy Demands in an Integrated Assessment Framework. *Applied Energy* **2014**, *113*, 1077–1088. https://doi.org/10.1016/j.apenergy.2013.08.034.
(20) Ellsworth-Krebs, K. Implications of Declining Household Sizes and Expectations of Home Comfort for Domestic Energy Demand. *Nat Energy* **2020**, *5* (1), 20–25. https://doi.org/10.1038/s41560-019-0512-1.
(21) Han, X.; Wei, C.; Cao, G.-Y. Aging, Generational Shifts, and Energy Consumption in Urban China. *Proceedings of the National Academy of Sciences* **2022**, *119* (37), e2210853119. https://doi.org/10.1073/pnas.2210853119.
(22) Wang, C.; Song, J.; Shi, D.; Reyna, J. L.; Horsey, H.; Feron, S.; Zhou, Y.; Ouyang, Z.; Li, Y.; Jackson, R. B. Impacts of Climate Change, Population Growth, and Power Sector Decarbonization on Urban Building Energy Use. *Nat Commun* **2023**, *14* (1), 6434. https://doi.org/10.1038/s41467-023-41458-5.
(23) Reyna, J. L.; Chester, M. V. Energy Efficiency to Reduce Residential Electricity and Natural Gas Use under Climate Change. *Nat Commun* **2017**, *8* (1), 14916. https://doi.org/10.1038/ncomms14916.
(24) Gillingham, K. T.; Huang, P.; Buehler, C.; Peccia, J.; Gentner, D. R. The Climate and Health Benefits from Intensive Building Energy Efficiency Improvements. *Science Advances* **2021**, *7* (34), eabg0947. https://doi.org/10.1126/sciadv.abg0947.

(25) Güneralp, B.; Zhou, Y.; Ürge-Vorsatz, D.; Gupta, M.; Yu, S.; Patel, P. L.; Fragkias, M.; Li, X.; Seto, K. C. Global Scenarios of Urban Density and Its Impacts on Building Energy Use through 2050. *PNAS* **2017**. https://doi.org/10.1073/pnas.1606035114.
(26) Hu, S.; Jiang, Y.; Yan, D. *China Building Energy Use and Carbon Emission Yearbook 2021: A Roadmap to Carbon Neutrality by 2060*; Springer Nature: Singapore, 2022. https://doi.org/10.1007/978-981-16-7578-2.
(27) IEA. *Partner Country Series - Energy Use in the Chinese Building Sector*; IEA: Paris, 2015. https://www.iea.org/reports/partner-country-series-energy-use-in-the-chinese-building-sector.
(28) Zhang, S.; Zhao, M.; Liu, Z.; Yang, F.; Lu, B.; Zhao, Z.; Gu, K.; Zhang, S.; Lei, M.; Zhang, C.; Wang, C.; Cai, W. City-Level Population Projection for China under Different Pathways from 2010 to 2100. *Sci Data* **2023**, *10* (1), 809. https://doi.org/10.1038/s41597-023-02735-6.
(29) Chen, Y.; Guo, F.; Wang, J.; Cai, W.; Wang, C.; Wang, K. Provincial and Gridded Population Projection for China under Shared Socioeconomic Pathways from 2010 to 2100. *Sci Data* **2020**, *7* (1), 83. https://doi.org/10.1038/s41597-020-0421-y.
(30) Xing, R.; Hanaoka, T.; Masui, T. Deep Decarbonization Pathways in the Building Sector: China's NDC and the Paris Agreement. *Environ. Res. Lett.* **2021**, *16* (4), 044054. https://doi.org/10.1088/1748-9326/abe008.
(31) Guo, S.; Yan, D.; Hu, S.; Zhang, Y. Modelling Building Energy Consumption in China under Different Future Scenarios. *Energy* **2021**, *214*, 119063. https://doi.org/10.1016/j.energy.2020.119063.
(32) Huo, T.; Ma, Y.; Xu, L.; Feng, W.; Cai, W. Carbon Emissions in China's Urban Residential Building Sector through 2060: A Dynamic Scenario Simulation. *Energy* **2022**, *254*, 124395. https://doi.org/10.1016/j.energy.2022.124395.
(33) Yang, T.; Pan, Y.; Yang, Y.; Lin, M.; Qin, B.; Xu, P.; Huang, Z. CO2 Emissions in China's Building Sector through 2050: A Scenario Analysis Based on a Bottom-up Model. *Energy* **2017**, *128*, 208–223. https://doi.org/10.1016/j.energy.2017.03.098.
(34) Xu, G.; Wang, W. China's Energy Consumption in Construction and Building Sectors: An Outlook to 2100. *Energy* **2020**, *195*, 117045. https://doi.org/10.1016/j.energy.2020.117045.
(35) Tan, X.; Lai, H.; Gu, B.; Zeng, Y.; Li, H. Carbon Emission and Abatement Potential Outlook in China's Building Sector through 2050. *Energy Policy* **2018**, *118*, 429–439. https://doi.org/10.1016/j.enpol.2018.03.072.
(36) Shi, J.; Chen, W.; Yin, X. Modelling Building's Decarbonization with Application of China TIMES Model. *Applied Energy* **2016**, *162*, 1303–1312. https://doi.org/10.1016/j.apenergy.2015.06.056.
(37) Chen, H.; Yang, L.; Chen, W. Modelling National, Provincial and City-Level Low-Carbon Energy Transformation Pathways. *Energy Policy* **2020**, *137*, 111096. https://doi.org/10.1016/j.enpol.2019.111096.
(38) Huo, T.; Xu, L.; Feng, W.; Cai, W.; Liu, B. Dynamic Scenario Simulations of Carbon Emission Peak in China's City-Scale Urban Residential Building Sector through 2050. *Energy Policy* **2021**, *159*, 112612. https://doi.org/10.1016/j.enpol.2021.112612.

(39) IEA. *An Energy Sector Roadmap to Carbon Neutrality in China*; IEA: Paris, 2021. https://www.iea.org/reports/an-energy-sector-roadmap-to-carbon-neutrality-in-china (accessed 2025-06-26).
(40) Maryland, C. for G. S. at U. of; University, D. of E. S. S. at T.; University, C. of E. S. and E. at P. Umd-Cgs/Gcam-China: Gcam-China-V6, 2024. https://doi.org/10.5281/zenodo.10819115.
(41) Pan, L.; Zhu, M.; Lang, N.; Huo, T. What Is the Amount of China's Building Floor Space from 1996 to 2014? *Int J Environ Res Public Health* **2020**, *17* (16), 5967. https://doi.org/10.3390/ijerph17165967.
(42) Li, X.; Song, L.; Liu, Q.; Ouyang, X.; Mao, T.; Lu, H.; Liu, L.; Liu, X.; Chen, W.; Liu, G. Product, Building, and Infrastructure Material Stocks Dataset for 337 Chinese Cities between 1978 and 2020. *Sci Data* **2023**, *10* (1), 228. https://doi.org/10.1038/s41597-023-02143-w.
(43) Gan, L. *2017 Analysis on China's Urban Housing Vacancy Rate*; Survey and Research Center for China Household Finance, 2018. https://chfs.swufe.edu.cn/__local/D/65/2B/57D2F2A832F77C8F3C1DDC4926E_ADF9EA0C_121D6C.pdf.
(44) Beike Research Institute. *2022 Survey on Housing Vacancy Rates in Major Cities of China*; Beike Research Institute, 2022.
(45) Zheng, H.; Zhang, R.; Yin, X.; Wu, J. Unused Housing in Urban China and Its Carbon Emission Impact. *Nat Commun* **2025**, *16* (1), 1985. https://doi.org/10.1038/s41467-025-57217-7.
(46) Hong, L.; Zhou, N.; Feng, W.; Khanna, N.; Fridley, D.; Zhao, Y.; Sandholt, K. Building Stock Dynamics and Its Impacts on Materials and Energy Demand in China. *Energy Policy* **2016**, *94*, 47–55. https://doi.org/10.1016/j.enpol.2016.03.024.
(47) Cao, Z.; Liu, G.; Duan, H.; Xi, F.; Liu, G.; Yang, W. Unravelling the Mystery of Chinese Building Lifetime: A Calibration and Verification Based on Dynamic Material Flow Analysis. *Applied Energy* **2019**, *238*, 442–452. https://doi.org/10.1016/j.apenergy.2019.01.106.
(48) Zhang, S.; Ma, M.; Zhou, N.; Yan, J.; Feng, W.; Yan, R.; You, K.; Zhang, J.; Ke, J. Estimation of Global Building Stocks by 2070: Unlocking Renovation Potential. *Nexus* **2024**, *1* (3). https://doi.org/10.1016/j.ynexs.2024.100019.
(49) Xu, Z.; Han, Y.; Tam, C.-Y.; Yang, Z.-L.; Fu, C. Bias-Corrected CMIP6 Global Dataset for Dynamical Downscaling of the Earth's Historical and Future Climate (1979–2100), 2021. https://doi.org/10.11922/sciencedb.00487.
(50) Xin, X.; Wu, T.; Shi, X.; Zhang, F.; Li, J.; Chu, M.; Liu, Q.; Yan, J.; Ma, Q.; Wei, M. BCC BCC-CSM2MR Model Output Prepared for CMIP6 ScenarioMIP, 2019. https://doi.org/10.22033/ESGF/CMIP6.3030.
(51) Vignola, F.; Michalsky, J.; Stoffel, T. *Solar and Infrared Radiation Measurements*; CRC Press, 2017.
(52) Johari, F.; Peronato, G.; Sadeghian, P.; Zhao, X.; Widén, J. Urban Building Energy Modeling: State of the Art and Future Prospects. *Renewable and Sustainable Energy Reviews* **2020**, *128*, 109902. https://doi.org/10.1016/j.rser.2020.109902.
(53) Gui, C.; Yan, D.; Guo, S.; An, J. Development of Prototype Building Model in Beijing Based on Actual Energy Consumption; 2020; pp 1187–1196. https://doi.org/10.1007/978-981-13-9528-4_120.

(54) Yang, L.; Zhao, S.; Zhai, Y.; Gao, S.; Wang, F.; Lian, Z.; Duanmu, L.; Zhang, Y.; Zhou, X.; Cao, B.; Wang, Z.; Yan, H.; Zhang, H.; Arens, E.; de Dear, R. The Chinese Thermal Comfort Dataset. *Sci Data* **2023**, *10* (1), 662. https://doi.org/10.1038/s41597-023-02568-3.
(55) Liu, S.; Guo, Y.; Wagner, F.; Liu, H.; Cui, R. Y.; Mauzerall, D. L. Diversifying Heat Sources in China's Urban District Heating Systems Will Reduce Risk of Carbon Lock-In. *Nat Energy* **2024**, *9* (8), 1021–1031. https://doi.org/10.1038/s41560-024-01560-4.
(56) Creutzig, F.; Baiocchi, G.; Bierkandt, R.; Pichler, P.-P.; Seto, K. C. Global Typology of Urban Energy Use and Potentials for an Urbanization Mitigation Wedge. *PNAS* **2015**, *112* (20), 6283–6288. https://doi.org/10.1073/pnas.1315545112.
(57) Haberl, H.; Löw, M.; Perez-Laborda, A.; Matej, S.; Plank, B.; Wiedenhofer, D.; Creutzig, F.; Erb, K.-H.; Duro, J. A. Built Structures Influence Patterns of Energy Demand and CO2 Emissions across Countries. *Nat Commun* **2023**, *14* (1), 3898. https://doi.org/10.1038/s41467-023-39728-3.
(58) Perera, A. T. D.; Javanroodi, K.; Mauree, D.; Nik, V. M.; Florio, P.; Hong, T.; Chen, D. Challenges Resulting from Urban Density and Climate Change for the EU Energy Transition. *Nat Energy* **2023**, *8* (4), 397–412. https://doi.org/10.1038/s41560-023-01232-9.