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Toward sustainable heating: Assessment of the carbon mitigation potential from residential heating in northern rural China

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ABSTRACT

Reducing carbon emissions from residential heating has become a global priority due to the urgency of mitigating climate change. In rural areas, there is a tension between the heavy reliance on traditional energy and the necessity for revitalization. Therefore, conducting a comprehensive assessment of heating energy consumption and carbon reduction potential is crucial. This study utilized a bottom-up statistical model to examine energy dynamics in northern rural China based on large-scale household surveys (n = 6150 rural households from 15 provinces) conducted between 2012 and 2017. Heating energy consumption was estimated to reach 175–275 Mtce in 2030 and 137–245 Mtce in 2050, and related carbon emissions were 466–736 million tons and 318–574 million tons, respectively. Furthermore, by implementing solid policies, including improving poorly installed building envelopes, enhancing renewable energy, promoting heat pumps adoption, and encouraging occupants' green behavior, carbon emissions can be reduced by 41.2%–76.2%. This study's findings offer governments valuable insights into strategies for reducing carbon emissions.

1. Introduction

Heating is essential for residents in regions with cold winters, especially with the increasing frequency of extreme weather events. People enjoy higher indoor temperature comfort as societies experience robust and sustained economic growth. This is marked by prolonged usage of heating equipment in multiple rooms and the adoption of higher-capacity heating systems (Gertler et al., 2016; Xiao et al., 2015). In recent years, there has been a significant increase in heating energy consumption, which poses a major challenge to achieving carbon-zero objectives. In 2020, buildings in China consumed 2.27 billion tons of standard coal equivalent (tce), accounting for 45.5% of China's total energy usage. Heating is responsible for the largest proportion (approximately 46%) of total final energy use in the building sector. In 2016, residential heating alone consumed 412 million tons of standard coal equivalent (Mtce) of commercial energy and 36.9 Mtce of biomass (BERC of Tsinghua University, 2019). Residential heating in China has led to severe air pollution in winter. This is because about 83% of the heating area relies on coal, and in 2016, approximately 200 Mtce of scattered coal was consumed, most of which was burned in rural areas (NDRC, 2017). Xiao et al. (2015) have highlighted a direct link between winter heating and increased $PM_{2.5}$ levels in over three-quarters of Central and Eastern China. According to Archer-Nicholls et al. (2016), residential heating and cooking combustion emissions account for 15.5–17.8% of premature deaths in China.

The Chinese government has implemented high energy-efficiency standards and provided preferential support to the heating industry, recognizing its significant impact. An example is the Clean Heating Plan in northern China, which has been in place with substantial subsidies and mandatory measures (Wang and Xie, 2023). Additionally, the government has issued multiple action plans that include heat pumps to decarbonize heating systems (MHURD, 2022). The residential heating sector has been transitioning towards electricity and natural gas, focusing on cleaner and more efficient energy. However, studies have shown that this transition may lead to energy poverty due to the higher cost of clean energy, particularly in rural areas (Wang et al., 2023a; Xie et al., 2022). This highlights the delicate balance between achieving carbon neutrality and promoting rural revitalization. Therefore, it is essential to have a comprehensive understanding of heating energy demand, carbon emissions, and potential energy transition pathways. However, this field of research is largely unexplored in the literature.

Heating systems in urban and rural areas of China differ significantly. Urban areas primarily use district heating, while rural areas rely on individual heating. These systems vary in techniques, accounting

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methods, and solutions. Urban district heating has been studied more extensively regarding energy consumption, carbon and pollution emissions, demand projection, and clean energy transition (IEA, 2017, 2023a; Lin and Lin, 2017; Lin and Lin, 2016, 2020). However, studies on rural heating face several challenges. First, the heating methods and entities are diverse and complex. Although rural areas occupy 62.13% of China's land, they are home to only 34.78% of the total population (NBS, 2023; NBS, 2021b). Rural heating tools include Kang, hot walls, stoves, electric heaters, heat pumps, and air conditioners (Zhu et al., 2020). Rural heating relies on various fuels, including dung, straw, wood, and coal. The measurements used to quantify these fuels are diverse, including baskets, hand carts, and piles.

Second, data on heating energy consumption in rural households is limited. Although there have been some national household energy consumption statistics, data from different sources could be more consistent. For instance, in 2016, the National Development and Reform Commission reported that approximately 200 Mtce of scattered coal was consumed for heating in northern rural China, while the National Bureau of Statistics indicated that coal consumption in rural areas was about 60 Mtce (NBS, 2017; NDRC, 2017). Some studies have also raised concerns about the accuracy of initial estimates of residential energy consumption, as they need to account for unreported and non-commercial energy. The use of biomass energy in rural areas decreased from around 59% in 2014 to approximately 10% in 2017. However, its significance has remained unchanged (Wu et al., 2020; Zheng and Wei, 2019). Despite its significant role in powering rural households, biomass energy is not included in the China Energy Statistical Yearbook (Wang et al., 2023b). Due to data limitations, most research relies on small-scale questionnaire surveys to study residential energy issues.

A comprehensive understanding of rural dynamics is necessary for policymakers' revitalization and carbon neutrality endeavors. Third, our understanding of future carbon emissions from rural heating and the carbon mitigation potential of solid policies remains limited (Deroubaix et al., 2021; Hu et al., 2016; Waite et al., 2017). Urbanization drives depopulation in rural areas, resulting in fewer people relying on individual heating. However, income growth concurrently increases thermal comfort. The trends in total heating energy demand in rural areas under these dynamic conditions are poorly understood. Additionally, the article lacks information on potential energy conservation and carbon reduction disparities that may arise from implementing robust policies such as promoting building envelopes, energy transitions, and changing occupant behavior (Xie et al., 2023).

To address these challenges, we utilized a unique large-scale national household survey to assess individual heating energy needs and potential transition scenarios, taking into account variations in climate, population growth, urbanization, and income growth. This study makes several contributions to the existing literature. We compiled a comprehensive household energy consumption dataset for rural China from 2012 to 2017, encompassing data from 6150 rural households across 15 provinces. This dataset revealed important patterns and characteristics of rural heating, providing information on energy types, consumption quantities, households demographics, and dwelling characteristics. Additionally, we employed a bottom-up statistical model to estimate heating energy consumption and associated carbon emissions in rural China. This task is pivotal for rural revitalization efforts and the pursuit of carbon neutrality. Furthermore, we explored the carbon mitigation potential under various policy scenarios projected to 2050, providing policymakers with comprehensive insights into strategies for reducing heating-related carbon emissions in rural China.

Three major findings of this paper are: (1) The average heating energy demand per household is approximately 1239 kgce, varying significantly based on household characteristics, the energy sources used for heating, and heating degree days (HDDs). (2) Heating energy consumption is projected to range from 175 to 275 Mtce in 2030 and 137–245 Mtce in 2050, with associated carbon emissions estimated at 466–736 million tons and 318–574 million tons, respectively. These projections are subject to uncertainties arising from unknown trends in income, population, and climate change. (3) Strategic policies such as improving building envelopes, transitioning toward renewable energy sources, promoting heat pumps, and fostering a green lifestyle demonstrate remarkable potential for carbon emission reduction. These measures could lead to significant reductions of approximately 50–78 million tons, 50–76 million tons, 25–77 million tons, and 18–34 million tons, respectively, by 2050, equivalent to 41.2%–76.2% of total heating-related carbon emissions.

2. Literature review

Multiple models have been used for energy simulation and prediction, often categorized into two overarching approaches: top-down and bottom-up (Reyna and Chester, 2017; Swan and Ugursal, 2009). The top-down approach does not consider individual end-uses. It typically associates historical aggregate energy consumption with long-term changes such as macroeconomic indicators, energy prices, general climate, and housing construction/demolition rates (Isaac and van Vuuren, 2009). For example, Saha and Stephenson (1980) developed a national residential energy model for New Zealand. Their model determined the annual energy consumption of each fuel used to support each end-use group as a function of stock, ownership, and appliance ratings and use. Lin and Lin (2017) projected China's heating energy demand by establishing a time-series relationship between total demand and gross domestic product (GDP), population density, heating area, and energy prices. However, the model does not differentiate between district and individual heating or rural and urban areas, leading to notable biases. Their estimate of 136.24 Mtce for 2015 diverged significantly from the actual 448.9 Mtce recorded in 2016 (BERC of Tsinghua University, 2019). This approach has strengths in its accessibility to abundant data, simplicity of the model, and capacity to estimate national and global energy supply requirements. However, the accuracy of historical trends diminishes when they intersect with disruptions such as economic depressions, rapid population growth, or transformative technological advancements (Hsu, 2015). Additionally, this approach overlooks vital micro-level factors that significantly influence energy consumption, hindering the precise identification of areas for improving energy use's physical and behavioral drivers.

Conversely, the bottom-up method, which includes engineering and statistical models, establishes connections between energy consumption and specific end-uses. It then extrapolates the entire building sector by aggregating representatives (Swan and Ugursal, 2009). A comprehensive engineering model can be as detailed as a complete thermodynamic and heat transfer analysis on all end-uses within the residential sector (Zhao and Magoulès, 2012). Various software tools have been developed to evaluate energy efficiency, renewable energy, and sustainable transformation. The U.S. Department of Energy maintains an updated list of simulation tools (EERE, 2011). However, these tools require detailed input data, expert work, and powerful informatics equipment. Therefore, a large body of literature turns to simple statistical models, which have been proven accurate (Caldera et al., 2008; Catalina et al., 2013). The bottom-up model has a distinct advantage in considering household characteristics and the impact of occupant behavior. This allows for investigating areas where energy savings may be possible (Hu et al., 2016).

In estimating and predicting residential heating energy demand, significant attention has been directed toward centralized district heating in urban areas (Caldera et al., 2008; Han et al., 2022; Hu et al., 2016; Lin and Lin, 2017; Waite et al., 2017) and national-level assessments (Ahern and Norton, 2015; Deroubaix et al., 2021; Gi et al., 2016; Leurent et al., 2018; Wahlström and Hårsman, 2015). For example, Gi et al. (2016) employed a statistical model to evaluate global heating demand until 2050 under various climate change scenarios. Their approach involved constructing a sigmoid function to represent energy demand correlated with GDP, HDDs, and cooling degree days. Hu et al. (2016) utilized a DeST engineering model to evaluate space heating energy consumption in urban residential areas in China's hot summer and cold winter areas until 2030. They incorporated influencing factors such as climate zones, house area, house age, occupant behavior, and equipment characteristics. Ma et al. (2021) distinguished between district heating in urban areas and individual heating in rural areas. Nevertheless, this study employed data on assumed heating demand from the Standard for Energy Consumption of Buildings, which falls short of precision.

The roadmap for optimizing energy systems emphasizes the significance of balancing energy supply with consumer demand to enhance efficiency and sustainability. Technical solutions on the supply side include improving thermal efficiency, reducing heat loss, harnessing energy recovery mechanisms, and selecting optimal heating methods for different climate zones (Xiong et al., 2015; Zhou et al., 2018a). For example, Xiong et al. (2015) showed that implementing a new heat strategy, which involves utilizing industrial heat surplus, transitioning from coal stoves to combined heat and power (CHP) systems, and reforming energy meter systems, could reduce the primary energy supply for district heating in China by over 50%. On the demand side, research has primarily focused on behavioral shifts, such as adopting high-efficiency technologies and modern energy sources and changes in response to interventions and policies (IEA, 2021). According to Wang and Xie (2023), over 60% of households participated in the clean heating energy transition program, resulting in an 80% reduction in coal consumption.

In summary, the mitigation strategy focuses on estimating and predicting heating energy consumption and potential energy and carbon reduction scenarios. Previous studies have limitations. First, there is a lack of literature evaluating future heating demand in rural China. Second, although current heating systems are unsustainable, a clear development strategy for individual heating systems remains elusive. The current approach to achieving cleaner, low-carbon heating focuses on advanced district heating and CHP systems. However, it does not adequately address the role of individual heating in economically challenged rural areas (Connolly et al., 2014).

3. Data and methodology

This study aims to estimate energy consumption and carbon emissions from residential space heating in rural areas predominantly using individual heating systems. We analyzed micro-level survey data on household heating energy consumption and identified the factors influencing it. Then, we developed a bottom-up statistical model to predict heating energy demand and assessed carbon mitigation potentials under various transition scenarios.

3.1. Household surveys and heating energy consumption

The data used in this study was obtained from samples collected in the Chinese Residential Energy Consumption Survey (CRECS), conducted by Renmin University of China since 2012. Detailed information and data support for CRECS are provided through the shared online platform (http://CRECS.ruc.edu.cn). The survey employed the three-layer Proportionate to Population Size (PPS) sampling method, which was introduced and used in the Chinese General Social Survey (CGSS, 2003). This database contains comprehensive information on household social demographics, dwelling characteristics, and energy-utilizing equipment and usage, gathered through face-to-face interviews. The device-based energy consumption accounting method is described in the *Household Energy Consumption in China: 2016 report* (Zheng and Wei, 2019).

This study utilizes a six-year combined sample from 2012 to 2017, focusing exclusively on rural heating energy consumption in China's northern provinces. The total sample consists of 6150 households across 15 provinces, with Appendix Fig. 1 illustrating their geographical distribution. Most provinces have approximately 200–500 observations, while Hebei and Beijing have more than 1000 observations due to targeted surveys conducted in 2016 and 2017 for the Clean Heating Plan in these two provinces. It important to note that although the data is not evenly distributed among provinces, this impact is minimized by including important social demographics, controlling both spatial and temporal dummies, and conducting the analysis and projection at the provincial level. Furthermore, robustness analysis excluding samples from Hebei and Beijing will also be presented.

The average heating energy demand per household in each province is depicted in Fig. 1. It shows that western provinces consume more energy than eastern areas, and northern provinces consume more energy than southern provinces. While cold winter weather plays a role, the predominant factor is likely combustion efficiency—achieving the same heating service may require more biomass or low-quality energy than higher-quality alternatives. A gradual increase is observed when comparing heating energy consumption within the same province, possibly linked to income growth. On average, winter heating energy consumption per household in rural northern areas during 2012–2017 was 910.8 standard kilogram of coal equivalent (kgce), 1074.3 kgce, 1059 kgce, 1250.7 kgce, 1391 kgce, and 1381.4 kgce, respectively.

3.2. Modeling heating energy demand

A model was developed to estimate northern China's total heating energy consumption and carbon emissions. Research has shown that when analyzing household heating energy, the per-household energy intensity indicator is superior to the per-floor area indicator. This is because owning and operating heating equipment are specific to individual families (Hu et al., 2016; Peng et al., 2015). Therefore, the total heating energy demand in northern rural China is calculated using Eq. (1) as referenced in Hu et al. (2016):

$$E_{rural} = HH * \sum\nolimits_{p=1}^{n} \left(I_p * D_p\right) \tag{1}$$

where E_{rural} denotes heating energy consumption, measured by *kgce*. *HH* is the total number of households in northern rural China, I_p represents the proportion of households in province *p* to total households, and D_p is the average heating intensity, i.e., the average heating energy consumption per household for province *p*.

Eq. (2) calculated total heating-related carbon emissions, of which *k* represents energy types used for heating, and Ef_k represents the emission factor for each kind of energy. Emission factors come from the database of the Intergovernmental Panel on Climate Change (IPCC, 2006).

$$C_{rural} = E_{rural} * \sum\nolimits_{k=1}^{m} (W_k * Ef_k) \tag{2}$$

Therefore, the key procedures for our estimation involve (a) estimating heating intensity in each province (D_p) and (b) obtaining the proportion of energy types used for heating (W_k).

3.2.1. Heating intensity

Heating intensity is derived using statistical functions presented in Eq. (3). This method is widely used in energy estimation models. It is based on household income, HDDs, household size, and house floor area (Auffhammer and Wolfram, 2014; Gertler et al., 2016). Achieving the same level of heating service may require more biomass or low-quality energy than higher-quality alternatives (Grubler et al., 2018). Therefore, we add a clean energy dummy variable, which equals one if households use more advanced energy than primary energy (definitions provided below). The theory of the energy ladder and energy stack suggest that as social and economic conditions improve, residents' energy preferences gradually evolve towards cleaner and higher-quality energy sources (Hosier and Dowd, 1987; Masera et al., 2000). Therefore, the interactive term between income and clean energy dummy is

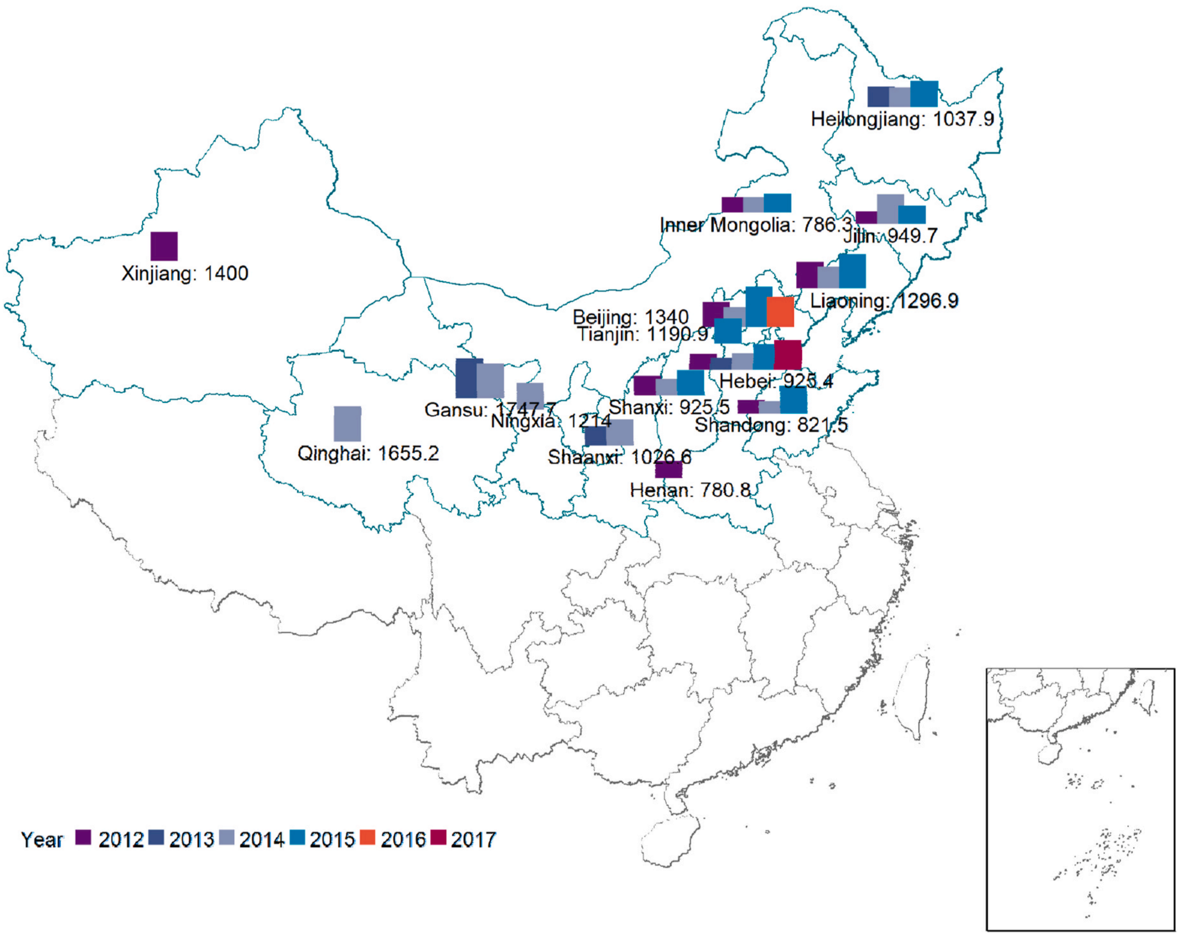

Fig. 1. The average heating energy demand per household.

also included. In addition, province dummies δ_p are included to account for unobservable province characteristics that may affect heating intensity, such as local governance, cultural background, agriculture, and industrial structure. The year dummies λ_t are used to control for national shocks and trends over time, such as changes in regulations and laws, long-term trends in efficiency improvement, etc.

$$log(D_{ip}) = \alpha_1 * log(inc_i) + \alpha_2 * log(HDD_p) + \alpha_3 * clean_i + \alpha_4 * log(inc_i) * clean_i + \beta_1 * hhsize_i + \beta_2 * area_i + \delta_p + \lambda_t + u_{it} \tag{3}$$

3.2.2. Heating energy proportions

Fig. 2 illustrates the proportion of different fuels used for heating. The combination of wood, straw, and coal energy accounted for 87.2%, 98%, 92.9%, and 92.4% of total energy consumption from 2012 to 2015, respectively. Biomass energy types decreased gradually, even without policy intervention. The clean heating initiative in northern China, which has been ongoing since 2016, aims to transition from traditional biomass and coal usage to cleaner options such as electricity and natural gas. Following the Clean Heating Plan, there was a rapid increase in electricity and gas energy, accounting for 59% of consumption in 2016 and 53.3% in 2017. However, rural residents still rely on conventional, lower-quality energy sources due to persistent challenges, including income constraints among rural residents, high fuel costs, unsustainable subsidies, unexpected gas shortages, and difficulty in altering residents' heating habits (Ma et al., 2021; Wang and Xie, 2023). Disposable income has emerged as a decisive determinant driving energy transitions in this context.

Fig. 3 depicts the relationship between income and the proportion of various energy types. Energy types have been categorized as primary (wood and straw), transitional (coal and charcoal), and advanced (electricity and natural gas) energy. Findings indicate that as income levels increase, the proportion of primary energy consumption decreases while the proportion of advanced energy consumption rises. To analyze this data, we utilize fractional response regression, a statistical approach used for dependent variables that take continuous values between zero and one, such as rates, proportions, and fractional data (Papke and Wooldridge, 1996). The fractional model is described in Eq. (4), where the dependent variable W_{ik} indicates the proportion of primary/advanced energy in household *i*. $\Lambda(\cdot)$ is a transformation function of the logit model. Independent variables are disposable income, climatic conditions, household size, and house floor area. Temporal and spatial dummies are also included.

$$W_k = E(W_{ik}) = \Lambda\left(\alpha_1 * log(inc_i) + \alpha_2 * log(HDD_p) + \beta_1 * hhsize_i + \beta_2 * area_i + \delta_p + \lambda_t + u_{it}\right) \tag{4}$$

3.2.3. Historical and scenario data collection

Historical temperature data comes from the National Oceanic and Atmospheric Administration (NCEI, 2023). The data is recorded on a station-based daily temperature and then transformed into city-based data using inverse distance weighting. A base temperature of 18 °C is used to calculate the HDD between November 15 and March 15 of the subsequent year.

Table 1 provides a summary of statistics for heating intensity, household social demographics, house floor area, proportion of households using clean energy, and the average HDDs. The average heating intensity across northern rural China is 1238.74 kgce. Average household income, household size, and floor area are approximately 16,133

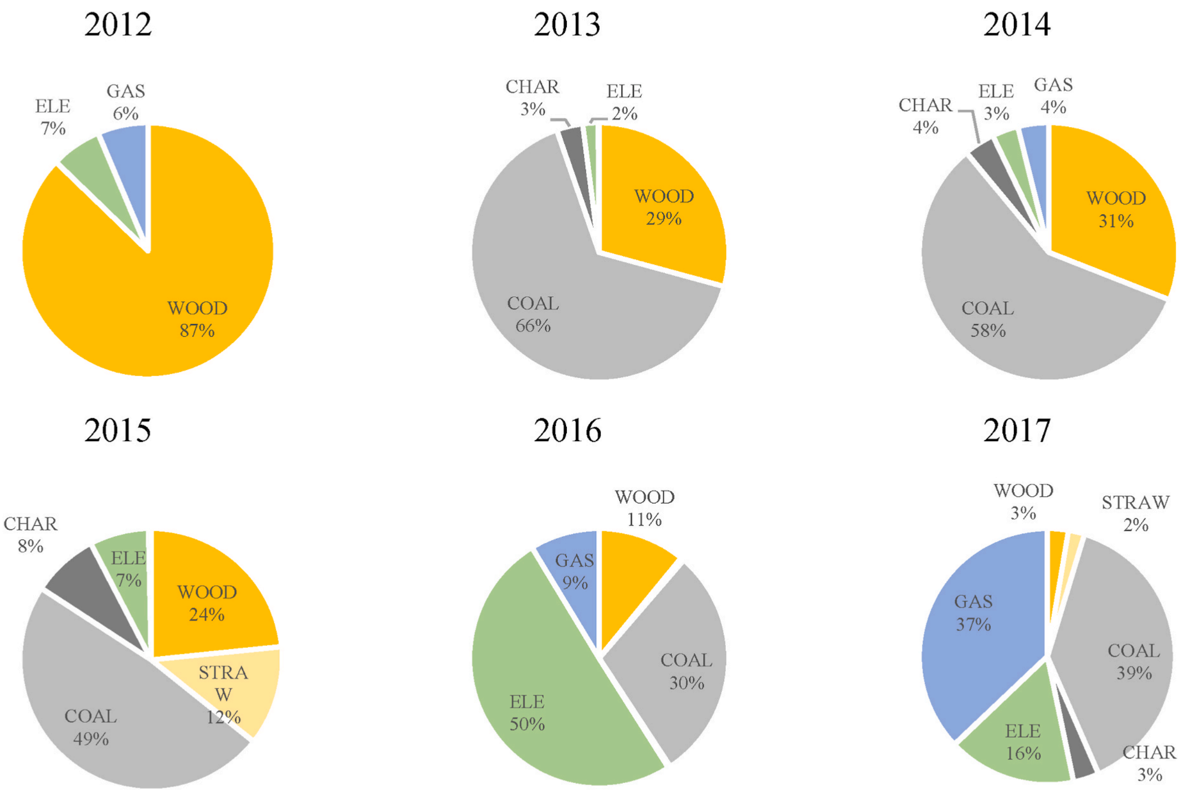

Fig. 2. Proportions of heating energy types from 2012 to 2017 in northern rural China.

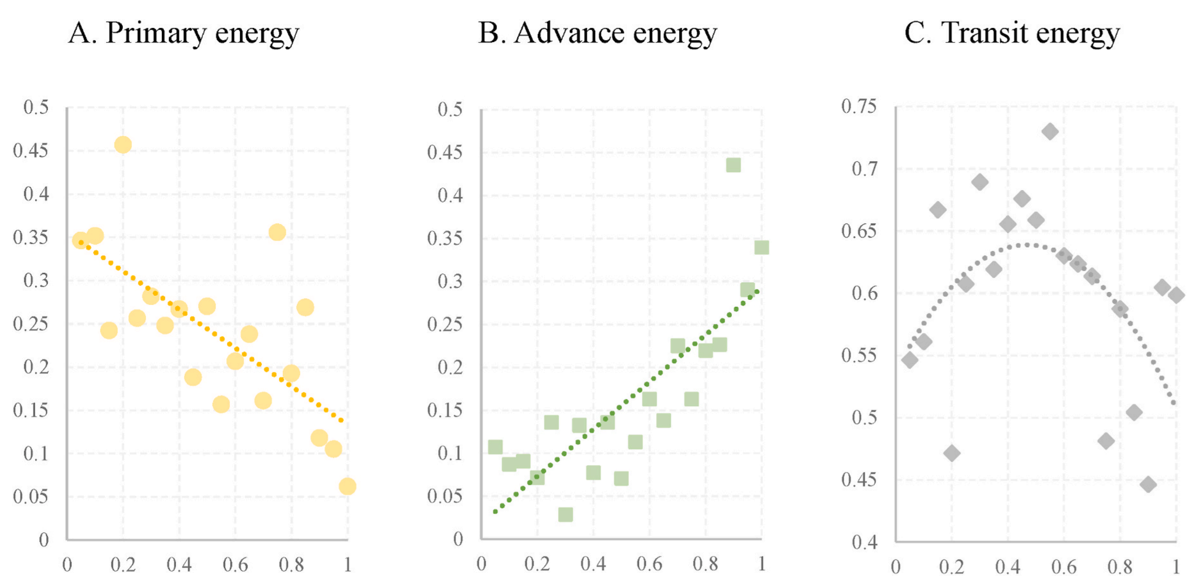

Fig. 3. Proportions of energy types with the level of disposal income. Notes: The x-axis represents household income percentiles, and the y-axis represents the proportion of different energy sources. Energy types have been categorized as primary (wood and straw), transitional (coal and charcoal), and advanced (electricity and natural gas) energy.

yuan, 3.6 people, and 122.4 square meters, respectively. To validate the findings, we compare household characteristics with national statistics. According to national data, the average disposal income per capita for northern rural provinces from 2012 to 2017 ranges from 5589–24,240 yuan (NBS, 2023), and the seventh national population census indicates that the average floor area per capita for northern provinces is between 32.5 and 46.5 square meters (NBS, 2021a). It is evident that the sample statistics are comparable to those at the national level.

The future provincial population growth, urbanization progress, income growth, and climate change scenarios were sourced from high-quality open data corresponding to various Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs) (Chen et al., 2020; Frieler et al., 2017; NBS, 2021a; Stefan Lange, 2017). Appendix Figs. 2-4 provide detailed information on data sources, calculation methods, and future trends. Table 2 summarizes the projections for 2025, 2035, and 2050. The average HDDs under RCP26, RCP60, and RCP8 are 2565, 2520, and 2468, respectively. Appendix Fig. 3 illustrates the decreasing trend of HDDs from about 2612 in 2022

Table 1
Summary statistics of variables in 2012–2017.

Variable	N	Mean	Sd	Min	Max
Heating intensity (D_i)	6150	1238.74	1103.36	30.42	6475.14
Household income (*inc*)	6150	16133.20	13350.78	1048.00	148617.00
Household size (*hhsize*)	6150	3.60	1.54	1	8
Floor area per household (*area*)	6150	122.43	56.77	30.00	304.64
Household uses more advance energy (*clean = 1*)	6150	0.23	0.42	0	1
Heating degree days (*HDDs*)	6150	2019.85	192.23	1477.86	2717.24

Table 2
Scenario values for provincial-level HDD, disposal income, and household number.

Variable		2025	2035	2050
HDD	RCP26	2442.92	2630.45	2595.92
	RCP60	2498.01	2616.04	2345.22
	RCP85	2413.71	2408.66	2447.54
Disposal income **(yuan)**	SSP1	24739.16	32127.49	38047.58
	SSP2	24281.71	30958.66	36212.23
	SSP3	23518.06	29263.34	33702.76
Household number **(million units)**	SSP1	5.93	5.53	5.31
	SSP2	6.12	5.92	6.13
	SSP3	6.36	6.43	7.12

to 2463 in 2050. Disposal income in rural areas is projected to increase by 81.4%, 74.2%, and 64.6% by 2050 under SSP1 to SSP3, respectively. Rural household numbers are expected to decreased by 12.3% under SSP1, increase by 11.9% under SSP3, and remain relatively stable under SSP2. The outcome of our projection on heating demand is contingent upon numerous uncertain parameters, including income, population, and climate change scenarios, which remain uncertain due to their unknown future evolution. In this paper, we adopt the middle pathway of these macro variables (RCP60 and SSP2) as a Business-As-Usual (BAU) scenario.

3.3. Scenario settings

Reducing heating intensity and increasing the use of clean and renewable energy sources is crucial to mitigate heating-related carbon emissions. This can be achieved by improving building performance, shifting to cleaner heating fuels and technologies, and promoting green behaviors in rural heating. We outlined potential energy conservation pathways and summarized each scenario in Table 3, with detailed descriptions provided in the subsequent subsections.

3.3.1. Improving building performance

Improving building envelope components, such as walls, windows, roofs, thermal insulation, infiltration, and airtightness (Sadineni et al., 2011), can achieve passive building energy efficiency. Building envelope standards in China have significantly improved, reflecting the increasing need for energy conservation. For instance, the *Civil Building Energy Conservation Standard (Heating Residential Buildings Section) JGJ26-86* proposed a 30% reduction in energy consumption compared to general residential design energy levels for 1980. This is commonly referred to as the first-step energy efficiency target (MHURD, 1986). The second-step target required an additional 30% reduction in energy consumption compared to 1986 (MHURD, 1995), and the third-step target required a further 30% reduction compared to 1995 (MHURD, 2010). Most regions in China have met the second-step building design standard (Zhou et al., 2018b). According to Hu et al. (2016), if all urban

Table 3
Scenarios description.

Scenarios	Description	Heating intensity (D_p)	Energy choice (W_k)
BAU	Business-as-usual for individual heating	As usual (see Appendix Fig. 5)	As usual (Appendix Fig. 6)
Low-BP	Rural heating with building performance enhancement	−15% by 2050	As usual
High-BP		−30% by 2050	As usual
Low-RE	Renewable energy used for rural heating	As usual	Achieving 15% by 2050
High-RE		As usual	Achieving 30% by 2050
Low-HP	Heat pump penetration for rural heating	Compound annual growth rate of 2%. Upon adoption, it would save 30% of electricity.	HP uses electricity
High-HP		Compound annual growth rate of 10%. Upon adoption, it would save 30% of electricity.	HP uses electricity
Low-GB	Encouraging occupants' green behavior to conserve energy	−5% by 2050.	As usual
High-GB		−10% by 2050	As usual

residential buildings in southern urban China comply with the third-step standard, heating energy consumption could be reduced by 14.3% by 2030. As many rural houses are poorly insulated, their heat transfer coefficient may not meet the recommended value set by the energy-saving standard (Shan et al., 2015). Therefore, we assumed two building performance improvement scenarios by 2050: a 15% low improvement scenario (Low-BP) and a 30% high improvement scenario (High-BP).

3.3.2. Shifting heating fuels and technologies

Renewable energy-based heating solutions provide advantages such as environmental preservation and safety. Recently, China implemented a series of policies to promote the adoption of renewable energy heating (NDRC, 2021, 2022b; NEA, 2021). The 14th *Five-Year Plan for Renewable Energy Development (2021–2025)* stipulates that non-electric uses, including solar thermal utilization, geothermal heating, biomass heating, and biomass fuels, should exceed 60 Mtce for non-electricity usage, including heating and hot water by 2025 (NDRC, 2022a). It was equivalent to 13.4% of total residential heating consumption in 2016 (BERC of Tsinghua University, 2019). By 2050, since there is no clear national target, we set a low renewable energy scenario (Low-RE) of 15%, as well as a high scenario (High-RE) of 30%.

Switching to electricity, in addition to significant improvements in electrical equipment efficiency, can significantly reduce energy demand (IEA, 2021). Heat pumps offer considerable energy savings. Modern air-source heat pumps can reduce electricity consumption by 50% compared to traditional furnaces and baseboard heaters, while geothermal heat pumps can save energy up to 30–60% (U.S. Department of Energy, 2023; Wahlström and Hårsman, 2015). Zhou et al. (2022) investigated the interdependencies between air quality, health, and carbon emissions from residential heating in northern China. They suggested that heat pumps would achieve the largest health-carbon synergies by 2030 and are cost-competitive for long-term use. The Chinese government has implemented proactive measures to improve the utilization of heat pumps in rural areas. The action plan focuses on integrating air-source heat pumps into clean energy initiatives to replace coal in rural areas (BJDRC, 2023). The sales growth rate of heat pumps in China was 13% in 2021 and 2% in 2022 due to a general economic slowdown (IEA, 2023b). Global heat pump sales increased by 13% in 2021 and 11% in 2022, close to the required 15% average compound annual growth to fully align with the Net Zero Scenario by 2050 (IEA, 2023c). Given the high capital cost of heat pumps and the lower affordability of rural households, we have set a compound annual growth rate of 2% in the Low-HP scenario and 10% in the High-HP scenario.

3.3.3. *Encouraging green behaviors*

There is often a significant discrepancy between the designed and actual total energy use of a building. The reasons for this divergence are poorly understood and often have more to do with human behavior than building design (Yan et al., 2017). Occupant interactions with building energy devices and systems, such as light and window opening/closing, curtaining/blind adjustment, light switching, air conditioner adjustment, and energy awareness, significantly affect residential energy consumption. Several studies have shown how much energy can be saved by changing human behavior. Zhou et al. (2018b) found that high indoor air temperature and window opening for ventilation are accountable for the high heating energy consumption. Hu et al. (2016) found that leading a green lifestyle and energy-saving behavior could save 6% of individual heating demand in China HSCW urban areas. Khanna et al. (2021) reviewed more than 100 studies on the role of behavioral change in residential building energy consumption and reported an average reduction of 6.24%. Therefore, we assumed that occupant energy demand intensity would be reduced by 5% in the Low-GB scenario and 10% in the High-GB scenario by 2050.

4. Results and discussion

4.1. *Heating energy demand*

The impact of influencing factors on heating intensity, as estimated with Eq. (3), is shown in Appendix Table A.1. It is observed that heating intensity increases with income growth, while the effect is inhibited when households use clean energy. Furthermore, climate conditions significantly impact heating demand, with heating intensity decreasing as global warming intensifies. Utilizing these coefficients alongside scenario data, the total heating energy demand for northern rural China is projected and illustrated in Fig. 4. The trajectory of heating demand in influenced by numerous opposing driving forces. Gradually increasing income tends to elevate energy demand, factors such as decreasing rural population and potential global warming tend to reduce energy demand.

Rural heating energy demand in northern China is expected to range from 175 to 275 Mtce in 2030 and 137–245 Mtce in 2050. Our estimate is comparable with existing research. For example, Zhou et al. (2018a) projected China’s residential heating energy demand for 2050 to be approximately 500 Mtce under a high energy demand scenario and 200 Mtce under a techno-economic potential scenario. Hu et al. (2016) modeled urban residential heating energy demand in the HSCW area, projecting it to be 28–189 Mtce by 2030. However, research specifically focused on rural areas is limited; only national statistical data shows that the demand for northern rural heating was about 60–200 Mtce in 2016 (NBS, 2017; NDRC, 2017).

4.2. *Heating-related carbon emissions and mitigation potential*

Heating-related carbon emissions under different scenarios are presented in Panel A of Fig. 5. Under the BAU scenario, carbon emissions are projected to reach 480 million tons in 2030 and 347 million tons in 2050. This decrease is attributed to two main factors: reduced energy demand and a higher proportion of advanced energy sources (refer to Fig. 4 and Appendix Fig. 6). Panel B demonstrates the mitigation potential through combined efforts to improve building performance (BP), promote renewable energy (RE), popularize heat pumps (HP), and cultivate green behavior (GB). Under low-level mitigation scenarios, carbon emissions gradually decline to 204 million tons, showing a 41.2% reduction compared to baseline emissions. High-level mitigation scenarios align with the carbon-neutral target, indicating a 76.2% reduction in carbon reduction. Analyzing the contributions of each scenario reveals that BP and RE offer the greatest emission reduction potential, accounting for approximately 50 million tons in the low mitigation pathway and 77 million tons in the high mitigation pathway. HP emerges as a promising method for emission reduction because it improves heating efficiency and accelerates electrification progress. Additionally, it is important to address the role of cultivating a green lifestyle in rural areas to achieve 16.8–33.6 million tons of carbon emission reduction by 2050.

The findings are consistent with other research investigating energy conservation in residential heating, albeit in different geographical contexts. For example, Reyna and Chester (2017) observed a 63% reduction in spacing cooling and heating energy in California’s residential sector by 2060 through strategies such as transitioning to high-efficiency heat pumps and promoting envelope energy efficiency. Zhou et al. (2018a) demonstrated that about 60% of energy conservation could be achieved by adopting the highest cost-effective energy-saving and renewable technologies for residential heating in China by 2050. Additionally, Xiong et al. (2015) found that a combined effort

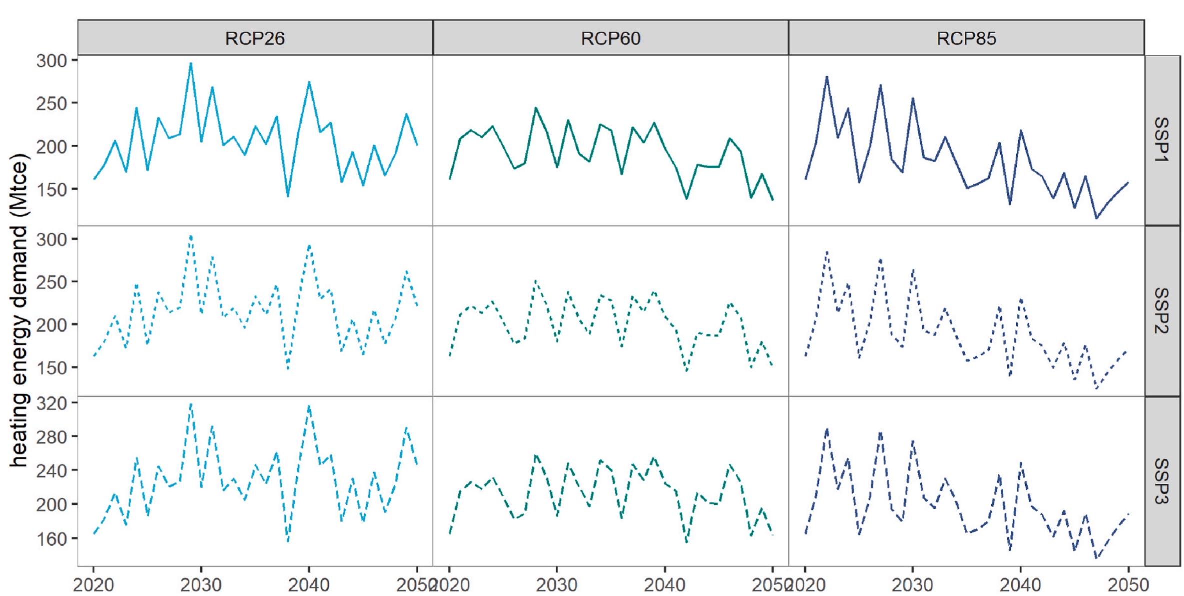

Fig. 4. The projection of heating energy demand in rural northern China by 2050.

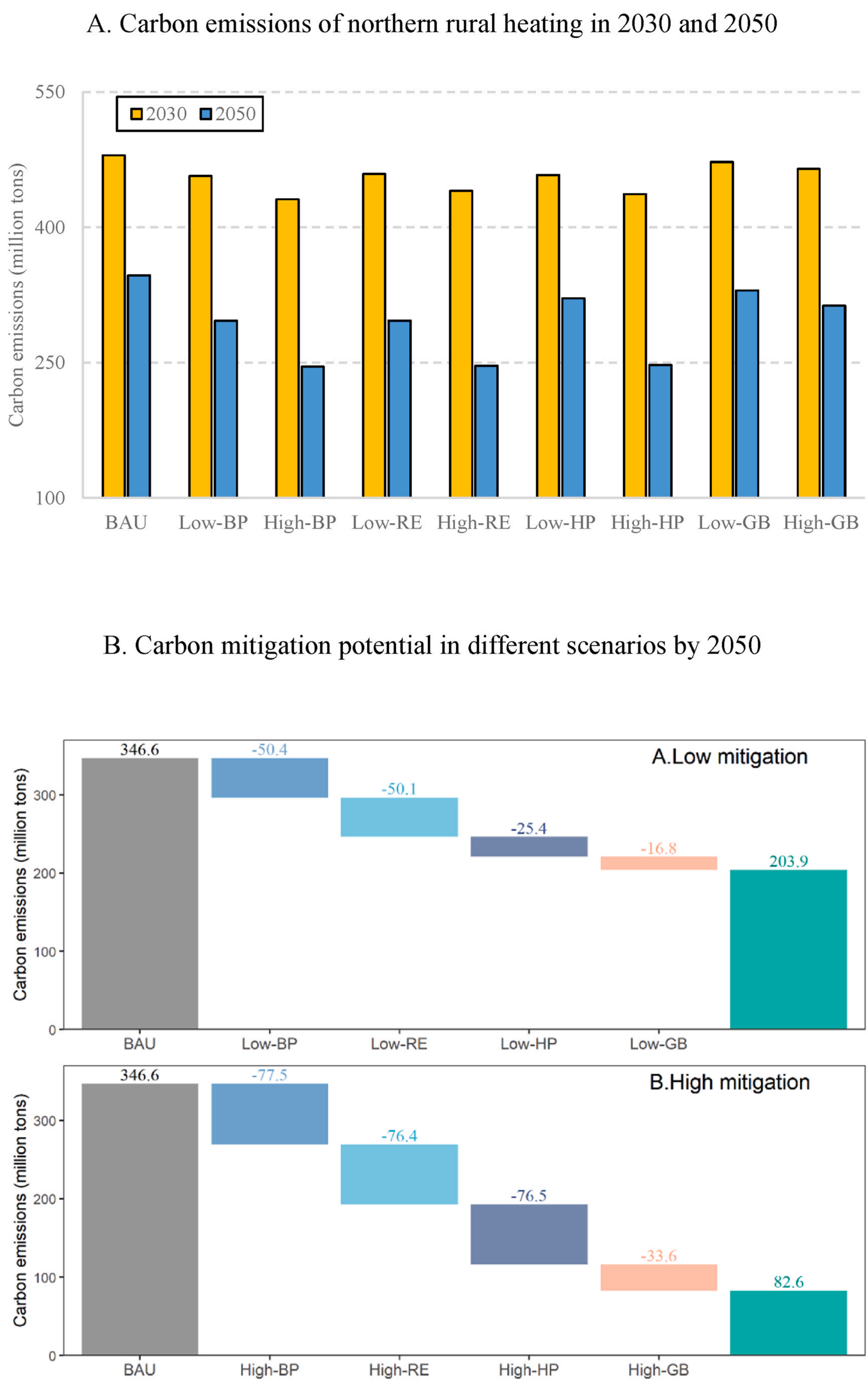

Fig. 5. Carbon emission and mitigation potential of northern rural heating.

involving the Heat roadmap China (HRC) scenario and a heat metering reform could contribute to a 60% reduction in primary energy supply for the district heating system in China by 2030. Rural areas consume significant amounts of low-quality energy for heating, presenting a significant opportunity to reduce emissions. Meanwhile, achieving carbon neutrality in rural areas is more complicated due to lower affordability among residents.

5. Conclusions and policy implications

The need to address climate change and establish sustainable energy systems has led to a focus on reducing carbon emissions from residential space heating. This study examined energy consumption and carbon emissions in rural northern China, where individual heating is the primary method. Through a comprehensive analysis of socioeconomic factors, energy sources, and climate change, we projected heating energy demand in rural northern China from 2020 to 2050. Subsequently, we sought to uncover potential pathways for reducing carbon emissions and advancing towards a cleaner, more sustainable energy future.

With a unique household energy consumption dataset, we provided insights into heating conditions across 15 provinces of northern rural China. The average heating energy demand per household was approximately 1239 kgce, with higher consumption observed in western and northern provinces compared to eastern and southern provinces. Both cold weather and the saturation of clean energy were identified as significant influences. Before the implementation of the Clean Heating Plan, wood and straw energy accounted for 36% of total heating energy; coal and charcoal accounted for 57%, bringing severe air pollution and health damages to rural residents. Transitioning to clean energy requires strong policy support but ultimately depends on income growth. Rural revitalization and rural low-carbon development are intricately linked to each other.

We then constructed empirical models to project residential heating energy demand and carbon emission in China's rural areas by 2050. Heating energy demand was estimated to reach 175–275 Mtce in 2030 and 137–245 Mtce in 2050, with related carbon emissions projected at 466–736 million tons and 318–574 million tons, respectively. The uncertainties come from unknown trends in income, population, and climate change. Under the development road of RCP60 and SSP2, we further estimated carbon mitigation potential under different policy scenarios, including improving building envelopes, utilizing renewable energy, adopting heat pumps, and cultivating a green lifestyle. Results showed that total carbon emissions could be reduced by 41.2% under lower-level mitigation scenarios and 76.2% under high-level mitigation policies.

The research findings have significant policy implications. Notably, the transition to high-quality and renewable energy has emerged as the primary driver of carbon reduction in rural heating. The empirical model demonstrated that a higher proportion of clean energy significantly reduce energy demand. The study estimated that carbon mitigation potential from utilizing renewable energy could be 50–76 million tons by 2050. Despite encountering challenges in coal-to-electricity and coal-to-gas programs since 2016, sustained efforts have led to high adoption rates and increased usage of clean energy across all provinces. Government initiatives should align with broader sustainability goals and emphasize transitioning from traditional, low-quality energy sources to cleaner alternatives.

Heat pumps are recognized as having the largest health-carbon synergies and the lowest operating cost in northern China (Zhou et al., 2022). However, their high capital cost has inhibited the rapid adoption in China, with only a 2% growth rate in 2022, compared to nearly 40% growth in Europe and 11% globally (IEA, 2023b). Our estimate demonstrated 25.4 million tons of carbon reduction if partially (9%[1]) adopting heat pumps in rural northern China. While considering the lower affordability of rural residents, substantial policy support and subsidies are necessary to facilitate widespread adoption. This highlights the importance of government intervention in providing financial incentives and supports to overcome barriers to adoption and accelerate the transition to cleaner energy technologies.

Improving the building envelope in rural areas is crucial for achieving future energy-efficient and environmentally friendly designs. It was estimated that approximately 50.4–77.5 million tons of carbon emissions could be reduced by improving building envelopes. This reduction potential could be even more prominent in rural areas due to poorly insulated structures. Governments and scientific communities worldwide have recognized the potential and necessity of energy efficiency in buildings and have made significant efforts in this direction (El-Darwish and Gomaa, 2017; Stefanović and Gordić, 2016). China has improved its building envelope standards over the years, but there is room for further regulation and focus, particularly in rural areas.

Demand-side strategies play a crucial role in driving behavioral change and ensuring the success of emission-reduction initiatives. It is important to raise awareness and promote energy-efficient practices among occupants. Our results showed encouraging green energy usage could save 16.8–33.6 million tons of carbon emissions. Incentives and subsidies can encourage the adoption of cleaner heating technologies, whereas educational campaigns can enhance the public understanding of the environmental and economic benefits of these changes. However, these endeavors are challenging. The persistence of traditional heating habits, inadequate access to clean energy options, and financial constraints of rural residents are significant barriers to rapid and comprehensive emission reduction. Effective policy implementation requires tailored solutions that address these challenges while considering the unique socioeconomic dynamics of rural areas.

CRediT authorship contribution statement

Manyu Wang: Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Chu Wei:** Conceptualization, Funding acquisition, Investigation, Resources, Validation, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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[1] We assumed a compound annual growth rate of 2% in the Low-HP scenario, thus by 2050 the saturation rate is about 9%.

Appendix

Acronyms and abbreviations

BERC	Building Energy Research Center
BJDRC	Beijing Development and Reform Commission
CBEEA	China Building Energy Efficiency Association
CGSS	Chinese General Social Survey
CHP	Combined heat and power system
CPC	Communist Party of China
CRECS	China Residential Energy Consumption Survey
HSCW	Hot summer and cold winter areas
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project
MHURD	Ministry of Housing and Urban-Rural Development
MNR	Ministry of Natural Resources
NCEI	National Centers for Environmental Information
NDRC	National Development and Reform Commission
NEA	National Energy Administration
PPS	Proportionate to Population Size
RCP	Representative Concentration Pathway
SSP	Shared Socioeconomic Pathway

Table A.1
The impact of influencing factors on heating intensity

	(1)	(2)	(3)
	Full sample	Samples excluding Beijing	Samples excluding Beijing and Hebei
ln_inc	0.039**	0.039*	0.031*
	(0.017)	(0.022)	(0.018)
clean	−0.999***	−0.832*	−0.898*
	(0.310)	(0.474)	(0.537)
hhsize	0.010	0.004	0.007
	(0.008)	(0.010)	(0.011)
ln_area	0.004***	0.004***	0.004***
	(0.0002)	(0.0003)	(0.0003)
ln_hdd	3.718***	3.694***	3.813***
	(0.217)	(0.220)	(0.244)
ln_inc#clean	−0.106***	−0.112**	−0.130**
	(0.032)	(0.051)	(0.057)
Constant	−22.303***	−22.058***	−22.774***
	(1.665)	(1.693)	(1.865)
Province FE	Y	Y	Y
Year FE	Y	Y	Y
Observations	6150	4158	3222
R^2	0.352	0.336	0.343
Adjusted R^2	0.349	0.332	0.338

Notes: We excluded the sample of Beijing in 2016 (column 2) and Hebei in 2017 (column 3) to show the robustness of the results. Because the survey was targeted on the Clean Heating Plan in 2016 and 2017, thus it only collected samples in these two provinces. Standard error in parentheses. $*p < 0.1$, $**p < 0.05$, $***p < 0.01$.

Table A.2
Regression results of energy proportions

	Primary energy	Advance energy
ln_inc	−0.045***	0.072***
	(-7.04)	(10.90)
hhsize	0.000	−0.007*
	(0.12)	(-2.14)
ln_area	−0.066***	0.007
	(-6.82)	(0.67)
ln_hdd	0.530***	−1.089***
	(6.58)	(-6.60)
Province FE	Y	Y
Year FE	Y	Y
N	6150	6150
R2	0.197	0.147

Notes: The proportional sum of primary, transit, and advance energy is 1; thus, we must determine the proportions of two kinds of energy. *t* statistics are shown in parentheses. $*p < 0.05$, $**p < 0.01$, $***p < 0.001$.

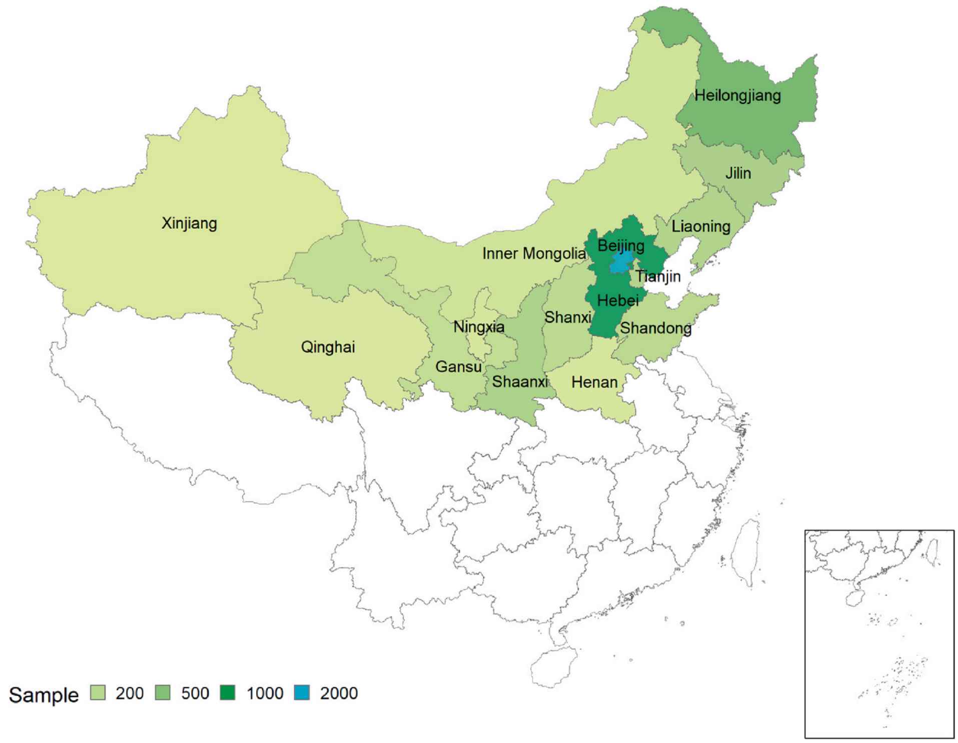

Fig. 1. Geographical distribution of sample units.

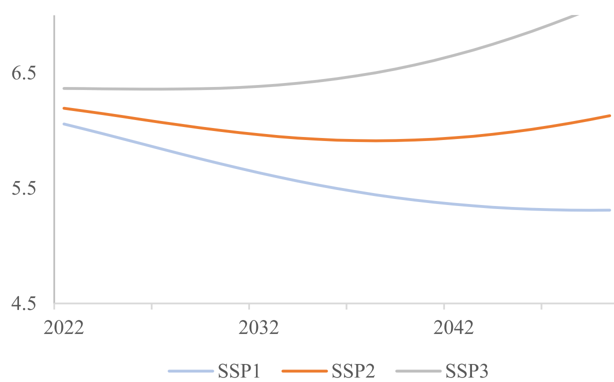

Fig. 2. Household number in northern rural China under different SSPs (million units). Notes: Province-specific age-based population data ranging from one-year-olds to 101-year-olds were extracted from scientific sources by Chen et al. (2020). The population figures were converted to the number of households based on the assumption of persons per household. Household size is predicted to decrease by 0.012 annually, reaching 1.68 by 2050, due to a decline of 0.48 over ten years (NBS, 2021a).

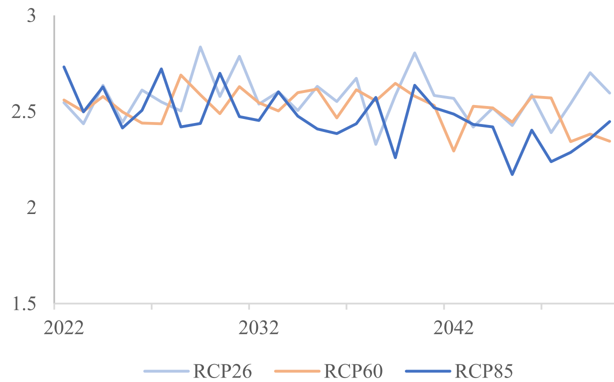

Fig. 3. Heating degree days under different RCPs (thousand). Notes: The future daily near-surface temperature data were obtained from the ISIMIP2b scenarios of the Inter-Sectoral Impact Model Intercomparison Project (Frieler et al., 2017). The inverse distance weighting method transformed station-based temperature data into city-based data. The ISIMIP2b scenarios draw from the CMIP5 archive and provide robust information about the impacts of 1.5 °C global warming and low-emission pathways. The scenarios contain bias-adjusted global downscaled atmospheric data for three RCPs. The grid points were separated into 0.5° latitude and 0.5° longitude, and the projection was obtained from the IPSL-CM5A-LR model (Stefan Lange, 2017).

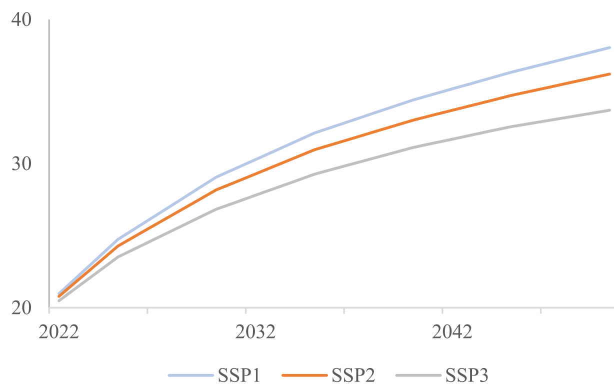

Fig. 4. Disposal income under different SSPs (thousand yuan). Notes: To project future provincial disposable income, it was assumed that the rate of increase would match provincial per capita GDP growth. The Cobb-Douglas production function is used to predict the long-term provincial GDP under three SSPs.

Fig. 5. The projection of heating intensity for rural household by 2050.

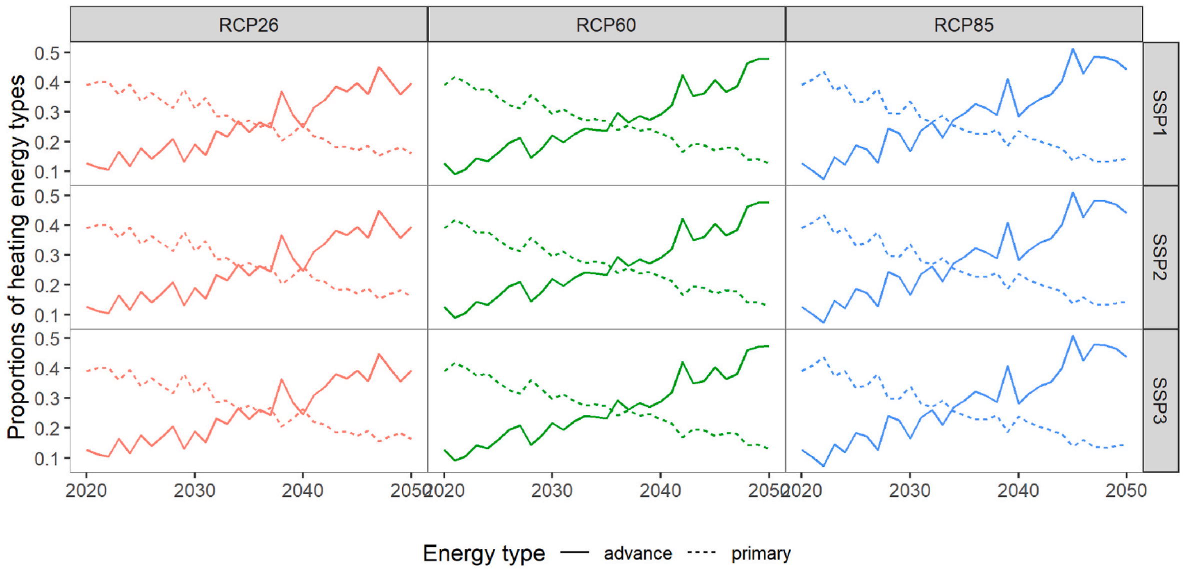

Fig. 6. The projection of proportions of heating energy types by 2050.

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