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Huili Wang,[1,12] Xiaojun Chen,[1,12] Yuanzhou Dong,[2] Zechen Zhang,[1] Yu Lei,[1,2,*] Shaobo Chen,[3,4,*] Ruxing Wan,[5] Jianhui Li,[4] Xiurong Hu,[6] Hui Xu,[7] Zhipeng Li,[8] Nan Ma,[9] Shuibing Wang,[10] Jinhai Yu,[11] Yixuan Zheng,[2] and Li Zhang[7,*]

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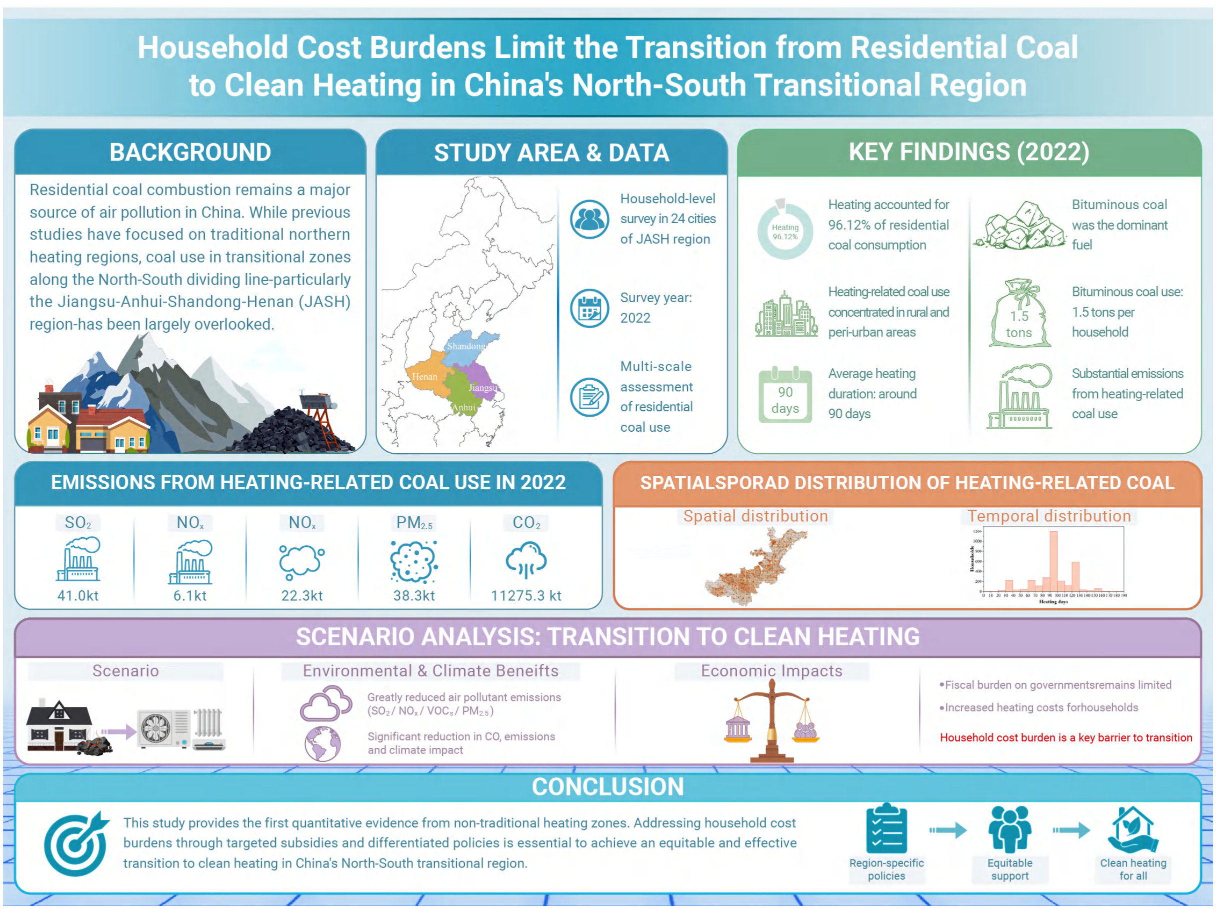
GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Residential coal use remains a major pollution source in China's JASH transition region.
- Heating accounted for 96.1% of household coal consumption, concentrated in rural and peri-urban areas.
- Heating-related coal use emitted substantial $PM_{2.5}$, SO_2, NO_x, VOCs, and CO_2 in 2022.
- Clean-heating transition could significantly reduce emissions and climate impacts.
- Higher household heating costs are a key barrier despite limited fiscal pressure on governments.

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Residential coal combustion continues to be a significant source of air pollution in China. While prior studies have primarily targeted traditional northern heating regions, coal use in transitional zones along the North-South dividing line, particularly the Jiangsu-Anhui-Shandong-Henan (JASH) region, has been largely overlooked. This study fills this critical gap by conducting a multi-scale assessment of residential coal use based on household-level survey data from 24 cities in JASH in 2022. Results indicated that heating accounted for 96.12% of residential coal consumption in the JASH region in 2022. Heating-related coal use exhibited strong spatial heterogeneity, concentrated in rural and peri-urban areas, with an average heating duration of around 90 days. Bituminous coal was the dominant fuel, with a median use of 1.5 tons per household. In 2022, air pollutant emissions from heating-related coal use were substantial, including 41.0 kt SO_2, 6.1 kt NO_x, 22.3 kt VOCs, 38.3 kt $PM_{2.5}$ and 11275.3 kt CO_2. We conducted scenario analyses to explore the environmental, climate, and economic impacts of transitioning to clean heating. The result revealed that eliminating residential coal use could greatly reduce emissions, although it may also lead to increased heating costs for households. While the fiscal burden on governments remains limited, the cost burden on residents presents a key barrier. This study provided the first quantitative evidence from non-traditional heating zones and offers actionable insights for developing region-specific, equitable clean heating policies.

INTRODUCTION

Residential coal combustion remains a significant contributor to air pollution and carbon emissions in China, particularly during the winter heating season in rural and peri-urban areas.[1,2] Although residential coal accounted for only 8.5% of national coal consumption in 2021,[3,4] it has a disproportionate impact on local air quality. In the North China Plain, $PM_{2.5}$ levels during the heating season have reached hourly peaks as high as 400 μg/m^3.[5] As more comprehensive understandings of residential coal consumption and corresponding environmental impacts the Chinese government realized, the adjustment of heating energy structure may be an effective way to address its environmental impacts.[6,7] Consequently, the Chinese government has launched a series of clean heating initiatives, including the "Winter Clean Heating Plan for Northern Regions (2017-2021)" and the "Three-Year Action Plan to Win the Blue-Sky Defense War".[8,9] The most recent policy goal targets the elimination of residential coal use in residential heating across plain areas by 2025.[10] Despite the ambitious nature of these policies, there remains a lack of integrated understanding regarding the energy structure, environmental impact and economic feasibility of clean heating transitions, particularly in non-traditional heating regions.

From the perspective of energy structure, existing studies have predominantly focused on traditional northern heating zones[11] with centralized systems, such as Beijing, Hebei and Inner Mongolia, while neglecting regions along the North-South climatic boundary that, despite not being officially designated as heating zones, still face substantial winter heating demand.[12,13] Additionally, researchers have revealed that the increasing heating demand in South China will consume 77-167 million tce (Mtce) of energy emitting more than 126 million tons of CO_2.[14] Obviously, there are significant differences in the characteristics of heating methods and energy use structures in southern and northern China, with electric heating in the south and residential coal burning in the north. However, there are few studies to investigate and evaluate the greening of heating energy structures and the corresponding environmental impacts in the border areas (Jiangsu-Anhui-Shandong-Henan, JASH). In the JASH region, residential coal use for household heating remains common, but the lack of household-level data on heating duration, consumption, and fuel types hinders accurate assessment and policy design.

From the environmental perspective, the development of air pollutant emission inventories (APRC) for residential coal has largely relied on aggregated data from statistical yearbooks.[15,16] Yet, inconsistencies across studies indicated that such top-down approaches may lead to considerable uncertainty.[17,18] Specifically, Xue et al. and Cheng et al. both developed APRC for Beijing in 2012, and there were differences in emissions between the two studies. For example, the emissions of SO_2 in the former study were a quarter of the latter, which can be attributed to the fact that Xue et al. applied data from statistical yearbooks and Cheng et al. applied data from field investigations. Data from field investigations and statistical yearbooks may cover the authenticity of APRC. Moreover, Peng et al. found that the estimated coal consumption from the survey was 62% higher than that reported in official statistics.[19] Therefore, current APRC may underestimate the emissions from coal burning by rural households. Furthermore, most studies have focused exclusively on conventional air pollutants (e.g., SO_2, NO_x, $PM_{2.5}$), while neglecting carbon dioxide (CO_2). In fact, the emission of CO_2 from residential coal combustion cannot be ignored.[20]

From an economic standpoint, clean heating transformations often require substantial investment in new technologies such as air-source heat pumps, electric heaters and gas-fired systems. These upgrades lead to increased capital and operating costs for households, especially in rural areas with relatively low-income levels.[21] While various subsidy schemes have been implemented to support the transition, current research rarely evaluates the economic burden on both residents and local governments under different cost-sharing scenarios. Designing a rational and equitable cost-sharing mechanism for clean heating first requires a detailed understanding of the spatial distribution and key drivers of residential coal consumption.[22] For example, a Chinese large-scale household energy consumption survey conducted in 2012 revealed the basic patterns of coal use,[23] while studies highlighted that the decline in per capita coal use in urban areas and rising rural incomes were key factors influencing the changing coal consumption structure.[24] Specifically, on a national scale, a 1% increase in urbanization rate may lead to a reduction of 420 million tons in residential coal consumption.[22] Yet to date, the energy, environmental and economic characteristics of residential coal use in the rural areas of the JASH region remain poorly understood.

To address these gaps, this study conducts a multi-scale analysis of residential coal use in the JASH region, integrating top-down statistical data and bottom-up household survey data. This study developed a comprehensive emission inventory for both air pollutants and carbon dioxide, quantified the spatial and structural characteristics of heating-related coal use, and assessed the environmental and economic implications of transitioning to clean heating under three subsidy-policy scenarios. This research provided the first integrated evaluation of the energy-environment-economic dimensions of residential coal use in a transitional heating zone and offered policy-relevant insights to support regionally adaptive and socially equitable clean heating strategies in China.

METHODS AND MATERIALS

Data from investigation

Household-level field investigations were conducted in cities and villages, taking into account both plains and mountains (Figure S1). Pre-investigations were initially conducted in village committees (a Chinese administrative system) to collect household-level information, including income and population, etc. Then, typical households were selected from pre-investigations for further investigation. Consequently, information on the number of households, the number of households consuming residential coal for heating, the average consumption of residential coal per household, types of heating equipment, coal quality information, the current situation and resource conditions of other energy sources such as biomass, geothermal, electricity and natural gas used for heating in the local area and the cost of various types of energy consumption were recorded. Questionnaires were shown in Table S1.

After that, the city-level residential coal consumption data were obtained via different administrative departments, such as the Agricultural Committee, Housing and Urbanization Bureau, Market Supervision Bureau, Developing & Reform Bureau and Statistics Bureau. Specifically, the city-level was composed of rural population, residential area, heating households, and total heating energy consumption (Table S2).

Residential coal consumption, as determined by the bottom-up method (household-level field investigation), reveals the actual consumption characteristics, whereas top-down methods (data collection across key departments) may only partially cover these characteristics. Limited household-level field investigation cannot reveal regional total coal consumption and air pollutants, as well as carbon emissions. Consequently, this study applied both methods mentioned above to obtain the activity level of residential coal consumption. Detailed methods for combining both bottom-up and top-down can be found in a previous study.[25]

Air pollutants and carbon emission inventory of residential coal consumption

Air pollutants and carbon emissions can be calculated by Equation 1.

$$E_i = \sum_j \sum_k \sum_p EF_i \times A_{j,k,p} \tag{1}$$

where E_i represented the emissions of air pollutant i (SO_2, NO_x, VOCs, $PM_{2.5}$, PM_{10} and CO_2) in the border regions. EF_i was the emission factor of air pollutant i, and emission factors were referenced by previous studies.[17,18] $A_{j,k,p}$ was the residential coal consumption in village j, city k and province p, and it can be obtained from the Household-level field investigation in this study.

Spatial allocation of emission inventory

A Previous study[17] has applied LandScan Global Population Data Set[18] to transform province-level air pollutant emissions from residential coal consumption to a gridded inventory. Consequently, based on the data from LandScan, this study followed the same method to allocate the emissions into the grids of 10 km × 10 km.

Emission reduction potential assessment

The Chinese government has set a more ambitious goal of achieving zero residential coal consumption in key regions for air pollution prevention and control by the end of 2025.[10] Currently, methods for clean heating are mainly electrification of heating devices, central heating and the applications of biomass and natural gas heating. Consequently, this study examined the air pollutant emissions, carbon emissions and costs of converting existing residential coal-based heating methods to clean heating ones to reveal the changes when the goal of achieving zero residential coal consumption in JASH plain areas by the end of 2030.

Scenario analysis

Based on survey data and experts' experience, the 24 cities in the study area were classified into three categories: high-demand heating cities, medium-demand heating cities and low-demand heating cities. The analysis considered investment from the perspective of the end-user application, excluding infrastructure-related costs such as power grid and pipeline construction. The annualized cost of heating equipment and its annual operating cost were combined to estimate the total annual cost. Clean heating technologies with lower total costs were selected under a cost-minimization constraint, and their adoption ratios were defined accordingly. Given the resource limitations of biomass fuels, their adoption share was set slightly lower.

Regarding funding mechanisms, this study referenced subsidy policies implemented in existing clean heating programs and designed three scenarios to assess the economic burden on both governments and residents: (1) Full Cost-Bearing by Residents (FBR), (2) Operation-Only Cost-Bearing by Residents (OBR), and (3) No Additional Cost Burden on Residents compared to traditional residential coal heating (NBR). These scenarios aim to provide a reference for determining region-specific clean heating strategies and subsidy schemes. The specific parameter settings for each scenario are presented in Tables S3 and S4.

Based on surveys conducted in regions where clean heating has already been implemented, data on the capital and operating costs of commonly used heating technologies were collected. Combined with heating duration and resource availability in the 24 cities located in the transitional zone, a comprehensive cost analysis was conducted for five clean heating options: air-source heat pump (ASHP) water heaters, ASHP air heaters, gas wall-hung boilers, electric thermal storage heaters, and specialized stoves for biomass briquettes. Equipment capital costs were annualized based on assumed service lifetimes.

The capital cost of heating equipment was annualized using a straight-line method, assuming a service lifetime of 20 years. The annualized capital cost (AC) was calculated as follows:

$$AC = \frac{C}{20} \tag{2}$$

where C is the equipment purchase cost (CNY), and 20 years is the assumed equipment lifespan.

Affordability pressure was evaluated using a widely adopted method from a previous study,[35] calculated as:

$$PS = \frac{P}{DI \times AP \times 5\%} \tag{3}$$

where P is the annual heating expenditure, PS is the affordability pressure (dimensionless), DI is the per capita disposable income (CNY/person·year), and AP is the average household size (persons/household). A benchmark of 5% is used as the reasonable proportion of household income allocated to heating. A value of PS>100% indicates that heating costs exceed the affordable threshold, implying high financial pressure; PS<100% indicates acceptable affordability, with lower values representing lower financial burden. Data on income and household size were obtained from local statistical yearbooks and the Seventh National Population Census, respectively.

RESULTS AND DISCUSSION

Characteristics of residential coal consumption in cities of JASH

Survey data from 2022 indicated that heating was the predominant purpose of residential coal consumption in cities of JASH (Figure 1A). Among various end uses, 53.85% of residential coal in Anhui was consumed for heating. In Shandong, heating accounted for 96.92% of total residential coal consumption, far surpassing usage in commercial stoves (0.65%) and agricultural production (2.43%). Similarly, residential coal consumption for heating in Henan accounted for 90.79% of the total local residential coal use, significantly exceeding that used in agricultural production (9.21%). Despite 64.29% of residential coal in Jiangsu being allocated to commercial stoves, the province's total consumption (0.014 million tons) was markedly lower than that of Shandong (5.679 million tons). These findings highlighted significant regional differences in both the scale and end-use structure of residential coal consumption, with heating dominating in northern provinces such as Shandong and Henan, while overall usage remained relatively low in southern provinces like Jiangsu. Taken together, these results suggested that residential coal consumption in these regions was primarily driven by heating demand, which was consistent with the research results of Yang et al (2019).[26]

The temporal heterogeneity in residential coal consumption reflected varying seasonal heating demands and regional energy use patterns. Specifically, Figure 1B showed the distribution of heating days in the borders of cities in four provinces. Households consumed coal for heating ranges from 0 to 190 days (d), with an average 90 d. When the number of heating days was less than 100 d, the number of heating households increased with the heating time. The number of households with heating days between 90 d and 100 d was 1200. Additionally, the number of households with heating days ranged from 120 to 130 d was about 600. As for the other heating intervals, the corresponding number of households is less than 90 d. As for residential coal used in agricultural production, its seasonal distribution was highly distinct: tobacco curing was concentrated from July to October, grain processing peaked between August and October, and greenhouse cultivation relied on coal use primarily during the winter months. In all four provinces, the majority of users operated for more than 300 days per year. This was largely attributed to the dominance of the catering industry among surveyed users, which was minimally affected by seasonal changes, resulting in stable year-round coal consumption, typically exceeding 360 days of use. In Shandong Province, in addition to catering, users from food processing and other industries with more pronounced seasonal characteristics were also surveyed. Consequently, usage durations of approximately 180 days and 90 days were observed in the data. For other sectors, residential coal consumption showed distinct seasonal patterns; for instance, bathhouses primarily operated from October to the following March, barbershops from November to February, while other sectors exhibited no clear seasonal variation.

According to data from household surveys, villages (communities) can be divided into large (more than 1000 households), medium-sized (between 300-500 households) and small ones (less than 200 households) (Figure 1C), among which the number of villages with 200-400 households was the largest. In terms of coal utilization structure, residential coal consumption ranged from 0.1 to 10 tons in the borders of four provinces. Specifically, average household coal consumption in Henan, Shandong, Jiangsu and Anhui was 0.5, 1.5, 0.2 and 0.2 tons, respectively, and the average total coal consumption in households was 1.44 tons. The spatial distribution of residential coal consumption also exhibited pronounced heterogeneity (Figure 1D). Heating-related coal consumption was primarily concentrated in rural areas and regions adjacent to major cities. Agricultural coal consumption was clustered in areas where tobacco curing was prevalent, while commercial stove usage was mainly distributed across township-level regions. Taking the spatial distribution of heating-related residential coal as an example, the hotspots of residential coal consumption were mainly concentrated in Shandong province. Specifically, the consumptions of residential coal in Zibo, Tai'an, Linyi and Qingdao were the largest. Among them, Weifang and Tai'an used more than 1 million tons of residential coal for heating, accounting for 42% of the total in the border region. Due to the influence of winter climate conditions, living habits and regional heating habits, there were few users in Henan, Jiangsu and Anhui provinces using residential coal for heating. Additionally, the average household consumptions of briquette, bituminous coal, anthracite coal and mixed coals (both briquette, bituminous and anthracite coal) were 0.79, 1.50, 1.48 and 0.96 tons, respectively (Figure 1E). It was obvious that the consumption of bituminous and anthracite coal was close to each other. It can be attributed to the fact that the price of bituminous coal is cheaper than that of anthracite coal, and the calorific value of bituminous coal is slightly lower than that of anthracite coal. In fact, coal consumption is significantly correlated with energy consumption factors.[27] For example, with the arrival of the heating season, local residents are hesitating whether to choose relatively environmentally friendly anthracite or low-priced bituminous coal. Moreover, the wide application of anthracite coal and mixed coals may pose additional health risks. Compared to the residential coal consumption related to heating reported in a previous study, the consumption in this study was larger than that of BTH (0.7 tons per year).[28] Differences in coal consumption may be due to regional characteristics.[28] Cheng et al. found a significant discrepancy between the actual level and structure of residential coal consumption and official data. Therefore, the household-level field investigated data in this paper could help to refine the energy consumption structure of the JASH region. In terms of heating methods, there were 540 thousand households that relied on residential coal for heating in 1377 villages. The number of households that applied electric heaters, coal, natural gas, central and biomass to heating accounted for 61.2%, 16.7%, 14.0%, 5% and 2% of the total residents, respectively (Figure 1F). Also, the ratios of coal consumption for heating in Shandong were larger than those in other provinces, which was consistent with the consumption of coal for regional heating in Shandong.

Characteristics of air pollutants and carbon emissions in the border regions

Building on the above findings, heating-related residential coal was identified as the primary source of coal consumption in the JASH region. Therefore, this study focused on this source and established corresponding air pollutants and carbon emission inventories (Figure 2). The emissions of SO_2, NO_x, VOCs, $PM_{2.5}$, PM_{10} and CO_2 were 41.0, 6.1, 22.3, 38.3, 49.5 and 11275.3 kt, respectively, in JASH in 2022.

The emissions of air pollutants in this study were lower than those in BTH, Shandong and Henan (Table 1). Also, air pollutant emissions in Liaoning and Beijing were lower than those of this study. It was mainly caused by the discrepancies in regional coal consumption. For example, although BTH has already completed the conversion program of clean heating before 2020, residential coal consumption remained stubbornly high. Specifically, the residential coal consumption in BTH was nearly 488 times larger than that in this study, resulting in lower air pollutant emissions in the borders of four provinces. As for carbon emissions, this paper found that carbon emissions in Hebei were 6.1 times those in this paper. This can be attributed to the fact

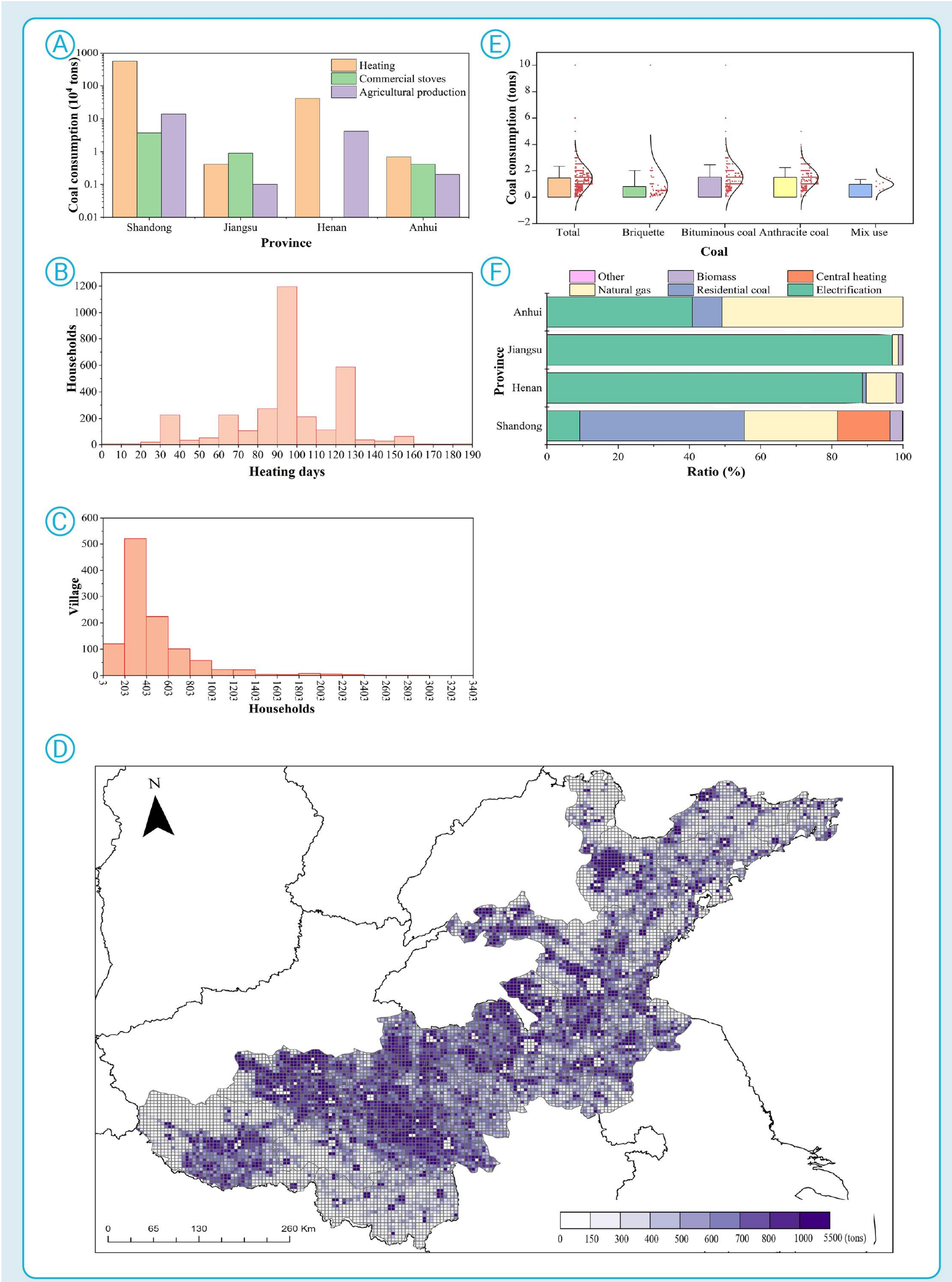

Figure 1. (A) Residential coal consumption from different end uses; (B) Distributions of heating days in JASH; (C) Distributions of villages and households in the survey; (D) Spatial distribution of residential coal consumption in JASH; (E) Average household residential coal consumptions; (F) Heating methods in JASH.

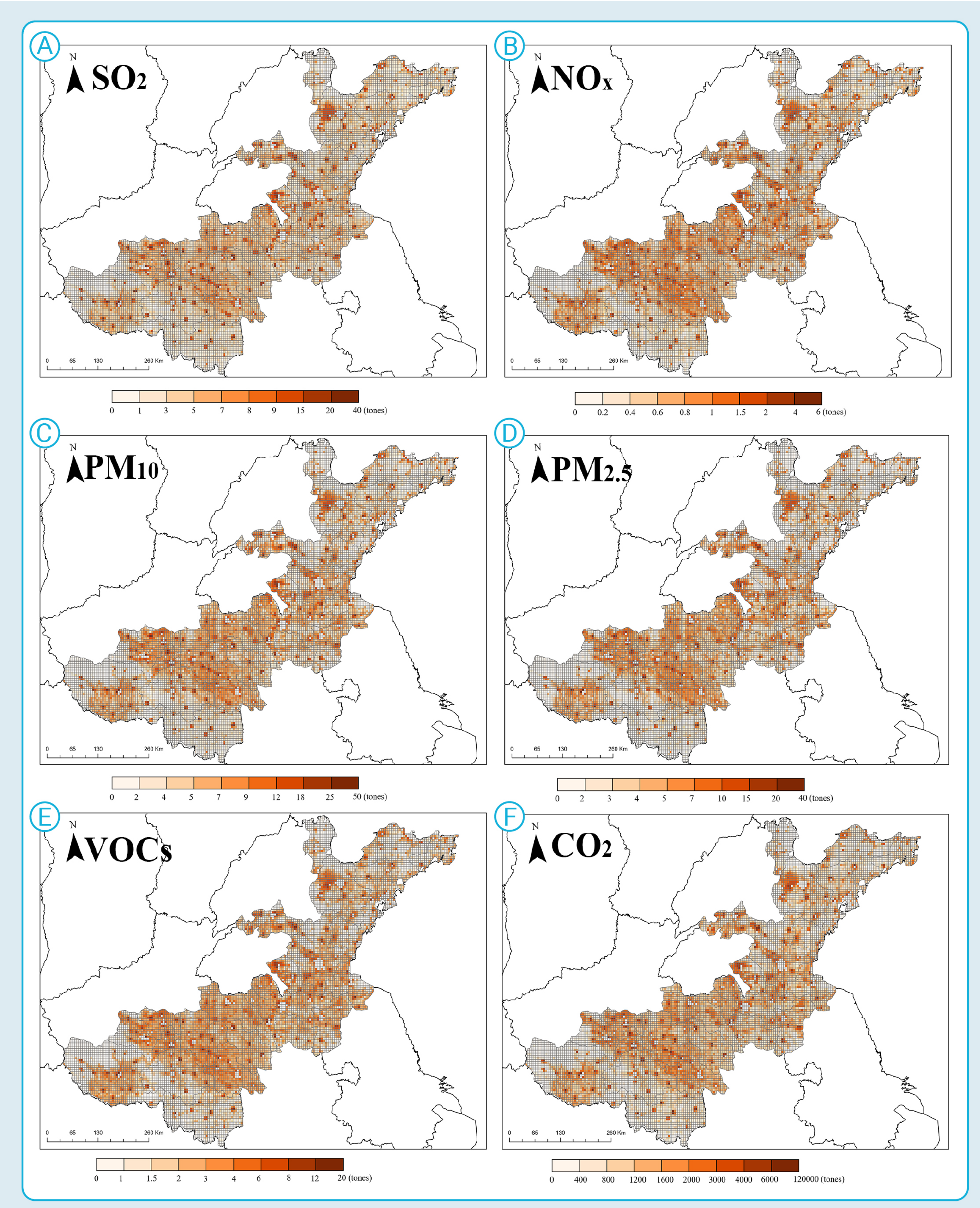

Figure 2. Spatial distribution of air pollutants (A-E)and CO2 (F)emissions from heating-relatedresidential coal in JASH.

that Hebei province did not conduct a large-scale conversion program for clean heating in 2016.

Emissions of SO_2, NO_x, VOCs, $PM_{2.5}$, PM_{10} and CO_2 in Shandong province accounted for 99.96%, 99.85%, 96.65%, 98.46%, 98.13% and 98.13% of the

Table 1. Comparison between this study and previous ones (unit: kt)

Year	Region	SO_2	NO_x	PM_{10}	$PM_{2.5}$	VOCs	CO_2
2020	BTH(Zhang et al., 2023)[16]	36670	3510	19580	15670	5870	-
2012	Beijing(Xue et al., 2016)[18]	2	2.4	9.2	7.1	1.3	-
2012	Beijing(Cheng et al., 2017)[17]	8	1.9	16	13	4.8	-
2015	Beijing(Cai et al., 2018)[34]	4	1	-	3	3	-
2017	Shandong(Zhou et al., 2020)[29]	260	330	-	110	820	-
2020	Liaoning(You et al., 2025)[36]	7.5	3	2.6	-	1.3	-
2016	Hebei(Zhou et al., 2024)[20]	-	-	-	-	-	68930
2017	Baoding(Zhao et al., 2020)[5]	-	-	-	-	-	-
2016	Henan(Zhu et al., 2020)[11]	110	30	100	70	110	-
2022	JASH (This study)	41	6.1	22.3	38.3	49.5	11275.3

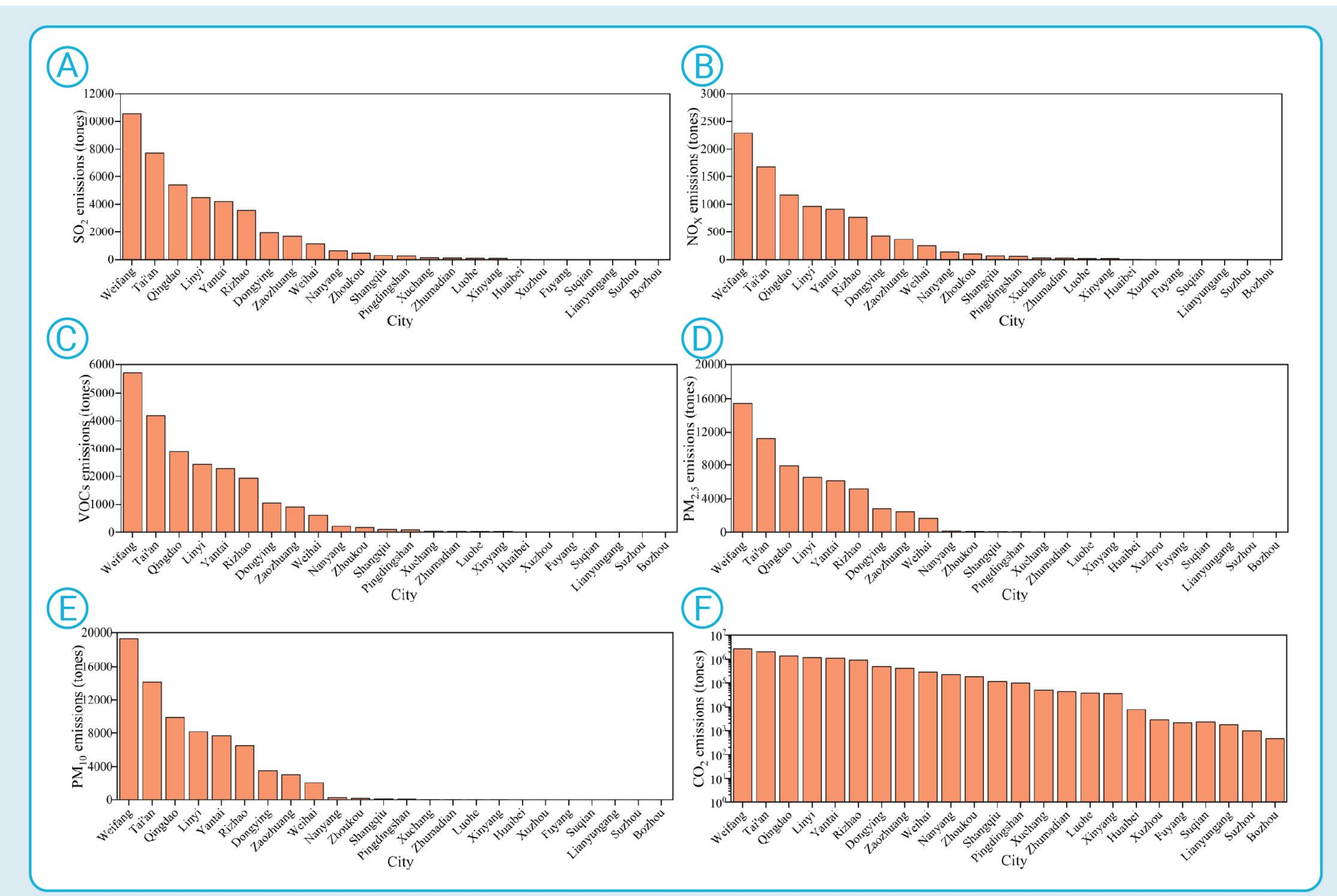

Figure 3. Air pollutants and CO_2 emissions at the city level. (A) to (F) were SO_2, NO_x, VOCs, $PM_{2.5}$, PM_{10} and CO_2, respectively.

total emissions in 2022, which can be attributed to the huge local residential coal consumption. Compared to a previous study,[29] the emissions of SO_2, NO_x, VOCs and $PM_{2.5}$ in Shandong in 2017 were 260, 330, 820 and 110 kt, respectively, the corresponding pollutant emissions in 2022 declined substantially to only 1.8%-34.8% of 2017 levels. This marked reduction in emissions was accompanied by a decrease in the contribution of residential coal combustion to ambient $PM_{2.5}$ concentrations during the heating season, from 20.5% in 2017 to 16.1% in 2022. Also, the emissions of SO_2, NO_x, VOCs, $PM_{2.5}$, PM_{10} and CO_2 were 2.1, 0.46, 0.75, 0.58, 0.91 and 799.5 kt, respectively, in Henan province. Similarly, emissions of SO_2, NO_x, VOCs, $PM_{2.5}$, PM_{10} and CO_2 were 0.33, 0.07, 0.01, 0.005, 0.007 and 11.4 kt, respectively, in Anhui province. And the emissions of SO_2, NO_x, VOCs, $PM_{2.5}$, PM_{10} and CO_2 were 0.17, 0.004, 0.006, 0.005, 0.008 and 6.8 kt, respectively, in Jiangsu province. As for city-level emissions, Weifang, Tai'an, Qingdao, Linyi, Yantai, Rizhao, Dongying, Zaozhuang and Weihai had the largest air pollutants and carbon emissions (Figure 3). It was mainly caused by the local huge coal consumption. The emissions in Nanyang, Zhoukou, Shangqiu, Pingdingshan, Xuchang, Zhumadian, Luohe and Xinyang were smaller than those in Shandong and larger than those in Jiangsu and Anhui. This was expected as there were fewer heating households and less coal consumption. In addition, only residents in northern Jiangsu and Anhui show heating needs during winter.

In response to the considerable emissions of air pollutants and CO_2 from heating-related coal use, the Chinese government has set a more ambitious goal of achieving zero residential coal consumption in key regions for air

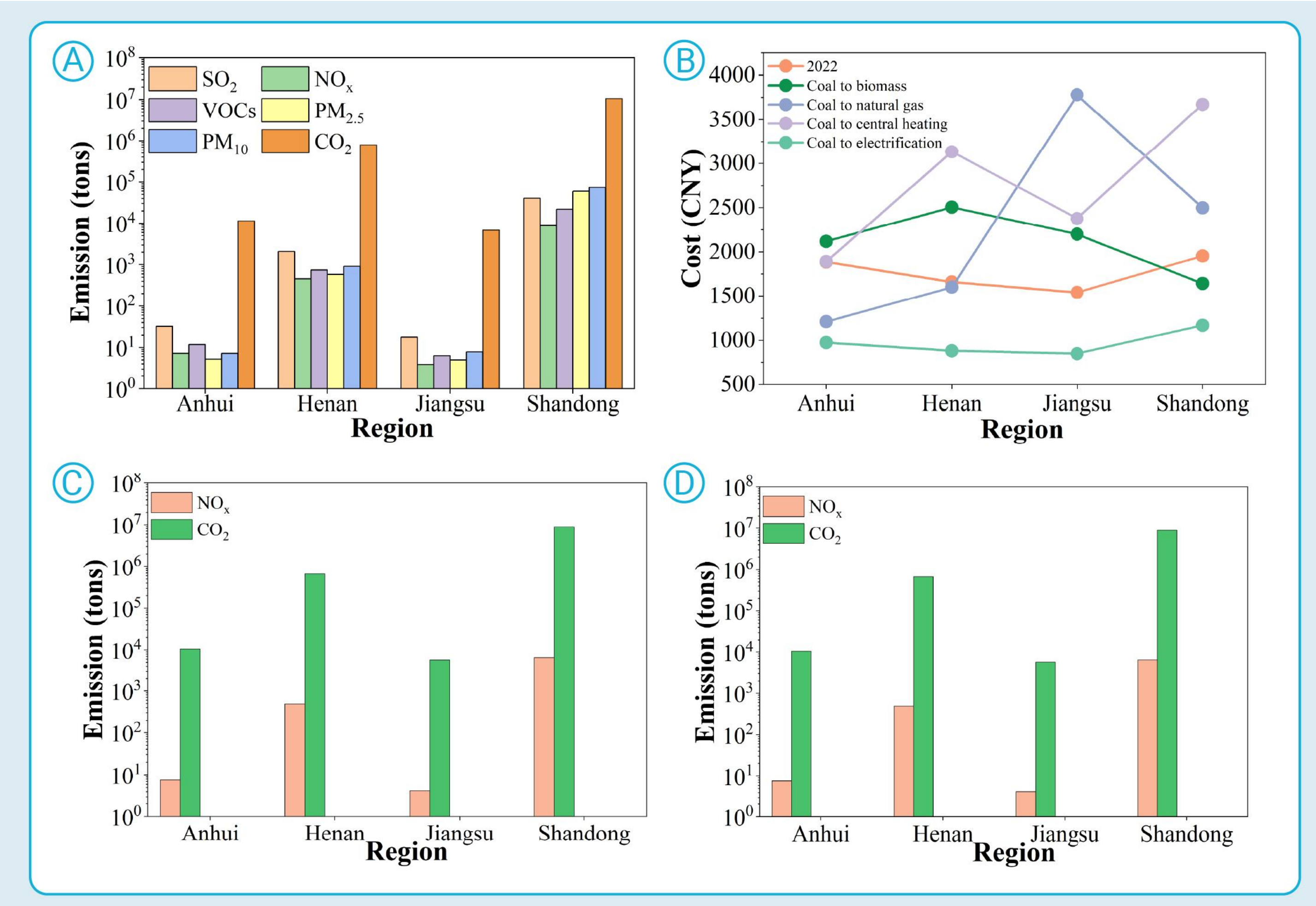

Figure 4. (A) Air pollutants and CO_2 emissions in 2022; (B) Heating cost under different extreme conditions; (C) Air pollutants and CO_2 emissions under “coal to biomass” condition; (D) Air pollutants and CO_2 emissions under “coal to gas” condition.

pollution prevention and control by the end of 2025. Consequently, this study examined the air pollutants and carbon emission reduction potential as well as costs of converting existing residential coal-based heating methods to clean heating ones , which reveals the changes when the goal of achieving zero residential coal consumption in JASH plain areas by the end of 2030.

Compared to the current emissions, the emissions of SO_2, $PM_{2.5}$, PM_{10} and CO_2 were projected to reduce by 51.6%, 53.1%, 55.6% and 100%, respectively, under the extreme condition that all residential coal consumptions were replaced by biomass (Figure 4A & C). However, the application of biomass increased the emissions of NO_x (7.9%) and VOCs (47.0%). Specifically, due to the application of biomass, the emission reductions of SO_2 (52.7%), $PM_{2.5}$ (56.0%) and PM_{10} (58.5%) were the largest in Shandong, and the increased NO_x and VOCs emissions were also the largest, which can be attributed to the huge heating demand in the winter of Shandong. Under the condition that all residential coal consumptions were replaced by natural gas, the emissions of SO_2, VOCs, $PM_{2.5}$ and PM_{10} dropped to zero, and the emissions of NO_x and CO_2 were reduced by 24.1% and 15.5% (Figure 4D). In addition, the application of natural gas would increase the emissions of air pollutants in Anhui, Henan and Jiangsu, while it will decrease the emissions in Shandong. It may show the huge clean heating conversion in Shandong. Replacing coal with natural gas for heating can alleviate emissions of air pollutants and CO_2, but it cannot increase residents' satisfaction. For example, after the implementation of "coal to gas" in the North China Plain, the overall satisfaction of residents is at a medium level.[30] The influencing factors of residents' satisfaction include heating level, perceived fairness, air quality and subsidy amount, among which residents have the highest satisfaction with heating level and the lowest satisfaction with subsidy amount. Emissions of central and electricity heating at the household level were zero. Although all electrification can reduce all air pollutants and carbon emissions in terms of households, the heating process of electrification could increase the load of the power plant, resulting in additional emissions of pollutants. However, with the development of wind and photovoltaic power generation in China, pollutants and carbon emissions will further decrease. Overall, existing research has examined the environmental effects of introducing clean energy into residential heating and found that this process can significantly reduce carbon emissions.[31] This conclusion aligns with the emission reduction analysis results presented in this paper. The cost of heating under different extreme conditions was shown in Figure 4B. The costs of residential coal for heating in Anhui, Henan, Jiangsu and Shandong were 1885, 1659, 1541 and 1593 CNY, respectively, in 2022. Also, the average heating cost in 2022 was smaller than the methods of biomass (2116 CNY), natural gas (2272 CNY) and central heating (2767 CNY).

Economic burden on the government and residents

The emission reduction analysis suggested that while the goal of “zero residential coal consumption” contributed significantly to reducing air pollutants, it also led to a rise in heating expenditures. For households, the cost may play an important role in heating strategies.[32] Heating costs are usually composed of equipment costs and energy costs. Although the cost of electricity heating was small, the price of electric heating equipment is higher than that of coal-fired stoves. For decision makers, they should consider heating cost, air quality and carbon emission control. Therefore, this study, drawing on the subsidy policies implemented in existing clean heating programs, designed three scenarios to assess the economic burden on both the government and residents resulting from clean heating transitions (1) Full Cost-Bearing by Residents (FBR), (2) Operation-Only Cost-Bearing by Residents (OBR), and (3) No Additional Cost Burden on Residents (NBR) compared to traditional residential coal use, with the goal of providing policy

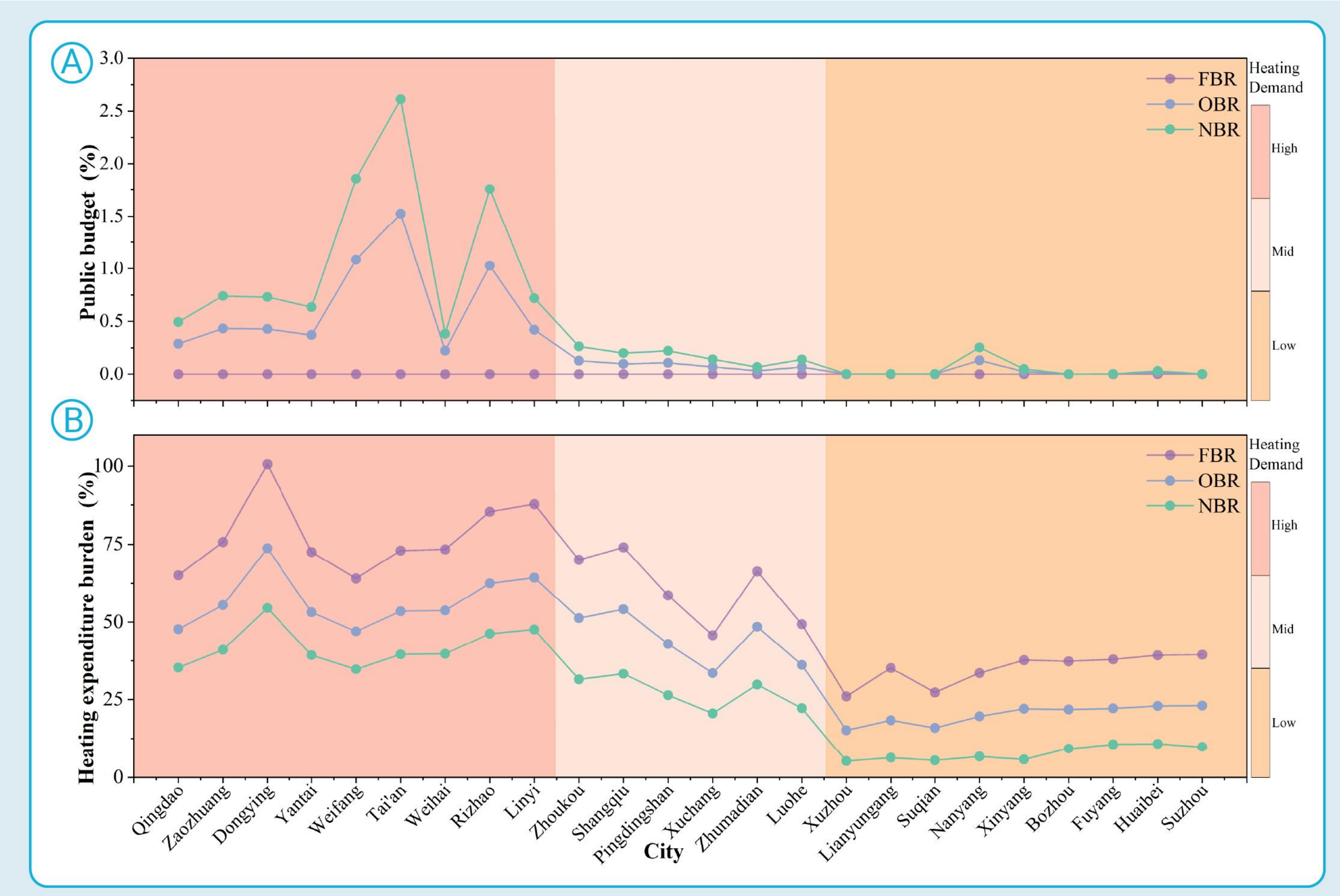

Figure 5. (A) Proportion of the public budget of the general treasury under three scenarios; (B) Heating expenditure burden of residents.

insights for tailoring clean heating strategies and financial support mechanisms across different regions.

Under the FBR scenario, where the government provided no financial support for residential heating, the heating expenditure burden on residents across cities ranged from 26% to 101%. Among all surveyed cities, heating expenses in Dongying were on par with residents' affordability, and in other cities, heating expenses did not exceed their affordability. In high-demand heating cities, the burden was relatively higher, exceeding 60% in all cases, and approaching 90% in Rizhao and Linyi, primarily due to longer heating periods that resulted in higher total costs. For medium-demand cities, the burden ranged from 46% to 74%, with Zhoukou and Shangqiu experiencing the highest pressure. This was largely attributed to their relatively low rural per capita disposable income, which is 23%-26% below the average for heating cities in Shandong, Jiangsu, Anhui and Henan. In contrast, low-demand cities showed a lighter burden, ranging from 26% to 39%, with Xuzhou and Suqian having the lowest levels, both under 30%. Under the OBR scenario, the government's clean heating expenditure accounted for 0.0%-1.5% of general public budget expenditure, indicating a relatively low fiscal burden. As a result, the heating expenditure burden on residents ranged from 15% to 74% across cities. This scenario still revealed a clear pattern of higher burden in high-demand heating cities, where residents' payment pressure generally exceeds 50%. In medium-demand heating cities, only Zhoukou and Shangqiu exhibited burdens above 50%. In contrast, in low-demand cities such as Xuzhou, Lianyungang and Suqian, the burden was relatively low, falling below 20%. Under the NBR scenario, the government's clean heating expenditure accounted for 0.0%-2.61% of the general public budget expenditure, indicating a modest fiscal burden. In this scenario, the heating expenditure burden on residents in high-demand cities was significantly reduced, with only Dongying exceeding the 50% threshold. In medium-demand cities, the burden declined to approximately 27%, while in low-demand cities, it fell further to around 10%.

Among three scenarios, although the clean heating expenditure imposed a minor burden on government budgets, significant inter-city differences in heating duration and rural per capita disposable income resulted in considerable disparities in the affordability of clean heating. For instance, in 2024, Dongying had the lowest rural per capita disposable income (20,000 CNY) among high-demand heating cities. In comparison, the incomes in Qingdao, Yantai and Weihai were 1.6, 1.5, and 1.5 times higher than that of Dongying, respectively. Although Zhoukou, Shangqiu and Zhumadian had lower heating costs than high-demand cities, their rural per capita disposable incomes were also below 20,000 CNY (18,000, 18,000 and 19,000 CNY, respectively), which was the lowest among the 24 cities surveyed. As a result, the heating expenditure burdens in these cities were comparable to those in wealthier cities such as Tai'an, Weihai and Yantai.

In summary, the burden on residents was a key determinant in designing the cost-sharing mechanisms for the construction and operation of clean heating systems. To ensure long-term sustainability and accommodate local heating habits, a dual-subsidy approach covering both capital and operating costs was recommended for high-demand heating cities. For medium-demand cities, subsidies should primarily target construction costs, with additional support for operating costs in cities such as Zhoukou and Shangqiu. This is similar to the assessment results of Zhang et al. in the BTH region, where they found that coal to electricity conversion in Hebei Province requires government subsidies to achieve net social benefits.[33] In low-demand heating cities, the full cost of clean heating can be borne by residents.

Uncertainty and limitations

This study provides a comprehensive assessment of residential coal consumption in the JASH region, yet several limitations should be acknowledged. First, although household-level survey data offer valuable insights into local energy use patterns, the data may be subject to self-reporting biases and seasonal variations that could affect the accuracy of fuel quantity estimates. Second, the emission factors applied in the inventory construction are based on existing literature and may not fully reflect the diversity of combustion technologies and fuel qualities in the region. Third, the heating cost analysis is based on representative equipment and standard operation assumptions, which may differ from actual household behaviors and regional energy prices. Lastly, this study does not quantitatively model the long-term environmental or health co-benefits of the clean heating transition, which are important for holistic policy evaluation. Future research should incorporate dynamic behavioral data, high-resolution emission measurements, and integrated cost-benefit frameworks to further refine the understanding of clean heating feasibility in transitional regions.

CONCLUSION

Based on extensive survey data in 2022, this study presented comprehensive multi-scale assessments of residential coal consumption in the borders of the JASH region, focusing on energy consumption, environmental impact and economic burden. The key findings were summarized below:

(1) There were more than 4 million households that consumed 5.92 million tons of residential coal for heating within the borders of four provinces. Influenced by regional heating characteristics, heating-related coal use was identified as the dominant contributor to residential coal consumption in the study area, accounting for an average of 96.21%. The average heating period was approximately 90 days, with usage primarily concentrated in rural areas and regions adjacent to major cities, indicating notable heterogeneity across the region.

(2) The emissions of SO_2, NO_x, VOCs, $PM_{2.5}$, PM_{10} and CO_2 from residential coal for heating were 41.0, 6.1, 22.3, 38.3, 49.5 and 11275.3 kt, respectively. The emission reduction analysis suggested that while the goal of "zero residential coal consumption" contributed significantly to reducing air pollutants, it also led to a rise in heating expenditures.

(3) Under the heating cost scenario analysis, clean heating expenditures posed only a minor burden on government budgets. However, the heating expenditure burden on residents is a key factor in determining the cost-sharing mechanism for the construction and operation of clean heating systems. Therefore, differentiated subsidy policies should be adopted based on regional heating demand levels.

Taking the conditions of sufficient funds, reduced energy constraints and improved technological capabilities in China into consideration, there was still a huge heating demand in cities located at the border of northern and southern China. We hope that this research can provide insights and support for future clean heating.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

Readers may contact the corresponding authors for data upon reasonable request.

SUPPLEMENTAL INFORMATION

It can be found online at https://doi.org/10.59717/ipj.energy-use.2026.100051