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Does low carbon energy transition impede air pollution? Evidence from China's coal-to-gas policy

Xueyang Wang, Xiumei Sun *, Mahmood Ahmad *, Haotian Zhang

Business School, Shandong University of Technology, Zibo, 255000, China

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ABSTRACT

Low carbon energy transition is deemed a viable way to fulfill the commitments outlined in the Paris Agreement and COP 26, which aims to restrict the rise in global temperature to 1.5 °C. One of the pivotal energy transition strategies in China, the coal-to-gas policy has been ambiguously executed, and its environmental impact remains unclear. In this context, this study employs the synthetic control method to examine the effects of the coal-to-gas policy on air pollution in pilot areas and explore its impact mechanism. The specific findings are as follows: (1) The concentration of $PM_{2.5}$ in China experienced a declining trend, ranging from 15.684 to 15.204, while and the growth rate of $PM_{2.5}$ concentration exhibited considerable fluctuations. (2) The coal-to-gas policy significantly contributed to a reduction in air pollution in pilot areas, except for Henan Province, where it exacerbated air pollution. In 2020, the policy's effects led to a decrease in air pollution levels by 1.73% in Beijing, 0.83% in Tianjin, 0.90% in Hebei, 1.63% in Shandong, and 0.64% in Shanxi, while air pollution levels in Henan Province increased by 0.34%. (3) The implementation of the coal-to-gas policy reduces air pollution by accelerating the transformation of the economic development and energy structure, as well as increasing foreign investment and technological investment.

1. Introduction

Since the reform and opening up, China has experienced remarkable economic development, propelling it to become the world's second-largest economy. Nevertheless, this accelerated economic expansion has exerted substantial pressure on China's ecological environment (Liu et al., 2021b; Zhao et al., 2020a). In recent years, pervasive and consequential issues of air pollution problem have detrimentally impacted human well-being. This substantial effect has elicited widespread concern from various sectors of society. According to the 2020 global air quality report, China's $PM_{2.5}$ concentration was ranked 14th at 34.7 μg/m^3 (IQAir, 2020), which also shows that the current air pollution situation in China is very serious. This deterioration of air quality can result in a number of negative consequences, such as less attractive cities for living, lower factor inflows, limited agglomeration effects (Wang et al., 2021b), slower human capital accumulation (Liu et al., 2021a), and reduced productivity (Cao et al., 2022). These issues can seriously impede the high-quality development of China's economy. Therefore, it is imperative to find new ways to balance economic growth with ecological protection. The fundamental solution to address the issue requires exploring the factors that affect environmental quality, developing suggestions and countermeasures, and rejecting the notion of sacrificing the environment for economic development. The old way of sacrificing the environment has turned economic growth into a positive catalyst for environmental governance. The Chinese government has recognized the importance of controlling air pollution and has implemented relevant measures such as the release of the "Ambient Air Quality Standards"in 2012 and the 2017 air pollution Prevention and Control Work Plan, etc., all aim to continuously improve China's air quality. The report of the 19th National Congress of the Communist Party of China emphasized the importance of fighting against pollution and vigorously promote the construction of ecological civilization.

Several studies have identified pollutants from coal combustion as the primary cause of declining air quality (Higginbotham et al., 2010; Shi et al., 2020). In response, some countries and regions have begun to optimize their energy structure by replacing coal with natural gas to reduce air pollution. Natural gas has been identified as a clean and environment-friendly energy source with low mining cost, high combustion efficiency, and convenient storage and transportation, which can effectively mitigate the problem of air pollution and accelerate

* Corresponding authors.
E-mail addresses: w17852030658@163.com (X. Wang), sxm1612@126.com (X. Sun), mahmood@sdut.edu.cn (M. Ahmad), zhanght1996@163.com (H. Zhang).

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China's low-carbon industry development (Li and Xia, 2013). Previous studies have also reported the inhibitory effect of natural gas use on air pollution (Gao and Zheng, 2022; Sharafian et al., 2019; Zhang et al., 2020). However, excessive use of natural gas has led to a "gas shortage", resulting in high energy transition costs and the return to coal usage, leading to the recurrence or even more serious environmental pollution problems (Li et al., 2021b). Thus, it is critical to rationalize the energy consumption structure makes the rationality of the energy consumption structure particularly important. In 2017, China implemented relevant energy structure adjustment policies across Beijing, Tianjin, Hebei, Henan, Shandong, and Shanxi provinces (cities) as pilot projects (see Fig. 1), aiming to reduce the proportion of coal consumption to reduce environmental pollution (see Fig. 1). Liu et al. (2022) suggested that the introduction and promotion of the coal-to-gas policy (CTGP) have effectively reduced the emission of anthropogenic volatile organic compounds in the air, which are the main contributor to $PM_{2.5}$, and also reduced the concentration of $PM_{2.5}$. Chen et al. (2019b) evaluated the inhibitory effect of the CTGP on air pollution in Beijing during two air pollution periods, and the results showed that the replacement of coal with natural gas significantly reduced the content of $PM_{2.5}$ in the air. Nevertheless, some scholars have indicated that the energy transition does not have an impact on AP (Lin and Zhu, 2019; Zeng et al., 2022). It can be seen that there is no unified conclusion on the impact of natural gas replacing coal on AP. Therefore, we sim to investigate the implementation effect of China's CTGP using the synthetic control method (SCM).

Based on the above background, the study aims to answer the following questions: 1. Does the coal-to-gas policy (CTGP) have an impact on air pollution in pilot areas? What is the impact? What are the policy effects? 2. If so, what is the magnitude of the impact, and what are the policy effects? To answer these questions empirically, this paper explores the impact of the CTGP on AP in pilot provinces using the SCM and analyzes the impact mechanism. This study distinguishes itself from previous studies in the following aspects: First, unlike the previous studies that use conventional policy analysis tools such as DID, and PSM-DID. DID requires that the processing group and control group be comparable before being impacted by policies. If there is heterogeneity between regions, the results of policy evaluation may deviate (Caliendo and Kopeinig, 2008). This paper uses the SCM to evaluate policy effects, which produce robust results and counter the endogeneity problems caused by the subjectivity of sample selection and excessive extrapolation. Second, this paper explores the differences in implementing the CTGP in different pilot areas, which is conducive to more clearly reflecting the air pollution situation in China's provinces and is

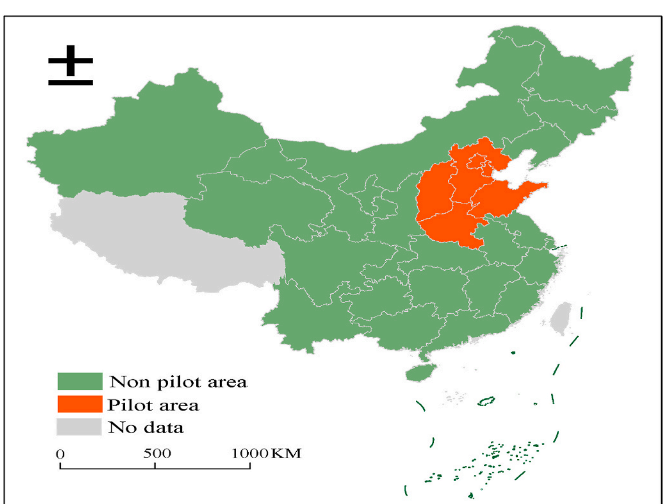

Fig. 1. Pilot Provinces for coal-to-gas policy.

conducive to formulating and modifying the policy. Third, to further comprehend the impact mechanism of policies on air pollution, this paper selects an economic level, industrial structure, foreign investment, technology investment, energy structure, and population density based on theoretical and practical analysis to explore the impact path of coal-to-gas on air pollution, which provides a significance interface for reducing air pollution in China.

The structural framework of the following paper is as follows: Section II provides a summary of relevant literature and identifies research gaps. Section III presents the method and data, consisting of the empirical method, the description of the variables, and the data source. Section IV discusses the process and results of the study, including policy effect evaluation, robustness test, and impact mechanism test. The section Vpresents the conclusion and policy recommendations, which generalize the whole experimental process and results, and puts forward policy recommendations accordingly.

2. Literature review

In recent years, environmental pollution has become an increasingly prominent issue, and the concept of green environmental protection has gained national attention. As a result, green development has become a key national policy objective, which involves adjusting the economic structure and energy structure s to mitigate air pollution. Previous studies have primarily focused on three aspects of air pollution: influencing factors, social impacts, and related policies. Therefore, the literature review of this chapter mainly focuses on the following three aspects: (1) Influencing factors and social impact of air pollution; (2) Studies on the impact of coal-to-gas conversion on air pollution; (3) Summary of existing literature and research gaps.

2.1. Influencing factors of air pollution

Air pollution is a phenomenon that arises when the concentration of specific substances in the atmosphere reaches a level that poses a threat to normal human activities and livelihood due to human social and economic activities or natural changes. Numerous factors, both direct and indirect influence air pollution during the course of human social activities, including urban expansion (Lu et al., 2021), population migration (Luo et al., 2022), technology research and development (Zhu et al., 2021), all of which exert varying degrees of impact on air quality. Zhu et al. (2019) identified an inverted U-shaped relationship between economic activities and air pollution and pointed out that foreign trade activities contribute the most to air pollution. Among the many factors of air pollution, the energy structure is of paramount importance. Pollutants emitted from fossil fuels combustion are the primary drivers of declining air quality (Wang et al., 2019). Consequently, scientifically and rationally adjusting energy structure can effectively reduce air pollution, presenting a viable strategy for governments to regulate the environment and foster harmonious economic and environmental development to improve air pollution (Wu et al., 2021). Cheng et al. (2017) revealed that an energy consumption structure dominated by coal and increased traffic intensity exacerbate haze pollution by examining the spatial effects and driving elements of urban $PM_{2.5}$. Furthermore, other studies have elucidated the related impact of bulk coal consumption on air pollution and pointed out that coal-scattered activities have a certain degree of inhibitory effect on various pollutants in the air (Li et al., 2021a).

Severe air pollution disrupts not only daily human activities and livelihood but also inflicts significant harm to physical and mental health (Kan and Chen, 2004; Pope et al., 2015; Shannon et al., 2004), Pope et al. (1995) investigated the relationship between airborne particulate pollutants and health and pointed out that airborne particles augment the incidence of respiratory diseases and cardiovascular diseases. Huang et al. (2018) examined the impact of continuous air pollution on public health and conveyed a signal to the public that air pollution poses a huge threat to human health. In addition to the threat to human physical health, air pollution also has adverse effects on mental health (Ao et al., 2021; Shen et al., 2021). Hu et al. (2021) found that air pollution can exacerbate depression and augment anxiety through its effects on mental health. Similarly, Zhang et al. (2017) also found that air pollution can augment the prevalence of depression and reduce people's well-being by examining the influence of air pollution on multiple dimensions, including mental health, and subjective well-being.

In conclusion, air pollution is influenced by a multitude of factors, with varying degrees of impact on air quality. Simultaneously, it poses a significant threat to daily human activities and well-being, necessitating the implementation of measures to reduce air pollution across all regions.

2.2. Coal-to-gas policy and air pollution

To effectively mitigate air pollution, various countries and governments have enacted a series of relevant policies aimed at reducing the concentration of airborne contaminants. Among them, the coal-to-gas policy (CTGP) has gained scholarly attention as a notable example, with differing opinions on its efficacy in curbing air pollution (Table 1). On the one hand, some scholars contend that the CTGP can reduce air pollution (Chen et al., 2022; Li et al., 2020b). Wang et al. (2021a) studied the implementation effect of the CTGP in Beijing, China, and the results showed that the CTGP improved Beijing's energy consumption structure and effectively reduced Beijing's AP, and this conclusion has also been confirmed by other scholars (Liu et al., 2020). Yu et al. (2021) employed a PSM-DID to quantify the impact of the CTGP on various air pollutants and affirmed the policy's effectiveness in reducing AP. Lueken et al. (2016) conducted an investigation to compare the coal-to-gas power plants and non-improved power plants in the United States and found that coal-to-gas can reduce SO_2 emissions by 90% and NO_x emissions by 60%. Li et al. (2016) explored the impact of using different fuels for cooking in the kitchen on air pollution and found that using natural gas or electricity instead of coal can reduce $PM_{2.5}$ in the air by 40–70%. Gi et al. (2019) explored the cost and efficiency of different strategies in the energy transformation system and pointed out that coal-to-gas and renewable energy are the optimal strategies for reducing emissions and saving costs. Chen and Chen (2019) have simulated the scenarios of coal-to-gas and coal-to-electricity, exploring the health and environmental benefits of energy transformation. The results show that the implementation of the coal-to-gas and coal-to-electricity policies can significantly reduce the emission level of pollutants in the air. Ahmad et al. (2023) pointed out through their research on the relationship between energy transformation and environmental sustainability that the use of green energy can reduce carbon dioxide emissions and improve environmental quality. In addition, Wang et al. (2020) also found that the implementation of the CTGP led to the transfer of pollution, which reduced air pollution in the north but aggravated the air pollution in the south. These studies have shown that the CTGP has an inhibitory effect on air pollution, but some scholars have pointed out that the policy cannot reduce air pollution (Zeng et al., 2022). Lin and Zhu (2019) found that energy replacement policies did not significantly improve indoor air quality through a survey of household energy use. Zhao et al. (2020b) analyzed air pollution through meteorological data and fuel data, and found that coal-to-gas policies have different impacts on different pollutants, and the impacts on different regions are also different. The above research shows that the impact of the CTGP on air pollution is still unclear and needs to be further explored.

Table 1
Literature research on air pollution (AP) caused by coal-to-gas (CTG) conversion.

Authors	Period	Data	Method	Results
Chen et al. (2022)	2009–2020	Time-series data	Dynamic recursive CGE model	CTG-AP ↓
Li et al. (2020)	2017	interview data	life cycle assessment	CTG-AP ↓
Wang et al. (2021)	2013–2016	Time-series data	VAR and ARDL models	CTG-AP ↓
Liu et al. (2020)	2014–2018	Panel data	first difference model	CTG-AP ↓
Yu et al. (2021)	2003–2016	Panel data	PSM-DID	CTG-AP ↓
Wang et al. (2020)	2016–2018	Measured data	The ground-based measurements, Localized emission estimates, Chemical transport model simulations	CTG-AP (north)↓ CTG-AP (south)↓
Wu et al. (2021)	2016	interview data	PSM	CTG-AP-
Zhao et al. (2020)	2017–2018	Observation data	Instrument detection	Different impacts on Pollutants

Note: ↓ indicate the decrease in AP.

2.3. Literature gaps

Although numerous studies have been devoted to examining to determinants of air pollution from many aspects of the low-carbon energy transition, as mentioned earlier, several research gaps persist. Firstly, the extant of literature primarily investigates the impact of replacing coal with natural gas on air pollution but did not elucidate the underlying mechanisms. The research on the impact mechanism of CTGP can provide new ideas for reducing air pollution from many aspects. Secondly, academia has not reached a consensus on whether the use of clean energy to replace coal can reduce air pollution. Finally, most of the existing studies only measure and analyze air pollution for a country or region as a whole, but different situations may occur within the same region. Few scholars have studied this heterogeneity deeply. Therefore, this article complements these shortcomings, enriches the research methods related to air pollution in the CTGP, makes the estimation results more accurate, and points out the specific factors that affect air pollution in the CTGP. In addition, compared to other similar studies, this article also considers the differences in air pollution caused by policy implementation in different regions and proposes more practical policy recommendations based on the empirical findings.

3. Methods and data

3.1. Synthetic control method

This paper adopts a policy evaluation method proposed by Abadie and Gardeazabal (2003)——SCM. Compared with the mainstream DID model, the SCM determines the relevant weights through data-driven, which reduces the subjective selection error and avoids the policy endogeneity issues (Ren et al., 2020); and the choice of weights requires positive numbers and sums to 1, thus avoiding excessive extrapolation (Athey and Imbens, 2017; Tan and Cheng, 2018). The specific method is as follows:

Assume that the economic growth data $Y_{i,t}$ of $N+1$ regions in T period can be observed; the first region is the target region affected by the CTGP, and the other N regions are the control regions that are not affected by the policy. The first region implemented the CTGP during the T_0 period, and $1 \leq T_0 < T$. The other N regions served as potential control groups. Use $Y_{i,t}^1$ to indicate the potential result of policy intervention in region i in period t, and $Y_{i,t}^0$ to indicate the potential result of policy intervention in region i in period t. Thus, the causal effect of policy intervention in region i is:

$$\tau_{i,t} = Y^1_{i,t} - Y^0_{i,t}, i = 1, \cdots, N+1, t = 1, \cdots, T \tag{1}$$

The causal effect of the policy intervention in the first region is $(\tau_{1,T_0+1}; \cdots, \tau_{1,T})$. According to formula (1), for $t > T_0$, there are:

$$\tau_{1,t} = Y^1_{1,t} - Y^0_{1,t} = Y_{1,t} - Y^0_{1,t} \tag{2}$$

The first region is subject to policy intervention, so the potential results $Y^1_{1,t}$ can be observed in the period $t > T_0$, but the potential results $Y^0_{1,t}$ cannot be observed if it is not subject to policy intervention. Therefore, the key to policy evaluation is how to estimate the counterfactual result $Y^0_{1,t}$ of the first region after T_0. To estimate the counterfactual results for Region 1, this paper adopts the factor model proposed by Abadie et al. (2010)

$$Y^0_{1,t} = \delta_t + \theta_t Z_i + \lambda_t \mu_i + \varepsilon_{i,t}, i = 1, \cdots, N+1, t = 1, \cdots, T \tag{3}$$

Among them, δ_t is the time-fixed effect, which has the same impact on all individuals; Z_i is the observable covariate of $K \times 1$ dimension is not affected by the policy and does not change with time; θ_t is the $1 \times K$ unknown coefficient vector; $\lambda_t \mu_i$ is the unobservable interactive fixed effect, that is, the individual fixed effect λ_t and time-fixed effect μ_i; $\varepsilon_{i,t}$ is a random disturbance term, which satisfies the zero-mean assumption.

At the same time, considering the construction of the weight vector $W = (w_2, \cdots, w_{N+1})$, the weight vector satisfies $w_i \geqslant 0$ and $w_2 + \ldots + w_{N+1} = 1$, each specific weight vector W represents a specific synthetic control combination, so the synthetic control model can be written as follows:

$$\sum_{i=2}^{N+1} w_i Y_{i,t} = \delta_t + \theta_t \sum_{i=2}^{N+1} w_i Z_i + \lambda_t \sum_{i=2}^{N+1} w_i \mu_i + \sum_{i=2}^{N+1} \varepsilon_{i,t} \tag{4}$$

Suppose there is a weight vector $W^* = (w^*_2, \ldots w^*_{N+1})$ such that:

$$\sum_{i=2}^{N+1} w^*_i Y_{1,t} = Y_{1,t}, \text{and} \sum_{i=2}^{N+1} w^*_i Z_i = Z_1 \tag{5}$$

If $\sum_{t=1}^{T_0} \lambda'_t \lambda_t$ non-singular, there are:

$$Y^0_{1,t} - \sum_{i=2}^{N+1} w_i Y_{i,t} = \sum_{i=2}^{N+1} w^*_i \sum_{s=1}^{T_0} \lambda_t \left(\sum_{n=1}^{T_0} \lambda'_n \lambda_n \right)^{-1} \lambda'_s (\varepsilon_{i,s} - \varepsilon_{1,s}) - \sum_{i=2}^{N+1} w^*_k (\varepsilon_{i,t} - \varepsilon_{1,t}) \tag{6}$$

Furthermore, according to Abadie et al. (2010), if the period before policy implementation is long enough, the right side of Equation (6) will approach to 0, so that during the policy implementation period, i.e. $t \in [T_0, T]$, the counterfactual results of the intervention group Region 1 can be approximately represented by the composite control group:

$$\widehat{Y}^0_{i,t} = \sum_{i=2}^{N+1} w^*_i Y_{i,t} \tag{7}$$

The policy effect of the intervention group Region 1 can be expressed as:

$$\widehat{\tau}_{1,t} = Y_{1,t} - \sum_{i=2}^{N+1} w^*_i Y_{i,t}, t \in [T_0 + 1, \cdots, T] \tag{8}$$

3.2. Variables and data

3.2.1. Dependent variable

As the focus of this study is to gauge the impact of the CTGP on air pollution, selecting the appropriate air quality proxy variable is crucial. In the existing literature, some scholars use $PM_{2.5}$ concentration as a proxy variable, and some use AQI as a proxy variable. Since $PM_{2.5}$ stays in the atmosphere longer than other pollutants and can easily spread to other places with airflow movement, resulting in a more significant environmental impact and poses greater risks to human health. Therefore, this paper selects $PM_{2.5}$ concentration as the proxy variable of air pollution.

3.2.2. Predictor variable

(1) Economic level (GDP). Previous studies have found that the level of economic development can substantially affect air quality (Zeng et al., 2019). Therefore, we choose the gross regional product to represent the economic level.
(2) Industrial structure (IS). Secondary industries, which predominantly include pollution-intensive sectors such as mining, electricity, and gas contribute significantly to pollution levels (Chen et al., 2019a). The industrial structure is measured as the ratio of secondary and tertiary industries' output values
(3) Technology investment (GEST). Technological advancements can lead to efficiency in production processes and method, thereby reducing pollution. However, such advancement requires substantial financial support (Chen et al., 2022a). Technological investment is measured as the percentage of total spending on technology.
(4) Foreign direct investment (FDI). When foreign companies invest in China, they will bring large amounts of money and some new technologies and business models, which are instrumental in the green and low-carbon transformation of companies and reduce air pollution (Jiang et al., 2018). It is expressed by the proportion of foreign investment amount to regional GDP.
(5) Energy structure (EC). The energy consumption structure refers to the proportion of various types of energy consumption in energy consumption. A higher proportion of coal consumption is associated with more severe pollution (Li et al., 2020a). Energy structure is proxied using the specific weight of natural gas consumption.
(6) Population density (PD). Higher population density necessitates increased energy and resource consumption, which can exacerbate pollution (Chen et al., 2020). It is expressed by population in the unit area.

3.3. Data sources

In terms of data sources, based on the principles of easy availability, continuity and accuracy, a panel data set from 2011 to 2020 was constructed with 30 provinces in China as the research objects (Due to excessive data missing, the sample does not include Hong Kong, Macao, Taiwan, and Tibet). Data were obtained from the "China Statistical Yearbook", "China Energy Statistical Yearbook", "China Rural Statistical Yearbook", "China Environmental Statistical Yearbook" and provincial statistical yearbooks and annual reports. The specific variable description statistics are shown in Table 2.

4. Results and discussion

4.1. Analysis of evolution characteristics of air pollution time series in China

In order to provide a clearer and more intuitive depiction of the trend and growth rate of air pollution in China during the study period, this study computed the change and growth rate of $PM_{2.5}$ in China from 2011 to 2020, and generated an air pollution evolution trend chart for China.

As shown in Fig. 2, the $PM_{2.5}$ concentration in China showed a downward trend figure period except for 2012–2013, which increased from 15.684 in 2011 to 15.204 in 2020.In contrast, the growth rate of $PM_{2.5}$ concentration varies each year considerably, with all years displaying a negative trend except for2013. It is noteworthy that the growth rate attained a maximum of 0.74% in 2018, which was also the first year of implementation of the CTGP. Based on these findings, we can speculate that the sharp drop in $PM_{2.5}$ concentration may be due to

Table 2
Variable descriptive statistics.

Group	Variable	N	Mean	sd	Min	Max
Treatment group	$\ln PM_{2.5}$	24	15.005	1.182	13.243	16.080
	lnGDP	24	11.051	0.466	10.390	12.011
	IS	24	0.721	0.274	0.191	1.104
	FDI	24	0.550	0.467	0.129	1.392
	GEST	24	0.026	0.015	0.010	0.059
	EC	24	0.351	0.194	0.012	0.619
	lnPD	24	7.902	0.546	7.035	8.528
Control group	$\ln PM_{2.5}$	276	15.547	1.127	12.113	18.253
	lnGDP	276	10.672	0.461	9.464	11.961
	IS	276	0.939	0.290	0.219	1.897
	FDI	276	0.350	0.327	0.048	1.584
	GEST	276	0.020	0.144	0.004	0.066
	EC	276	0.405	0.144	0.084	0.687
	lnPD	276	7.873	0.404	6.639	8.669
Total	$\ln PM_{2.5}$	300	15.504	1.139	12.112	18.253
	lnGDP	300	10.703	0.472	9.464	12.011
	IS	300	0.922	0.294	0.191	1.897
	FDI	300	0.366	0.343	0.048	1.584
	GEST	300	0.020	0.015	0.004	0.068
	EC	300	0.400	0.149	0.012	0.687
	lnPD	300	7.875	0.416	6.639	8.670

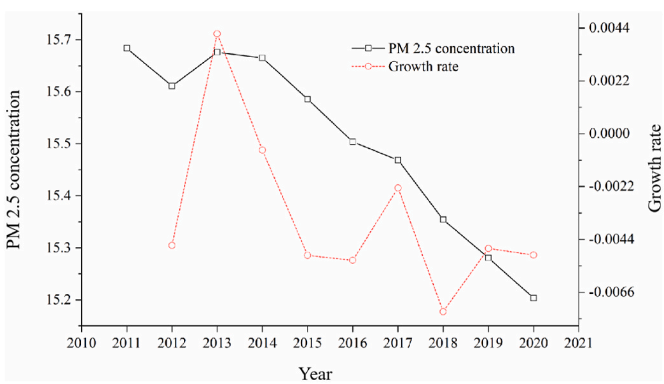

Fig. 2. Evolution trend of air pollution in China.

the implementation of the CTGP. The growth rate began to decline in the subsequent years. If our conjecture is correct, this also shows that the policy has a short period of potency and cannot effectively suppress $PM_{2.5}$ concentrations for a long time. We will validate these suppositions later and verify whether the implementation of a series of energy policies, such as the CTGP posed a certain impact on China's air pollution.

4.2. Weight construction of synthesized provinces

The Synthetic Control Method (SCM) is employed to evaluate the implementation effect of the pilot by constructing a synthetic object area for each pilot area. In order to accurately analyze the effect of the CTGP on air pollution in different regions in China, this study selected Beijing, Tianjin, Shandong, Shanxi, Henan, and Hebei as the experimental group, while the remaining 24 provinces as the control group. Multiple variables are selected as the prediction variable, with the selection criteria for weights is to minimize the mean square error of $PM_{2.5}$ in pilot provinces and synthetically controlled provinces in the period before the start of the CTGP. In the fitting result, the weight coefficient of the control group provinces is positively correlated with the similarity to the pilot provinces. If the weight coefficient of the control group provinces is 0, it indicates that it does not match the features of the pilot provinces and cannot be used to fit the virtual control provinces. Based on this, this paper obtained the weight coefficients of provinces in the synthetic control group of different pilot provinces, as shown in Table 3. When

Table 3
Weight coefficient table.

Province	Beijing	Tianjin	Hebei	Henan	Shandong	Shanxi
Anhui						
Fujian	0.391	0.296				
Gansu					0.018	
Guangdong						
Guangxi			0.389			
Guizhou						
Hainan	0.507	0.539				
Heilongjiang			0.029			
Hunan						
Hubei				0.322		
Jilin					0.077	
Jiangsu						
Jiangxi						
Liaoning						
Inner Mongolia				0.134	0.400	
Ningxia				0.044	0.365	0.036
Qinghai						
Shannxi						0.964
Shanghai	0.101	0.161	0.090	0.031		
Sichuan				0.469	0.105	
Xinjiang			0.331		0.035	
Yunnan						
Zhejiang		0.004	0.161			
Chongqing						

Beijing is the research object, the fitting provinces of the pilot include Fujian, Hainan, and Shanghai, and the weight coefficients are 0.391, 0.507, and 0.101 respectively; when the research object is Tianjin, the synthetic control group of the pilot includes Fujian, Hainan, Shanghai and Zhejiang, the weight coefficients are 0.296, 0.539, 0.161, and 0.004 respectively; when the research object is Hebei, the synthetic control group includes Guangxi, Heilongjiang, Shanghai, Xinjiang, and Zhejiang, with the weight coefficients of 0.389, 0.029, 0.090, 0.331, and 0.161, respectively. When the research object is Henan, the synthetic control group includes Hubei, Inner Mongolia, Ningxia, Shanghai, and Sichuan, and the corresponding weight coefficients are 0.322, 0.134, 0.044, 0.031, 0.496; the synthetic control group corresponding to Shandong includes Gansu, Jilin, Inner Mongolia, Ningxia, Sichuan, and Xinjiang, with the weight coefficients of 0.018, 0.077, 0.400, 0.365, 0.105, and 0.035, respectively. The synthetic control groups in Shanxi were Ningxia and Shaanxi, and the corresponding weight coefficients

Table 4
Comparison of predictors of the Real pilot and synthetic pilot.

Variables	Beijing Synthetic	Tianjin Synthetic	Hebei Synthetic
lnGDP	11.094 10.6752	11.1001 10.7161	10.3838 10.5334
IS	0.2454 0.2992	0.8090 0.7333	1.1052 0.9422
FDI	0.6476 0.6386	0.9519 0.7020	0.1528 0.2774
GEST	0.0557 0.0192	0.0351 0.0211	0.0105 0.0205
EC	0.1330 0.2099	0.3055 0.1909	0.6587 0.3636
lnPD	7.2586 7.7961	8.0212 7.8227	7.8232 7.8079
$\ln PM_{2.5}$ (2011)	14.0027 14.0253	13.8440 13.8432	16.3287 16.3269
$\ln PM_{2.5}$ (2013)	13.9927 13.9862	13.8026 13.8194	16.3871 16.3755
$\ln PM_{2.5}$ (2015)	13.8718 13.8425	13.6812 13.6758	16.3871 16.3755
$\ln PM_{2.5}$ (2017)	13.7499 13.7520	13.5615 13.5613	16.1399 16.1378
$\ln PM_{2.5}$ (2020)	13.2435 13.4765	13.1856 13.2969	15.7874 15.9310
Variables	Henan Synthetic	Shandong Synthetic	Shanxi Synthetic
lnGDP	10.4035 10.5326	10.7685 10.5209	10.3496 10.5789
IS	1.3710 1.0651	1.1322 0.9692	1.3923 1.2951
FDI	0.1079 0.2084	0.2423 0.1565	0.1919 0.1473
GEST	0.0212 0.0150	0.0206 0.0105	0.0133 0.0116
EC	0.4943 0.4578	0.4595 0.4901	0.6287 0.4745
lnPD	8.5343 7.7072	7.2505 7.3005	8.1405 8.4882
$\ln PM_{2.5}$ (2011)	16.2699 16.2674	16.1611 16.1624	16.0081 15.9998
$\ln PM_{2.5}$ (2013)	16.2778 16.2724	16.1439 16.1450	15.8888 15.8861
$\ln PM_{2.5}$ (2015)	16.1316 16.1212	16.1615 16.1624	15.7765 15.7723
$\ln PM_{2.5}$ (2017)	15.9804 15.9740	15.9987 16.0034	15.7489 15.7388
$\ln PM_{2.5}$ (2020)	15.7929 15.7391	15.5715 15.8297	15.4122 15.5103

were 0.036 and 0.964. In addition, Table 4 lists the true values and fitting values of various variables before and after the implementation of the CTGP in 2017. It is apparent from the table that there is only a small gap between most of the real values and the synthetic values; the fitting degree is good, which also shows that the change of the synthetic value after the implementation of the CTGP can more accurately represent the changing trend of the air pollution degree in the pilot provinces without the implementation of the policy after 2017.

4.3. Analysis of the effect of the CTGP

In order to demonstrate the impact of the CTGP on air pollution in the pilot provinces, the present study uses the SCM to evaluate the policy effect. Fig. 3 shows the trends and policy effects of air pollution levels in each pilot province prior to the implementation of the CTGP. The solid-line curve and the dashed line in the figure represent the actual change trend of air pollution in the pilot area, and the red dashed line represents the evolution trend of air pollution levels in the synthetic provinces. The vertical dashed line represents the year in which the CTGP was implemented. As shown in Fig. 3a–f, the findings reveal that prior to the policy, the solid-line curve and the dashed line almost overlapped, indicating a good fit between the characteristics of the synthetic provinces and the pilot provinces. This suggests that the synthetic provinces could effectively represent the changes in air pollution in the pilot provinces in the absence of the policy. After the implementation of the CTGP, the two lines began to diverge, and the gap between the actual value and the synthetic value of $PM_{2.5}$ in each pilot province gradually widened over time, but the difference was that the air pollution in each region changed significantly. Among them, the air pollution level in Beijing experienced a relatively large decline in only one year from 2017 to 2018, and in the following two years, although the rate of decline slowed down, it continued to decline. The air pollution levels of Tianjin, Hebei, and Shanxi provinces began to differ from those of the synthetic provinces after the implementation of the policy and gradually increased over time, while the trends of air pollution levels of the three provinces were roughly the same as those of Beijing, and they all dropped sharply in the first year, and then followed by rates below the first stage continued to decline. However, the effect of the CTGP in Henan Province is different from the other provinces, as the policy produced a negative effect and aggravated the air pollution level in the region.

For Shandong Province, the implementation of the CTGP has significantly reduced the $PM_{2.5}$ content in the region, And the strong effectiveness period of the policy is longer than that of the other five provinces, declining at a higher rate from 2017 to 2019. After 2019, the rate decreases, and the $PM_{2.5}$ concentration continues to decline. By using the SCM method to evaluate the implementation effect of the CTGP in each pilot province, it is evident that the implementation of the CTGP has indeed had an impact on the air pollution of the pilot provinces and this impact is different from place to place. Assuming that compared with the synthetic provinces that have not implemented the CTGP, the implementation of the CTGP can indeed alleviate the air pollution in some pilot areas, but this high-efficiency inhibitory effect

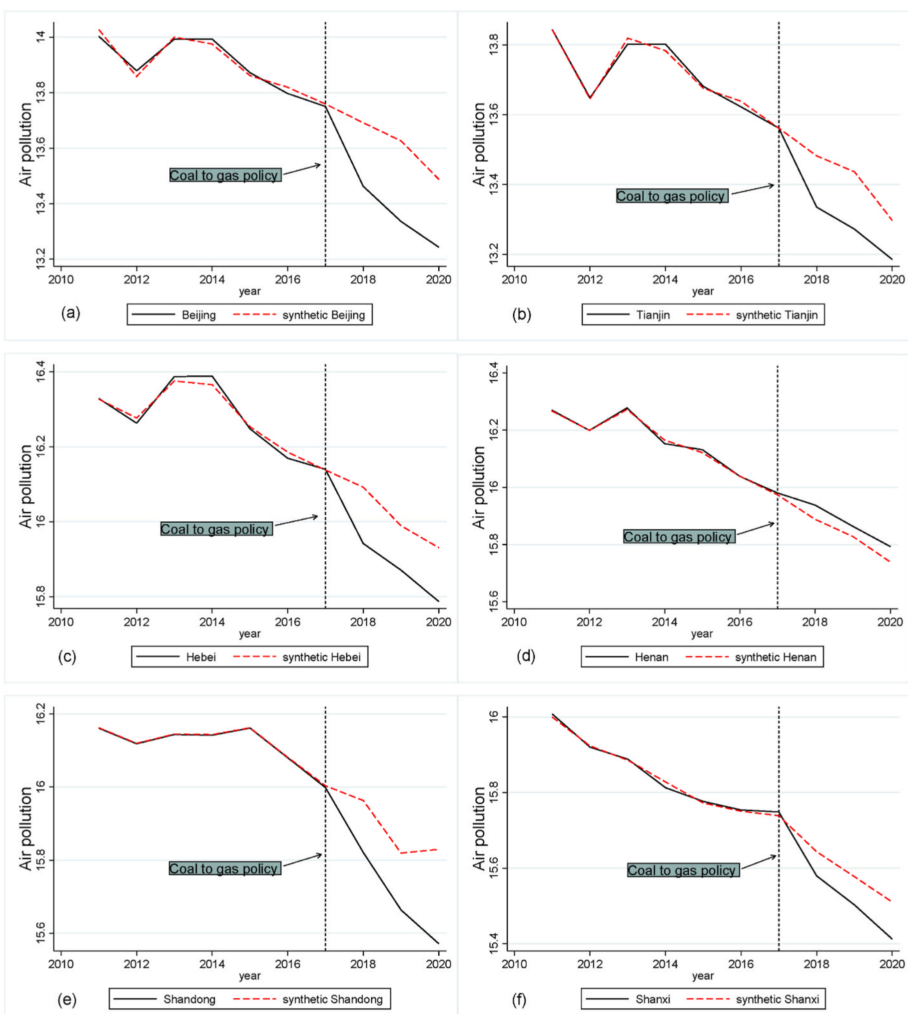

Fig. 3. Effect of the CTGP

lasts for a short time. Except for Henan Province, and air pollution in the other five provinces (cities) has dropped significantly, and the $PM_{2.5}$ concentration in 2020 is far lower than before the implementation of the policy, which also shows that the final result of the implementation of the CTGP will reduce air pollution in each pilot area.

For the existing literature on the impact of middling coal-to-gas on air pollution, this paper draws different conclusions through empirical analysis. The implementation of the CTGP has both inhibitory and promoting effects on air pollution. This result is due to the comprehensive effect of various reasons, such as policy implementation strength and resource endowment in different regions.

Moreover, based on the SCM concept, the policy net effect of the CTGP can be assessed by comparing the actual $PM_{2.5}$ concentration in pilot provinces' policy implementation with the $PM_{2.5}$ concentration of synthetic provinces. As shown in Fig. 5, the difference between the two before the performance of the policy is almost zero. After the performance of the policy, the net policy effects of Beijing and Tianjin are similar, and they both exhibit a downward from 2017 to 2019 before rebounding at the end of 2019. Although the net effect demonstrates an upward trajectory, it remains negative. Conversely, The net effect of Hebei Province shows a trend of first decline, then rise, and then decline, but the value is negative, which means that the policy has reduced air pollution in Hebei Province; Henan Province The net policy effect is positive, which means that the performance of the CTGP has aggravated the air pollution in the region. The net policy effect of Shandong Province and Shanxi Province is negative, and has been showing a downward trend since the implementation of the policy, which also shows that the policy effect in the two places The implementation effect is good, and the policy effect lasts for a long time. Fig. 4 shows the comparison of the average $PM_{2.5}$ concentrations in each pilot area before and after the performance of the policy. As of 2020, the actual values of $PM_{2.5}$ concentrations in Beijing, Tianjin, Hebei, Henan, Shandong, and Shanxi were 13.243, 13.186, 15.787, 15.793, 15.572, and 15.412, while the $PM_{2.5}$ concentrations of the synthetic provinces in 2020 were 13.476, 13.297, 15.931, 15.739, 15.830, and 15.511, indicating that the implementation of the CTGP made the $PM_{2.5}$ concentrations of the pilot provinces respectively decreased by 1.73%, 0.83%, 0.90%, −0.34%, 1.63%, and 0.64%, which also reflects that the policy effect of CTGP has a strong inhibitory effect on regional air pollution.

In summary, the diverse social environment, economic development, and resource endowments of the pilot provinces result in varying policy implementation outcomes. Although the implementation of the CTGP has reduced air pollution in the five provinces (cities) of Beijing, Tianjin, Hebei, Shandong, and Shanxi, it has exacerbated the air pollution in Henan Province. The reduction in air pollution through the substitution of coal with natural gas may be attributed to the significant improvement in China's energy structure and the decreased reliance on coal (Li and Lu, 2019; Raza and Lin, 2022). articulate matter and other substances are the main culprits of air pollution (Sun et al., 2018). Natural gas combustion primarily emits carbon dioxide, carbon monoxide, nitrogen oxides, sulfur dioxide, and particulates, which are considerably lower than coal emissions, thus significantly reducing air pollutant concentrations (Zhang et al., 2022a). The increase in air pollution within Henan Province may be due to its extensive pollution base, high background pollutant concentrations, unique geographical location, and adverse meteorological conditions, all of which contribute to elevated pollutant concentrations In addition, the structural pollution in Henan Province is prominent, the industrial structure is unreasonable, and there is too much high energy consumption, high pollution, and resource-based "two high and one capital" projects, with large pollutant emissions, these factors also hindered the implementation of the CTGP and failed to achieve the expected objectives of the policy.

4.4. Robustness check

4.4.1. Sorting test

To validate the accuracy of the above empirical results and prove that the experimental results are indeed attributed to the performance of the CTGP rather than some other incidental factors, this paper refers to the test method proposed by Abadie et al. (2010) to determine whether other provinces will have the identical or better results than the pilot provinces when implementing the CTGP. The method of this test is to first assume that all provinces in the control group implemented the CTGP in 2017, and use the SCM to construct synthetic provinces of these provinces and appraise the policy effect. Then compare the policy effects of the pilot provinces with those of other provinces under the assumption. If there is a significant difference between the policy effects of the two, it proves that the pilot policy effects are significant and that the experimental results are caused by the performance of policies rather than other fortuitous elements.

Since this method requests a quite nice matching effect on the synthetic control object in the policy implementation, if the fitting effect of a province before 2017 is not ideal, that is, the RMSPE value is relatively large, then even if the difference between the predicted variables obtained in the later period of the policy is large, it cannot reflect the effect of the policy. Thus, to increase the accuracy of the test, provinces with RMSPE values higher than twice that of the pilot provinces were excluded in the ranking test. The sorting test results are revealed in Fig. 6. It is evident from the figure that before 2017, there was no obvious difference between Beijing and other provinces in terms of air pollution. Since the performance of the policy, the difference between Beijing and other provinces in terms of $PM_{2.5}$ concentration has begun to

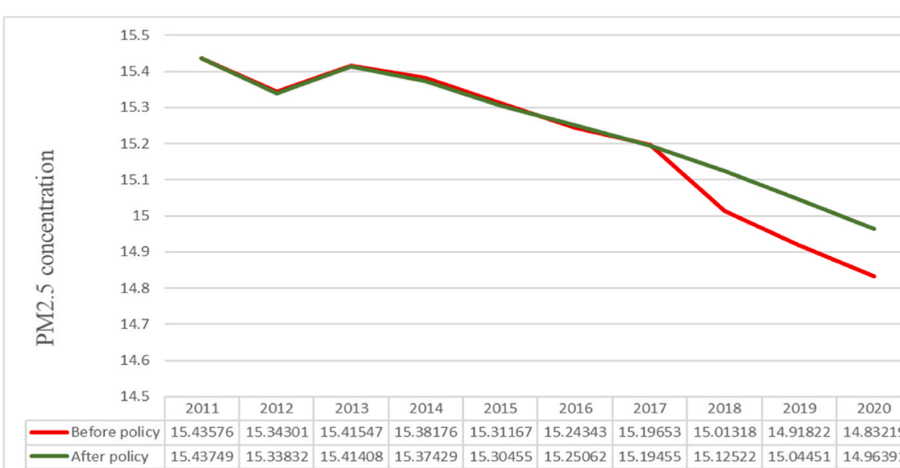

Fig. 4. Comparison of $PM_{2.5}$ concentrations before and after policy implementation.

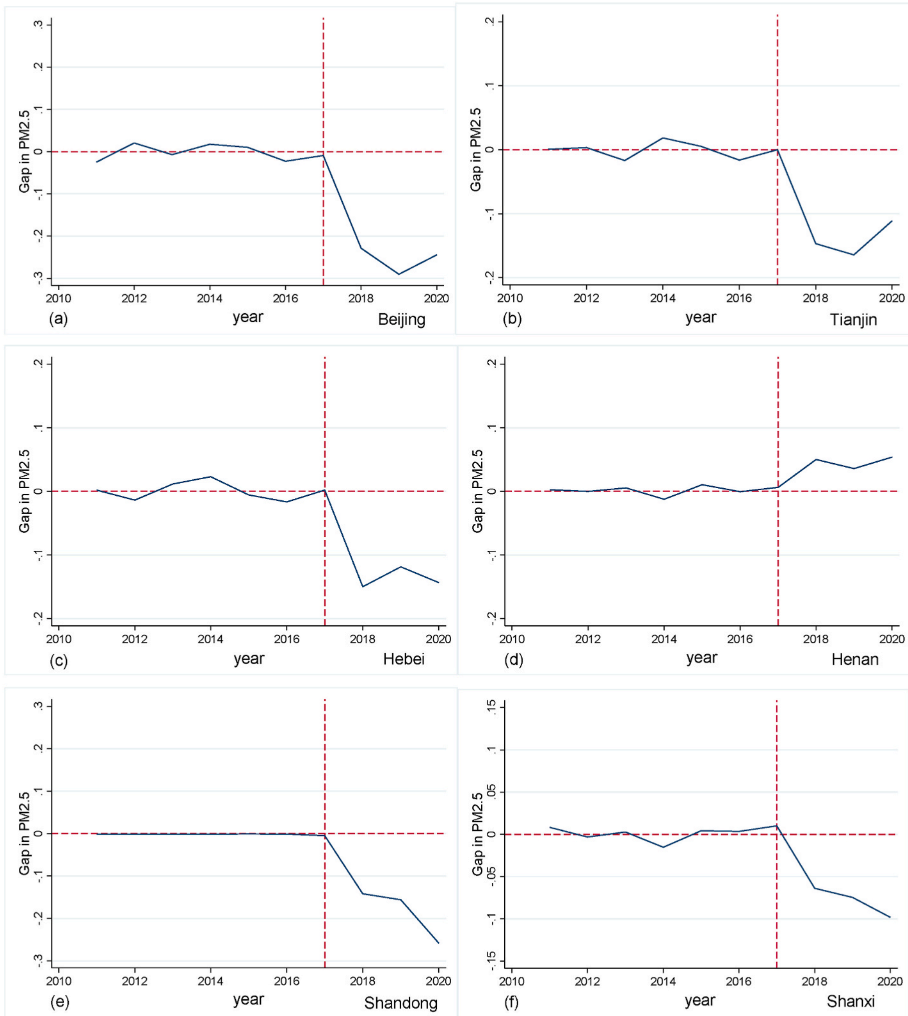

Fig. 5. Net effect of the CTGP.

appear and gradually expanded, and it is distributed in the outermost part of all. This illustrates that the implementation of the CTGP has reduced the air pollution in the region, and there is only a 1/22 or 4.55% chance of the same situation as that of Beijing. In a statistical sense, it can be considered that the inhibition of the policy on air pollution in pilot provinces at a significant level of 5% is not caused by other external accidental factors. Similarly, Tianjin, Hebei, Shandong, and Shanxi also have small differences from other provinces before the performance of the policy. After 2017, $PM_{2.5}$ concentration began to decrease and separated from other provinces, and finally, it was the outermost of all provinces, and there were 4.35% (1/23), 4.35% (1/23), 4.55% (1/22) and 4.76% (1/21) probabilities respectively, that is, at a significant level of 5%, to reject the impact of fortuitous external elements on air pollution. At the same time, it also shows that the increase in $PM_{2.5}$ concentration is indeed caused by policy implementation rather than other factors, which proves that the policy effect analysis results above are robust. Although Henan Province fits well with other provinces before the policy takes place, after the policy is implemented, there is no significant difference compared with the synthetic control results of other provinces, and it is located in the middle of all provinces, which means that the air pollution situation in Henan Province is aggravated. The reason is not only due to the performance of the CTGP, but also some other unobservable external fortuitous elements, which together have caused the increase of air pollution in Henan Province, which also confirms the results of the net effect analysis above.

4.4.2. Placebo test

To further prove the reliability and robustness of the analysis of policy effects and net effects, the current study employs a placebo test method developed by Abadie et al. (2015) to select a sample that has not been established as a pilot of coal-to-gas in the study period. We selected the provinces that had the most similar characteristics to the pilot provinces, namely, the control group provinces that have the highest synthetic contribution rate when fitting the pilot provinces. We first assume that these provinces also implemented the CTGP in 2017, and then use the SCM to evaluate the policy effect of the province's policy implementation. If the policy effect obtained from the analysis results is far from that of the pilot provinces, it shows that the decrease of $PM_{2.5}$ concentration is indeed caused by the performance of the CTGP. This also confirms the reliability and robustness of the policy effect analysis discussed earlier. If the difference between the two is insignificant, the above analysis results are deemed invalid. Therefore, we selected the alternative pilot provinces based on the weights in Table 3. Since the highest weighted areas in Beijing and Tianjin are the same, we selected the alternative pilot areas in Beijing as Fujian Province with the second weight, and respectively Hainan, Guangxi, Sichuan, Ningxia and Shaanxi are selected as new pilot areas, and the policy effect analysis is carried out according to the steps of the SCM. The results are manifested in Fig. 7. It can be inferred from the figure that although Fujian Province has a fine matching with the synthetic provinces before the policy occurs, the policy effect brought by the implementation of the CTGP after the policy occurs is much smaller than that of Beijing. Hainan Province

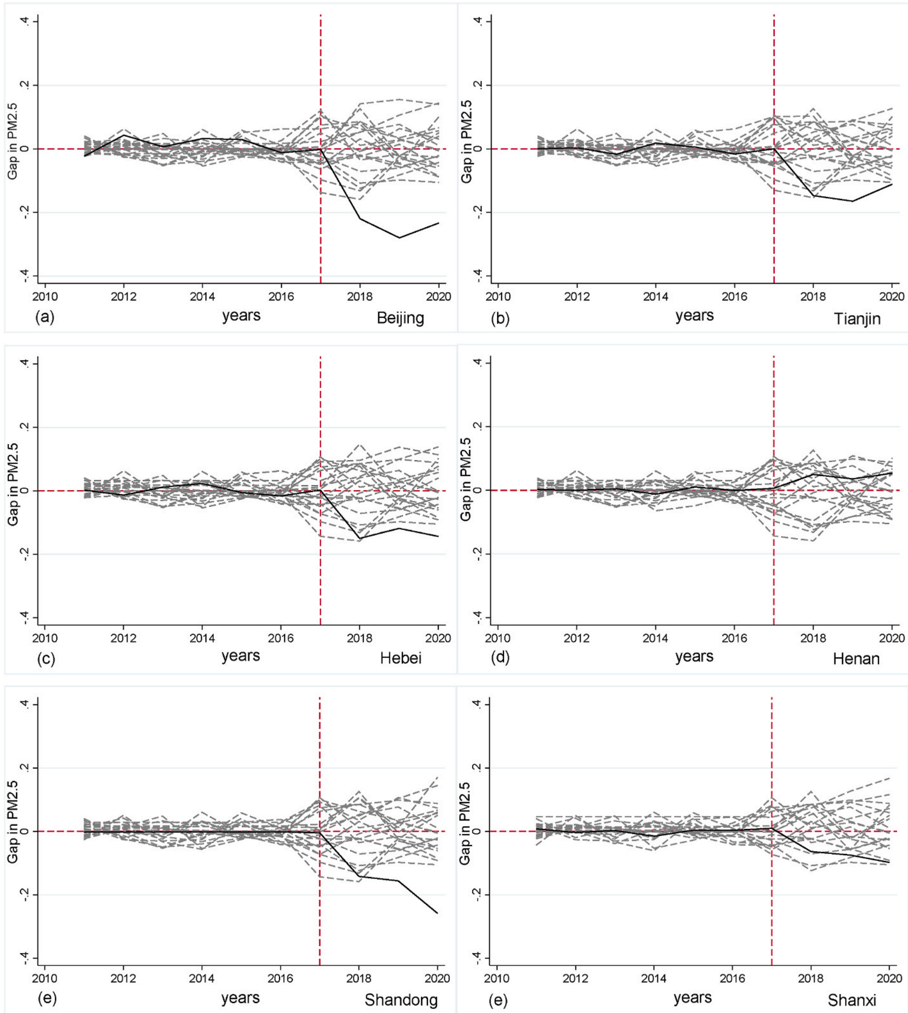

Fig. 6. Sorting test analysis.

and Shaanxi Province had a large difference between the fitting values of the synthetic provinces before the policy took place, resulting in a poor fit between the solid-line curve and the dashed line, and the gap between the real value and the synthetic value after the implementation of the policy was relatively small, and the policy is less effective. Guangxi and Ningxia provinces also fit well with the composite provinces before the policy was implemented, but the policy effect after the policy is implemented is too small. Sichuan Province exhibited a different scenario, with the policy effect after the policy implementation being larger than that in Henan Province. This result also showed that the results of policy analysis in Henan Province were not stable, and the experimental results may be due to various reasons, which also echo the results of the ranking test. Based on the experimental results, it is found that the control group province with the largest weight coefficient when the remaining five provinces other than Henan Province are fitted with the pilot provinces, under the assumption that the same policy is implemented, the policy effect is not ideal, and it also shows that the above experimental results are reliable and that the changes in air pollution are indeed due to the performance of the CTGP and not some other unobserved external factors.

4.4.3. Differences-in-differences method

The Difference in Difference (DID) method is a traditional policy analysis tool that is widely favored by scholars as it can avoid endogeneity problems to a large extent. In this section, the DID method to further investigate the impact of the implementation of the CTGP on air pollution in pilot provinces, after estimating the net effect of the implementation of the CTGP on regional air pollution, compare it with the net effect obtained by the SCM. The model settings are as follows:

$$lnPM_{2.5_{it}} = \beta_0 + \beta_1 treated_i * time + \lambda X_{it} + \delta_i + \gamma_t + \varepsilon_{it} \tag{9}$$

In Equation (9), $lnPM_{2.5_{it}}$ is the air pollution level. For pilot provinces implementing the CTGP, $treated_i$ is assigned a value of 1, and the remaining provinces are given a value of 0. The CTGP was implemented in 2017. Since 2017, *time* has been assigned a value of 1, and previously it was assigned as 0. The coefficient β_1 of the interaction term of $treated_i * time$ is the net effect of the implementation of the CTGP on AP in the pilot provinces. X_{it} is a series of control variables.

Table 5 reveals that the coefficient of the multiplication term is −0.0708 and the p-value is less than 0.01. This suggests that the implementation of the CTGP reduces the overall air pollution in the pilot provinces without the inclusion of control variables. After adding a series of control variables, the regression coefficient of the multiplication term is −0.0824, which is still negative, which also points out that the implementation of the CTGP has suppressed the air pollution in the region, and the policy has a more significant inhibitory effect on air pollution after adding the control variable. Therefore, our analysis supports the robustness of the SCM method's conclusion, that is, the implementation of the CTGP reduces air pollution in the pilot provinces.

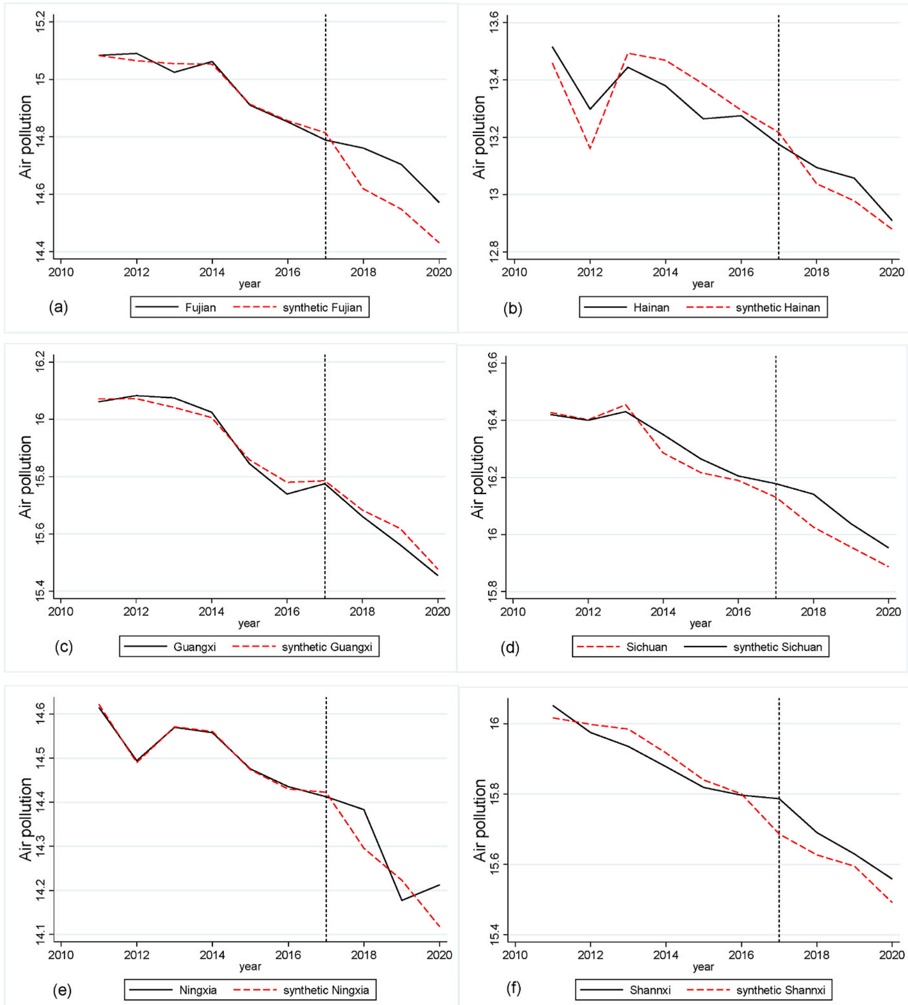

Fig. 7. Placebo test results.

Table 5
DID experimental results.

VARIABLES	(1)	(2)
	$lnPM_{2.5}$	$lnPM_{2.5}$
time*treated	−0.0708***	−0.0824***
	(0.0234)	(0.0304)
lnGDP		−0.2563***
		(0.0383)
IS		0.1516***
		(0.0451)
FDI		−0.2807***
		(0.0558)
GEST		0.0065
		(0.0047)
EC		0.8081***
		(0.1666)
lnPD		−0.0597
		(0.0399)
Constant	15.6804***	18.3605***
	(0.0145)	(0.5238)
Observations	300	300
R-squared	0.826	0.747
Province	Yes	Yes
Year	Yes	Yes
Control variables	No	Yes

Note: ***p < 0.01,**p < 0.05 and * p < 0.1; the values in brackets represent standard errors.

4.5. Research on influence mechanism

The CTGP can have a direct impact on reducing air pollution, as well as an indirect impact through other means. According to the EKC, the degree of pollution will change with the income situation in the process of economic development (Kaika and Zervas, 2013). Additionally, environmental quality can also be affected by the level of urbanization (Pang et al., 2022). Some researchers suggest that the adjustment of industrial structure and energy structure can effectively reduce air pollution (Hong et al., 2022; Li et al., 2020c), and foreign investment and technological investment may also have an inhibitory effect on air pollution (Guo, 2019; Wang et al., 2022). Economic level (lnGDP), industrial structure (IS), foreign investment (FDI), technology input (GEST), energy structure (EC), and population density (lnPD) were selected as mechanism variables to explore the impact mechanism of CTGP on air pollution. The following mediation effect test model is constructed to test the mechanism of action:

$$Mechanism_{it} = \alpha_0 + \alpha_1 treated_i * time + \alpha_2 X_{it} + \lambda_t + \mu_i + \varepsilon_{it} \tag{10}$$

In Equation (10), $Mechanism_{it}$ represents a series of mechanisms (lnGDP, IS, FDI, GEST, EC, lnPD). $\mathrm{treated}_i$ is the regional dummy variable, *time* is the policy time dummy variable, X_{it} is a series of control variables, λ_t and μ_i represents the time fixed effect and individual fixed effect respectively, and ε_{it} is the random disturbance term. Statistical results are manifested in Table 6.

Table 6 presents the test results of multiple mechanism variables. It is

Table 6
Mechanism test results.

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
	lnGDP	IS	FDI	GEST	lnPD	EC
treated *time	−0.1105***	−0.0245	0.1108***	1.4787***	0.0511	−0.0459***
	(0.0275)	(0.0302)	(0.0311)	(0.4002)	(0.0482)	(0.0108)
Constant	10.4175***	−3.1978***	−0.3345	−8.3310	8.5355***	0.9698***
	(0.2864)	(0.7327)	(0.8006)	(10.3215)	(1.0912)	(0.2756)
Observations	300	300	300	300	300	300
R-squared	0.910	0.787	0.437	0.169	0.116	0.676
Number of provinces	30	30	30	30	30	30
Province	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Control variables	Yes	Yes	Yes	Yes	Yes	Yes

Note: ***$p < 0.01$,**$p < 0.05$ and * $p < 0.1$; the values in brackets represent standard errors.

evident from (2)(5) that the industrial structure and population density have not passed the significance test, indicating that the CTGP has no significant impact on these two factors. The regression coefficients of the CTGP on the economic level, foreign investment, technological input, and energy structure are −0.1105, 0.1108, 1.4787, and −0.0459, respectively, and are significant at the 1% level. These results suggest tha the policy's implementation can effectively transform the economic development model, attract foreign investment, increase technology investment, improve energy structure and achieve the objective of reducing air pollution. Since the pilot provinces are selected based on various factors, they will suffer greater pressure, which can compel the pilot provinces to focus on quality to alleviate air pollution (Zhang et al., 2022b). At the same time, the pilot provinces can attract more foreign investment due to their superior resource endowments. These funds and related government subsidies can be used to increase technical investment and improve or develop clean technologies to reduce pollutant emissions in daily production and life, thereby reducing pollution (Huang et al., 2019). Furthermore, it is observed that the regression coefficients of economic level, foreign investment, and technological investment are relatively large, indicating that these three are the major and most effective ways in which the CTGP impacts air pollution.

5. Conclusions and policy recommendations

5.1. Conclusions

China's energy structure consumption is dominated by coal, with less oil, and a lack of gas. This excessive reliance on coal has led to severe air pollution. To tackle this issue, China has adopted energy transition strategies and commitments to global climate change mitigation goals during the 2015 United Nations Climate Change Conference. China's coal-to-gas policy (CTGP) can play a pivotal role in this transition, as it aims to shift the nation's energy consumption from coal to natural gas. However, the environmental implications of CTGP implementation remain unclear. Unlike previous studies, this article not only assesses the impact of the implementation of the CTGP on regional air pollution but also identifies the shortcomings of existing policies, such as insufficient stability and sustainability. Therefore, conducting a thorough analysis of the implementation effects of policies in each pilot area can provide more authentic and reliable evidence for the revision and formulation of air pollution control policies in the future. To do this, this study employed SCM to construct a synthetic control object for each pilot area to analyze the impact of the CTGP on air pollution in the pilot areas and study the policy effect and impact mechanism. The main findings are as follows:

- By analyzing the evolution characteristics of China's air pollution time series, it has been proved the $PM_{2.5}$ concentration in China showed a downward trend during the entire study period, decreasing from 15.684 in 2011 to 15.204 in 2020. The growth rate of $PM_{2.5}$ concentration exhibited fluctuating changes, with the exception of positive growth in 2013. The rest of the years showed a negative growth, and the growth rate reached a maximum of −0.74% in 2018. It shows that the implementation of CTGP has indeed had a significant impact on China's air pollution.
- The evaluation of policy effects in each pilot area reveals that, overall, the implementation of the CTGP reduces the air pollution in the pilot areas, but the performance of the policy in the pilot areas varies depending on economic development and resource endowments, with the exemption of Henan Province, the air pollution levels of the other five provinces (cities) have declined under the influence of the policy and have withstood a series of robustness tests. After the implementation of the policy, the air pollution in Henan Province has increased rather than decreased, but the robustness test results show that this phenomenon is not caused by CTGP, but is the result of the comprehensive effect of multiple factors. The policy net effect results indicate that the CTGP has effectively alleviated the air pollution in the pilot areas. In 2020, the policy impact reduced the air pollution level in Beijing, Tianjin, Hebei, Henan, Shandong and Shanxi by 1.73%, 0.83%, 0.90%, −0.34%, 1.63% and 0.64%, respectively. According to Fig. 5, although the policy has effectively reduced the air pollution in the pilot areas during the implementation process, it lacks certain stability. The policy's effects weaken one to two years after its promulgation, resulting in a rebound in air pollution.
- This study also investigates the impact mechanism of CTGP on air pollution by analyzing theory and practice. Economic level, industrial structure, foreign investment, technological input, energy structure and population density are used as intermediary variables to verify whether they impact the relationship between the two. The results show that the policy does not significantly affect the industrial structure and population density but strongly influences the economic level, foreign investment, technological investment, and energy structure. The regression coefficient of economic level, foreign investment, and technological investment are high, indicating that these three factors are the primary means through which the CTGP affects air pollution in the pilot areas.

5.2. Policy recommendations

Based on the empirical analysis and in light of the actual situation of CTGP on air pollution in China, this study proposes the following policy implications.

- Eliminate the "one size fits all" approach in policy formulation and adhere to adopting measures that suit local conditions. Policy implementation have different effects in different regions, so policy formulation should consider each region's unique circumstances. Targeted formulate relevant measures, respect objective economic laws, prevent impatience, make the transition from coal to gas steadily promoted and implemented, and strengthen the continuity and effectiveness of policies. For example, for cities such as Beijing and Tianjin, where coal consumption accounts for a relatively low proportion and is dominated by high-tech industries, it is still affordable for the society and economy to completely ban coal. The major provinces immediately ban coal completely, which will have an unbearable impact on regional economic development. Therefore, a step-by-step approach should be adopted to formulate differentiated policy objectives based on local economic development status and affordability. For key AP areas such as Hebei, financial support can be appropriately increased. Simultaneously, taking into account regional energy endowments, a flexible approach should be employed to adopt various heating methods. Incorporating biomass fuels like straw, wind energy, solar energy, and other new energy sources into the coal-to-gas project, a multi-energy complementary mode should be utilized to achieve the replacement of bulk coal effectively. This approach ensures that energy transition strategies are adapted to the specific needs and resources of each region, promoting a more sustainable and efficient shift from coal to cleaner energy sources.

- Considering that air pollution has a certain spatial spillover, the phenomenon of "free-riding" in individual cities is likely to occur during the implementation of the CTGP. Therefore, the implementation should take into account the benefits for cities both within and outside the pilot areas, striving for overall benefits, dismantling rigid barriers of territorial management, and engaging in comprehensive planning and coordinated efforts to minimize the overall economic cost within the region as much as possible, given environmental constraints. A holistic evaluation and tracking of policy formulation, introduction, and implementation should be conducted, and negotiations should be carried out to establish an assessment and accountability mechanism for joint defense and control of air pollution. Moreover, the fairness of the atmospheric environment in each pilot area resulting from industrial transfer should be taken into consideration. By collaboratively promoting the upgrading of regional industrial structures and energy replacement projects, the root cause of air pollution can be effectively addressed.
- The impact mechanism test results demonstrate that the economic level, foreign investment, technological input, and energy structure are the main channels for reducing air pollution through the CTGP. Consequently, it is imperative to change the economic development mode in the policy implementation process to ensure the quality and pace of development, strengthen the introduction of foreign investment, and establish a coordinated promotion mechanism for promoting the intelligent upgrading and transformation of traditional industries in the Beijing-Tianjin-Hebei region. Support should be provided for the establishment of cross-regional intelligent technology sharing platforms, financial service platforms, etc., and explore the establishment of mechanisms to promote the intelligent upgrading and transformation of traditional industries jointly. By fully utilizing high-tech industrial park collaboration methods, the level of scientific and technological research and development can be enhanced, the transformation of green achievements accelerated, the intelligence level of traditional industries improved, and their core competitiveness increased. Furthermore, a rigorous assessment, reward, and punishment system should be established, and the enthusiasm of local enterprises to participate in air pollution prevention and control should be stimulated through market-based economic measures such as tax incentives, financial support, and carbon emission rights trading.

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Credit author statement

Xueyang Wang: Conceptualization, Methodology, Software, Data curation, Formal analysis, Writing-Original Draft. Xiumei Sun: Conceptualization, Validation, Writing, review & editing, Supervision, Funding acquisition, Project management. Mahmood Ahmad: Conceptualization, Writing-Original Draft, Writing, review & editing, Supervision. Haotian Zhang: Visualization, Software.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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