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RESEARCH ARTICLE

Assessing the effect of the coal-to-gas program on air pollution: evidence from China

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Abstract
This paper studies the relationship between the coal-to-gas program and air pollution in China and provides micro-evidence of the mechanism from the perspective of households. Using daily air pollution and meteorological data between January 1, 2016, and January 1, 2020, we assessed the effect of the coal-to-gas program on air pollution by introducing the regression discontinuity designs in time (RDiT). We found that the coal-to-gas program significantly improved air quality and brought significant economic benefits. In the short term, the coal-to-gas program can lead to more than 10 units of reduction in SO_2, $PM_{2.5}$, and AQI in the treatment group, while it can lead to more than 50 units in the long term. Using the difference-in-differences approach, we found that the coal-to-gas program has significantly reduced air pollution. Combined with the micro-panel data of the China Health and Retirement Longitudinal Study from 2011 to 2018, we found that the coal-to-gas program changes the household heating energy choices and that the probability of coal-fired heating of households in pilot areas is decreasing. The study suggests that non-clean energy in households should be further replaced to continue improving air quality.

Keywords Coal-to-gas program · Regression discontinuity design · Clean energy · Air pollution

Introduction

With the continuous development of the global economy, coal consumption in China is gradually expanding. It has become more popular since the reform and opening-up in China in 1978 (Zheng and Kahn 2017). Figure 1 shows the tendency in coal consumption in China and other countries. It could be seen that China's coal consumption has increased since 1980 and has exceeded that of the rest of the world since 2010. Coal plays an important role in China's economic growth. As shown in China Energy Consumption Statistical Yearbook 2017, coal accounts for 62% of the total energy consumption in China.

Coal is the primary energy for household heating in North China. Large centralized coal-fired boilers provide free or heavily subsidized indoor heating to households during winter-heating seasons. However, these boilers cause a significant deterioration in air quality (Liu et al. 2017; Chen and Chen 2019; Jha and Muller 2018; Yun et al. 2020). Coal combustion for household heating can result in significant particulate matter emissions, contributing to severe air pollution (Deng et al. 2021). Then, air pollution has a negative impact on economic activities, reducing the productivity of enterprises and individuals (Chang et al. 2019), changing the value of real estate, etc. (Zheng et al. 2010). Air pollution also brings a lot of harm and suffering to human health, such as increasing the mortality rate of infants and adults (He et al. 2020a, b; DeCicca and Malak 2020), reducing individual cognitive ability (Zhang et al. 2018), and shortening the life span of residents (Lelieveld et al. 2015; Chen

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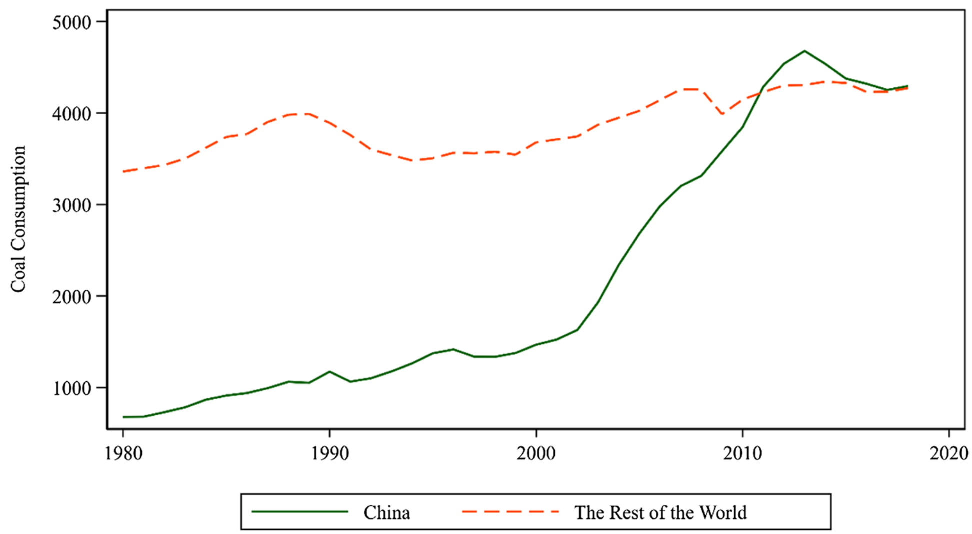


Fig. 1 Coal consumption in China and the rest of the world (unit: million short tons) (source: https://www.eia.gov/international/data/world/coal-and-coke/coal-and-coke-consumption)

et al. 2013; Ebenstein et al. 2017, 2015; Fan et al. 2020). Solving problems about air pollution is closely related to the improvement of the well-being of humankind (Bonasia et al. 2022). Coal consumption reduction not only helps improve air quality but also reduces sickness and illness (Qiao et al. 2019; Shon et al. 2020).

Based on the above literature, this paper evaluates the effect of another environmental policy in China. Considering the massive cost of air pollution, especially the environmental pollution caused by winter heating in North China, China launched a multi-sectoral coal-to-gas program in 2017 mainly to reduce coal consumption to achieve better air quality. However, there are few studies on the effect of this policy. To enrich environmental policy assessment, this paper aims to evaluate this policy and provide micro-evidence from the household level, which provides theoretical support for the orderly promotion of the coal-to-gas program. Notably, the high-frequency air pollution data provides the conditions for RDiT application. Air pollution data in hours can be used to assess the impact of public transport on environmental governance (Chen and Whalley 2012), as well as the impact of traffic restriction policies on air quality (Ye 2017). Due to the high requirements of RDiT's data, this kind of literature is relatively rare. Therefore, using daily air pollution and meteorological data, this paper employs RDiT to evaluate the effect of the coal-to-gas program. The results show that the coal-to-gas program has a great effect on air pollution. In the short term, SO_2, $PM_{2.5}$, and AQI are significantly reduced. In the long run, the policy effect gradually strengthens over time. According to preliminary estimates, the improved air quality due to the coal-to-gas program will bring a currency gain of 1,104.1 billion yuan. Based on willingness-to-pay calculations, each family would also have significant benefits. After changing the identification strategy and using DID for robustness tests, the results still show that the coal-to-gas program has a significant effect on air quality improvement.

Furthermore, based on the data of household energy consumption from the China Health and Retirement Longitudinal Study (CHARLS[1]), this paper also explores the impact of the coal-to-gas program on household energy choices and finds that the coal-to-gas program significantly reduces the probability of coal-fired heating of households by 16–24%. This finding provides micro-evidence of the air quality improvement mechanism. It is suggested that the use of non-clean energy in households should be further replaced to achieve continuous improvement of air quality.

The contribution of this paper is mainly reflected in three aspects. First, this study contributes to the literature on environmental policy assessment (Yan et al. 2020; He et al. 2020a, b; He et al. 2020a, b; Viard and Fu 2015; Davis 2008) and distinguishes the relationship between the coal-to-gas program and air pollution (Li et al. 2021; Liu et al. 2022; Zeng et al. 2022a, b; Wang et al. 2021). To make the estimation more credible (Hausman and Rapson 2018; He et al. 2020a, b; Lee and Lemieux 2010), this paper employs high-frequency diurnal data and RDiT to analyze the effect of the coal-to-gas program. Second, we analyzed the economic and social effects of the policy of the coal-to-gas program. According to a back-of-the-envelope calculation, the long-term monetary gain from improved air quality from coal to gas is 1,104.1 billion (RMB). Combined with the panel data of the micro-survey, this paper further provides direct evidence for the coal-to-gas influence mechanism from the perspective of households. It shows that households can make a greater contribution to air quality improvement by reducing coal consumption. The use of clean energy in households

[1] In the data section, we will introduce CHARLS in detail.

should be further encouraged. Third, we contribute to studies that government intervention can address energy market inefficiency. For example, the environmental whistle-blowing platform significantly promotes air pollution abatement (Leng et al. 2022). We provide direct evidence that government intervention helps solve environmental problems.

The remainder of this paper is structured as follows. The second section briefly describes the background and literature review. The third Sect. 3 describes the data and variables. The fourth section consists of identification strategies and basic results. The fifth section is a robustness test to check the reliability and consistency of the results. The sixth section is the microscopic evidence at the household level, that is, to explore whether the coal-to-gas program can reduce coal heating in households, and the last section is the conclusion.

Background and literature review

The background of the coal-to-gas program

Environmental pollution in developing countries has caused huge economic and social costs. The use of dirty energy for heating in winter will cause severe pollution and even reduce residents' lifetime (Chen et al. 2013; Ebenstein et al. 2017). During the heating period, dust particles emitted from coal combustion aggravate the haze weather and make the air pollution in urban agglomerations more serious (Deng et al. 2021). One of the most important ways to control air pollution is reducing coal consumption and realizing clean energy heating.

Background In 2017, the air pollution situation in China remained severe, especially in Beijing, Tianjin, Hebei, and surrounding areas where heavy polluting weather occurred frequently in autumn and winter, making it a key and difficult task to improve the quality of the air environment. As a result of the heavy weather in January and February 2017, the average concentration of fine particulate matter ($PM_{2.5}$) in cities along the Beijing-Tianjin-Hebei air pollution transmission corridor increased by 5.4% year on year in the first half of the year, which is the first time since 2013 that the concentration rose instead of falling, and with that in cities such as Taiyuan and Shijiazhuang even rising by more than 30%. Under this background, the Chinese government has proposed that more stringent means must be adopted to effectively reduce the intensity of pollutant emissions in autumn and winter and to reduce the frequency and extent of heavily polluted weather.

Aim From October 2017 to March 2018, the average $PM_{2.5}$ concentration in cities along the Beijing-Tianjin-Hebei air pollution transmission corridor dropped by more than 15% year on year, and the number of heavily polluted days dropped by more than 15% year on year.

Scope Beijing, Tianjin, and Hebei air pollution transmission channel cities (HTB, also named "2 + 26" cities), including Beijing, Tianjin, Shijiazhuang, Tangshan, Langfang, Baoding, Cangzhou, Hengshui, Xingtai, and Handan in Hebei Province; Taiyuan, Yangquan, Changzhi, and Jincheng in Shanxi Province; Jinan, Zibo, Jining, Dezhou, Liaocheng, Binzhou, and Heze in Shandong Province; and Zhengzhou, Kaifeng, Anyang, Hebi, Xinxiang, Jiaozuo, and Puyang in Henan Province. Figure 2 shows the map of the affected regions.

Tasks (a) Fully complete the task of replacing coal with gas, (b) strictly prevent the re-burning of loose coal, (c) strengthen the supervision and management of coal quality, (d) comprehensively investigate coal-fired boilers, (e) further expand the scope of coal-fired small boiler elimination, (f) fully complete the task of "clearing" coal-fired small boilers, (f) promote the upgrading of boilers, and (g) strictly control coal consumption.

Compared with the pollution control policies, this policy comprehensively promotes clean heating in winter and lists the "2 + 26" cities as the first implementation scope of clean heating planning in winter in North China. Beijing, Tianjin, Langfang, and Baoding should complete "coal ban zones" by October 2017 to achieve clean heating in winter. At the same time, other affected cities should complete the program of replacing coal with gas or electricity for 50,000–100,000 households by the end of October 2017. The official start date of the action plan is March 1, 2017.

The coal-to-gas policy is the key program for comprehensively promoting clean heating, which is also the critical content of the work plan. The main element of the coal-to-gas program is to phase out the use of coal and provide more clean energy such as natural gas to households. Banning the use of coal as heating fuel would reduce emissions of polluting gases and improve air quality. Coal is one of the main energy sources for household heating in winter. If the implementation of the coal-to-gas program brings better air quality, we can indirectly prove that the probability of coal-fired heating of households in pilot areas is significantly reduced. Therefore, the main content of this paper is divided into two parts. One is to analyze whether the coal-to-gas program reduces air pollution and brings clean air. Second, from the perspective of households, we discussed whether the coal-to-gas program reduces the probability of coal-fired heating of households, further providing micro-evidence for air quality improvement mechanisms.

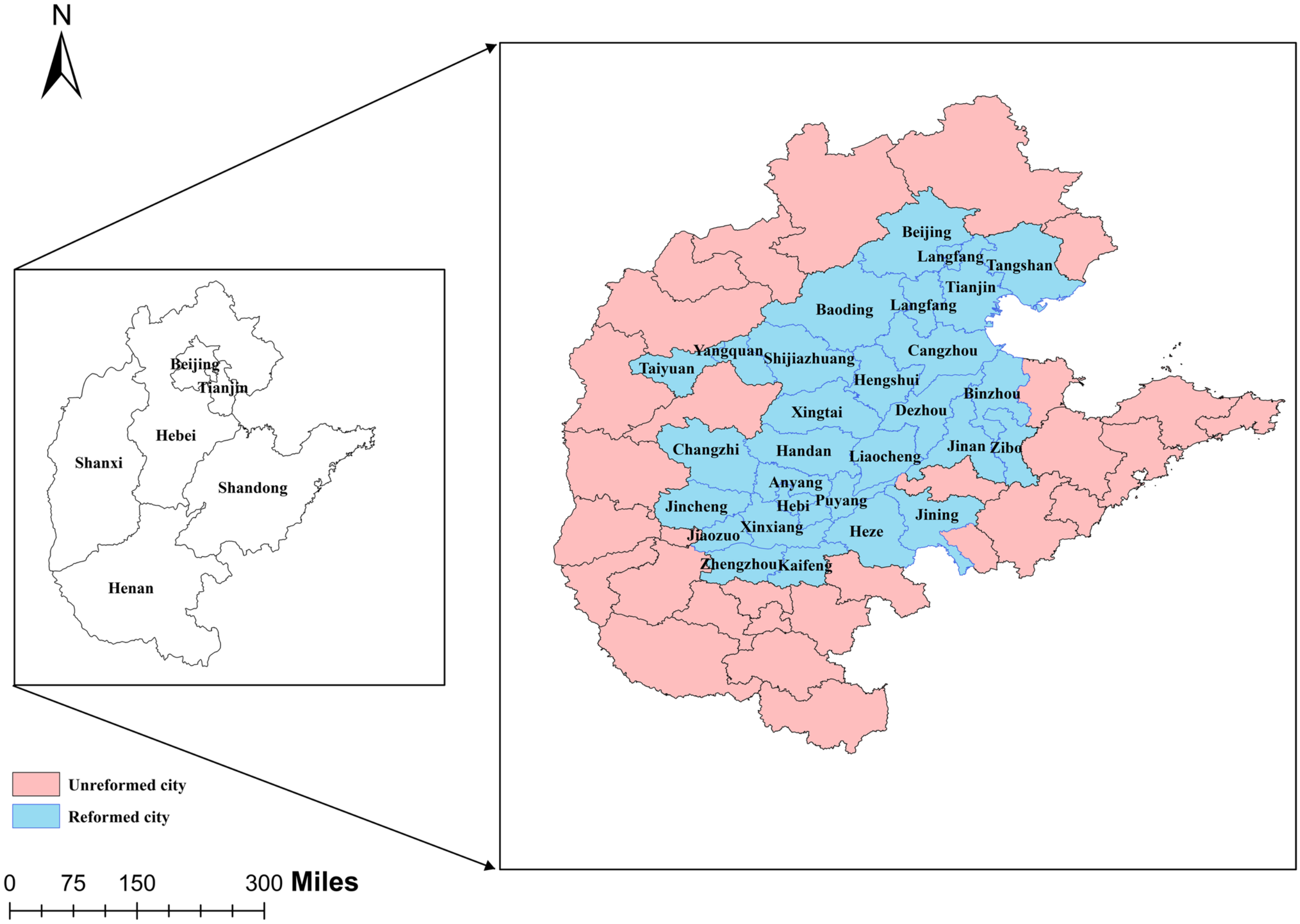


Fig. 2 Map of the affected regions

Literature review

Since the beginning of the twenty-first century, China's central government has paid more and more attention to environmental governance. Prevention and control of pollution have become one of China's three critical battles.[2] The Chinese government adopts a command-and-control policy to clean the environment (Lin et al. 2021; Zheng et al. 2022). More importantly, environmental governance is included in the assessment of local officials, which has a great incentive effect on local officials to carry out environmental governance (Kahn et al. 2015). Traffic restrictions are usually adopted to alleviate congestion and pollution in big cities. During the 2008 Beijing Olympic Games, air pollution decreased by 19% as a result of driving restrictions (Viard and Fu 2015). However, not all urban road restriction policies are effective. If the cost of the policy game is small, road restrictions may not improve air quality (Ye 2017). Zheng and Kahn (2017) made a comprehensive review of this literature. When mandatory-style regulation does not work well, the Chinese government will supplement it with incentives. The central government has started to provide subsidies to farmers and enterprises for straw recycling since 2016. Studies have shown that agricultural straw burning leads to more pollution and increased mortality, and policies such as the straw recycling plan can effectively reverse this trend (He et al. 2020a, b).

This paper is most relevant to studies examining the effects of the coal-to-gas policy (Li et al. 2021; Liu et al. 2022; Zeng et al. 2022a, b). A related study found that the coal-to-gas program can reduce $PM_{2.5}$ concentrations in the heating season by about 20 μg/m^3 (Li et al. 2021). However, this paper just shows the related relationship, not the causal relationship. Another study used a spatial difference-in-differences analysis and found that the implementation of the coal-to-gas program was strongly associated with reduced air pollution. On average, cities that transitioned to gas witnessed a 5.9 and 1.2% drop per year in SO_2 and $PM_{2.5}$ emissions, respectively (Zeng

[2] Three tough battles: major risk prevention, targeted poverty alleviation, and pollution control.

et al. 2022a, b). However, the high-frequency air pollution data provides the conditions for RDiT application. We know that RDiT can distinguish the causal relationship between the coal-to-gas program and air pollution clearer. In our study, using daily air pollution and meteorological data between January 1, 2016, and January 1, 2020, we assessed the effect of the coal-to-gas program on air pollution by introducing RDiT. We found that the coal-to-gas program significantly improved air quality. One study concludes that the coal-to-gas program can effectively reduce pollutant emissions and have health co-benefits (Wang et al. 2021). However, none of the studies has analyzed the behavioral changes of micro-households in the face of the coal-to-gas program.

Data and variables

Data sources

An empirical analysis is conducted by combining four different datasets.

Air quality data The air pollution–related data ($PM_{2.5}$, SO_2, AQI, CO, and NO_2) used in our study are from urban air quality dailies published by the China Environmental Monitoring Administration (https://www.mee.gov.cn/). Before the year 2021, the Ministry of Ecology and Environment of the People's Republic of China had a column on its website dedicated to urban air quality data. Chinese citizens can access and directly download air pollution–related data for each city and each day after 2013 by registering for logging in to the Ministry of Ecology and Environment of the People's Republic of China via email.

Household-level heating energy data We use the household-level heating energy data from the China Health and Retirement Longitudinal Study (CHARLS), which aims to collect a set of high-quality micro-data representing families and individuals of middle age and older people aged 45 years and above in China (http://charls.pku.edu.cn/). The CHARLS conducted a national baseline survey in 2011, covering 150 county-level units, 450 village-level units, and 17,000 people out of about 10,000 households. The follow-up would be conducted every 2 to 3 years. A total of 4 formal surveys have been completed including one baseline survey and three follow-up surveys. The survey includes the main energy sources of households for heating, which provides an opportunity to study the influence of the coal-to-gas program on households' micro-behavior.

The coal-to-gas program data The coal-to-gas program took place on March 1, 2017, and was piloted in "2 + 26" cities around the Beijing-Tianjin-Hebei region. We can obtain this information from the government document (https://www.mee.gov.cn/gkml/hbb/bwj/201708/t20170824_420330.htm).

Weather data The weather data are obtained from the China Meteorological Data Sharing Service System (CMDSSS), which records daily minimum, average, and maximum temperatures; humidity; wind speed; angle; and air pressure (http://data.cma.cn/).

Definition of variables

This paper explores whether the coal-to-gas program can bring better air quality. First, the coal-to-gas program is evaluated from the urban macro-level, whether it will lead to air quality improvement. Then, combined with the household data, direct evidence is provided for the program's micro-influence mechanism. Therefore, the main research of this paper is divided into two parts. The dependent variables are air quality information at the city level and heating energy information at the household level.

Air quality at the city level This paper mainly uses two frequently used indicators to reflect the air quality at the city level: one is $PM_{2.5}$ and the other is AQI. Both of them are daily data, which can better reflect the daily air quality of a city. The higher the value of the two variables, the worse the air quality of the city is. We also evaluate the policy effect on SO_2, as coal consumption will directly affect SO_2 emission.

Household-level heating energy Household heating energy can directly reflect the main energy used for heating at the household level. According to the information in the questionnaire, what are the main sources of energy for home heating? We can get the answer. In order to directly measure whether the use of coal decreases, this paper defines coal-fired heating as 1 and the others as 0. The data were panel data from 2011 to 2018, and the survey samples covered 2011, 2013, 2015, and 2018. Among these, the coal-to-gas program had already occurred in 2018.

The coal-to-gas program The key explanatory variable in this paper is the time when the policy takes place. In RDiT, the sample only includes the "2 + 26" cities around the Beijing-Tianjin-Hebei region, defined as 0 before March 1, 2017, and 1 after that. When DID is employed for the robustness test, dummy variables of the pilot city interact with dummy variables after policy occurrence (Treat × Post). Specifically, at the city level, this paper defines "2 + 26" city samples as 1 and the others as 0. In terms of time, the sample after March 1, 2017, is defined as 1, and the others are defined as 0. When we use the CHARLS household-level data, we define households in "2 + 26" cities as the treatment group with a value of 1 and the others with a value of 0. The sample value in 2018 was set as 1, and the other (2011, 2013, 2015) values were set as 0.

Table 1 Summary statistics

Var name	Obs	Mean	SD	Min	Median	Max
SO_2 (μg/m^3)	471,037	16.05	17.272	1	11	814
$PM_{2.5}$ (μg/m^3)	471,037	43.04	37.981	0	33	1852
AQI (-)	471,037	78.73	47.707	10	68	500
Treat (-)	471,037	0.09	0.290	0	0	1
Max temperature (℃)	471,037	18.95	11.421	–34.3	20.9	48.5
Min temperature (℃)	471,037	10.56	11.780	–60	12.4	38.8
Aver temperature (℃)	471,037	14.57	11.383	–38.6	16.5	42.6
Humidity (%)	471,037	66.75	19.352	2	70	1278
Wind speed (m/s)	471,037	2.05	1.164	0.1	1.8	18.9
Angle (°)	471,037	166.94	106.973	0	160.9	360
Air pressure (hPa)	471,037	971.73	62.770	546	997	1078
Coal	30,191	0.33	0.47	0	0	1
Treat × Post	30,191	0.02	0.14	0	0	1

Table 1 shows the summary statistics of main variables in this paper. The units are in parentheses

Control variables In the absence of significant changes in pollution source emissions, meteorological conditions such as temperature, wind, and precipitation will directly affect air quality (Chen et al. 2020, 2022; Zhang et al. 2021). Therefore, we also add these weather variables. We add maximum temperature, minimum temperature, average temperature, relative humidity, average wind speed, daily wind angle, air pressure, and fixed effect of city and time. This paper also controlled the city-month trend interaction fixed effect to further control the monthly linear variation of urban air quality. At the household level, we controlled for household fixed effect, annual fixed effect, and province-time trend fixed effect to eliminate the influence of other interference factors as far as possible.

Table 1 presents summary statistics for full samples. The average $PM_{2.5}$ is around 43.04 μg/m^3, while the $PM_{2.5}$ concentration reaches 1852 μg/m^3 when air pollution is worse. The mean value of AQI is 78.73, with a maximum and a minimum of 500 and 10, respectively. The maximum temperature, minimum temperature, and average temperature vary greatly, and the maximum and minimum of the three are all separated by more than 80 °C. There exists a considerable gap in relative humidity, with an average of 66.75%. On average, the wind speed is 2.05 m/s, with a maximum of 18.9 m/s. The mean daily wind angle and the average air pressure are 166.94° and 971.73 hPa, respectively. Table 2 provides the variable definitions.

Identification strategies and basic results

Identification strategy

Regression discontinuity in time (RDiT) The coal-to-gas program was officially implemented on March 1, 2017. The high-frequency daily degree data allows for using regression discontinuity in time (RDiT) identification. Regression discontinuity is considered to be the causal inference method closest to natural experiments (Athey and Imbens 2017). Since Lee and Lemieux reviewed this method (Lee and Lemieux 2010), more and more economic studies have adopted RD or RDiT for causal identification, including a series of literature in the field of environmental economy (Auffhammer and Kellogg 2011; Davis 2008; Chen and Whalley 2012; He et al. 2020a, b). The coal-to-gas program was officially implemented on March 1, 2017, and daily air pollution and weather data provided the conditions for RDiT application. March 1, 2017, is taken as the breakpoint, and 6 months is used as the bandwidth in the benchmark regression. If it can be observed that the air quality has abrupt changes before and after the point where the coal-to-gas program is introduced and other influencing factors can be regarded as continuous changes, then it is reasonable to believe that the implementation of the coal-to-gas program causes changes in air pollution.

Relative to other applied microeconomic fields, the availability of high-frequency time series pollution data has led to the rapid development trend of RDiT in energy and environmental economics (Hausman and Rapson 2018). Therefore, this paper employs RDiT to analyze the effect of the coal-to-gas program on air quality improvement. The "2 + 26" pilot cities were selected as the samples for causal identification using breakpoints. In RDiT, the assignment variable is time, and the policy was implemented on March 1, 2017. Since the coal-to-gas program is a policy issued by the Ministry of Ecology and Environment of China, it has the characteristics of compulsory execution and applies to regression

Table 2 Variable definition

Var Name	Definition
Panel A: City-level variables	
SO_2 (μg/m^3)	Daily concentration of SO_2 in the city
$PM_{2.5}$ (μg/m^3)	Daily concentration of $PM_{2.5}$ in the city
CO (μg/m^3)	Daily concentration of CO in the city
NO_2 (μg/m^3)	Daily concentration of NO_2 in the city
AQI (-)	Daily air quality index in the city
Treat (-)	Dummy variable (after policy = 1, otherwise = 0)
Max temperature (℃)	Daily maximum temperature in the city
Min temperature (℃)	Daily minimum temperature in the city
Aver temperature (℃)	Daily average temperature in the city
Humidity (%)	Daily humidity in the city
Wind speed (m/s)	Daily wind speed in the city
Angle (°)	Daily angle in the city
Air pressure (hPa)	Daily air pressure in the city
Panel B: Family-level variables	
Coal	Equals to 1 if the main heating energy is coal, otherwise equal to 0
Treat × Post	Treat (2 + 26 cities equals to 1, otherwise equals to 0)*Post(after 2017 equals to 1, otherwise equals to 0)

discontinuity.[3] When time > c, the sample is defined in the treatment group, otherwise in the control group. As the implementation of the coal-to-gas program involves the installation and debugging of part facilities, the policy effect cannot be fully reflected within a short period. Therefore, the bandwidth of 6 months was chosen. The specific identification equation is as follows:

$$\begin{aligned} lY_{i,t} =& \gamma_0 + \gamma_1 I(Date_t > T) + \gamma_2 (Date_t - T) \\ &+ \gamma_3 f(Date_t - T) \cdot I(Date_t > T) + \varepsilon_{i,t} s.t. - h \le Date_t \le h \end{aligned} \quad (1)$$

The dependent variable in Eq. (1) is the index reflecting air quality, including SO_2, $PM_{2.5}$, and AQI. RDiT identified the main coefficient as γ_1. This paper also added the driving variable as the control variable in the equation, as well as the interaction term between the driving variable and the policy, allowing the inconsistent impact slope on air quality before and after the policy. We used RDiT to analyze the impact of the coal-to-gas program on air quality.

Difference-in-differences (DID) at city level On March 1, 2017, the coal-to-gas program was implemented in surrounding areas of the Beijing-Tianjin-Hebei region. High-frequency diurnal data not only provided support for RDiT estimation but also laid a foundation for DID identification in this paper. Although the estimated results of RDiT above show that the coal-to-gas program has a significant promoting effect on environmental improvement, there may be some problems in RDiT identification. We also adopt the DID method to test robustness. The Beijing-Tianjin-Hebei region and surrounding "2 + 26" cities and regions are the main pilot cities for the coal-to-gas program. The inconsistency of policy implementation in time and geography also provides conditions for the use of differential identification. Specifically, the "2 + 26" cities in the Beijing-Tianjin-Hebei region and its surrounding areas were taken as the treatment group. In contrast, other cities in Chinese interior cities were taken as the control group. The policy took place on March 1, 2017. Before March 1, 2017, the policy had not started, and then the policy was implemented. The dummy variables of the experimental group were used to interact with the dummy variables after the policy to construct the main explanatory variables. The identification equation is shown in Eq. (2):

$$Y_{i,t} = \beta \text{Treat}_\text{i} \times \text{Post}_t + \varphi_i + \delta_t + Z_{i,t} + \varepsilon_{i,t} \quad (2)$$

The explained variable in the above equation is SO_2, $PM_{2.5}$, and AQI. The coefficient reflecting the policy effect is β, and this paper also controls for the city fixed effect, time fixed effect, and meteorological information.

Difference-in-differences (DID) at family level To explore how the coal-to-gas program can lead to better air quality,

[3] In 2017, 2+26 cities have completed replacing coal with electricity and gas in 3.94 million households, reducing coal consumption by about 10 million tons, eliminating more than 56,000 small coal-fired boilers, treating 803 coal-fired boilers with 50,000 tons of steam, cleaning and rectifying 62,000 gas-related "chaos and pollution" enterprises, and comprehensively rectifying more than 3000 volatile organic compounds. See http://fgs.mee.gov.cn/dtxx/201811/t20181129_676665.shtml.

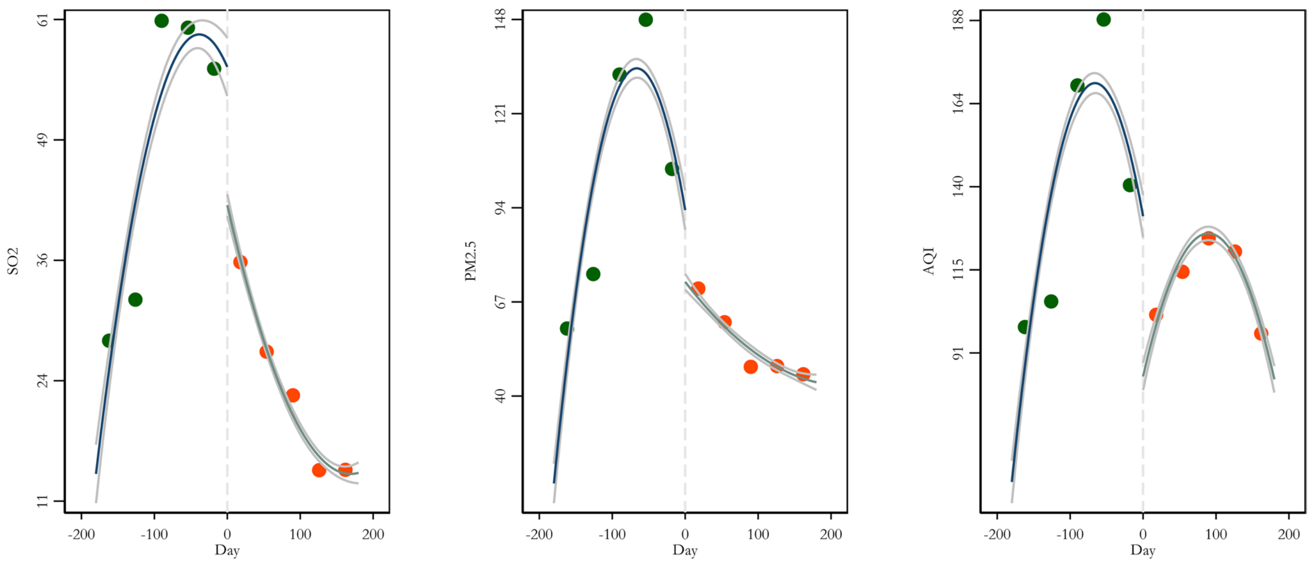


Fig. 3 Coal to gas and air quality. Note: Fig. 3 shows the relationship between the coal-to-gas program and SO_2 (left), $PM_{2.5}$ (middle), and AQI (right). The horizontal axis is the time, the driving variable, and 0 represents the policy occurrence point, March 1, 2017. The left side of 0 indicates before the policy occurred, and the right side of 0 indicates after the policy occurred. The bandwidth used was 180 days

this section uses panel data from the CHARLS between 2011 and 2018 to estimate the influences of the coal-to-gas program on household heating energy choices. This section aims to answer the question: Does the coal-to-gas program reduce the probability of coal-fired heating in households? With the method of DID, we identify the impact of the coal-to-gas program on coal heating in households. The identification equation is shown in Eq. (3):

$$\text{Coal}_{i,t} = \beta\text{Treat}_{\text{i}} \times \text{Post}_t + \varphi_i + \delta_t + \varepsilon_{i,t} \tag{3}$$

In Eq. (3), $\text{Coal}_{i,t}$ is the dummy variable, 1 is set for coal as the household heating energy, and 0 is set for others. β is the coefficient of the policy effect, and others correspond to the individual fixed effect and time fixed effect in turn. We use the DID approach to analyze the mechanisms of the impact of coal-to-gas policies on air pollution by combining micro-data at the household level.

Basic results

Figure 3 shows that coal substitution can bring better air quality. The horizontal axis in Fig. 3 is the time variable, which is also the driving variable, and 0 indicates the time when the policy occurs. The left of 0 indicates before the policy occurs, and the right indicates after the policy occurs. The results on the left side of Fig. 3 show that the SO_2 value dramatically declined when the policy occurred, which means that the coal-to-gas program has reduced SO_2 emissions in the cities. Moreover, $PM_{2.5}$ and AQI have improved significantly in the middle and right of Fig. 3. It can be argued that the coal-to-gas program has brought clean air in return even though AQI has tended to rise following the implementation of the policy. We are concerned about the change in AQI before and after the policy. Furthermore, we believe that the nonlinear changes in AQI post-policy are mainly the result of seasonal differences.

In regression discontinuity in time (RDiT), it is a common practice to assess the credibility of the design by testing the continuity of the density of the control variables. When the coal-to-gas program occurs, if the control variables do not jump at the breakpoint, the coal-to-gas program is responsible for the improvement in air quality. The continuity test will be performed below.

Continuity test

The key assumption of RDiT is that the predetermined variable does not jump at the cutoff. The predetermined variables used in this paper are minimum air temperature, maximum air temperature, average air temperature, wind speed, air pressure, and rainfall. These meteorological conditions will affect SO_2, $PM_{2.5}$, and AQI. RDiT causality identification should satisfy the premise that these predetermined variables are continuous when the policy occurs. To show the continuity of the predetermined variables, this paper graphically presents them, and the results are shown in Fig. 4. The confidence intervals of all the predetermined variables overlap each other when the policy occurs, indicating that there is no jump in the control variable

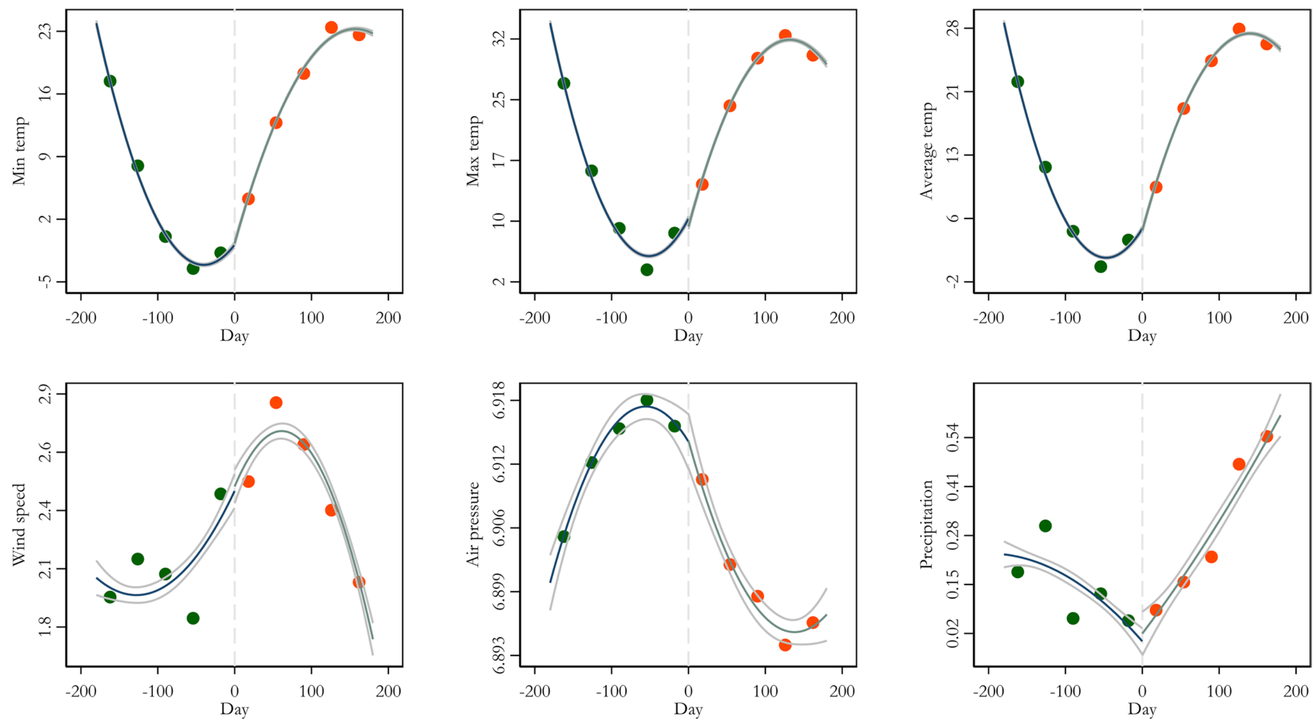


Fig. 4 Predetermined variables. Note: Fig. 4 is a continuity test for predetermined variables. From left to right and from top to bottom, the explained variables are minimum temperature, maximum temperature, average temperature, wind speed, air pressure, and humidity. These predetermined variables have no significant jump before and after the policy occurrence, which proves that the RDiT's identification hypothesis is valid

before and after the policy occurs. This further suggests that the improvement in air quality is not driven by the control variables.

RDiT dynamic effect

Using RDiT for causal inference usually needs to face a choice: how to set the bandwidth. If the bandwidth is set too small, a large number of samples will be lost. If the bandwidth is set too large, randomness may not be satisfied.

One method is based on the thumb rule, and the other is based on the optimal bandwidth. This section provides an alternative that presents the results of different bandwidths, which allows for direct observation of policy dynamic effects. Therefore, this paper selected continuous values in 30–240 days as the bandwidth, and RDiT was used to estimate the dynamic policy effects. The result is shown in Fig. 5. The explained variables are SO_2, $PM_{2.5}$, and AQI. Figure 5 shows that the coal-to-gas program has a certain effect on air quality improvement in the short term. As time goes by, the increasing intensity and depth of the policies further improve the air quality. After 8 months of implementation of the coal-to-gas program, the improvement effect on air quality tends to be stable. In October 2017, the improvement effect of the coal-to-gas program on air quality was stable. October 2017 is the deadline stipulated when the coal-to-gas policy is promulgated, which indicates that the estimates are consistent with the policy timing.

RDiT nonparametric estimation results

Figure 3 shows the estimated results of RDiT graphically. To quantify the air quality improvement of the coal-to-gas program, RDiT non-parameter is employed to estimate. The results are shown in Table 3. The results showed that implementing the coal-to-gas program resulted in a significant reduction of SO_2 by 13.4 units. In addition, the coal-to-gas program has not only reduced SO_2 but also curbed the other pollutants' emissions. In terms of $PM_{2.5}$, the coal-to-gas program significantly reduced the $PM_{2.5}$ by 22.5 units. This result shows that the coal-to-gas program has contributed to air pollution control.

Analysis of long-term economic benefits of air quality improvement

In the short term, the improvement of air quality will reduce household pollution defense expenditure (Ito and Zhang 2020; Zhang and Mu 2018). In the long run, after air pollution is reduced, the social expenditures for treating diseases caused by environmental pollution, and the loss of agriculture

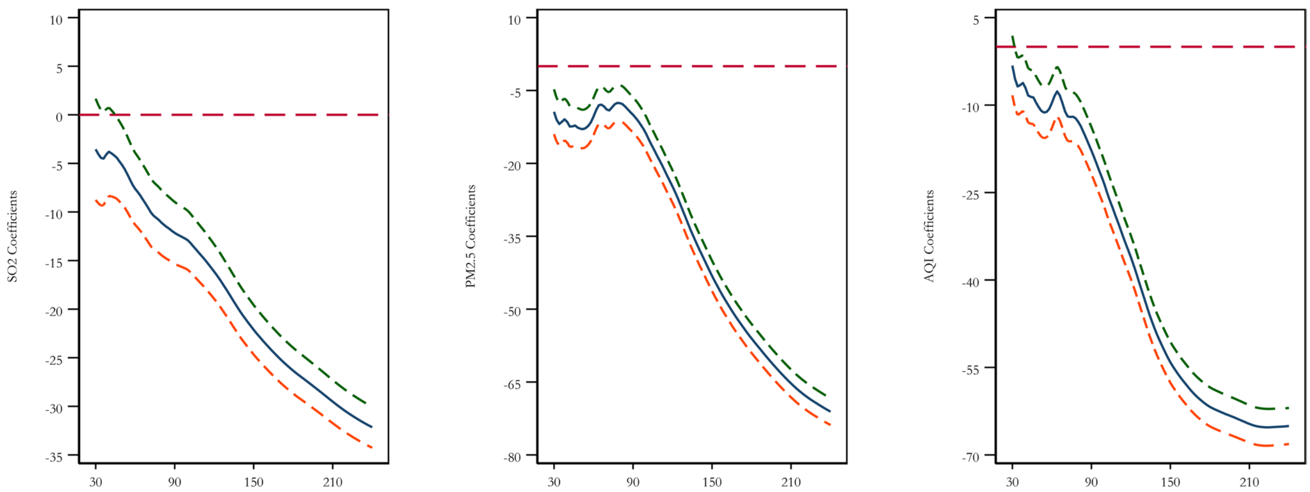


Fig. 5 RD dynamic effect. Note: Fig. 5 shows the dynamic effect estimated by RDiT. The horizontal axis is the bandwidth used for RDiT recognition. The explanatory variables are SO_2, $PM_{2.5}$, and AQI. After October 2017, the improvement effect of the coal-to-gas program on air quality tended to be stable. The time is consistent with the time limit stipulated in the policy promulgation

Table 3 RDiT nonparametric estimation results

	(1) SO_2	(2) $PM_{2.5}$	(3) AQI
RD_Estimate	– 13.401***	– 22.478***	– 45.448***
	(3.73)	(4.10)	(4.62)
Control var	Yes	Yes	Yes
N	43,829	43,829	43,829

In Table 3, we use the default kernel, triangular, to construct the local polynomial estimators. The explained variable in column (1) is SO_2, that in column (2) is $PM_{2.5}$, and that in column (3) is AQI. The control variables used in Table 3 are minimum air temperature, maximum air temperature, average air temperature, wind speed, air pressure, and rainfall. The standard errors are in parentheses

$^{*}p<0.10$, $^{**}p<0.05$, and $^{***}p<0.01$

and the ecological environment were reduced, which could cause huge economic benefits (Sattler et al. 2018). This paper roughly estimated the economic benefits of coal substitution. A study has shown that an increase of 10 μg/m^3 PM_{10} in air results in a decrease in individual life expectancy of 0.64 years (Ebenstein et al. 2017). The RDiT results in Fig. 5 show that the coal-to-gas program reduces $PM_{2.5}$ by nearly 70 μg/m^3. By simple data conversion,[4] the coal-to-gas program reduces PM_{10} by nearly 27.3 μg/m^3 and increases life expectancy by 1.75 years. According to the calculation by Ebenstein et al. (2017) and Fan et al. (2020), an increase in life expectancy of 3.1 years would result in an annual monetary gain of 195.6 billion yuan. This paper calculated that the rise in life expectancy by 1.75 years would result in an annual monetary gain of 1,10.4 billion yuan. Weighted according to treatment group population, the economic benefit is 8.59 billion yuan per year. The detailed formulas are as follows:

$$\text{Economic Benefit} = \left(PM_{10}\text{reduction}\right) \times \beta_1 \times \beta_2 \times \text{Weight} \tag{4}$$

where β_1 is equal to 0.064 (Ebenstein et al. 2017) and β_2 is equal to 606.36 (Ebenstein et al. 2017; Fan et al. 2020). Weight is population weight, the “2 + 26” cities’ population/national population, and is equal to 7.78%.

A related study shows that the coal-to-gas program will avoid 162–328 premature deaths annually based on different health impact assessment methods (Zhao et al. 2021). During the 13th Five-Year Plan period (2016–2020), by improving air quality in the BTH region, the clean heating policies brought cumulative health benefits of 36.73 billion yuan (Liu et al. 2022). We found that the economic benefit is 8.59 billion yuan per year. During the 13th Five-Year Plan period (2016–2020), we found that the economic benefit is about 42.95, slightly higher than the result of Liu et al. (2022).

In addition to calculating the long-term economic benefits of air quality improvements at a societal level, we can also use willingness to pay for clean air as a first approximation to calculate the impact of air quality improvements on household welfare, as shown in Ito and Zhang (2020), which used data from the Chinese domestic air purifier market to calculate the willingness to pay for clean air. The results show that each household is

[4] $PM_{2.5}$ belongs to PM_{10}, and the ratio of the two coefficients in the sample data is 0.39. Therefore, it is approximately considered that $PM_{2.5}$ decreases by nearly 70 μg/m^3, while PM_{10} decreases by nearly 27.3 μg/m^3.

willing to pay US$ 1.24 (approximately RMB 8) per year for a 1-unit reduction in PM_{10}. From Fig. 5 and the calculations above, the coal-to-gas program reduces PM_{10} by nearly 27.3 μg/m^3, so it can be calculated that a reduction in PM_{10} would increase the welfare by 27.3*8 = 218.4 RMB per household per year. Given the very large size of China's population and households, an increase in the welfare of 218.4 RMB per household annually would result in a huge gain for the whole country.

Coal-to-gas program and the micro-household energy choices

We found that the coal-to-gas policy can improve air quality. Whereas coal-to-gas policies may affect both firms' and households' energy choices, we are not totally sure whether coal-to-gas policies affect air quality by influencing households' energy choices. In this part, we distinguish the relationship between the coal-to-gas program and micro-household energy choices.

Table 4 Does the coal-to-gas program reduce coal heating in households

	(1) Coal	(2) Coal	(3) Coal	(4) Coal
Treat × Post	– 0.244**	– 0.159**	– 0.234**	– 0.233**
	(0.11)	(0.07)	(0.09)	(0.09)
Electricity policy	N	N	N	0.011
				(0.01)
Constant	0.331***	0.329***	0.331***	0.329***
	(0.00)	(0.00)	(0.00)	(0.00)
Year FE	Y	Y	Y	Y
Individual FE	Y	Y	Y	Y
Year FE#Province FE	N	Y	N	N
Year Trend#City FE	N	N	Y	Y
R^2	0.776	0.788	0.795	0.795
Adjusted R^2	0.571	0.591	0.604	0.604
F	5.236	5.393	6.823	4.593
N	30,092	30,092	30,092	30,092

Table 4 shows the effect of policy (coal substitution) on the heating energy source, especially for coal. The data comes from a panel survey, the China Health and Retirement Longitudinal Study (CHARLS). The CHARLS includes 4 waves (2011, 2013, 2015, 2018). The dependent variable is a dummy variable equal to 1 if the main heating energy source is coal, otherwise equal to 0. The indicator post is equal to 1 for years after 2015. The basic specification includes individual FE and Year FE in column (1), and column (2) adds Year FE-Province FE. Column (3) adds Year Trend-City FE. Column (4) adds add the dummy variable of electricity energy to control the coal-to-electricity policy. The standard errors in parentheses are clustered at the city level

$^{*}p<0.10$, $^{**}p<0.05$, and.$^{***}p<0.01$

Basic results

Equation (3) in the "Identification strategy" section is used to analyze the influence of the coal-to-gas program on household heating behavior. One of the keys to replacing coal is to reduce the amount of coal, especially for heating households. At the same time, coal energy is replaced by other cleaner energy for heating to realize clean heating. The results in Table 4 show that the coal-to-gas program significantly reduced the coal-fired heating probability in the pilot cities by 24.4%. Because the pilot policies cover multiple provinces and cities and other policies to improve air quality are introduced in different provinces and cities, the estimates may be biased. This paper added the interactive fixed effect of year and province in the second column of Table 4 to further eliminate the influence of pollution prevention and control policies at the provincial level and obtain the actual effect of the coal-to-gas program.

Column (2) of Table 4 shows that the coal-to-gas program had a significant effect on household heating energy choices. The implementation of the program decreased the probability of coal-fired heating in the pilot cities by 15.9%. In addition, with

Table 5 Parallel trend test

	(1) Coal	(2) Coal	(3) Coal
c.treat#c.post_2011	– 0.047		
	(0.04)		
c.treat#c.post_2013		– 0.104	
		(0.10)	
c.treat#c.post_2015			– 0.159**
			(0.07)
Constant	0.331***	0.330***	0.329***
	(0.00)	(0.00)	(0.00)
Year FE	Y	Y	Y
Individual FE	Y	Y	Y
Year FE#Province FE	Y	Y	Y
R^2	0.788	0.788	0.788
Adjusted R^2	0.591	0.591	0.591
F	1.298	1.092	5.411
N	30,190	30,190	30,190

Table 5 shows the placebo test results. The dependent variable is a dummy variable equal to 1 if coal is the main heating energy source (otherwise equal to 0). The indicator post_2011 is equal to 1 for years after 2011; the indicator post_2013 is equal to 1 for years after 2013; the indicator post_2015 is equal to 1 for years after 2015; the specification includes individual FE, Year FE, and Year FE-Province FE in all the columns. The standard errors in parentheses are clustered at the city level

$^{*}p<0.10$, $^{**}p<0.05$, and.$^{***}p<0.01$

Table 6 Regression results

	(1) SO_2	(2) SO_2	(3) $PM_{2.5}$	(4) $PM_{2.5}$	(5) AQI	(6) AQI
Treat#Post	– 15.440***	– 14.575***	– 12.960***	– 10.399***	– 8.988***	– 6.741***
	(2.30)	(2.09)	(1.45)	(1.40)	(1.64)	(1.59)
Max temperature	0.816***	0.706***	1.637***	1.677***	1.824***	1.969***
	(0.09)	(0.07)	(0.15)	(0.13)	(0.19)	(0.16)
Min temperature	– 0.017	– 0.065*	0.538***	0.483***	– 0.205	– 0.236
	(0.05)	(0.04)	(0.15)	(0.12)	(0.19)	(0.15)
Aver temperature	– 1.374***	– 0.614***	– 2.164***	– 1.091***	– 1.099***	– 0.141
	(0.14)	(0.09)	(0.27)	(0.20)	(0.33)	(0.26)
Humidity	– 0.133***	– 0.059***	0.180***	0.304***	– 0.098**	– 0.002
	(0.01)	(0.01)	(0.03)	(0.03)	(0.04)	(0.03)
Wind speed	– 1.654***	– 1.465***	– 3.664***	– 3.717***	– 3.356***	– 3.241***
	(0.13)	(0.11)	(0.31)	(0.27)	(0.40)	(0.34)
Angle	– 0.003***	– 0.003***	– 0.003*	– 0.005***	– 0.005**	– 0.005**
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Air pressure	– 0.303***	– 0.164***	– 0.081	– 0.238***	– 0.219***	– 0.259***
	(0.04)	(0.03)	(0.06)	(0.04)	(0.07)	(0.04)
Constant	328.735***	180.209***	113.267**	242.517***	290.152***	305.749***
	(41.68)	(26.94)	(57.56)	(34.69)	(69.93)	(41.20)
Daily FE	Y	Y	Y	Y	Y	Y
City FE	Y	Y	Y	Y	Y	Y
City-month trend	N	Y	N	Y	N	Y
R^2	0.496	0.608	0.443	0.535	0.395	0.482
Adjusted R^2	0.494	0.603	0.441	0.529	0.393	0.476
F	50.656	57.075	61.718	79.200	43.739	100.201
Observations	471,018	471,011	471,037	471,030	471,037	471,030

The standard errors in parentheses are clustered at the city level

$^{*}p<0.10$, $^{**}p<0.05$, and $^{***}p<0.01$

the continuous strengthening of pollution prevention and control in China in recent years, local governments tend to have stricter control over the use of coal. Although we controlled for the time-fixed effect in the baseline regression, the differences between different cities cannot be controlled. Therefore, based on column (1), it is assumed that there are differences in the time trend of different cities, and we controlled for the time trend of different cities in column (3). The results still show that the coal-to-gas program resulted in a significant reduction in the probability of coal heating in the pilot cities by 23.4%.[5] To avoid the impact of electricity policies, we add a dummy variable for electricity energy in column (4) to control the coal-to-electricity policy. The result is displayed in column (4) of Table 4.

This also provides household evidence of the coal-to-gas influencing mechanism for clean air, namely, the coal-to-gas program significantly reduces the probability of heating homes with coal. This may be one of the effective ways to improve air quality and provide a reference for the gradual promotion of household clean energy use decisions.

Parallel trend test

An important assumption in using the difference-in-differences policy assessment is that parallel trends are satisfied. If the hypothesis of parallel trends holds, then the impact of the coal-to-gas program on household heating energy choices only occurs after the policy is implemented. Before the policy is implemented, there should be no significant difference in the trend of changes between pilot cities and non-pilot cities for the coal-to-gas program. We performed the following parallel trend test to test whether there is a difference in household heating energy choices by households in pilot cities and non-pilot cities before the policy.

Columns (1)–(3) of Table 5 correspond to assumptions that occurred after 2011, 2013, and 2015, respectively. The real policy occurred after 2015. The results showed that there was no significant difference between the experimental group and the treatment group when the policy is assumed to occur in advance. It explains the identification hypothesis satisfying the difference-in-differences: parallel trend. It also further illustrates the robustness of the mentioned estimates.

[5] According to rough calculations, only the coal replacement reduces the coal consumption by 75.21–115.43 million tons.

Table 7 Regression results: other pollution outcomes

	(1) CO	(2) CO	(3) NO_2	(4) NO_2
Treat#Post	– 0.406***	– 0.364***	– 5.837***	– 5.264***
	(0.03)	(0.03)	(0.92)	(0.91)
Max temperature	0.031***	0.027***	1.075***	0.986***
	(0.00)	(0.00)	(0.06)	(0.06)
Min temperature	0.001	– 0.002	– 0.364***	– 0.380***
	(0.00)	(0.00)	(0.04)	(0.04)
Aver temperature	– 0.038***	– 0.016***	– 0.721***	– 0.406***
	(0.01)	(0.00)	(0.10)	(0.09)
Humidity	0.005***	0.006***	0.024***	0.026***
	(0.00)	(0.00)	(0.01)	(0.01)
Wind speed	– 0.057***	– 0.054***	– 3.798***	– 3.813***
	(0.00)	(0.00)	(0.17)	(0.18)
Angle	– 0.000	– 0.000	0.000	– 0.000
	(0.00)	(0.00)	(0.00)	(0.00)
Air pressure	– 0.006***	– 0.005***	0.012	– 0.122***
	(0.00)	(0.00)	(0.02)	(0.02)
Constant	6.672***	4.882***	18.389	145.543***
	(1.14)	(0.95)	(21.00)	(21.46)
Daily FE	Y	Y	Y	Y
City FE	Y	Y	Y	Y
City-month trend	N	Y	N	Y
R2	0.534	0.623	0.684	0.732
Adjusted R^2	0.532	0.619	0.682	0.728
F	95.600	125.477	179.872	168.648
Observations	471,032	471,025	471,019	471,012

The standard errors in parentheses are clustered at the city level

$^{*}p<0.10$, $^{**}p<0.05$, and $^{***}p<0.01$

Robustness test

However, RDiT is based on time as the cutoff, and the samples are the "2+26" regions for policy implementation, so the overall trend of regional changes cannot be completely stripped away. Besides, RDiT only estimates the local effects and cannot observe the long-term effects of the policy on air governance. We also apply DID to check for robustness in our study.

DID results

The results of DID identification estimation are shown in Table 6. In columns (1)–(6) of Table 6, the explained variable in the first two columns is SO_2, that in columns (3) and (4) is $PM_{2.5}$, and that in columns (5) and (6) is AQI. The estimation results showed that the coal-to-gas program reduces SO_2, $PM_{2.5}$, and AQI significantly at 1%. This is further evidence that the coal-to-gas program has brought better air quality. We also controlled for meteorological variables that might affect air quality in the regression.

Other pollution outcomes

Although AQI is a composite indicator that provides a quantitative description of air quality, it is a good indicator of air quality conditions. However, AQI is a composite indicator based on a combination of pollutants, and in the previous paper, we found that the coal-to-gas program resulted in significant reductions in SO_2 and $PM_{2.5}$ concentrations. However, NO_2 and CO can be generated by burning coal, and they account for a large share of pollutants. Analyzing the effect of coal-to-gas conversion on NO_2 and CO will not only help to assess the effect of the policy more comprehensively but also contributes to robustness tests. The results are shown in Table 7, where we found that the coal-to-gas conversion resulted in significant reductions in NO_2 and CO concentrations, especially for NO_2.

Placebo test

Placebo test of the coal-to-gas policy and air pollution To further promote environmental governance in the Beijing-Tianjin-Hebei region and surrounding areas, there may be other pollution control policies before and after the implementation of the coal-to-gas program. Other omissive policies may lead to overestimation of the coal-to-gas effect. At the same time, the Beijing-Tianjin-Hebei region may have taken some measures to clean the environment before the coal-to-gas implementation. To further test whether other environmental governance policies had an impact on the results, 1000 time points were randomly selected within the sample time (except March 1, 2017) as the placebo test of policy occurrence, and the results are shown in Fig. 6. Among them, the explained variables are SO_2, $PM_{2.5}$, and AQI. The results of the placebo test show that no other policies interfered with SO_2, $PM_{2.5}$, or AQI during the sample period, or that other policies interfered less with environmental governance.[6] This further proves the reliability of causality identification using RDiT in this paper and indicates it is unlikely that missing variables interfere with the estimation results.

Placebo test of coal-to-gas policy and the micro-household energy choices The coal-to-gas program reduced the probability of heating with coal. Meanwhile, the above has proved that the parallel trend test is satisfied, and that a causal relationship between the coal-to-gas program and decrease in coal heating can be identified. However, there may be omitted variables

[6] The real policy effect of this paper exceeds 50 units, while the maximum value of placebo test does not exceed 10.

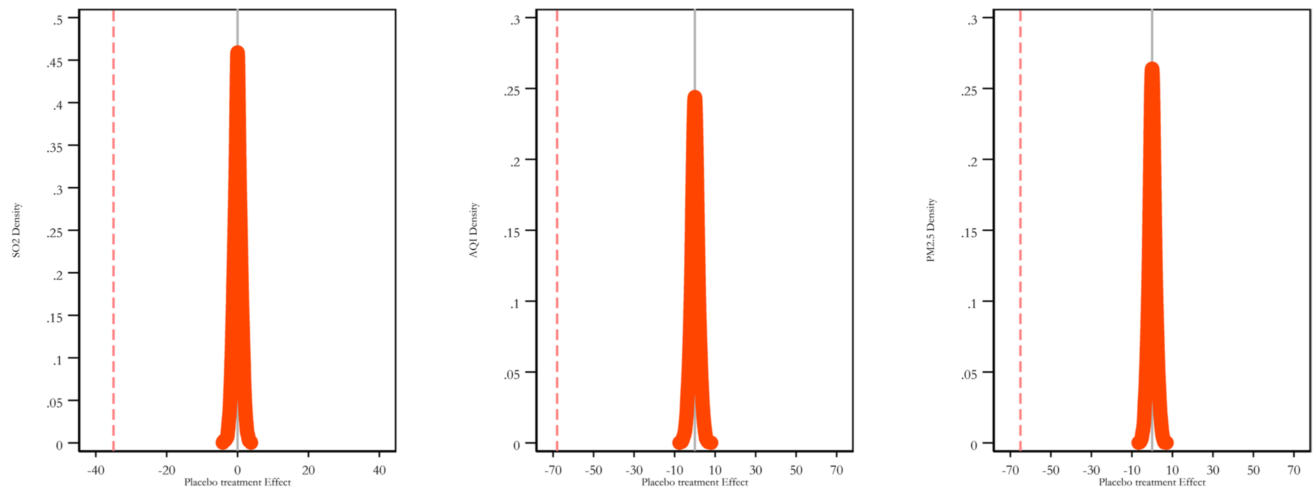
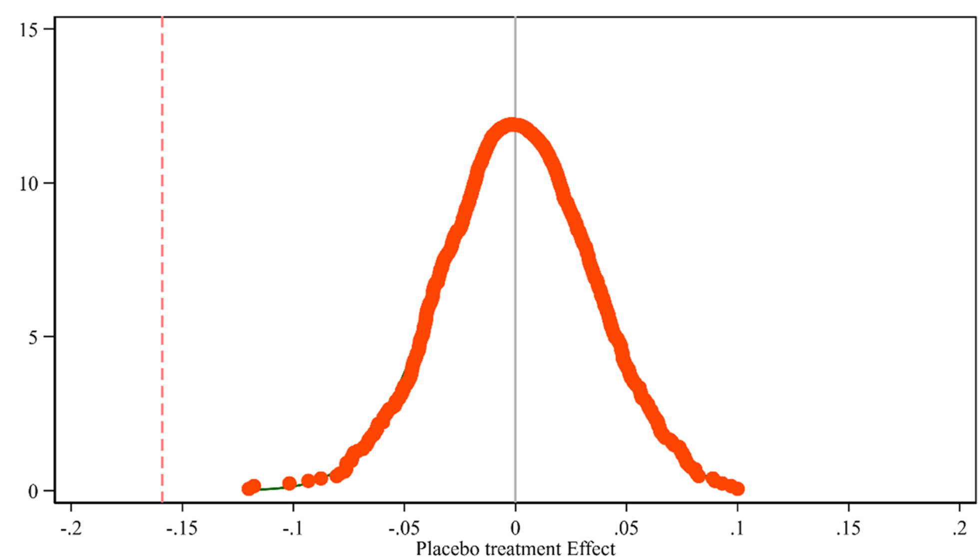


Fig. 6 Placebo test. Note: Fig. 6 shows the placebo test results. The explained variable in the figure on the left is SO_2, in the middle is AQI, and the explained variable in the figure on the right is $PM_{2.5}$. Among them, the dotted line in red is the real policy treatment effect, and the placebo effect obtained by the placebo test is normally distributed

Fig. 7 Placebo test



affecting both the coal-to-gas program and coal heating in households. In order to test whether there is such an omitted variable, this section conducted a placebo test by randomly selecting the treatment group. Specifically, we randomly selected 13% of the total sample as the treatment group and repeated it 1000 times.[7] Figure 7 shows the kernel density distribution of the estimated coefficients, with the estimated coefficients on the horizontal axis. The left dashed line is the true policy treatment effect value, and the right dashed line is the estimated coefficient of the simulated policy treatment group for the placebo test. It can be seen that the placebo test coefficients tend to be normally distributed, and that the real policy effects are larger than all the simulated policy effects. It further suggests that it is unlikely to omit variables affecting both policy generation and environmental governance in the above estimates.

Conclusion

This paper distinguishes a causal relationship between the coal-to-gas program and air pollution. We found that the coal-to-gas program significantly improved air

[7] The real treatment group accounts for 13% of the whole sample, so 13% samples are randomly selected here, and it is assumed that the treatment group will be tested by placebo.

quality, which yielded cleaner air. The estimation result is still robust, while the identification strategy changed from RD to DID, confirming our main conclusions. According to a back-of-the-envelope calculation, the long-term monetary gain from improved air quality from coal to gas is 1,104.1 billion (RMB). Based on willingness-to-pay calculations, there would also be significant benefits for the families in our study.

We also examined the influence of the coal-to-gas program on household heating energy choice behavior with CHARLS 2011–2018 panel data. We found that the coal-to-gas program significantly reduced the likelihood of coal-fired heating in households by nearly 20%. This provides microscopic evidence for the influence mechanism of the coal-to-gas program in air quality improvement. Compared with the previous analysis of air pollution control from the perspective of enterprises, this paper provides micro-evidence from the perspective of household- and supplement-relevant literature.

However, this study also has limitations. The household data in this paper is elderly care and health tracking survey, and the respondents are all middle-aged and older adults. It does not fully reflect how other Chinese households will respond to the coal replacement policy, such as the younger generation.

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Author contribution Xuan Leng: conceptualization, methodology, and writing (original draft preparation, review, and editing). Xuemei Zhao: methodology and writing (original draft preparation, review, and editing). Houjian Li: supervision, investigation, data collection, methodology, software, and writing (review and editing).

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Data availability The authors do not have permission to share data.

Declarations

Ethics approval and consent to participate The experimental protocol was established, according to the ethical guidelines of the Helsinki Declaration, and was approved by the Human Ethics Committee of Sichuan Agricultural University. Written informed consent was obtained from individuals or guardians of the participants.

Consent for publication The work described has not been published before (except in the form of an abstract or as part of a published lecture, review, or thesis); it is not under consideration for publication elsewhere; its publication has been approved by all the co-authors, if any; its publication has been approved (tacitly or explicitly) by the responsible authorities at the institution where the work is carried out.

Competing interests The authors declare no competing interests.

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