



Pollution and carbon reduction effects of the pilot policy on clean winter heating in Northern China: Evidence from the county level

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ARTICLE INFO

Keywords:

Pilot policy on clean winter heating
Pollution and carbon reduction
Multiperiod difference-in-differences model
County-level analysis
Northern China

ABSTRACT

Coal dependence and inefficient decentralized heating have significantly increased China's energy consumption for winter heating, increasing air pollution and exacerbating the greenhouse effect. In 2017, China implemented the Pilot Policy on Clean Winter Heating in Northern China, aiming to achieve high central heating coverage and cleaner energy consumption. Studying the effects of this policy can help promote its implementation and serve as a reference for effective adjustment of the contents in the future. However, few studies have investigated this policy and its carbon reduction effects, and most focus on the provincial or city levels. Therefore, this paper considers the policy's influence on air pollution and carbon emissions at the county level to provide a precise and comprehensive assessment of the policy effects. We use panel data from 1 290 counties in 15 provinces in Northern China from 2014 to 2021, applying a multiperiod difference-in-differences model to quantify the impact of the policy on carbon emissions and air quality in the pilot area. We then conduct a series of tests to demonstrate the robustness of the results and analyze the mechanisms of the policy effects from two perspectives, namely, central heating and natural gas use, through a mediating effect model. Finally, we examine the heterogeneity of policy effects between counties based on geographic location and per capita income levels of rural residents through a moderating effect model. The results reveal that the policy significantly reduces air pollution and carbon emissions in the pilot area by increasing the central heating area and natural gas use. Compared with the central and western regions in the north and areas with low-income rural residents, the policy effects in the eastern regions in the north and areas with high-income rural residents are more pronounced.

1. Introduction

An increase in energy consumption for winter heating intensifies air pollution and exacerbates the greenhouse effect, seriously threatening human survival and development. In this regard, China, a highly populous country that accounts for a quarter of the world's heating needs (Chen et al., 2022), has long suffered from the environmental pressure caused by winter heating. In 2013, the State Council issued the *Action Plan for Air Pollution Prevention and Control*, explicitly proposing to accelerate coal-to-electricity and coal-to-gas projects. As a foundation of this policy, China's northern region, which has low temperatures and considerable heating energy consumption in winter, has become a key target area for transformation. In 2017, the Ministries of Finance, Housing and Urban-Rural Development, and Environmental Protection, and the National Energy Administra-

tion implemented a targeted regional governance policy—the Pilot Policy on Clean Winter Heating in Northern China (hereafter, the “clean heating pilot policy”). The pilot demonstration period was set at three years, requiring the pilot cities to undertake clean heating retrofits on the heat source and user sides to swiftly establish a clean heating model that is “enterprise-oriented, government-promoted, and affordable to residents”. In addition, the Ministry of Finance and other relevant departments conducted annual performance appraisals of pilot cities and liquidated incentive funds to improve the efficient use of special funds. In recent years, China has continued to add new clean heating pilots. The experience of initial pilots can provide a valuable reference for the cities that follow them, helping them complete their clean heating transformation more efficiently. Additionally, policy effects directly reflect the quality of the policy, providing reliable evidence and support for adjusting the contents promptly,

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<https://doi.org/10.1016/j.cjpre.2025.01.008>

Received 15 August 2024; Accepted 17 December 2024

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thus contributing to its promotion and optimization.

Previous studies on clean heating have primarily focused on three perspectives: residents' behavioral motivation, implementation effects, and optimization paths. In terms of residents' behavioral motivation, as end consumers of winter heating, their behavioral motivations are crucial for advancing the clean transformation of heating. Using questionnaires (Liu et al., 2022a) and various social psychological models (Emmerich et al., 2020), scholars have quantitatively analyzed the influencing factors of residents' decisions to adopt clean heating, classifying them into personal or external factors. Personal factors refer to the psychological differences among residents (Li et al., 2022c), including their perceptions of the severity of environmental challenges (Bai et al., 2023), education (Swain and Mishra, 2020), personal habits (Mi et al., 2018), and satisfaction with policies (Xu and Ge, 2020), which can significantly impact residents' clean heating decisions. Meanwhile, external factors are related to the external environment established by the government and society, influencing residents' acceptance of clean heating through cost-benefit analysis and social networks (Luo et al., 2023), including government subsidies (Gong et al., 2020), energy costs (Wang et al., 2019b), income (Xie and Zhou, 2021), technical performance of equipment (Su et al., 2019), and support from family members (Li et al., 2022b). Regarding implementation effects, scholars have used methods such as difference-in-differences (DID) models and regression discontinuity designs to explore the economic, environmental, and human health benefits of clean heating. From the perspective of economic benefits, while clean heating can improve individuals' social status, this phenomenon is expected to gradually weaken over time (Zhao et al., 2022). Furthermore, the high cost of clean energy and equipment increases low-income households' burden for heating, exacerbating the wealth gap to an extent (Feng et al., 2021). Concerning environmental benefits, clean heating improves air quality by optimizing the energy structure and reducing emissions of air pollutants such as fine particulate matter ($PM_{2.5}$ and PM_{10}), CO, SO_2 , NO_x , and O_3 (Song et al., 2023; Xue et al., 2023; Zhang et al., 2020). Regarding human health benefits, clean heating has a significant positive impact, indirectly reducing morbidity and mortality from cardiovascular and respiratory diseases (Li et al., 2022a) due to the improved air quality (Liu et al., 2022c). Concerning optimization paths, scholars have proposed strategies from political, energy use, and technological perspectives. From a political point of view, the intensity of government intervention can positively affect residents' clean heating practices (Li et al., 2022c). Establishing a management and monitoring platform, differential pricing (Zhang et al., 2021), and subsidy policies (Hou et al., 2022) can contribute to advancing clean heating. From the energy use perspective, natural gas, electricity, biomass, solar energy, industrial waste heat, clean coal, and other energy sources represent low-emissions heating (Tang et al., 2021). Among them, studies have shown that electricity and biomass energy are suitable for most areas and will become primary energy sources for rural heating (Xu and Ge, 2023). Finally, from the technological point of view, energy consumption can be reduced by optimizing the clean operation of heat exchange networks (Trafczynski et al., 2023), improving the energy efficiency of the building envelope (Liu et al., 2022b), and introducing electric heating devices and thermal energy storage systems (Wang et al., 2019a).

Although previous studies have discussed related contents of clean heating from multiple angles, some areas for improvement remain concerning the implementation effect. First, while the clean heating pilot policy is directly related to clean heating, few studies have investigated the effects of this policy. Most studies have focused on air pollution but neglected its impact on carbon emissions. Second, the clean heating pilot policy focuses on the governance of scattered coal heating, a phenomenon that generally occurs in rural areas that have not yet been covered by central heating. However, existing studies have predominantly focused on provinces and cities, which have a

substantial gap in terms of administrative division level compared with rural areas; therefore, their data may not be specific and representative of the implementation of the policy in rural areas.

This study uses panel data from 1 290 counties in 15 provinces in northern China as the research sample to analyze the pollution and carbon reduction effects of the clean heating pilot policy. We first construct a multiperiod DID model to quantitatively estimate the policy's effects on air quality and carbon emissions. Second, we demonstrate the robustness of the results using parallel trend, placebo, dependent variable substitution, shortened sample period, control variable lag, propensity score matching (PSM)-DID model, and endogeneity tests. We then explore the mechanisms of the policy from the perspectives of central heating and natural gas use with a mediating effect model. Finally, we analyze the heterogeneous policy effects between counties based on differences in geographic location and rural residents' per capita income by applying a moderating effect model. The specific research framework is illustrated in Figure 1.

This paper makes the following contributions and innovations. First, in addition to the air quality index (AQI), the study also considers carbon emissions. This approach is essential for realizing China's carbon peak and neutrality goals and evaluating the policy effects of the pilot more scientifically and comprehensively. Second, we refine the data scale by using county-level data to analyze the policy effects. Counties' administrative division is more microcosmic compared with that of provinces and cities; therefore, the data used in this study are more reflective of the policy focus—managing the scattered use of coal heating in rural areas. Additionally, microscopic administrative divisions reflect specific regional characteristics and economic conditions, making county-level data on carbon emissions and air quality more accurate. With counties as the study object, this paper provides robust evidence to confirm the effectiveness of the policy in reducing pollution and carbon emissions; further, it explores the mechanism of the policy more specifically in terms of heating mode and energy type.

The rest of the paper is organized as follows. Section 2 presents the research hypotheses. Section 3 describes the research methodology and data. Section 4 describes the research results and their analysis. Section 5 presents conclusions and gives policy recommendations.

2. Research hypotheses

The clean heating pilot policy is intended to encourage local governments to innovate regulations, improve policy implementation measures, and guide enterprises and society to increase capital investment with central financial incentives to eliminate scattered coal heating in pilot areas and establish a demonstration effect from clean energy substitution. Coal has a high carbon emission factor, and its combustion emits large amounts of SO_2 , nitrogen oxides, and other harmful gases. Therefore, a strong correlation has been demonstrated between coal consumption, carbon emissions, and air quality (Deng et al., 2021; Wang et al., 2020; Wang et al., 2021). Accordingly, we propose hypothesis H1:

H1: The implementation of the clean heating pilot policy will help improve the pilot areas' carbon emissions and air pollution.

The pilot policy focuses on the issue of scattered coal burning, starting with heating mode and energy type, to advance the clean transformation of heating in northern China. Regarding the heating mode, local governments have increased the central heating area and reduced traditional decentralized heating based on the principle of "centralization as the mainstay and decentralization as a supplement". Central heating refers to constructing a centralized heating station to deliver heat to users through a heat pipe network, which is effective in fulfilling the national goal of energy conservation and emissions reduction. According to the scale effect theory (Huang and Guo, 2024), central heating can improve resource allocation and heat output efficiency. First, the central heating system can unify energy use

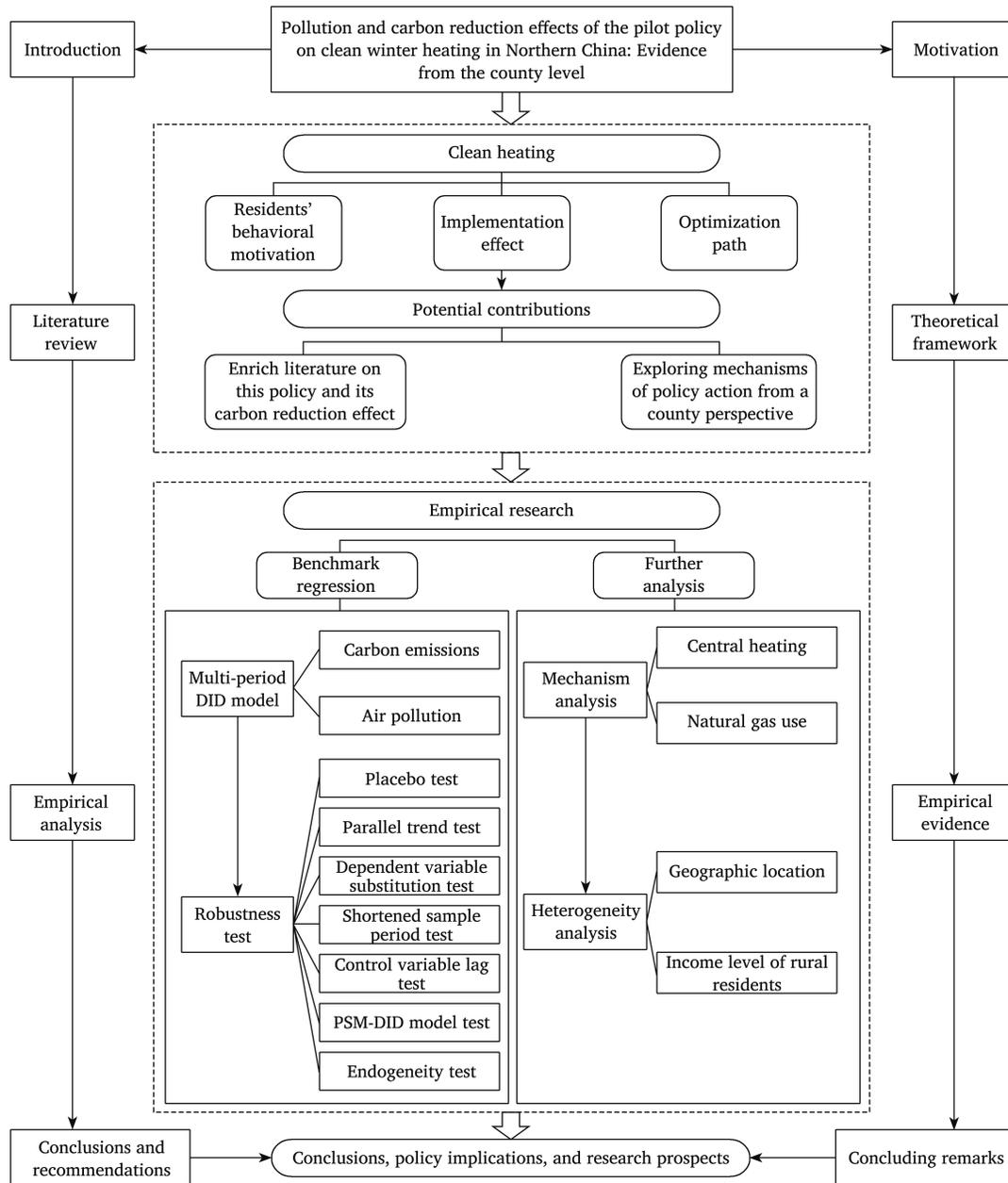


Figure 1. Technical roadmap for policy effect research

and consumption management to ensure stable heat output. Second, centralized fuel combustion has superior thermal efficiency (Guo et al., 2015). Finally, heating equipment’s centralized placement can reduce the considerable heat loss that occurs during the transportation of energy sources such as coal. From the externality theory perspective, central heating is cleaner and has stronger positive resource and environmental externalities (Chen, 2021). Central heating systems are fully equipped with dedusting equipment to prevent substantial pollutant emissions from the combustion process (Chen et al., 2023). Moreover, heat recycling can also be achieved between heat sources. According to the circular economy theory (Wang et al., 2024), this initiative can effectively reduce energy consumption and reduce pollution and carbon emissions. Accordingly, we propose hypothesis H2:

H2: The clean heating pilot policy advances pollution and carbon reduction by increasing the central heating area.

Regarding energy type, the government actively promotes using clean energies such as natural gas and accelerating the clean transfor-

mation of heat sources. The implementation of this transformation involves two main actors: enterprises on the supply side and residents on the consumption side. Policy support and financial input from the central government will generate policy benefits for enterprises. According to signaling theory, to establish a positive image, maintain a good reputation, and gain strong support from the government, enterprises tend to respond to policy calls for clean production (Bu and Zhao, 2022) and increase the natural gas supply to meet the heating demand. For residents, comprehensive promotion of the concept of green development and accelerated construction of ecological civilization has helped environmental protection to be generally recognized across society (Yu and Ma, 2023), promoting residents’ transformation from “rational economic” actors to “ecological economic” actors, meaning that they weigh environmental benefits from the perspective of ecological rationality while considering economic benefits. As a result, residents will voluntarily choose more energy-saving and low-carbon heating methods within their financial means. Moreover, a se-

ries of clean energy subsidies provided by local governments have eased the price barrier of coal-to-gas transitions, further strengthening the energy substitution effect of natural gas and guiding residents’ green consumption behavior. Energy consumption for heating in northern China has been dominated by coal for a long time, and transitioning to natural gas will effectively optimize the energy structure. As a clean energy source, natural gas has much lower carbon emissions intensity than coal, and its main component is methane, with extremely low sulfur and nitrogen content (He et al., 2022). Therefore, the increased use of natural gas will effectively reduce the environmental burden (Kuang and Lin, 2023; Qin et al., 2018). Accordingly, we propose hypothesis H3.

H3: The clean heating pilot policy reduces pollution and carbon emissions by incentivizing enterprises to expand the supply of natural gas for heat and residents to increase the proportion of natural gas heating applications.

3. Research design

3.1. The multiperiod DID model

The DID model is an effective approach for assessing the impacts of policy interventions as it eliminates gaps related to time and individual factors, mitigating estimation bias (Lin et al., 2021). The time dummy variables in the traditional DID model can only be set to a uniform treatment time point, whereas they can be set separately for different individuals in the multiperiod DID model. Therefore, the multiperiod DID model can distinguish individuals exposed to policy shocks in different periods. In this paper, we use the clean heating pilot policy as a quasi-natural experiment and limit the study to 15 provinces in northern China. We set the pilot areas as the experimental group and the remaining areas as the control group. Given the existence of different time points for the implementation of the pilot, the multiperiod DID model is more appropriate for our research purposes. The model is constructed as follows:

$$Y_{it} = \alpha_0 + \alpha_1 D_{it} + \alpha_2 CTL_{it} + \varphi_i + u_i + \varepsilon_{it}, \tag{1}$$

Where, i represents the region and t represents the year. Y_{it} and D_{it} are the dependent and independent variables, respectively. The coefficient of the independent variable α_1 is the parameter of focus in this study, where positive and negative statistical significance indicates the effectiveness of the clean heating pilot policy, denoting the direction of policy effects, and its size implies the extent of the policy’s influence on the dependent variable. CTL_{it} and α_2 denote the set of control variables that may affect the dependent variable and their coefficients, respectively. φ_i represents a time-fixed effect that

only varies across counties. u_i is an area-fixed effect that only varies across time. ε_{it} is the error term, and α_0 is the intercept term.

3.2. Variable selection and data sources

3.2.1. Variable selection

The specific variables for the study are presented in Table 1. The dependent variables are AQI and CO_2 . AQI is a comprehensive indicator that effectively measures air quality (Yang et al., 2024) and is also the main reference for ecological benefits when the Ministry of Finance conducts annual pilot performance evaluations. CO_2 is the direct cause of the greenhouse effect and one of China’s most concerning environmental challenges (Huang et al., 2022). Therefore, we use the two indicators as dependent variables to explore the effects of the clean heating pilot policy. We also perform robustness tests using $PM_{2.5}$ and CEI as substitute variables for AQI and CO_2 , respectively.

The independent variable is CHPP, the interaction of treat and time. If the county belongs to the policy pilot and is affected by the policy, $treat = 1$, otherwise, $treat = 0$. Suppose the year of becoming the pilot is T , if $t \geq T$, then $time = 1$, otherwise, $time = 0$. Five batches of cities have been selected as policy pilots for the transformation of clean heating. Considering the maturity of pilot implementation, we take 43 pilots from the first three batches as our research object. The policy was implemented in 2017, 2018, and 2019, corresponding to the publication of three pilot lists.

To control for potential interference from unobservable external factors on the research findings, we use industrial development, industrial structure, financial development, population density, public financial support, and economic development as control variables (Bi et al., 2024; Cheng et al., 2018; Zhang and Liu, 2024). X1 represents industrial development. As the sector that consumes the most energy in China (Wang et al., 2020b), industrial development is intimately intertwined with carbon emissions and air pollution. X2 denotes industrial structure, the optimization of which facilitates the transition of development advantages from primary and secondary industries to the tertiary industry. Relevant studies have demonstrated that tertiary industry growth contributes to improving energy utilization efficiency, reducing air pollution and carbon emissions (Wu et al., 2023). X3 reflects counties’ financial development. Areas with high financial development generally have easier access to funds to combat environmental challenges (Bi et al., 2024). X4 denotes population density; a denser population engages in more frequent production and consumption activities, which exacerbates environmental problems. X5 represents public financial support; local finances provide economic support for environmental governance, and increased fiscal revenue will likely help reduce air pollution and carbon emissions. X6 and X7 re-

Table 1
Main variables

Type of variables	Abbreviations	Definitions
Dependent variables	CO_2	Annual per capita carbon emissions
	AQI	Natural logarithm of the annual air quality index
	CEI	Annual carbon emissions intensity
	$PM_{2.5}$	Natural logarithm of annual $PM_{2.5}$ emissions concentrations
Independent variables	CHPP	Clean heating pilot policy
	X1	Ratio of industrial value added to gross domestic product (GDP)
	X2	Ratio of tertiary industry value added to GDP
	X3	Ratio of the sum of the balance of residents’ savings deposits and loans from financial institutions at the end of the year to GDP
Control variables	X4	Ratio of the registered population to the administrative area
	X5	Ratio of general public budget revenue to GDP
	X6	Natural logarithm of total retail sales of consumer goods
	X7	Natural logarithm of total fixed asset investment in the whole society

flect the results of economic and social development, which are strongly correlated with air pollution and carbon emissions (Huang et al., 2023; Zhang and Liu, 2024). To address multicollinearity, we calculate the variance inflation factor among the variables, revealing that they are all less than 5 with no multicollinearity.

3.2.2. Data sources

As noted previously, we use panel data for 1 290 counties in 15 provinces in northern China from 2014 to 2021. The 15 provinces include Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Henan, Shandong, Shaanxi, Gansu, Ningxia, Xinjiang, and Qinghai (Zheng et al., 2020). Table 2 presents the descriptive statistics of each variable. Counties’ carbon emissions data are obtained from the Emissions Database for Global Atmospheric Research. PM_{2.5} data are obtained from a dataset published by the atmospheric composition research group at Washington University in St. Louis. The remaining data are obtained from the *China County Statistical Yearbook* and the *China Regional Economic Statistical Yearbook*. Natural gas and central heating data are from the *China County Construction Statistical Yearbook*. We deflate the GDP data using 2014 as the base period to eliminate the effect of inflation and enhance comparability. We also use the linear interpolation method to fill in missing values for all variables and shrink the data tails by 1%. Samples that still have missing data after interpolation are excluded from the dataset in the regression.

Table 2
Descriptive statistics

Variables	Number	Mean	Standard deviation	Min	Max
CO ₂	9 958	3.062	4.130	0.165	25.358
AQI	9 469	4.362	0.294	3.584	5.070
CEI	8 196	0.559	0.615	0.071	3.788
PM _{2.5}	10 184	3.692	0.452	2.185	4.603
X1	4 972	0.380	0.234	0.016	1.285
X2	8 018	0.403	0.145	0.136	0.883
X3	7 063	1.560	0.863	0.254	4.840
X4	9 308	0.066	0.171	0.001	1.270
X5	8 186	0.053	0.030	0.011	0.185
X6	10 031	12.971	1.304	9.491	15.741
X7	8 884	14.035	1.023	11.234	16.120

4. Results and discussion

4.1. Benchmark regression

To verify the pollution and carbon reduction effects of the clean heating pilot policy posited in hypothesis H1, we use AQI and CO₂ as the respective dependent variables in equation (1), presenting the regression results in Table 3. Columns (1) and (3) present estimates of the policy’s impact on carbon and air pollution emissions without control variables. Columns (2) and (4) include the control variables. The findings reveal that the CHPP coefficients are significantly negative at the 1% level before and after introducing control variables, indicating that the clean heating pilot policy significantly reduces carbon emissions and air pollution. Furthermore, the CHPP coefficients in Columns (2) and (4) are -0.143 9 and -0.075 7, indicating that the policy has decreased carbon and air pollution emissions in the pilot areas by 14.39% and 7.57%, respectively. Specifically, the special bonuses established by the central government have eased financial pressure on local governments and incentivized them to increase investments for the governance of scattered coal heating, fully realizing the

multiplier and leverage effects of financial support. By the end of 2022, the clean heating area in the northern region increased by 9.4 billion square meters from 2016, and coal consumption decreased by more than 70 million tons. As a major source of air pollution and greenhouse gases, reducing coal consumption has directly lowered carbon and air pollution emissions. Therefore, hypothesis H1 is verified.

Table 3
Benchmark regression

Variables	(1)	(2)	(3)	(4)
	CO ₂	CO ₂	AQI	AQI
CHPP	-0.168 1*** (0.030 8)	-0.143 9*** (0.042 2)	-0.067 1*** (0.003 4)	-0.075 7*** (0.004 7)
X1		0.324 7** (0.164 0)		0.091 2*** (0.015 4)
X2		-0.139 8*** (0.046 6)		-0.008 7*** (0.002 6)
X3		-0.213 6 (0.147 3)		-0.037 9*** (0.005 6)
X4		-0.193 1* (0.101 0)		0.004 6 (0.003 0)
X5		0.180 9* (0.092 7)		0.011 6 (0.009 3)
X6		-0.339 8* (0.191 9)		0.013 0** (0.006 3)
X7		-0.100 0** (0.038 6)		-0.008 7* (0.004 8)
Constant	3.088 9*** (0.011 4)	10.226 9*** (2.746 8)	4.373 0*** (0.001 0)	4.428 6*** (0.109 8)
Area-fixed effect	YES	YES	YES	YES
Time-fixed effect	YES	YES	YES	YES
N	9 953	4 079	9 469	3 716
R ²	0.9522	0.9747	0.9060	0.928 9

Notes: Robust standard errors are in parentheses. *, **, and *** indicate significance at 10%, 5%, and 1% levels, respectively.

4.2. Robustness tests

In the previous section, we demonstrate that the clean heating pilot policy significantly reduces carbon and air pollution emissions in pilot areas. However, these results could be affected by time trends, other unobservable factors, dependent variable selection specificity, earlier relevant policies, correlations between control and dependent variables, sample selection bias, and reverse causality. Therefore, we apply a series of tests to rule out these possible influences and demonstrate the robustness of our findings.

4.2.1. Parallel trend test

Exploring the clean heating pilot policy’s pollution and carbon reduction effects should satisfy the parallel trend assumption, demonstrating no trend difference in CO₂ and AQI between regions prior to the policy implementation. To exclude the effect of time trends, we use the event study method to obtain coefficient estimates for each year, presenting the results of parallel trend tests in Figures 2 and 3. The policy was implemented in 2017. To prevent the inclusion of extraneous factors that may affect the results because the time frame is too early and avoid the environmental impact of the national carbon emissions trading market opening in 2021, we set the time frame of the test to 2014–2021. In addition, to avoid multicollinearity, we take the first year before policy implementation as the base year and omit it. The results reveal that the 95% confidence interval of the regression coefficients prior to policy implementation contains 0, implying

that the coefficients are insignificant. In other words, no significant difference is evident between the experimental and the control groups at this stage. Meanwhile, after policy implementation, the coefficients are all significantly less than 0, indicating that, compared with the control group, the experimental group experiences a remarkable decrease in carbon and air pollution emissions under the policy shock, passing the parallel trend test.

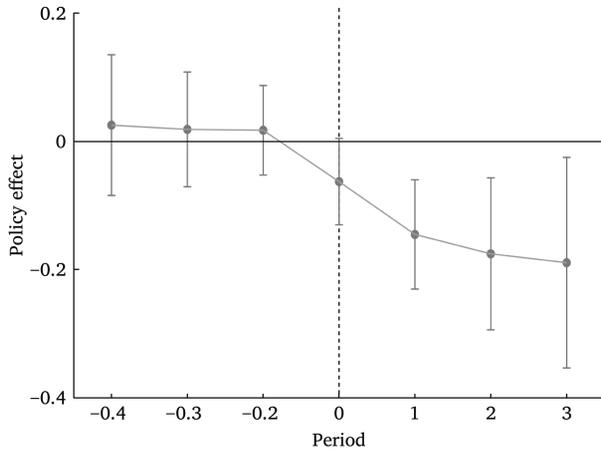


Figure 2. Parallel trend test for CO₂

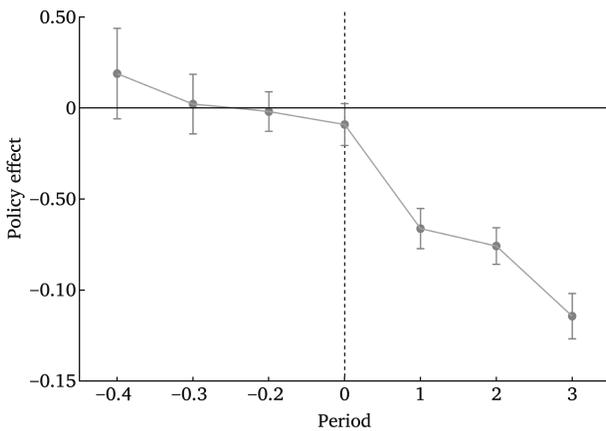


Figure 3. Parallel trend test for AQI

4.2.2. Placebo test

To exclude the influence of other unobservable factors on the estimation results, we reference the previous literature (Pan et al., 2024), randomizing the pilot areas and policy time and conducting 500 sampling regressions. The results in Figures 4 and 5 show that the coefficient estimates of the sampling regressions are uniformly distributed around 0, and most *p*-values are greater than 0.1, suggesting that the policy does not have a significant effect on CO₂ and AQI in the sample. In addition, the coefficient estimates of the sampling regressions are all on the right of the benchmark regression coefficients, implying that the previous regression results were not obtained by chance. This finding aligns with placebo test expectations and provides additional evidence that the pollution and carbon reduction effects of the clean heating pilot policy are not causally related to other unknown factors.

4.2.3. Dependent variable substitution test

Currently, air pollution in China is dominated by PM_{2.5} (Bai et al., 2019), and its emissions concentration is a specific reference for air quality level. As a relative indicator, CEI can effectively reflect the

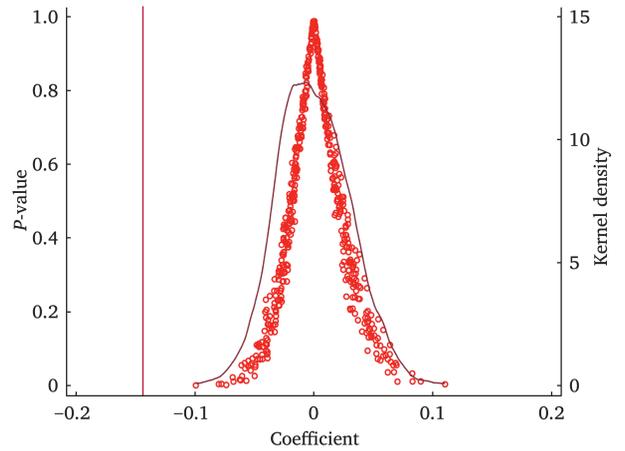


Figure 4. Placebo test for CO₂

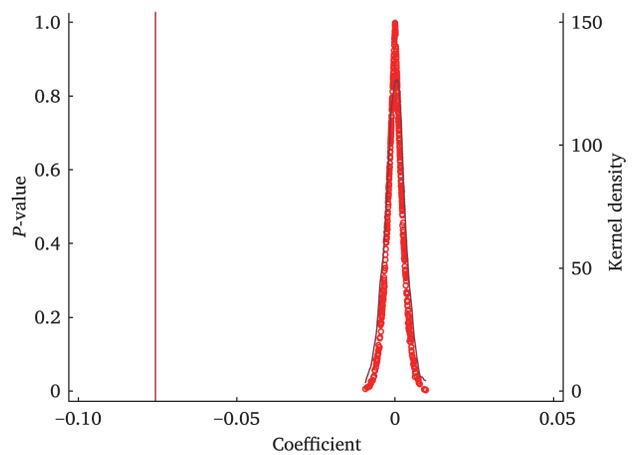


Figure 5. Placebo test for AQI

relationship between economic development and carbon emissions, contributing to the realization of national sustainable development. Therefore, to avoid the influence of dependent variable selection specificity on the empirical results, we use PM_{2.5} and CEI as substitute variables for AQI and CO₂, respectively, presenting the new regression results in Table 4. The CHPP coefficient is negatively significant at the 1% level regardless of whether control variables are included, further verifying the pollution and carbon reduction effects of the clean heating pilot policy.

Table 4
Dependent variable substitution tests

Variables	(1) CEI	(2) CEI	(3) PM _{2.5}	(4) PM _{2.5}
CHPP	-0.036 7*** (0.006 7)	-0.015 5*** (0.005 7)	-0.068 3*** (0.003 3)	-0.072 7*** (0.004 7)
Control variables	NO	YES	NO	YES
Constant	0.567 2*** (0.002 6)	1.100 4*** (0.233 5)	3.7044*** (0.001 1)	3.958 0*** (0.118 1)
Area-fixed effect	YES	YES	YES	YES
Time-fixed effect	YES	YES	YES	YES
<i>N</i>	8 196	4 151	10 184	4 115
<i>R</i> ²	0.924 2	0.975 5	0.964 5	0.965 6

Notes: Robust standard errors are in parentheses. *** indicates significance at the 1% level.

4.2.4. Shortened sample period test

As the first batch of pilots was established in 2017, to make the results more precise and reduce the possibility of interference from other relevant policies in the previous period, we reference previous research (Yu and Li, 2021) and reduce the sample period to 2016–2021. The regression results are presented in Columns (1) and (2) of Table 5. The coefficient remains significantly negative, further supporting the main finding that the clean heating pilot policy reduces carbon emissions and air pollution in pilot areas.

4.2.5. Control variable lag test

Considering the correlations between the selected control variables and dependent variables in this paper, to address potential endogeneity, we reference previous literature (Sun and Zeng, 2023), and lag all the control variables by one period to rerun the regression. As indicated by the results in Columns (3) and (4) of Table 5, the clean heating pilot policy still brings significant pollution and carbon reduction effects to pilot areas after the control variables are lagged.

4.2.6. PSM-DID model test

To address the influence of sample selection bias and time and individual differences, we employ the PSM-DID estimation method as a robustness test. We use the control variables as matching variables and re-select control samples with the same characteristics as the experimental group using one-to-three nearest-neighbor matching. According to the balance test results in Tables 6 and 7, no significant differences are observed between the two groups after matching. We then rerun the regressions with the matched samples, presenting the results in Columns (5) and (6) of Table 5. The direction and significance of the CHPP coefficients remain consistent with the benchmark results, confirming the robustness of the results.

4.2.7. Endogeneity test

Pilot implementation is based on a voluntary declaration and multisectoral evaluation where local governments consider the status of their carbon and air pollution emissions in the process of declaring the pilot, which could lead to reverse causality. To overcome this potential endogeneity concern, we reference previous literature (Deng et al., 2024; Wen et al., 2022), using the one-period lagged term of the independent variable as an instrumental variable (IV) and regress it using the two-stage least squares method. The results are presented in Table 8. The first-stage regression in Column (1) is significant, implying a strong association between the IV and CHPP. In Columns (2) and (3), the Kleibergen–Paap rk Wald *F* statistics are greater than the 10% critical value, passing the weak IV test. The Kleibergen–Paap rk LM statistics all reject the original hypothesis at the 1% level, satisfying IV identifiability. The two tests jointly indicate that the chosen IV is reasonable and valid. After considering endogeneity concerns, the

direction and significance of the second-stage regression results in Columns (2) and (3) of Table 8 remain consistent with the benchmark regression, further validating the reliability of our results.

4.3. Mechanism analysis

The previous analysis demonstrates that the clean heating pilot policy can have significant pollution and carbon reduction effects on the pilot areas. However, whether these effects are through the mechanisms posited in hypotheses H2 and H3 requires exploration. We reference Jiang (2022) to verify the influence of the policy on the mechanism variables, where a significant value indicates a mediating effect. We analyze the mechanisms of the policy effects from the perspectives of central heating and natural gas use. The central heating area in the county (M1) is used to measure the central heating mechanism. Meanwhile, natural gas use is measured from the supply side by the volume of gas sold for central heating (M2) and from the consumption side by the number of natural gas-using households (M3) and the share of the natural gas-using population in the total population (M4).

Table 9 reveals that the CHPP coefficients are all positive and significant at the 1% level, indicating that the clean heating pilot policy expands the central heating area and promotes the use of natural gas for heating in pilot areas. In the case of central heating, the scale effect of the centralized combustion of fuel and placement of heating equipment improves thermal efficiency while avoiding energy losses during transportation. Studies have demonstrated that the combined thermal efficiency of central heating is 80%–90%, saving nearly one times the fuel than decentralized heating (Chen et al., 2023). In addition, central heating systems are equipped with heat recovery and utilization devices and cleaner de-dusting devices to take full advantage of recycling economic benefits and positive resource and environmental externalities when transitioning from decentralized heating, effectively reducing carbon and air pollution emissions. Statistically, the combustion of coal in decentralized coal-fired boilers emits four to ten times more air pollutants and CO₂ emissions than centralized coal-fired boilers under the same heating conditions (Zhang et al., 2021). Therefore, hypothesis H2 is verified.

In the case of natural gas heating, the selection of regions as a policy pilot typically sends a message to the market about the government’s attitude toward the clean heating sector and the flow of dedicated financial resources. To gain financial support while advancing sustainable development, energy companies often respond to such policies by changing their production models and increasing the supply of natural gas heat sources. Furthermore, with the promotion of environmentally friendly practices in society, residents’ environmental awareness is increasing, and they tend to prefer cleaner heating methods. Moreover, the government has continued to provide heating

Table 5
Other robustness tests

Variables	(1) CO ₂	(2) AQI	(3) CO ₂	(4) AQI	(5) CO ₂	(6) AQI
CHPP	-0.118 3** (0.049 1)	-0.062 7*** (0.004 7)	-0.111 7** (0.047 4)	-0.068 2*** (0.004 5)	-0.207 2*** (0.073 8)	-0.061 5*** (0.006 8)
Control variables	YES	YES	YES	YES	YES	YES
Constant	11.549 6*** (3.117 9)	4.633 9*** (0.113 6)	8.377 7*** (2.196 8)	4.153 1*** (0.107 0)	14.598 8*** (5.238 8)	4.021 1*** (0.171 5)
Area-fixed effect	YES	YES	YES	YES	YES	YES
Time-fixed effect	YES	YES	YES	YES	YES	YES
<i>N</i>	2 948	2 739	3 617	3 343	2 223	1 786
<i>R</i> ²	0.969 7	0.947 1	0.972 7	0.941 6	0.973 5	0.935 9

Notes: Robust standard errors are in parentheses. ** and *** indicate significance at 5% and 1% levels.

Table 6
Balance test for CO₂

Variables		Mean		%bias	%reduct bias	T-test	
		Treated	Control			t	P> t
X1	Unmatched	0.430 9	0.339 9	39.2	93.0	13.85	0.00
	Matched	0.422 0	0.415 6	2.8			
X2	Unmatched	4.183 7	3.917 4	18.4	97.2	8.14	0.00
	Matched	3.8811	3.873 6	0.5			
X3	Unmatched	1.624 7	1.517 3	12.5	49.6	5.13	0.00
	Matched	1.626 4	1.572 3	6.3			
X4	Unmatched	8.908 1	5.401 6	20.5	96.5	9.38	0.00
	Matched	4.743 4	4.867 3	-0.7			
X5	Unmatched	0.567 3	0.499 1	22.7	94.3	10.15	0.00
	Matched	0.583 0	0.586 9	-1.3			
X6	Unmatched	13.397 0	12.730 0	54.8	94.4	25.37	0.00
	Matched	13.004 0	13.041 0	-3.0			
X7	Unmatched	14.338 0	13.844 0	50.9	97.3	22.82	0.00
	Matched	14.201 0	14.2150	-1.4			

Table 7
Balance test for AQI

Variables		Mean		%bias	%reduct bias	T-test	
		Treated	Control			t	P> t
X1	Unmatched	0.430 9	0.339 9	39.2	93.6	13.85	0.00
	Matched	0.407 2	0.401 3	2.5			
X2	Unmatched	4.183 7	3.917 4	18.4	79.0	8.14	0.00
	Matched	3.946 3	4.002 1	-3.9			
X3	Unmatched	1.624 7	1.517 3	12.5	49.4	5.13	0.00
	Matched	1.682 8	1.628 5	6.4			
X4	Unmatched	8.908 1	5.401 6	20.5	92.9	9.38	0.00
	Matched	4.970 3	5.219 9	-1.5			
X5	Unmatched	0.567 3	0.499 1	22.7	96.3	10.15	0.00
	Matched	0.565 3	0.562 8	0.8			
X6	Unmatched	13.397 0	12.730 0	54.8	89.6	25.37	0.00
	Matched	13.062 0	13.132 0	-5.7			
X7	Unmatched	14.338 0	13.844 0	50.9	85.0	22.82	0.00
	Matched	14.252 0	14.326 0	-7.6			

subsidies in recent years; the heating subsidies invested by the government in 2017–2019 amounted to 112.8 billion yuan (Chen et al., 2022). The initiative reduces the transfer costs of residents’ clean heating options, further increasing natural gas heating demand. As a clean energy source, the environmental benefits of natural gas as a substitute for coal have been well documented in previous studies. Specifically, with the same energy consumption, the quantity ratio of dust pollutants emitted from coal and natural gas is 148:1, that of SO₂ is 700:1, and that of NO_x is 29:1 (Tang and Liang, 2018). In addition, the carbon emissions factor of natural gas is only 0.59 times that of coal (He et al., 2022), and the greenhouse gases produced by gas-fired boilers are about half of those produced by coal-fired boilers (Cui et al., 2019). Therefore, an increased proportion of natural gas use for heating will have a positive effect on the environment, indicating that hypothesis H3 is valid.

4.4. Heterogeneity analysis

4.4.1. Geographic location

Considerable differences in population size and development ex-

Table 8
Endogeneity tests

Variables	(1)	(2)	(3)
	First-stage CHPP	Second-stage CO ₂	Second-stage AQI
CHPP		-0.233 4*** (0.078 5)	-0.091 5*** (0.005 2)
IV	0.601 7*** (0.017 4)		
Control variables	YES	YES	YES
Area-fixed effect	YES	YES	YES
Time-fixed effect	YES	YES	YES
N	3 586	3 521	3 247
R ²	0.398 8	0.049 8	0.131 5
Kleibergen-Paap rk LM		1 085.823 {0.00}	1 461.222 {0.00}
Kleibergen-Paap rk Wald F		1 199.050 [16.38]	4 125.989 [16.38]

Notes: Robust standard errors are in parentheses. Pvalues for the Kleibergen-Paap rk LM statistic are in curly brackets. The 10% critical value for the Stock-Yogo weak ID test is in square brackets. *** indicates significance at the 1% level.

Table 9
Mechanism tests

Variables	M1	M2	M3	M4
CHPP	0.202 7*** (0.063 9)	0.145 3*** (0.042 6)	0.188 3*** (0.050 5)	0.013 9*** (0.004 0)
Control variables	YES	YES	YES	YES
Constant	3.515 4** (1.467 5)	0.783 9 (1.090 8)	-2.768 1** (1.086 1)	0.022 8 (0.083 0)
Area-fixed effect	YES	YES	YES	YES
Time-fixed effect	YES	YES	YES	YES
N	2 200	1 015	2 581	2 507
R ²	0.847 0	0.749 2	0.838 9	0.832 5

Notes: Robust standard errors are in parentheses. ** and *** indicate significance at 5% and 1% levels, respectively.

ist across China; therefore, the implementation effects of the policy may vary depending on the pilot areas’ geographic location. We multiply geographic location (District) with CHPP, constructing a new district interaction term (CHPP × District) to rerun the regression. Compared to the central and western regions, the eastern region has a larger population, richer resources, and faster economic development, therefore we use it as a distinguishing condition. The district takes a value of 1 if the county is located in the eastern region in the north and a value of 0 if it is located in the central or western regions in the north. The results in Columns (1) and (2) of Table 10 reveal that the newly constructed district interaction term is significantly negative at the 1% level, which is consistent with the benchmark regression results, implying that geographic location positively moderates the air pollution and carbon emission reduction effects of the clean heating pilot policy, and the policy effect in the eastern regions is greater than that in the central and western regions.

First, the eastern region is superior to the central and western regions in terms of resource endowments, financial capacity, and degree of market development. Superior economic foundations can provide more financial and resource support to improve the infrastructure for clean heating. Second, the eastern region has more high-technology industries, establishing innovative conditions in heating facilities for an increase in heating energy efficiency. Finally, the si-

phoning effect of the higher levels of social development in the eastern region has contributed to attracting a higher quality of human capital and subsequently increased public demand for environmental improvements (Jia et al., 2023). The high public responsiveness ultimately enhances the policy effects in the eastern region.

Table 10
Heterogeneity tests

Variables	(1) CO ₂	(2) AQI	(3) CO ₂	(4) AQI
CHPP × District	-0.256 7*** (0.054 6)	-0.125 7*** (0.006 8)		
CHPP × Rural			-0.138 0*** (0.040 7)	-0.023 8*** (0.006 7)
Control variables	YES	YES	YES	YES
Constant	10.777 1*** (2.769 5)	4.672 9*** (0.105 3)	10.256 4*** (2.747 0)	4.439 2*** (0.109 5)
Area-fixed effect	YES	YES	YES	YES
Time-fixed effect	YES	YES	YES	YES
N	4 079	3 716	4 079	3 716
R ²	0.974 8	0.934 4	0.974 7	0.929 1

Notes: Robust standard errors are in parentheses. *** indicates significance at the 1% level.

4.4.2. Rural residents’ per capita income

The clean heating pilot policy focuses on controlling scattered coal heating in rural regions. Therefore, rural residents’ income may impact policy effects. We construct a new income interaction term (CHPP × Rural), multiplying rural residents’ per capita disposable income (Rural) with CHPP. Rural takes a value of 1 if it is above the median and 0 if it is not. Columns (3) and (4) of Table 10 reveal that the income interaction term is significantly negative, indicating that counties with higher incomes exhibit more apparent pollution and carbon reduction effects.

High costs can discourage low-income residents from making clean heating decisions. Pilot areas have adopted measures such as stepped electricity prices and subsidies for clean energy use, aiming to increase residents’ willingness to use clean heating through income effects, which could contribute to addressing scattered coal heating in rural regions. Although these measures have eased price barriers to energy substitution to some extent, clean energy is still more expensive than coal, and the cost of clean heating for rural residents remains high. Consequently, rural residents with lower incomes will choose relatively low-cost heating methods due to economic pressure, which has suppressed the policy’s role in reducing pollution and carbon emissions. Furthermore, high-income residents are more likely to be satisfied with clean heating. Energy consumption for winter heating in China has been dominated by coal for a long period, and the manufacturing technology of coal-fired equipment is therefore extremely mature. In contrast, clean energy has only been gradually promoted in recent years; therefore, the corresponding technology is relatively immature, and the quality of clean heating equipment in the market can vary (Li et al., 2022b). High-income residents are more willing to purchase high-quality heating equipment, which can give them a clear sense of the heating effects of clean heating equipment and prevent them from returning to coal-fired heating.

5. Conclusions and policy recommendations

This paper uses panel data from 1 290 counties in 15 provinces in northern China from 2014 to 2021 as the research sample, constructing a multiperiod DID model to empirically test the effects of the clean heating pilot policy on pollution and carbon reduction.

First, we employ the model to quantify the effects of the policy on air quality and carbon emissions. Second, we verify the robustness of the results through a series of tests. Third, we employ a mediating effect model to explore the mechanisms of the policy from the perspectives of central heating and natural gas use. Finally, we analyze the heterogeneity of policy effects based on differences in geographic location and rural residents’ per capita income using a moderating effect model. The main conclusions obtained in this paper are as follows.

(1) The start and end points of the clean heating pilot policy are the elimination and substitution of scattered coal heating. After the implementation of the pilot, this problem has been effectively addressed, significantly reducing air pollution and carbon emissions. This conclusion remains robust after a variety of tests.

(2) The policy can start with the heating mode and energy type to achieve its pollution and carbon reduction function. Specifically, expanding the central heating area in a county effectively brings the scale effect and its positive environmental externalities into play, and promoting natural gas heating optimizes the energy structure. Both modes contribute to the realization of the policy’s effects in reducing air pollution and carbon emissions.

(3) Significant heterogeneity is evident in terms of geographic location and rural residents’ per capita income. The superior economic foundation and quality of human capital in the eastern region in the north establish favorable technical conditions and increased public responsiveness for more effective policy implementation. For areas with higher per capita income, the subjective willingness of residents to use clean heating is stronger, leading to more apparent effects in reducing air pollution and carbon emissions.

Based on these conclusions, we propose three main recommendations. First, the scope of the pilot scheme should be expanded to fully leverage the pilots’ demonstration of the effects of the policy. The clean heating pilot policy significantly lowers air pollution and carbon emissions in the pilot areas. Therefore, the government should widen the scope of the pilot after comprehensively considering regional financial circumstances to realize the full-scale transformation of clean heating in winter as expediently as possible. Second, policymakers should smooth the channels through which the pollution and carbon reduction effects of the policy can be realized, including expanding the central heating area and increasing natural gas use. In terms of central heating, the first step should be to determine specific locations and the scope for expansion based on regional development plans and heating demand. The second step would be to promote the laying of heating pipes and increase their length to improve the coverage of central heating. The third step should be to accelerate the construction of heat source stations to strengthen heating capacity and ensure the stability of the central heating. Meanwhile, in terms of natural gas heating, the government should improve the natural gas pipeline network and provide gas storage devices and other supporting infrastructure to enhance the effective supply of natural gas. Furthermore, the government should increase publicity for natural gas heating, promoting its importance and significance for society through various media channels to enhance residents’ awareness and support. Third, efforts should be made to narrow inter-regional disparities concerning the policy’s effects. The government should strengthen financial support for the central and western regions in the north and actively promote the circulation and cooperation of resources between these regions and the eastern regions to advance synergistic innovation and reinforce technological support for the transition to clean heating. For areas with low-income rural residents, the government should provide targeted subsidies after considering regional economic levels and local energy prices to increase residents’ acceptance of clean energy. Furthermore, the government should continue to promote the research and development of clean heating technologies and standardize and improve their performance to safeguard residents and enhance their overall satisfaction.

The features and innovations of this study cover two consider-

ations. First, in addition to the AQI, this study also considers carbon emissions. This approach is essential for achieving China's carbon peak and neutrality goals and helps evaluate the pilot's effects scientifically and comprehensively. Second, we further refine the data scale by incorporating county-level data to analyze the policy effects at a micro level, providing reliable evidence of the policy's effectiveness in reducing pollution and carbon emissions while also exploring the mechanisms of the policy in terms of heating mode and energy type more specifically.

The clean heating pilot policy not only targets residents but also heating enterprises. As this paper's research object is the county, it does not encompass relevant enterprise-level data. In subsequent research, we plan to explore the impacts associated with this policy using enterprise micro survey data. Moreover, although we demonstrate the positive impact of the policy on the environment, we are unable to determine whether it is successful because it also involves residents' livelihoods. Therefore, in a subsequent study, we will also examine the policy's influence on enhancing social heating security to further explore its effectiveness.

Data availability

Data and materials are available from the authors upon request.

Disclosure statement

No potential conflicts of interest are reported by the authors.

CRedit authorship contribution statement

Yan Chen: Writing – review and editing, Funding acquisition, Supervision. Jiaqi Li: Writing – original draft, Validation, Methodology. Yue Zhang: Methodology. Fan Yang: Writing – review and editing.

Funding

This study was supported by the National Social Science Fund of China [Grant No. 21BGL181] to Yan Chen.

References

- Bai, C.Y., Zhan, J.Y., Wang, H.H., Yang, Z., Liu, H.Z., Liu, W., Wang, C., Chu, X., Teng, Y.M., 2023. Heating choices and residential willingness to pay for clean heating: evidence from a household survey in rural China. *Energy Policy* 178, 113617.
- Bai, K.X., Ma, M.L., Chang, N.B., Gao, W., 2019. Spatiotemporal trend analysis for fine particulate matter concentrations in China using high-resolution satellite-derived and ground-measured PM_{2.5} data. *Journal of Environmental Management* 233, 530–542.
- Bi, S.H., Hu, J., Shao, L.S., Feng, T.C., Appolloni, A., 2024. Can public transportation development improve urban air quality? Evidence from China. *Urban Climate* 54, 101825.
- Bu, X.N., Zhao, L.H., 2022. Voluntary environmental regulations and enterprise pollution emission: based on the empirical test of government energy-saving procurement policy. *Journal of Finance and Economics* 48(04), 49–63 (in Chinese).
- Chen, Q., 2021. District or distributed space heating in rural residential sector? Empirical evidence from a discrete choice experiment in South China. *Energy Policy* 148, 111937.
- Chen, S.Y., Xue, M.T., Wang, Z.H., Tian, X., Zhang, B., 2022. Exploring pathways of phasing out clean heating subsidies for rural residential buildings in China. *Energy Economics* 116, 106411.
- Chen, X.R., Zhu, Y.M., Huang, D., Li, Y.D., Shen, J.K., 2023. Research progress of biomass briquette for rural heating in China. *Clean Coal Technology* 29(S2), 136–144 (in Chinese).
- Cheng, Z.H., Li, L.S., Liu, J., 2018. Industrial structure, technical progress and carbon intensity in China's provinces. *Renewable and Sustainable Energy Reviews* 81, 2935–2946.
- Cui, Y.Z., Zhang, W.S., Wang, C., Streets, D.G., Xu, Y., Du, M.X., Lin, J.T., 2019. Spatiotemporal dynamics of CO₂ emissions from central heating supply in the North China Plain over 2012–2016 due to natural gas usage. *Applied Energy* 241, 245–256.
- Deng, M.S., Ma, R.J., Lu, F., Nie, Y.Z., Li, P.C., Ding, X.L., Yuan, Y.P., Shan, M., Yang, X.D., 2021. Techno-economic performances of clean heating solutions to replace raw coal for heating in Northern rural China. *Energy and Buildings* 240, 110881.
- Deng, Y.Y., Dong, K.Y., Sun, Q., Xue, J.J., 2024. Impact of carbon emission trading on regional development disparities and its mechanisms. *China Population, Resources and Environment* 34(03), 39–49 (in Chinese).
- Emmerich, P., Hüllemeier, A.G., Jendryczko, D., Baumann, M.J., Weil, M., Baur, D., 2020. Public acceptance of emerging energy technologies in context of the German energy transition. *Energy Policy* 142, 111516.
- Feng, T., Du, H.B., Coffman, D., Qu, A.Y., Dong, Z.F., 2021. Clean heating and heating poverty: a perspective based on cost-benefit analysis. *Energy Policy* 152, 112205.
- Gong, Y.C., Cai, B.F., Sun, Y., 2020. Perceived fiscal subsidy predicts rural residential acceptance of clean heating: Evidence from an indoor-survey in a pilot city in China. *Energy Policy* 144, 111687.
- Guo, J., Huang, Y., Wei, C., 2015. North–South debate on district heating: evidence from a household survey. *Energy Policy* 86, 295–302.
- He, D.B., Jia, C.Y., Wei, Y.S., Guo, J.L., Ji, G., Li, Y.L., 2022. Current situation and development trend of world natural gas industry. *Natural Gas Industry* 42(11), 1–12 (in Chinese).
- Huang, H.X., Guo, J.H., 2024. The effect of National Low-Carbon Strategy Coordination on pollution reduction and carbon emission reduction. *On Economic Problems* (12), 45–57 (in Chinese).
- Huang, W.Q., Wang, Q.F., Li, H., Fan, H.B., Qian, Y., Klemeš, J.J., 2022. Review of recent progress of emission trading policy in China. *Journal of Cleaner Production* 349, 131480.
- Huang, Y.C., Zou, C., Ye, Z., 2023. Carbon emission reduction effect of innovative city pilot policies in China: based on the staggered difference-in-difference model. *Environmental Science and Pollution Research International* 30, 110812–110825.
- Hou, L.S., Ding, H.T., Liu, Y.N., Wang, S.S., 2022. Evaluation and suggestion on the subsidy policies for rural clean heating in winter in the Beijing-Tianjin-Hebei region. *Energy and Buildings* 274, 112456.
- Jiang, T., 2022. Mediating effects and moderating effects in causal inference. *China Industrial Economics* (05), 100–120 (in Chinese).
- Jia, R.N., Shao, S., Zheng, Y.J., Fan, M.T., Yu, Y.T., 2023. High-speed railway and haze-governing performance in China: an empirical investigation based on the spatial difference in differences model. *China Soft Science* (11), 109–121.
- Kuang, Y.M., Lin, B.Q., 2023. Unwatched pollution reduction: The effect of natural gas utilization on air quality. *Energy* 273, 127247.
- Li, H., Zhang, L.Y., Chen, T.Q., Liao, H., 2022a. Environmental and health impacts of heating fuel transition: evidence from Northern China. *Energy and Buildings* 276, 112483.
- Li, N., Luo, X., Luo, F.Z., Zhang, D.Y., Liu, J.H., Gao, Y.R., Xing, M.L., Zhou, T.T., Zhu, K.X., 2022b. Exploring the influencing factors of Chinese rural households' clean heating choice considering the attitude–behavior gap based on two-level classification methods. *Energy and Buildings* 273, 112357.
- Li, N., Luo, X., Xing, M.L., Liu, J.H., Gao, Y.R., Zhou, T.T., Zhang, M., Li, J., Liu, Y.F., 2022c. Exploring the formation conditions and dynamic trends of rural residents' clean heating behaviour in northern China based on reinforcement learning. *Journal of Cleaner Production* 344, 131142.
- Lin, C., Shao, S., Sun, W., Yin, H., 2021. Can the electricity price subsidy policy curb NOX emissions from China's coal-fired power industry? A difference-in-differences approach. *Journal of Environmental Management* 290, 112367.
- Liu, J.H., Luo, X., Liu, X.J., Li, N., Xing, M.L., Gao, Y.R., Liu, Y.F., 2022a. Rural residents' acceptance of clean heating: an extended technology acceptance model considering rural residents' livelihood capital and perception of clean heating. *Energy and Buildings* 267, 112154.
- Liu, S.W., Liu, H.X., Mauzerall, D.L., 2022b. Improving building envelope efficiency lowers costs and emissions from rural residential heating in China. *Environmental Science & Technology* 57, 595–605.
- Liu, W.L., Zhang, J., Yang, T.R., 2022c. Will China's household coal replacement policies pay off: a cost-benefit analysis from an environmental and health perspective. *Journal of Cleaner Production* 357, 131904.
- Luo, X., Gao, Y.R., Liu, X.J., Sun, Y.K., Li, N., Liu, J.H., 2023. ACHRA: a novel model to study the propagation of clean heating acceptance among rural residents based on social networks. *Applied Energy* 333, 120644.
- Mi, L.Y., Yu, X.Y., Yang, J., Lu, J.W., 2018. Influence of conspicuous consumption motivation on high-carbon consumption behavior of Residents: an empirical case study of Jiangsu province, China. *Journal of Cleaner Production* 191, 167–178.
- Pan, X.F., Wang, M.Y., Pu, C.X., 2024. Effect of marine ecological compensation policy on coastal water pollution: Evidence from China based on a multiple period difference-in-differences approach. *Science of the Total Environment* 923, 171469.
- Qin, Y., Tong, F., Yang, G., Mauzerall, D.L., 2018. Challenges of using natural gas as a carbon mitigation option in China. *Energy Policy* 117, 457–462.
- Song, C.B., Liu, B.W., Cheng, K., Cole, M.A., Dai, Q.L., Elliott, R.J.R., Shi, Z.B., 2023. Attribution of air quality benefits to clean winter heating policies in China: combining machine learning with causal inference. *Environmental Science & Technology* 57, 17707–17717.
- Su, D.J., Zhou, W.L., Gu, Y.D., Wu, B., 2019. Individual motivations underlying the adoption of cleaner residential heating technologies: evidence from Nanjing, China. *Journal of Cleaner Production* 224, 142–150.
- Sun, C.W., Zeng, Y.F., 2023. Does the green credit policy affect the carbon emissions of heavily polluting enterprises? *Energy Policy* 180, 113679.
- Swain, S.S., Mishra, P., 2020. Determinants of adoption of cleaner cooking energy: Experience of the Pradhan Mantri Ujjwala Yojana in rural Odisha, India. *Journal of Cleaner Production* 248, 119223.
- Tang, B.J., Zou, Y., Yu, B.Y., Guo, Y.Y., Zhao, G.P., 2021. Clean heating transition in the building sector: the case of Northern China. *Journal of Cleaner Production* 307, 127206.

- Tang, Y., Liang, R.B., 2018. Does energy substitution improve air quality: analysis from energy pricing mechanism. *China Population, Resources and Environment* 28 (06), 80–92 (in Chinese).
- Trafczynski, M., Markowski, M., Urbaniec, K., 2023. Energy saving and pollution reduction through optimal scheduling of cleaning actions in a heat exchanger network. *Renewable and Sustainable Energy Reviews* 173, 113072.
- Wang, B., He, L.T., Yuan, X.C., Sun, Z.M., Liu, P.S., 2021. Carbon emissions of coal supply chain: an innovative perspective from physical to economic. *Journal of Cleaner Production* 295, 126377.
- Wang, G., Deng, J.G., Zhang, Y., Zhang, Q., Duan, L., Hao, J.M., Jiang, J.K., 2020. Air pollutant emissions from coal-fired power plants in China over the past two decades. *Science of the Total Environment* 741, 140326.
- Wang, J.D., Zhou, Z.G., Zhao, J.N., Zheng, J.F., Guan, Z.Q., 2019a. Optimizing for clean-heating improvements in a district energy system with high penetration of wind power. *Energy* 175, 1085–1099.
- Wang, N., Bai, Y.B., Guo, Z.Q., Fan, Y., Meng, F.X., 2024. Synergies between the circular economy and carbon emission reduction. *Science of the Total Environment* 951, 175603.
- Wang, Y., Yang, H.X., Sun, R.X., 2020. Effectiveness of China's provincial industrial carbon emission reduction and optimization of carbon emission reduction paths in "lagging regions": efficiency-cost analysis. *Journal of Environmental Management* 275, 111221.
- Wang, Z., Li, C., Cui, C., Liu, H., Cai, B.F., 2019b. Cleaner heating choices in northern rural China: Household factors and the dual substitution policy. *Journal of Environmental Management* 249, 109433.
- Wen, S.Y., Jia, Z.J., Chen, X.Q., 2022. Can low-carbon city pilot policies significantly improve carbon emission efficiency? Empirical evidence from China. *Journal of Cleaner Production* 346, 131131.
- Wu, F.E., He, J.A., Cai, L.Y., Du, M.Z., Huang, M.Z., 2023. Accurate multi-objective prediction of CO₂ emission performance indexes and industrial structure optimization using multihead attention-based convolutional neural network. *Journal of Environmental Management* 337, 117759.
- Xie, L.Y., Zhou, O.F., 2021. What improves subjective welfare during energy transition? Evidence from the clean heating program in China. *Energy and Buildings* 253, 111500.
- Xu, S., Ge, J.P., 2020. Sustainable shifting from coal to gas in North China: an analysis of resident satisfaction. *Energy Policy* 138, 111296.
- Xu, S., Ge, J.P., 2023. Sustainable development of clean heating in rural northern China: locally tailored energy options. *Sustainable Production and Consumption* 35, 655–667.
- Xue, W.H., Wang, L.Y., Yang, Z., Xiong, Z.W., Li, X.Y., Xu, Q.Q., Cai, Z.X., 2023. Can clean heating effectively alleviate air pollution: an empirical study based on the plan for cleaner winter heating in northern China. *Applied Energy* 351, 121923.
- Yang, H.F., Gao, Y.Y., Zhao, F.S., Wang, J.Z., 2024. An intelligent interval forecasting system based on fuzzy time series and error distribution characteristics for air quality index. *Environmental Research* 251, 118577.
- Yu, D.J., Li, J., 2021. Evaluating the employment effect of China's carbon emission trading policy: Based on the perspective of spatial spillover. *Journal of Cleaner Production* 292, 126052.
- Yu, Z.L., Ma, L.L., 2023. Impact of low-carbon city construction on the coordination of energy production and consumption coupling in China. *Journal of Beijing University of Technology (Social Sciences Edition)* 23(06), 161-178 (in Chinese).
- Zhang, X.Q., Liu, Q., 2024. Policy effect analysis of cross-regional environmental regulations on carbon emission reduction: a quasi-natural experiment based on coordinated development policies in the Yangtze River delta. *Resources and Environment in the Yangtze Basin* 33(08), 1715–1727 (in Chinese).
- Zhang, Y.L., Li, W.Q., Wu, F., 2020. Does energy transition improve air quality? Evidence derived from China's Winter Clean Heating Pilot (WCHP) project. *Energy* 206, 118130.
- Zhang, Z.X., Zhou, Y.G., Zhao, N., Li, H., Tohniyaz, B., Mperejekumana, P., Hong, Q., Wu, R.C., Li, G., Sultan, M., Zayan, A.M.I., Cao, J.X., Ahmad, R., Dong, R.J., 2021. Clean heating during winter season in northern China: a review. *Renewable and Sustainable Energy Reviews* 149, 111339.
- Zhao, J., Zhu, J.M., 2022. Household energy transition and social status: evidence from large-scale heating renovation in China. *Environmental Research Letters* 17, 115011.
- Zheng, W., Zhang, Y.C., Xia, J.J., Jiang, Y., 2020. Cleaner heating in northern China: potentials and regional balances. *Resources, Conservation and Recycling* 160, 104897.