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RESEARCH ARTICLE

Do China's coal-to-gas policies improve regional environmental quality? A case of Beijing

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Abstract

Clean energy transition has been considered as an indispensable way to attain sustainable development for China, where the coal-to-gas initiative plays a vital role towards the goal. This paper takes Beijing, China's political and economic center as well as a national pioneer in the energy transition, as a case to systematically analyze the co-mitigation of air pollution ($PM_{2.5}$) and carbon emissions (CO_2) achieved by the policy-driven natural gas-coal consumption substitution. Firstly, a qualitative analysis of the relationship of Beijing's coal-to-gas policies and its air quality has been conducted. Then, VAR and ARDL models are employed to quantitatively analyze the impacts of coal-to-gas policies on $PM_{2.5}$ and CO_2, respectively. Results show that (i) an innovation of natural gas/coal consumption ratio will reduce $PM_{2.5}$ concentrations, and the effect decreases over time; and (ii) an increase of 1% in natural gas/coal consumption ratio in Beijing will cause a decrease of 0.0784% in CO_2 emissions in the long run. Therefore, the coal-to-gas policies do increase the usage of natural gas and improve Beijing's air quality. The assessment methods and conclusions can be regarded as a reference for not only China's policymakers, but also other countries, especially nowadays when air quality is becoming more valued and GHGs are being tightly controlled.

Keywords Environmental policy · Coal-to-gas project · $PM_{2.5}$ concentrations · CO_2 emissions · China

Highlights
• Coal-to-gas policies in Beijing have been systematically reviewed and analyzed.
• The effect of policy implementation is analyzed qualitatively and quantitatively.
• Results show that coal-to-gas policies do improve Beijing's air quality significantly.
• Impacts of policies on $PM_{2.5}$ are significant in short term and stabilize in the long term.
• The dampening effect of policies on CO_2 emissions is significant in the long run.

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Introduction

Research background

Air pollution is one of the major environmental issues around the world. The two most important aspects of air pollution are climate change and haze. Both aspects are closely related to the large-scale usage of high-carbon fossil energies (e.g., coal). In this case, promoting the energy transition and low-carbon development has been seen as an effective pathway for solving these environmental issues. A number of measures have been adopted worldwide to achieve the low-carbon development, and one of the most important initiatives is the coal-to-gas policy, i.e., by releasing policies to increase gas consumption and reduce coal consumption. China is the largest carbon emitter and has just experienced the worst smog in its history. Also, China itself is one of the forerunning nations actively implementing coal-to-gas policies. Therefore, understanding the impacts of China's coal-to-gas policies on regional environmental quality will be important and helpful not only for China's policymakers, but also for other countries since they could gain lessons or experiences from China's policy practice.

Literature review

To verify the impact of environmental policies (in this study the coal-to-gas policies) on air quality, large numbers of research aiming at analyzing the impact of clean energy transition on the concentration of various air pollutants have been conducted. Specifically, studies in this area can be divided into two categories: qualitative analysis and quantitative analysis.

Qualitative analysis of the policies themselves or their implementation effects is one of the most widely used approaches by scholars. For instance, Wu (2020) reviews the characteristics and implementation effects of Chinese rural energy policies in four evolution stages; Yuan and Zuo (2011) analyzed the implementation and effects of Chinese low-carbon energy conversion policy in historical Five-Year Development Plans; Steinbacher and Röhrkasten (2019) evaluate the foundations, likely directions, and challenges for Germany's international sustainable energy policies; Laes et al. (2014) analyzed energy substitution policies in three different countries, evaluate the effectiveness of their implementation, and identifies best governance practices; Monstadt and Wolff (2015) sort out policies related to energy transitions and urban climate to examine the capability of urban energy regimes in adapting to environmental policy pressures; Li and Taeihagh (2020) conducted an in-depth analysis of the policy mix development in the field of Chinese sustainable energy transition; Erdiwansyah et al. (2019) review and compare energy policies related to renewables within Southeast Asian countries, hindrances to the sustainability detected; Müller et al. (2020) turn to 34 African countries to analyze their energy transition, going from policy designing, driving forces in the process, implementation, to energy justice issues and stakeholder coalitions involved. However, from the perspective of environmental policy evaluation, more in-depth studies could be conducted, as only qualitative discussions and analysis of the effects, without a quantitative empirical perspective that proves the correlation between improvement and policies, can be found.

Moreover, some scholars have directly used the changes in one aspect of the outcomes that may result from the implementation of the policies to quantitatively examine the impact(s) on atmospheric environmental quality. In recent decades, driven by coal-to-gas policies and other environmental policies, natural gas and renewable energy consumption in China has grown rapidly. In response, some scholars have used gas consumption or renewable energy consumption as variables to study their environmental impacts. For instance, Dong et al. (2018a) explore effects of increasing natural gas consumption in Beijing on $PM_{2.5}$ emissions within the environmental Kuznets curve using ARDL model; Li and Su (2017) adopt VAR model to quantify the influence of renewable energy consumption on CO_2 emissions; Dong et al. (2018b) analyze the effects of natural gas and renewable energy on CO_2 and confirm the environmental Kuznets curve for CO_2 emissions in China; Xu and Lin (2019) investigate the relationships between gas consumption and CO_2 emissions by applying nonparametric additive regression model; Zhou et al. (2019) figure out and explain the diffusion of renewable energy policies across Europe by comparing and applying different models; Ortega-Ruiz et al. (2020) evaluate India's CO_2 emissions by analyzing the main driving forces including energy consumption with LMDI method; Zhang et al. (2020) applied panel DID means to quantitatively identify if the WCHP project is effective in maintaining air quality; Hong et al. (2020) establish a model of Taiwan power system and stressed the importance of the full implementation of renewable energy projects by employing the model.

In addition to assessing the direct impact of the coal-to-gas conversion process, other scholars have assessed changes in environmental indicators in other sectors covered by environmental policies to reveal the effects of policy implementation. For instance, Ma et al. (2019) find that carbon emissions from the residential construction sector were reduced by 18,169,900 tons with significant emission reduction effects from 2002 to 2016, driven by China's energy conservation and emission reduction policies. Similarly, Ma et al. (2018) employ the Kaya-LMDI method to bottom-up account for carbon emission reductions from commercial buildings in China from 2001 to 2015 and found that the promotion of emission reduction policies still has positive effects in the commercial building sector. Such studies also include other perspectives, e.g., Ma et al. (2020) argue for the possibility of achieving a "carbon peak" in 2030 in the building sector, finding that the peak in the building sector should be limited to 1.258 $BtCO_2$ in order to achieve the target on time.

These studies provide innovative and adequate quantitative approaches to environmental policy evaluation and give logically rigorous estimation of the impacts of the energy transition. With these exciting attempts, however, it is still challenging to fully explain the impact of relevant environmental policies on air quality. To our knowledge, few studies have considered the role of environmental policies on both air pollution and GHG emissions, or the co-mitigation of air pollution and carbon emissions. Since air pollution remains a major concern in China, and GHG emissions will greatly affect the achievement of the "30–60" target, it is of vital importance to assess the impact of the same environmental policy on both environmental indicators, especially for Beijing, the capital of China. Moreover, most of the existing studies give the results of empirical analysis based on the status quo and might not fully consider the impact of policy factors. Therefore, current environmental policies need to be evaluated quantitatively to determine their environmental impact, thus informing subsequent policy development.

Aim, contribution, and organization

Based on the description in the background and deficiencies in the literature review, this paper aims to study impacts of China's coal-to-gas policies on regional air quality. Comparing current literature, the contributions of this paper are as follows: (i) the study carried out in this paper combines the qualitative and quantitative analyses; (ii) the study for the first time examines the co-mitigation of air pollution and carbon emissions driven by the transition of coal to gas, which means both CO_2 and $PM_{2.5}$ are considered in our paper (see Fig. 1). In addition, since Beijing serves as one of the leading pioneers in the implementation of coal-to-gas policies, and also considering the availability of data, Beijing is chosen as a case for study.

Following the introduction and literature review given above, the remains of this paper is organized as follows: Qualitative analysis of the impacts of coal-to-gas policies on regional environmental quality is carried out in the "Coal-to-gas policies, gas consumption, and environmental status in Beijing" section. Quantitative models for assessing the impacts of coal-to-gas policies on regional environmental quality are presented in the "Data and methodology" section and their results are given in the "Empirical results" section. The last section summarizes the "Conclusions and policy implications."

Coal-to-gas policies, gas consumption, and environmental status in Beijing

This section aims to qualitatively observe and analyze the changes in the quality of Beijing's air environment under the policy by examining Beijing's coal-to-gas policy, the changes in related natural gas and coal projects after the implementation of the policy, and the patterns of natural gas consumption and changes in $PM_{2.5}$ and CO_2.

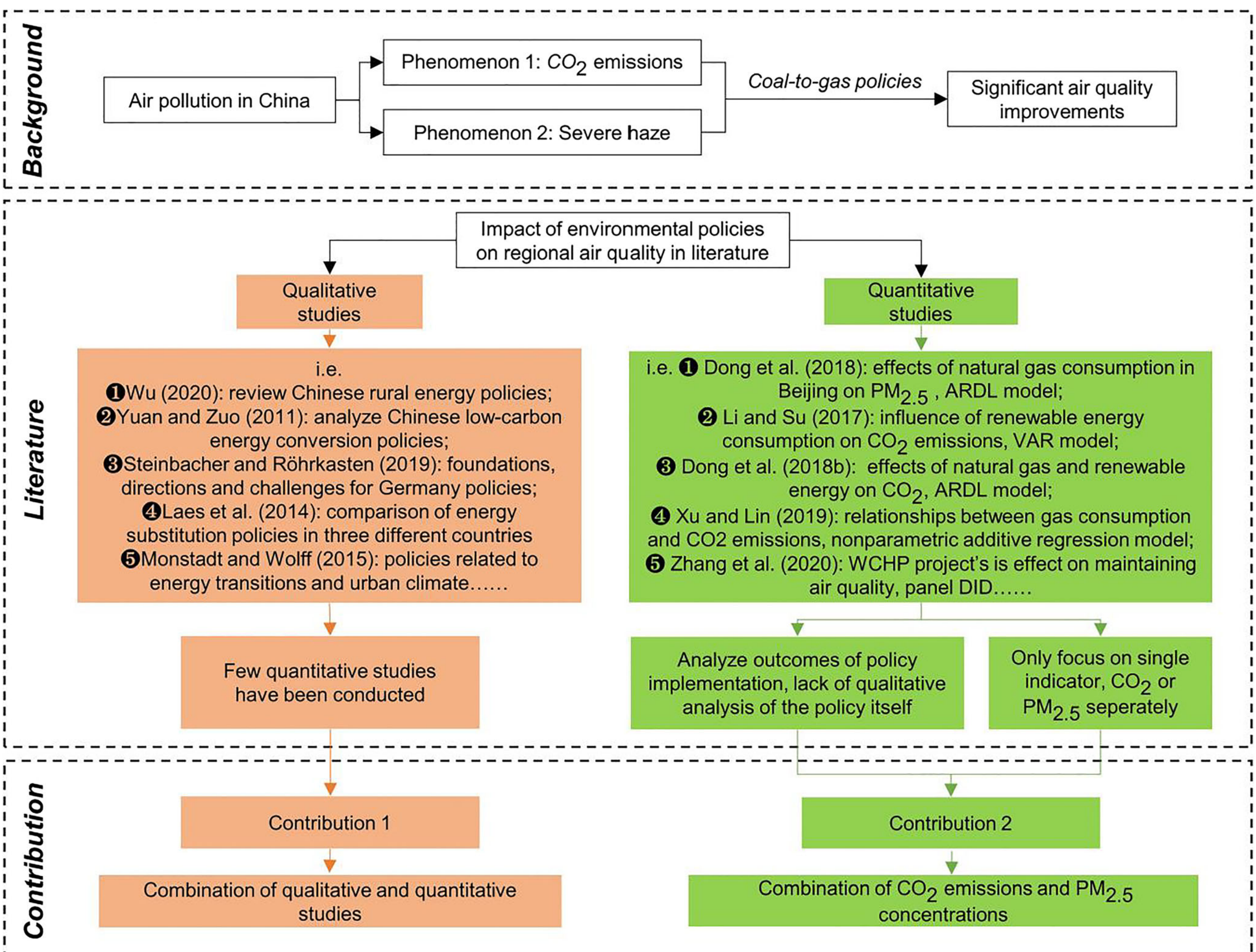


Fig. 1 Contributions of this research

Coal-to-gas policies and the resulting boost in gas consumption

Beijing has a long history of issuing and implementing coal-to-gas policies, dating back to the 1990s. In any of these policies, natural gas serves either as an end in itself (providing clean fuel to a wider range of residents and industries) or as a means (towards controlling air pollution, improving the energy mix, and/or reducing carbon emissions); in some policies, these two roles may be intertwined.

Whatever the case, the growth of natural gas consumption is closely tied to policies introduced. This is because of one thing, the urban demand for natural gas is soaring in China and supply side becomes the major constraint. For another, natural gas is an energy source that relies heavily on infrastructure deployment (pipelines), which requires considerate upfront investment, while gas utilities have long been controlled by state-owned enterprises in China, who have obligations to implement policies. With both factors combined, Beijing's natural gas consumption has always grown with the implementation of related policies.

Based on chronology and policy intensity, the overall process can be divided into five stages: initial attempts, strategic adjustment, policy innovations, process advancement, and frontier development.

Initial attempts

The first stage—initial attempts—lasted from 1997 to 2009 (Fig. 2), during which time a series of policies were issued, targeting mainly at scope of gas supply and renovation of small-to-middle-sized coal-fired boiler. Thanks to the construction of the pipeline network and the consequent nearly fourfold growth in population with access to gas, as well as the shift in the fuel of those boilers, there was an upsurge in the natural gas consumption from 165.65 million m^3 in 1997 to 6828.39 million m^3 in 2009.

In 1997, the clean energy promotion and the continuous issuing of coal-to-gas policies began as a result of two policies issued. Besides, the Shaanxi-Beijing natural gas pipeline system was completed, guaranteeing an adequate supply of natural gas resources in Beijing.

In 2001, the *Beijing Municipal Energy Structure Adjustment Plan* was issued, targeting natural gas as a vital clean energy in the energy structure adjustment. In 2002, the *Beijing 10th Five-Year Plan for Natural Gas Development and Implementation* was issued, emphasizing the need to improve the reliability and scope of gas supply, stipulating that the use of coal would be prohibited on all new constructions within the city limits of Beijing, and substitutes would be gas or liquid fuels. In 2005, a shortage of natural gas supply happened during the heating period. To ensure a functioning municipal heating system, which was dependent on fuel burning heavily, the Beijing Municipal Development and Reform Commission announced a suspension of the coal-to-gas project and increased use of coal for heating. After the gas shortage in late 2005, Beijing began to focus on the construction of the natural gas pipeline network. The shutdown of polluting enterprises and the renovation of coal-fired boiler houses were also in full swing in the meantime.

In 2006, the *Beijing 11th Five-Year Plan for Energy Development and Conservation* was issued, announcing substitution of high-quality energies for coal; subsequently, the coking plant was closed in July, reducing the coal consumption by 2.96 million tons per year. In May 2007, the *Beijing 11th Five-Year Plan for Natural Gas* was announced, specifying pipeline construction, coal consumption control, and development of electricity and natural gas networks. By the end of 2007, the renovation of coal-fired boiler houses of less than 20 tons/h in the urban area was completed.

In 2008, the *Measures to Safeguard Air Quality in Beijing for the 29th Olympic Games* was issued, requiring both coal-fired power plants and boilers to reduce emissions by 30%. By the end of 2008, 16,000 coal-fired boilers in downtown Beijing had been converted to clean energy facilities.

In 2009, the alteration works on coal-fired boiler houses of 20 tons/h or more in the urban districts began.

Policy innovations

Following the first stage, Beijing's natural gas supply has risen significantly; nevertheless, the air quality in the winter months remained not encouraging. Here came a much more radical proposal that coal power plants should be entirely superseded by four gas-fired thermal power centers (Fig. 3). With the construction of thermal power centers, the renovation of coal-fired boilers in a larger range of urban areas and transformation of domestic cooking fuels in the suburbs had led to an increase in natural gas consumption from 7,197.40 million m^3 in 2010 to 11,368.74 million m^3 in 2014.

In August 2010, the Southeast Thermal Power Center phase 2 was under construction, signifying the beginning of the substitutions of energy supply facilities. At the end of 2010, the third Shaanxi-Beijing natural gas pipeline opened, which further filled the gas supply gap in Beijing.

In January 2011, Shougang Shijingshan Plant was shut down, and in August, the *Beijing's 12th Five-Year Plan for Energy* and *Beijing's 12th Five-Year Plan for Energy Conservation and Climate Change Response* were issued to maintain the upward trend of the clean energy proportion.

In May 2012, Beijing stated that the coal use was expected to be reduced to 15 million tons within the 12th Five-Year Plan period to reduce $PM_{2.5}$ emissions and improve air quality.

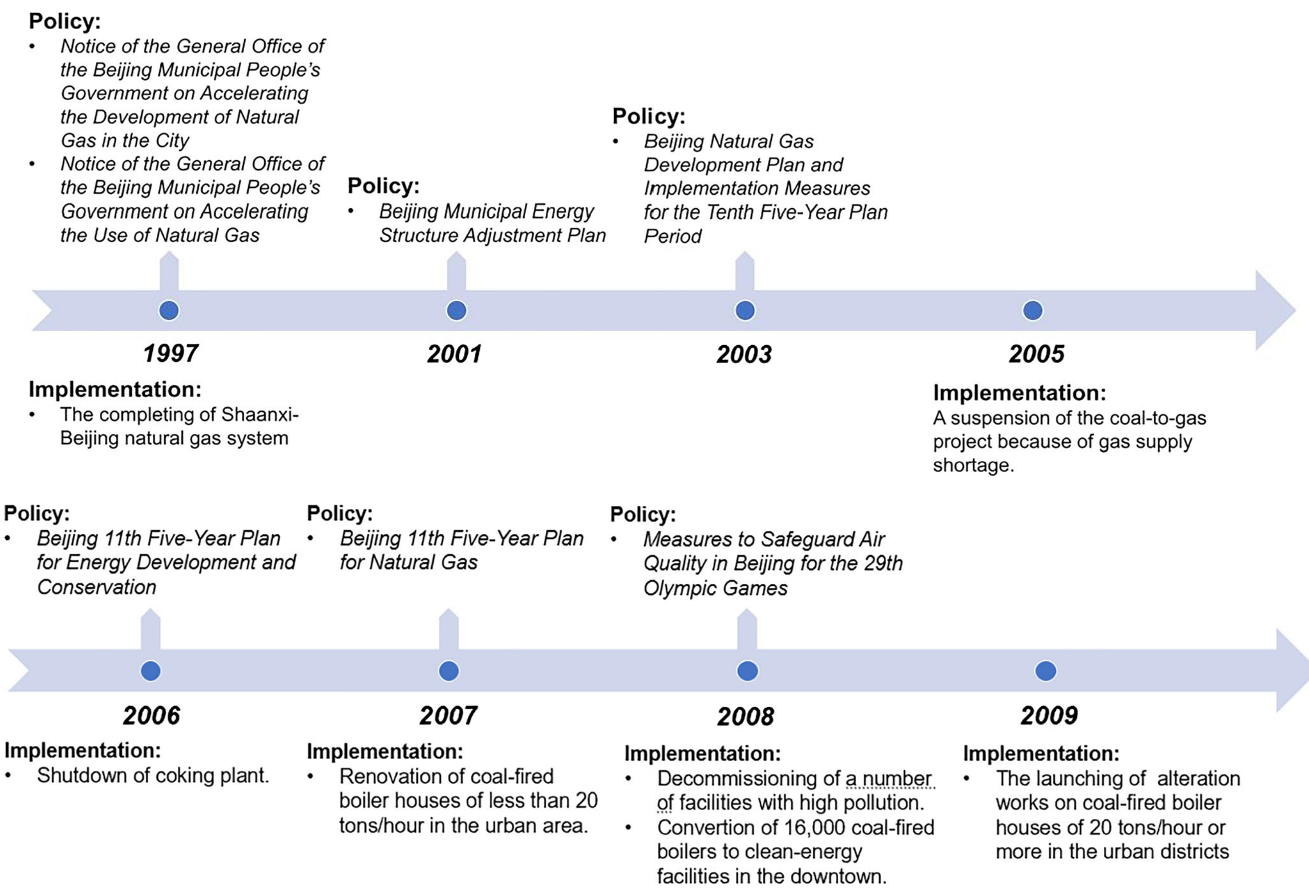


Fig. 2 Timeline of the initial attempts stage

In February 2013, the Southwest Thermal Power Center was put into operation. On September 2, the *Beijing Clean Air Action Plan 2013–2017 Key Task Breakdown* was proposed to upgrade residential heating from coal to electricity, the industrial boilers and cooking facilities in remote suburbs from coal to gas. By the end of 2013, all coal-fired boilers within the 4th Ring Road were replaced with clean energy.

Process advancement

As early as 2010, the four power plants named Gaojing, Jingneng Shijingshan, Guohua, and Gaobeidian Huaneng Phase 1 coal-fired unit were proposed to be shut down. The implementation eventually began in July 2014 (Fig. 4). In the ensuing four years, those four coal-fired plants had been gradually closed and replaced by their corresponding gas-fired

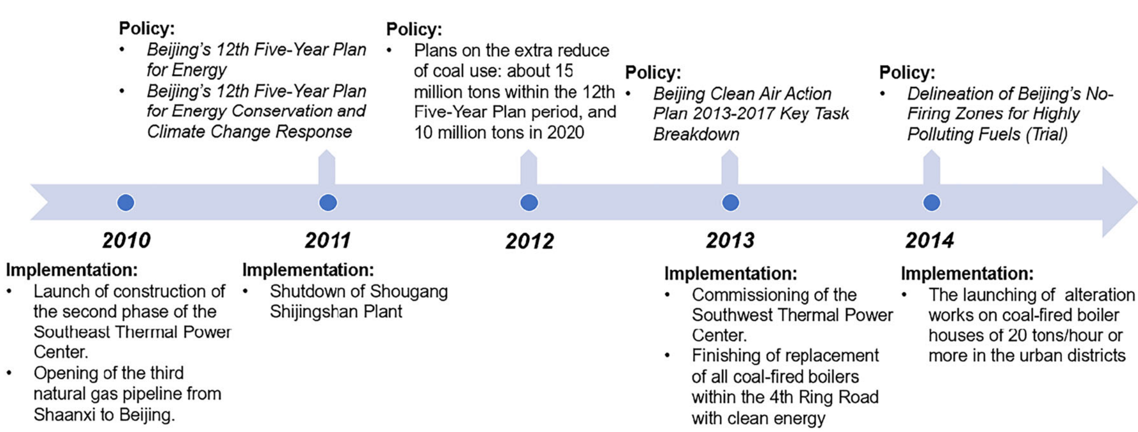


Fig. 3 Timeline of the policy innovations stage

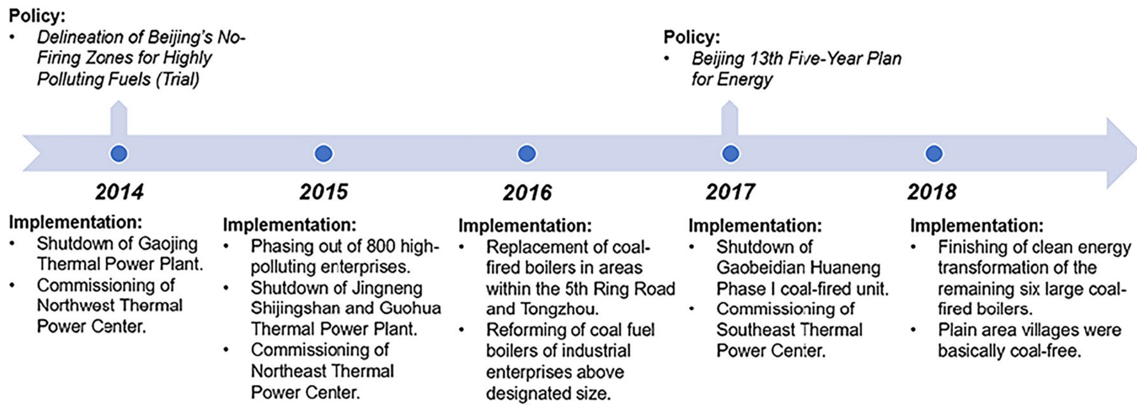


Fig. 4 Timeline of the process advancement stage

thermal power centers, resulting in an immediate increase in natural gas consumption from 11,368.74 million m^3 in 2014 to 19,159.78 million m^3 in 2018.

In July 2014, the Gaojing Thermal Power Plant was shut down. In August, the *Delineation of Beijing's No-Firing Zones for Highly Polluting Fuels (Trial)* was issued. In November, the Northwest Thermal Power Center was put into operation.

In 2015, 800 high-polluting enterprises were phased out. In March, the Jingneng Shijingshan and the Guohua Thermal Power Plant were shut down. In November, the Northeast Thermal Power Center was put into operation.

In 2016, the government introduced a strict production quota on high energy-consuming and high-emission industries, advancing the work of coal to clean energy extraordinarily. By the end of 2016, areas within the 5th Ring Road and Tongzhou District were free of coal-fired boilers, and industrial enterprises above designated size all completed the reform tasks of coal-fired boilers.

In 2017, six urban districts and the plain areas of Tongzhou, Daxing, and Fangshan Districts were largely coal-free. In March, the only coal-fired power unit left then (Gaobeidian Huaneng) Phase I coal-fired unit was shut down. In July, the *Beijing 13th Five-Year Plan for Energy* was issued. In November, the Southeast Thermal Power Center was put into operation. Since then, the construction of all four major gas-fired thermal power stations has been completed, leading to a coal-fired reduction of 9.2 million tons annually.

Before the heating season of 2018, the clean energy transformation of the remaining six large coal-fired boilers was completed. By the end of that year, Beijing's plain area villages were basically coal-free. Centralized heating systems with clean fuels in urban areas were basically accomplished.

Frontier development

After the four phases above, Beijing has basically realized coal-free in urban and plain areas. However, the shortage of gas supply caused by the coal-to-gas project persisted, and Beijing has been exploring new opportunities to alleviate the gas shortage (Fig. 5).

In July 2019, the National Energy Administration issued a request for *Related Issues on Proposals to Address the Promotion of Clean Heating Including Coal to Gas and Coal to Electricity Process* opinion letter, proposing to develop clean coal and biomass to cope with the inadequate natural gas supply. In October, the State Ministry of Ecology and Environment released the *Action Plan for Comprehensive Control of Air Pollution in 2019-2020 Autumn and Winter in the Beijing-Tianjin-Hebei and Surrounding Regions*.

According to the plan, by 2020, the city's total coal consumption will be controlled to less than 5 million tons, and the proportion of high-quality energy consumption will increase to more than 95%. The city's plain areas will be basically coal-free.

Environmental status

In this paper, air quality is studied in a broad sense, i.e., including both air pollution and greenhouse gas emission indicators. For air pollution, $PM_{2.5}$ has been selected as the representative indicator of air pollution. On the one hand, it is the primary cause of haze weather, which can have adverse impacts on public health and have attracted wide attention from the society, while coal combustion exhaust released from industrial stacks is an important source of particulate matter (PM) in China. Moreover, according to Cao et al. (2012) and Elser et al. (2016), secondary components formed by the chemical transformation of sulfur dioxide (SO_2), nitrogen oxides (NO_x), and volatile organic compounds (VOCs) are the main components of $PM_{2.5}$ in China, especially in the coal consumption sector. Thus, $PM_{2.5}$, a vital factor of air pollution, is capable of being a comprehensive indicator characterizing the emissions of multiple pollutants. On the other hand, with the introduction of emission charges and emission trading system of SO_2, its emissions have already been at the standard in the whole country (according to the latest Five-Year Plan). Therefore, other pollutants like SO_2 are not

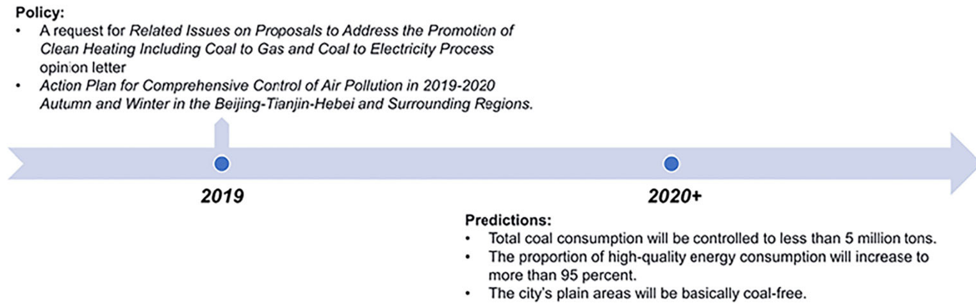


Fig. 5 Timeline of the frontier development stage

analyzed in this study. v bb CO_2 is the most emitted and influential greenhouse gas among existing greenhouse gases. Also, it is a key factor in determining whether carbon peaking and carbon neutrality targets can be achieved. Hence, CO_2 has been chosen as a GHG characterization indicator.

$PM_{2.5}$

In order to conduct a qualitative analysis of the environmental status and the impact of the coal-to-gas policies in Beijing, $PM_{2.5}$ concentration is selected as the indicator of air quality, and the hourly data of 35 monitoring stations (BJMEMC 2020) are summarized to conduct a multidimensional comparison and visualization. Considering the availability of the hourly data for $PM_{2.5}$ concentration, the scope of the study is from 2014 to 2019. The distribution of $PM_{2.5}$ concentration monitors is shown in Fig. 6.

In 2014, Beijing's gas supply exceeded 10 billion m^3, and fully extended to the 4th Ring Road area as the implementation of *Air Pollution Prevention and Control Regulations* and No-Firing Zones. At the end of 2014, $PM_{2.5}$ concentrations decreased significantly, which could be attributed to those

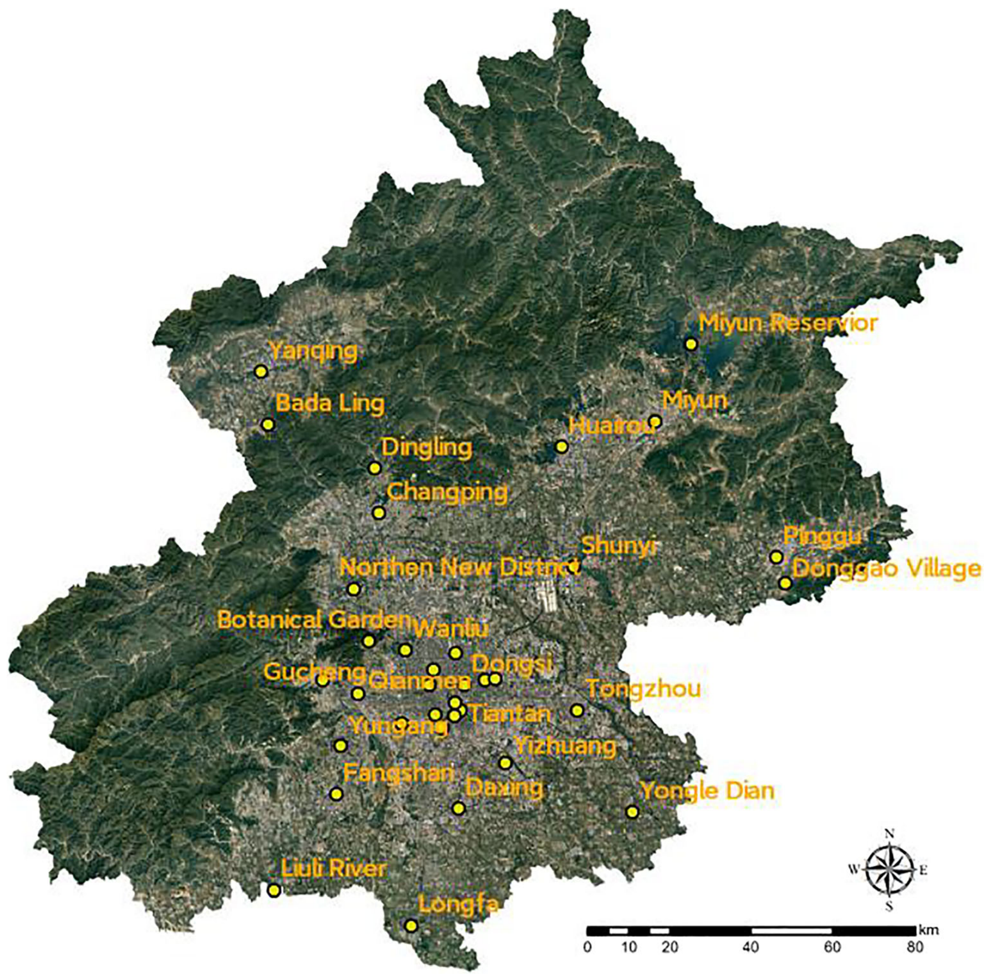


Fig. 6 Distribution map of 35 monitoring points in the research area

initiatives, including the shutdown of the Gaojing thermal power plant and the replacement of coal-fired boilers within the 4th Ring Road. Additionally, the 22nd APEC summit was held in Beijing in December of the same year, leading to much more stringent environmental regulations and fewer pollutions thereby.

As time passed, the air quality in 2015's winter, however, was not as good as in the previous year, despite a series of policies implemented, including shutdowns of two major thermal power plants, cuts in cement production, and the relocation of high-pollution companies. The deterioration in air quality could be ascribed to extreme weather phenomena caused by El Niño, when $PM_{2.5}$ in the Beijing-Tianjin-Hebei region became not easy to disperse, because of intermittent high humidity, low wind speed, and strong adverse temperature.

At the beginning of 2016, cold air incoming provided a good dispersion condition; $PM_{2.5}$ concentrations fell rapidly and reached its year-round trough in February. During 2016, areas within the 5th Ring Road and Tongzhou District were free of coal-fired boilers, and Beijing's natural gas supply exceeds 15 billion m^3 for the first time. Nevertheless, $PM_{2.5}$ concentrations were still not optimistic in the winter due to the La Niña phenomenon. Its duration and impacts were much slighter than those of El Niño.

In 2017, the coal-free district further expanded, and the coal-fired units of Gaobeidian Huaneng Phase 1 were shut down; coal consumption of the whole city reduced to 11 million tons. The average concentration of $PM_{2.5}$ in November and December controlled below 50 $\mu g/m^3$, with only 5 days above the level of light pollution (compared to 19 days during the same period in 2016). The air quality was significantly improved due to energy transformation.

In 2018, six main coal-fired boilers in the suburbs were retrofitted. The growth of gas consumption accelerated after the fluctuation in 2017. However, the figure for the $PM_{2.5}$ in March was noticeable, which could be caused by persistent dusty weather during that month. In November, $PM_{2.5}$ concentrations rebounded again, but a steadily weakening trend is observable throughout these three unfavorable meteorological conditions, in terms of the intensity and duration of their impacts.

The growth rate of natural gas supply slowed again in 2019; still, all months, except for January, February, and March, maintained the index below 50, with no high intensity or frequency of concentrated air pollution.

In order to visualize the impact of the implementations of coal-to-gas policies on the overall air quality during the heating season of Beijing, the interpolation in ArcGIS is used to display $PM_{2.5}$ concentrations for five heating seasons from December 2013 to March 2019. Figure 7 shows the interpolated average $PM_{2.5}$ concentrations for each winter in Beijing from December 2013 onwards. It is concluded that that with an increase in natural gas consumption and a decline of coal use, Beijing's $PM_{2.5}$ concentrations dropped steadily during heating seasons; that is, the environmental status in Beijing has been improved significantly.

CO_2

To qualitatively analyze the effects of coal-to-gas policies and the underlying energy transition, we selected the REASv3.1 China's provincial Carbon dioxide emissions data (Kurokawa and Ohara 2019) as the data source, from which figures for 1995 to 2015 are extracted (Fig. 8).

CO_2 emissions due to energy consumption in Beijing from 1995 to 2015 rose from 76697.65 to 99192.14 kt, with an annual average increase of 1.29%. It could be divided into three phases according to the policy implementation and emission patterns: steady increase (1995–2000), rapid growth (2001–2007), and downward trend (2008–2015), with GDP and energy consumption of each phase shown in Fig. 9.

During the steady increase, the figure for CO_2 emission rose from 76,697.65 kt in 1995 to 807,798.15 kt in 2015, which is due mainly to the rapid economic growth and the consequent massive demand for energy. In 1995, Beijing's GDP exceeded 150 billion, a dramatic increase of 31.64% over the previous year. The following years also witnessed a high growth rate of 16% on average; during this period, energy consumption also saw a wave of growth, from 35.18 mtce in 1995 to 41.44 mtce in 2000, with a growth rate of 3.3%. As the dominant power source during this period, coal contributed an average of 64.85% of CO_2 emission, whereas gas made a 1.7% contribution merely (shown in Fig. 10).

In the period of rapid growth, the amount of CO_2 emissions within Beijing has accelerated noticeably, during which time the annual growth rate increased from 1.05% previously to 6.13 %. This shift is consistent with that of the national level, stemming from high economic growth and a large-scale introduction of oil, typical high-carbon energy.

Considering that 2001 is the first year of the Tenth Five-Year Plan, when "optimizing the energy structure" was the core of the national energy development strategy, the municipal government of Beijing stated in the *Beijing Energy Restructuring Plan* that "the coal-based energy structure is one of the root causes of serious air pollution," and formulated a plan for adjusting Beijing's energy structure in the short term (to 2005) and long term (to 2010) to replace coal-fired energy with high-quality energy.

Beijing did make progress in energy efficiency. While China's overall primary energy intensity rebounded slightly between 2001 and 2007 (Fig. 11), Beijing maintained a steadily lower trend, whose carbon intensity was 3.1 t C/thousand yuan, far better than Shanghai's 4.1 t C/thousand yuan and the national average of 6 t C/thousand yuan. However, Beijing's GDP grew by $613.881 billion during this period, with a

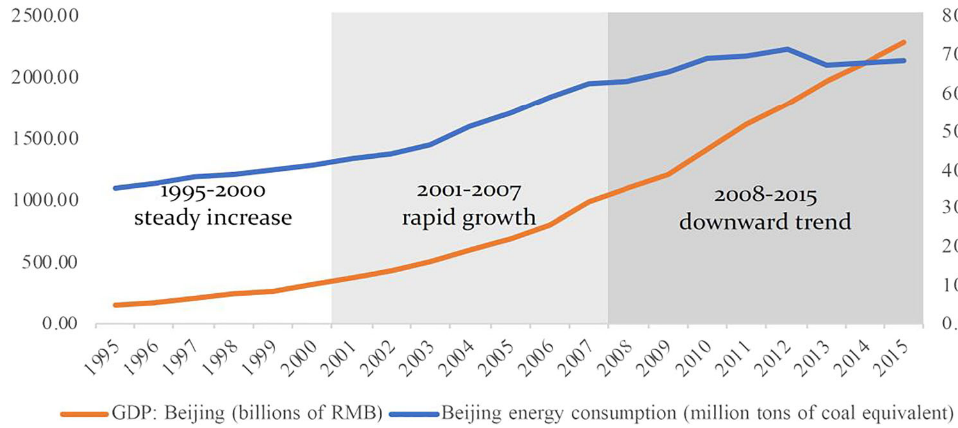


Fig. 9 GDP and energy consumption in Beijing, 1995–2015

growth rate of 17.68%; meanwhile, the role of economic growth in driving the growth of Beijing's carbon dioxide emissions was increasingly significant. These two factors combined to offset the benefit of improved energy efficiency. Additionally, the petroleum, a typical high carbon-intensive fuel, was widely introduced and consumed during this stage, giving rise to an increase in CO_2 emission of 10.6% annually, well above the 2.31% from coal consumption.

The year 2008 was a turning point, after which Beijing's carbon emissions gradually declined, entering the downward trend.

On one hand, the financial crisis swept across the world, the world GDP growth falling to 1.85% in 2008 and negative in the following year. China was also facing a slowdown, with growth rate returning to 10% in 2018 and entering a new economic stage called "New Normal" in 2012, which emphasized stable and sustainable growth. Beijing, as the political and economic center of China, has been still above average and stable at 10%, but far behind the previous 17.68%, leading to a slowdown in the energy growth consequently. The average rate from 2008 to 2015 was only 0.89%. On the other hand, the 2008 Olympic Games were held in Beijing. "Green Olympics" was one of its major concepts, which prompted the local government to implement a number of environmental protection measures, including reducing coal-fired units and promoting alternative fuels. After the Olympic Games, those large-scale environmental measures did not come to a standstill but became an environmental legacy.

In 2011, Beijing released the Beijing Energy Development and Construction Plan for the Twelfth Five-Year Plan period, proposing to promote natural gas application, upgrade large coal-fired thermal power plants and boilers, and convert coal-fired household furnaces to clean energy. Shortly afterward, four major coal-fired power plants were shut down, while gas-fired thermal power centers were established under the Beijing Clean Air Action Plan (2011–2015 Air Pollution Control Measures). The Beijing Energy Development Plan for the Thirteenth Five-Year Plan period indicated a cumulative reduction in coal use of nearly 14 million tons during this period, the proportion of coal consumption decreasing from 29.6% in 2010 to 13.7%, Beijing's CO_2 emissions from coal reduced by 23,200 pt.

After analyzing the natural gas consumption and the environmental status selecting $PM_{2.5}$ and CO_2 as two key environmental indicators, we can conclude that, on one hand, gas consumption was driven by coal-to-gas policy significantly. On the other hand, influenced by the series of coal-to-gas policies and increased gas consumption, the two key environmental indicators did change positively in Beijing from a qualitative perspective.

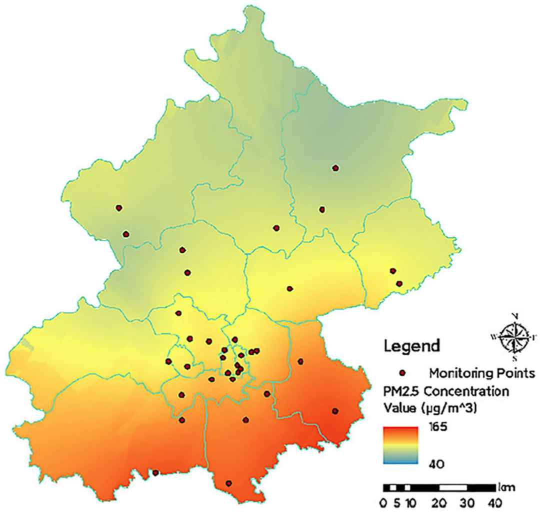
Data and methodology

The significant result of the implementation of coal-to-gas policies has been an increase in gas consumption and the resulting change in the ***RATIO*** of natural gas to coal consumption. Quantitative analysis is used in this and the next section to investigate whether this change is related to improvements in environmental quality in Beijing.

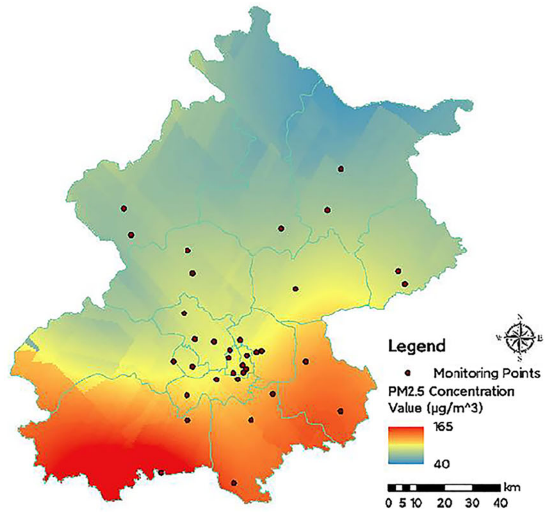
Data sources and description

In this study, time-series data are employed to explore both the relationship of $PM_{2.5}$ and gas consumption (daily, from January 1, 2013, to December 31, 2016) and the impacts of gas consumption on CO_2 emissions (monthly, from 2013M01 to 2016M12).

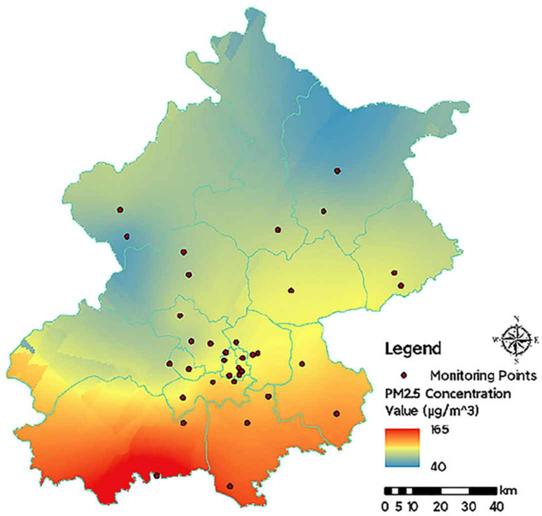
In $PM_{2.5}$ part, the study takes $PM_{2.5}$ concentrations (denoted by *PM*) as the dependent variable, and the *RATIO* of gas to coal consumption (denoted by $G2C_1$, daily) as the explanatory variable. To assess the improvement that policies brought, a change in energy structure is modeled by calculating the *RATIO* of natural gas and coal consumption.



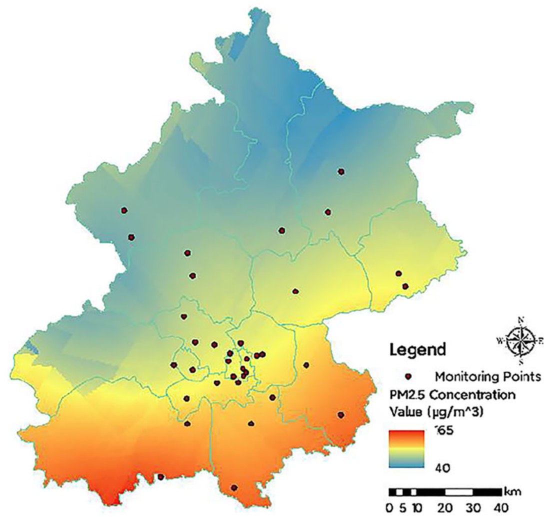
a. Heating season in 2013-2014



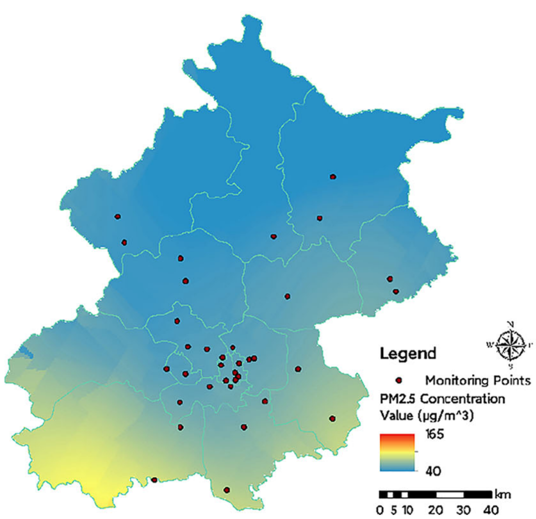
b. Heating season in 2014-2015



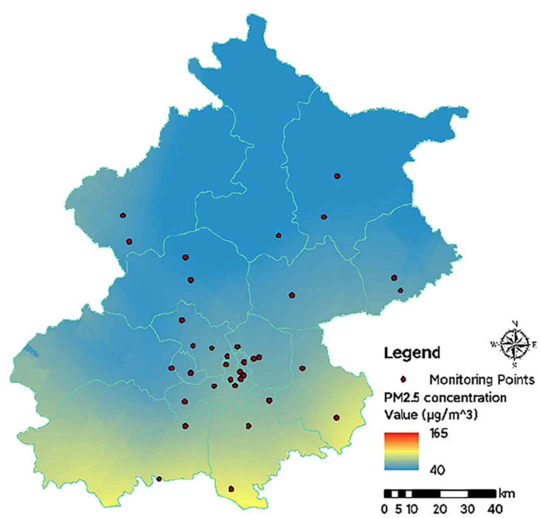
c. Heating season in 2015-2016



d. Heating season in 2016-2017



e. Heating season in 2017-2018



f. Heating season in 2018-2019

◀ **Fig. 7** Interpolated average $PM_{2.5}$ concentrations for each Heating season from 2013 to 2019. **a** Heating season in 2013–2014. **b** Heating season in 2014–2015. **c** Heating season in 2015–2016. **d** Heating season in 2016–2017. **e** Heating season in 2017–2018. **f** Heating season in 2018–2019. *Note*: The heating period in China is from November to March each year

For *PM* ($PM_{2.5}$ concentrations), measured in μg/m^3, daily data are obtained by calculating the arithmetic mean values of hourly $PM_{2.5}$ concentrations from 35 outdoor monitoring sites across Beijing (BJMEMC 2020). For $G2C_1$, it has been obtained by calculating natural gas consumption/coal consumption, where the natural gas consumption is measured in ten thousand m^3, and coal consumption is measured in ten million tons. As daily or monthly energy consumption data are not available on the government's channels like Beijing Municipal Bureau of Statistics (Dong et al. 2018a), daily energy consumption data obtained from Beijing Gas Group Research Institute (BGGRI 2020) has been used in the $PM_{2.5}$ part.

In CO_2 part, CO_2 emissions (denoted by CO_2) are taken as the dependent variable. The *RATIO* of natural gas to coal consumption (denoted by $G2C_2$ monthly) and natural gas consumption (denoted by *NG*) are selected to be explanatory variables. $G2C_2$ shares the same selected reason as $G2C_1$'s in $PM_{2.5}$ part, and natural gas consumption was chosen to isolate the effect on the model of the mechanism by which CO_2 is directly produced during the combustion of gas as a fossil fuel. For CO_2, measured in thousand tons, the data have been obtained by implementing zonal statistics in ArcGIS 10.5 using the raw data extracted from CAMS v4.2 (Granier et al. 2019, available at https://eccad3.sedoo.fr/#CAMS-GLOB-ANT).

Since the highest precision available of CO_2 emissions is monthly, in this section, we change the interval to monthly. For $G2C_2$ and *NG*, the monthly value of the *RATIO* has been obtained by aggregating daily data in the $PM_{2.5}$ part. Besides, the natural logarithmic transformation of the variables is performed in this paper, in that: (i) after comparison, the model effect after natural logarithmic transformation of the variables is better than that before the transformation; (ii) after natural logarithmic transformation, the variables will be given an elastic meaning, which will be more helpful for the interpretation and analysis of the results.

The descriptions of data used are presented in Table 1.

Model specification and modeling approach

VAR model for analyzing the relationship between PM2.5 and gas consumption

The vector autoregressive (VAR) model was first introduced by Sims (1980). It is a system of simultaneous equations where each variable depends on the current and lagged values of all other variables in it (Sack 2000). VAR is an ideal approach for estimating the relationship between $PM_{2.5}$ and gas consumption, in that: (i) For a large sample that includes 1461 observations, VAR estimates are fully efficient (Mirmirani and Cheng Li 2004). (ii) It is based on the statistical features of the data and is capable of analyzing the relationship between non-economic but interrelated variables, including energy consumption and pollutant concentrations that have been researched in this study. (iii) Through the impulse analysis in VAR model, the impact of exogenous shocks (for instance, policies, accidents, and sudden events) from variables on other variables can be identified (Pereira and Pereira 2010). Thus, the implementation effect of "coal-to-gas" policy can be predicted.

Fig. 8 CO_2 emissions by energy type in Beijing, 1995–2015

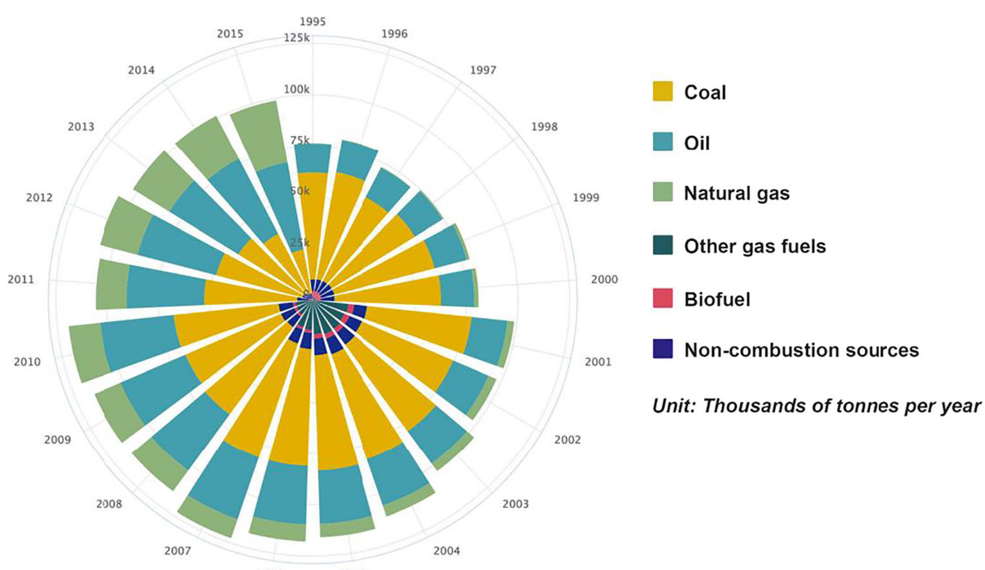
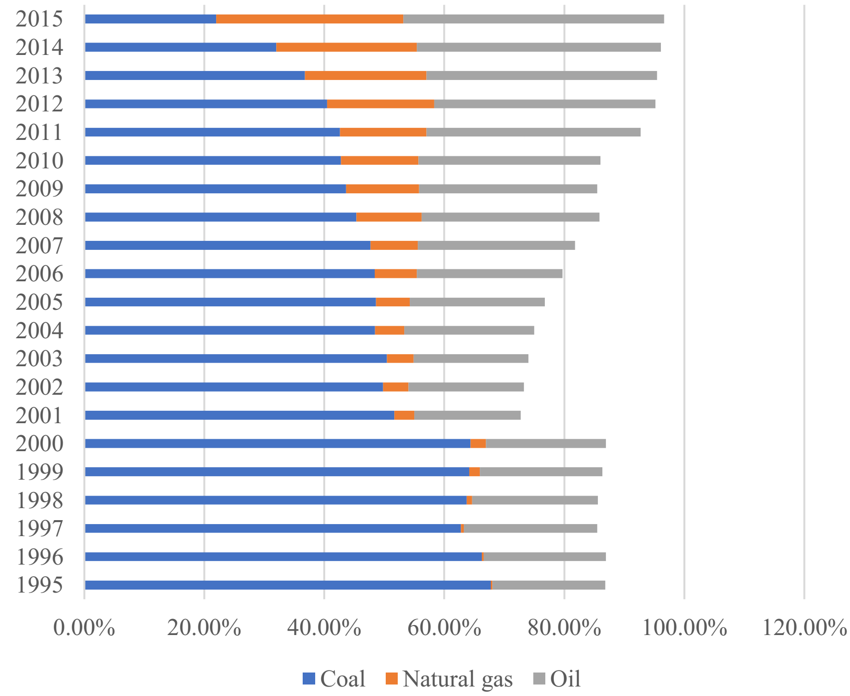


Fig. 10 Coal, oil, and natural gas share in Beijing's energy contribution to CO2 emissions, 1995–2015



The mathematical representation of a VAR model can be written as:

$$X_t = C + \sum_{i=1}^{p} A_i X_{t-i} + \mu_t. \tag{1}$$

where X is the matrix of the original variables, and X_{t-i} is that with p lags. A is the matrix of coefficients, and C is the vector of the intercepts. μ_t is a 2 × 1 matrix consisting of a random error term, where the random error term is a vector of white noise sequences. In this study, $X_t = (lnPM_t, lnG2C_{1t})^{-1}$, in which $lnPM$ denotes the natural log of $PM_{2.5}$ concentration and $lnG2C_1$ stands for the natural log of the *RATIO* of natural gas to coal consumption. Besides, a time trend variable is also added to the VAR model as an exogenous variable to eliminate the gradual trend of the time series data. As

The estimation procedures are as follows. To ensure the stationary of variables, Dickey-Fuller (ADF) unit root test is used, succeeded by two cointegration tests, Trace and Max-eigenvalue tests, in which the existence of long-run equilibrium relationship between $PM_{2.5}$ concentrations and the *RATIO* is examined, followed by the implementation of Granger causality test and the final establishment of VAR model.

ARDL model for analyzing the impacts of gas consumption on CO2 emissions

In this analysis, autoregressive distributed lag model (ARDL) proposed by Pesaran et al. (1996) is applied. It is a widely used approach for quantifying the relationships between or among time series variables. Based on the bound cointegration test, CO_2 emissions can be explained by lags of itself and current

Fig. 11 China's primary energy intensity

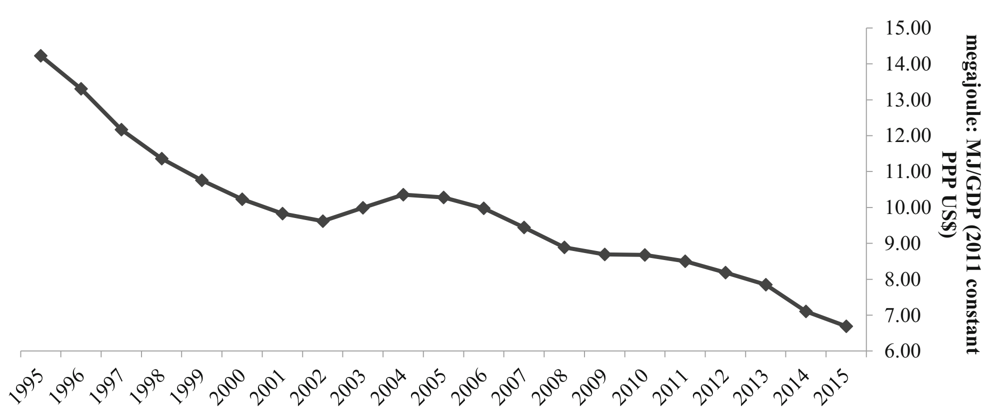


Table 1 Description of data

Variable	Def.	Unit	Average	St. dev.	Obs.
$\ln PM$	Natural log of $PM_{2.5}$ concentrations	$\mu g/m^3$	4.043131	0.887192	1461
$\ln G2C_1$	Natural log of the *RATIO*, daily	-	2.772740	1.253495	1461
$\ln CO2$	Natural log of CO2 emissions	Million tons	5.654273	0.272568	48
$\ln NG$	Natural log of gas consumption	Million m^3	3.341239	0.644641	48
$\ln G2C_2$	Natural log of the *RATIO*, monthly	-	2.769196	1.234666	48

*$G2C_1$ and $G2C_2$ are dimensionless, as they are the ratio of two energy consumption data

*Due to the different precision of the available data, this paper uses daily and monthly data for PM2.5 and CO2, respectively. Therefore, for the variables used to analyze $PM_{2.5}$, the number of observations of is 1461, while for CO_2, it is 48

and lagged values of explanatory variables. Both ARDL and VAR have been widely used, but the small sample size of monthly data compared to daily data should be taken into consideration. Given the robustness of the ARDL model in (i) estimating parameters for small samples (Pesaran 1997). As the highest precision carbon emissions data that can be found is monthly data, there are only 48 observations in the researched period; (ii) providing an unbiased estimation of short- and long-run parameters (Harris and Sollis 2005); (iii) the allowance of estimating the relationships with the underlying variables integrated at both $I(0)$ and $I(1)$ (Rahman and Kashem 2017); (iv) solving the problems associated with non-stationary time series data (for instance, spurious regression), ARDL is selected to quantify the impacts of coal-to-gas policies on CO_2 emissions. Its mathematical representation can be written as:

(i) Long-run relationship:

$$\begin{aligned}\Delta \ln CO2_t &= c + \sum_{i=1}^{n} \Delta\beta_i \ln CO2_{t-i} + \sum_{i=1}^{n} \Delta\beta_{2i} \ln NG_{t-i} \\ &\quad + \sum_{i=1}^{n} \Delta\beta_{3i} \ln(G2C_2)_{t-i} + \delta_1 \ln CO2_{t-1} \\ &\quad + \delta_2 \ln NG_{t-1} + \delta_3 \ln(G2C_2)_{t-1} + \mu_1 \qquad (2)\end{aligned}$$

(ii) Short-run relationship:

$$\begin{aligned}\Delta \ln CO2_t &= c + \sum_{i=1}^{n} \Delta\beta_i \ln CO2_{t-i} + \sum_{i=1}^{n} \Delta\beta_{2i} \ln NG_{t-i} \\ &\quad + \sum_{i=1}^{n} \Delta\beta_{3i} \ln(G2C_2)_{t-i} + \delta_1 \ln CO2_{t-1} \\ &\quad + \delta_2 \ln NG_{t-1} + \delta_3 \ln(G2C_2)_{t-1} + \theta ECM_{t-i} \\ &\quad + \mu_1 \qquad (3)\end{aligned}$$

where Δ indicates the 1st different operator, c represents the drift component, n signifies the maximum lag length, $\beta_1 \sim \beta_3$ represent error correction dynamics, $\delta_1 \sim \delta_3$ denote the long-run relationships, μ_1 means white noise error term, ECM_{t-i} is the error correction term, $lnPM$, $lnG2C_2$ andΔ $ln\ CO2$ denote the natural log of $PM_{2.5}$ concentration, the *RATIO* and CO_2 emissions. In the above equation (ii), θ should be negative, as it indicates the speed of adjustment parameter and for significant ECM model. Besides, a time trend variable is also added to the ARDL model to eliminate the gradual trend of the time series data.

The estimation procedures are as follows. Firstly, ADF unit root test is used to examine the stationarity, after which is the bound test, aiming to test the long-run relationship among the variables. The final step is to explore the impacts of gas consumption on CO_2 emissions by using ARDL approaches. Also, cumulative sum (CUSUM) and the cumulative sum of squares (CUSUMSQ) tests released by are used to ensure the stability.

Empirical results

VAR results

This section presents and discusses the results obtained from VAR model and the revealed relationship between $PM_{2.5}$ and gas consumption.

Prior to testing for cointegration, this study starts with the stationarity tests for both selected variable series using ADF unit root test, whose results are demonstrated in Table 2. The results reveal that both $\ln PM$ and $\ln G2C_1$ are stationary at the level $I(0)$ at both 1% and 5%, respectively.

The results of the cointegration test from trace test and max-eigenvalue test are shown in Table 3, indicating that null hypothesis “None” should be rejected, while “at most 1” should be accepted at 5% level respectively. It is concluded that only one cointegrating vector exist in the level between variables $\ln PM$ and $\ln G2C_1$, and can be described as:

Table 2 Unit root tests results

Variable		t-statistics	Test critical values at 1%	P value	Conclusion
ln*PM*	(C, T, 0)	-22.436^{***}	-3.964347	0.0000	Stationary
	(C, 0)	-22.055^{***}	-3.434624	0.0000	Stationary
$\ln G2C_1$	(C, T, 0)	-4.4651^{***}	-3.964347	0.0017	Stationary
	(C, 0)	-1.8819	-1.881883	0.3411	Non-stationary

Note: ***, **, and * indicate statistical significance at 1%, 5%, and 10%

$$\ln PM = -0.091975 \times \ln G2C_1 \quad (4)$$

Employing the lag selection criteria including LR, FPE, AIC, SC, and HQ, we select 2 as the optimal lag, as it is suggested by all the five criteria, and then carried out a series of tests to confirm the validity of the model.

Firstly, the results of the Granger causality test are reported in Table 4. At 1% and 5% level, respectively, we can reject the null hypothesis "$\ln G2C_1$ does not Granger Cause ln*PM*", that is, ln $\ln G2C_1$ Granger Cause ln*PM*, which leads to the conclusion that the VAR model is reasonable. Then, to check for the statistical adequacy of the model, a stability test is performed. The four unit roots in this model are 0.994807, 0.326087 - 0.308377i, 0.326087 + 0.308377i, and − 0.108453. As we expected, none of them are outside the unit circle, indicating that the VAR model is stable. Passing the tests performed above, a valid VAR model can be established.

The impulse responses are dynamic reactions of each variable to a one-time shock or innovation to a series. The middle line in Fig. 12 shows the response of $PM_{2.5}$ to a one-unit standard deviation shock to the *RATIO*. The two borderlines represent confidence interval. In Phase 1, ln*PM* gives an immediate and significant negative response to the shock from $\ln G2C_1$. As time progresses, a gradually weakening negative effect appears from Phase 2 onwards. After Phase 4, the effect becomes positive in a short period, then gradually remains stable near zero.

To explain it, we can classify the effect of coal-to-gas policies on $PM_{2.5}$ concentrations into two effects: the substitution effect and the creation effect. The substitution effect means that the increase of natural gas consumption and the decrease of coal consumption led by the coal-to-gas policies will reduce the total amount of pollution emissions to a certain extent, as the burning process of natural gas emits less pollutants, while the creation effect is totally opposite. It indicates that the implementation of the coal-to-gas policies will create additional energy demand or activate the potential energy consumption, which will impact the air quality negatively. From the results of the impulse response, the offsetting of these two effects can be detected. The substitution effect is most significant at the beginning of the policy implementation, and as time advances, residents adapt to the policy in various ways (e.g., by increasing total energy consumption), leading to a gradual creation effect and offsetting the substitution effect. Therefore, the final improvement utility tends to stabilize. Cumulating the effects of the shocks at each time point, we find that the shock from $\ln G2C_1$ will bring improvements in ln*PM*.

These findings confirm that the switch in energy consumption structure from gas to coal will reduce $PM_{2.5}$ concentrations in Beijing. On the one hand, as mentioned above, the increase in natural gas consumption in Beijing is closely related to the introduction of the coal-to-gas policy. With policy drivers (e.g., the 12th Five-Year Plan, which clearly states that multiple transportation pipelines, gas gateways and storage depots will be completed by 2015), various types of infrastructure are supposed to be constructed to meet the conditions of natural gas supply, thereby increasing natural gas consumption. On the other hand, due to China's resource endowment, coal has a strong competitive advantage of low price over other fossil energy sources, coal consumption thus accounts for over 60% of China's total energy consumption during the period included in the empirical study (National Bureau of Statistics of China 2021). To reduce the coal consumption, the government needs to use both regulatory and control measures and economic incentives to reduce coal consumption. The coal-to-gas policies include both instruments (e.g., the 12th Five-Year Plan specifies the reduction of coal consumption in that period; subsidies funded by the local government),

Table 3 Cointegration tests results

Null hypothesis	Trace test			Max-eigenvalue test		
	Statistic	Critical Value	Prob.**	Statistic	Critical Value	Prob.**
None	218.8707	15.49471	0.0001	216.2075	14.26460	0.0001
At most 1	2.663205	3.841466	0.1027	2.663205	3.841466	0.1027

Table 4 Granger causality test results

Null hypothesis	F-Statistic	Prob.
lnPM does not Granger Cause ln$G2C_1$	1.32919	0.265
ln$G2C_1$ does not Granger Cause ln*PM*	4.84583	0.008

effectively achieving the expected reduction in coal consumption.

ARDL results

This section presents and discusses the results obtained from the ARDL model that analyzes the impacts of gas consumption on CO_2 emissions.

Similar to the VAR model, the implementation of ARDL model also starts with the stationarity tests for all selected variable series using ADF test. The results in Table 5 indicate that all these three variables are integrated at $I(0)$ or $I(1)$, making it valid to carry out further tests of the cointegrating relationship between these three chosen variables using the ARDL estimator.

The results of ARDL cointegration test are shown in Table 6, in which we have a greater F-statistics of 7.923511 than the bounds on significant level of 10%, 5%, and 1%, proving the existence of long-run relationship between the variables. Furthermore, ECM_{t-1} has been introduced to examine the presence of short-run cointegration. We have a significant and negative value of ECM_{t-1} in Table 6, confirming the existence of a short-run relationship, which serves the basic purpose and lays the groundwork for follow-up studies on the impacts of gas consumption on CO_2 emissions.

Based on the results in Table 7, analysis is carried out to assess the short-run and long-run impacts. The upper part details the long-run estimation results, and the lower part describes the short-run ones

For *NG*, results both in upper and lower parts of Table 7 show significant positive coefficients, suggesting that there are both long-run and short-run relationships between CO_2 emission and natural gas consumption; the more natural gas consumed, the more CO_2 emitted, which is consistent with the consensus on the nature of natural gas as a fossil fuel itself.

For the *RATIO* of gas to coal consumption in Beijing, its effect is not significant for CO_2 emissions in the short run. While in the long run, a significant dampening effect on CO_2 emissions can be found, which can be described in elasticity: an increase of 1% in the *NG* in Beijing will cause a decrease of 0.0784% in CO_2 in the long run. This could be explained by the fact that coal combustion causes about 61% more CO_2 emissions per unit of heat than natural gas (Shen 2013); therefore, the substitution of natural gas for coal naturally reduces CO_2 emissions. Such an empirical result supports the conclusion from the qualitative study that the development and implementation of the coal-to-gas polices do reduce Beijing's CO_2 emissions to some extent.

As for the reason behind the gap between coefficients in the short and long run, policies played a crucial role in the short term, when command and control (CAC) regulation leads to immediate shutdowns of coal-fired boilers and plants, resulting in a surge in natural gas consumption and a sharp decline in coal consumption. Such large volatilities in energy consumption and significant substitution effect over short periods result in a weak effect of short-term natural gas consumption on CO_2 growth. However, in the long term, as the room for coal reduction shrunk inevitably (Fig. 13), the inherent increase in demand for natural gas (the creation effect) became the primary factor to an increase in CO_2 emission, making the CO_2 emission effect of natural gas reflected more accurately. Nevertheless, due to the substitution effect, the effect of coal-to-gas policy implementation is still to reduce CO_2 emissions.

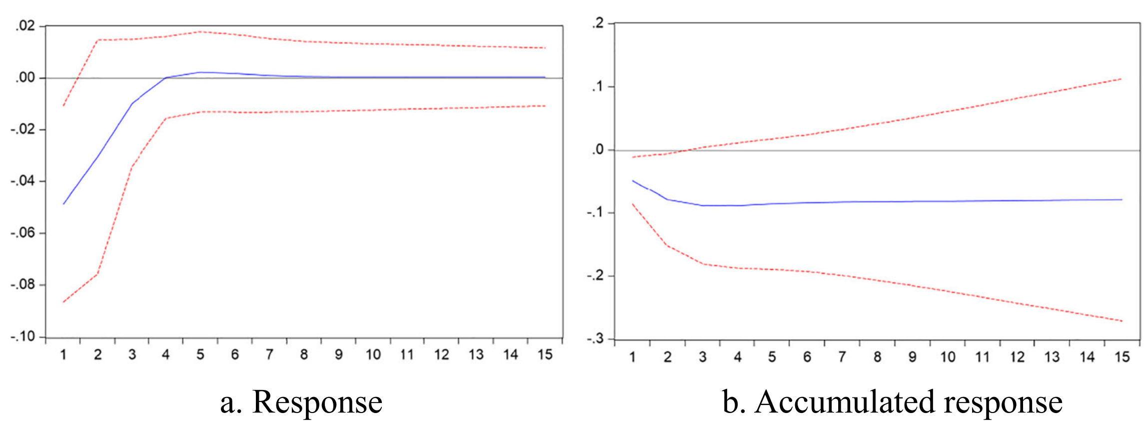


Fig. 12 Response of $PM_{2.5}$ to a one-time shock in the *RATIO*. **a** Response. **b** Accumulated response. **Note*: Red dotted lines denote critical bounds at 5% significance level.

Table 5 Unit root tests results.

Variable		t-statistics	Test critical values at 1%	P-value	Conclusion
$\ln CO2$	(C, T, 0)	− 11.59840***	− 4.211868	0.0000	Stationary
	(C, 0)	− 9.831450***	− 3.610453	0.0000	Stationary
$\ln NG$	(C, T, 0)	− 6.369744***	− 4.211868	0.0000	Stationary
	(C, 0)	− 1.203285	− 3.615588	0.6631	Non-stationary
$\ln G2C_2$	(C, T, 0)	− 2.629709	− 4.165756	0.2697	Non-Stationary
	(C, 0)	− 0.554893	− 3.57772	0.8706	Non-stationary
$\Delta\ln CO2$	(C, T, 1)	− 5.895592***	− 4.226815	0.0001	Stationary
	(C, 1)	− 6.173042***	− 3.621023	0.0000	Stationary
$\Delta\ln NG$	(C, T, 1)	− 9.382948***	− 4.226815	0.0000	Stationary
	(C, 1)	− 9.532182***	− 3.621023	0.0000	Stationary
$\Delta\ln G2C_2$	(C, T, 1)	− 5.789774***	− 4.170583	0.0001	Stationary
	(C, 1)	− 5.808645***	− 3.581152	0.0000	Stationary

Note: ***, **, and * indicate statistical significance at 1%, 5%, and 10%. Δ is the sign of at 1st difference

Finally, the regression is stable as the plots of CUSUM and CUSUMSQ statistics (Fig. 14) stay within the critical bounds, according to Durbin et al. (1975).

Conclusions and policy implications

Conclusions

This study attempts to verify the existence of co-mitigation of air pollution ($PM_{2.5}$) and carbon emissions (CO_2) achieved by the policy-driven natural gas-coal consumption substitution both from qualitative and quantitative way. For that, a VAR model and an ARDL model have been established. The results indicate that:

1) The qualitative analysis shows that under the continuous implementation of the coal-to-gas policies, there have been an increase in Beijing's natural gas consumption and a decrease in that of coal, resulting in the upward trend of the natural gas/coal consumption *RATIO*. Correspondingly, throughout the implementation of this policy in recent decades, considerable improvements can be found on Beijing's air quality, with significantly decreasing $PM_{2.5}$ concentrations and gradually declining CO_2 emissions.
2) The quantitative analysis indicates that:

   (i) For $PM_{2.5}$, an innovation of natural gas/coal consumption *RATIO* will significantly reduce $PM_{2.5}$ concentrations, and the effect decreases over time, which means the impacts of coal-to-gas policies on $PM_{2.5}$ reduction is significant in the period 2013–2016. As the implementation of the coal-to-gas policies will significantly change the supply and demand in the energy market, the substitution effect and the creation effect of clean energy transition driven by coal-to-gas policies have been introduced to explain the fluctuation from short-term to long-term. Backtracking the results of quantitative analysis, we can also detect that the introduction and implementation of coal-to-gas policies (both CAC and EI), the continuously increasing gas consumption and decreasing coal consumption driven by the policies, and decreasing in $PM_{2.5}$ concentration in the qualitative analysis all match the results of VAR model.

   (ii) For CO_2, an increase of 1% in natural gas/coal consumption ratio in Beijing will cause a decrease

Table 6 ARDL cointegration test results.

Significant level	10%		5%		1%	
	$I(0)$	$I(1)$	$I(0)$	$I(1)$	$I(0)$	$I(1)$
Critical value	2.63	3.35	3.1	3.87	4.13	5
F-statistics	19.09006		ECM_{t-1}(t-stat.)	− 1.98***(− 9.10)	*Result: Cointegration*	

Note: ***, **, and * indicate statistical significance at 1%, 5%, and 10%

Table 7 Long-run and short-run analysis

Variables	Coefficient	Std. Error	T-statistic	Prob.
Long-run analysis				
ln*NG*	*0.280356****	0.028050	9.994798	0.0000
ln*G2C*$_2$	*− 0.078233****	0.027687	− 2.825609	0.0077
Constant	*4.908180****	0.073099	67.14465	0.0000
Short-run analysis				
Δln*NG*	*0.172689***	0.081990	2.106218	0.0422
Δln*G2C*$_2$	*− 0.120793*	0.103795	− 1.163761	0.2522
T	*0.000057***	0.000023	2.493185	0.0174
ECM(−1)	*− 1.982067****	0.217923	− 9.096027	0.0000

Note: ***, **, and * indicate statistical significance at 1%, 5%, and 10%.

of 0.0784% in CO_2 emissions in the long run, which indicates the existence of the positive effect of coal-to-gas policies and the clean energy transition driven by them on carbon emission reduction in the period 2013–2016. The reduction is mainly caused by the substitution effect of natural gas-coal conversion driven by coal-to-gas policies, as coal and natural gas have significant carbon emission factors when burned due to their different nature. In conclusion, according to the revision of policy and declining historical emissions, the energy transition behind the coal-to-gas process has a significant dampening effect on CO_2 emissions.

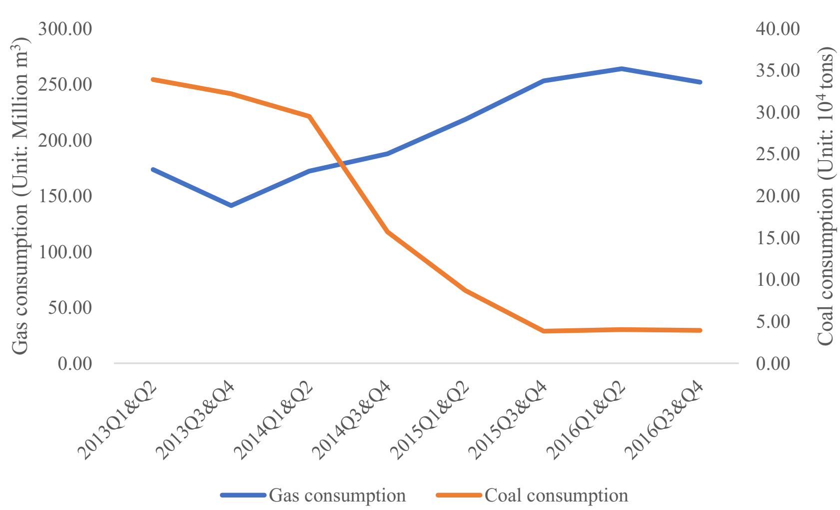
In summary, the existence of co-mitigation of air pollution ($PM_{2.5}$) and carbon emissions (CO_2) is detected to be significant. Therefore, coal-to-gas policies derived gas consumption in Beijing do improve environmental quality.

Policy implications

The findings and results above highlight several vital policy implications.

1) Due to the co-mitigation of air pollution ($PM_{2.5}$) and carbon emissions (CO_2) of policy-derived gas consumption growth and coal consumption reduction, relevant authorities should further revise and improve their policies to promote the coal-to-gas project. From this perspective, measures as follows can be taken: (i) open the upstream and downstream gas markets and establish competitive gas supply chain structures, which can ensure a sustainable supply, high quality, and price that is more in line with market trends on one hand, and activate the natural gas market on the other hand. (ii) Smoothly complete all clean energy transition in Beijing. (iii) Optimize energy transition subsidies and increase consumption taxes on high carbon emitting/high polluting energy sources.
2) The promotion of natural gas is strongly related to the infrastructure construction level, the government is suggested to: (i) increase supply capacity to guarantee abundant storage and supply of potential natural gas consumption. (ii) Promote the pipeline deployment to extend the population with access to natural gas.
3) The use of fossil fuels has a negative impact on environmental indicators, including but not limited to $PM_{2.5}$ concentrations and CO_2 emissions, and natural gas, as a clean energy source, is no exception. Coal-to-gas utilizes gas to mitigate this negative impact. As can be seen, the effect of increasing natural gas consumption on air quality improvement has gradually diminished and stabilized over time. Therefore, to completely solve this problem, authorities should plan and implement the project in stages. Short-termly, air quality should be improved by

Fig. 13 Gas and coal consumption from 2013 to 2016, semi-annually



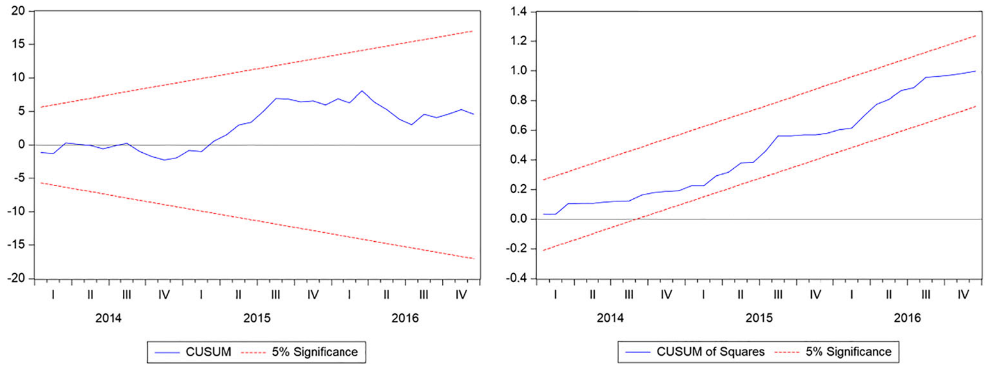


Fig. 14 Plots of cumulative sums of recursive and cumulative sums of squares of recursive residuals. **Note*: The red dotted lines denote critical bounds at 5% significance level

promoting coal-to-gas and vigorously develop renewable energy sources, while in the medium and long term, reduction in total energy consumption and introduction of mature renewable energy should be realized to consolidate environmental improvements.

Limitations and future study directions

Several gaps that exist in this study can be addressed in the future.

First, there are difficulties in obtaining daily and monthly data on natural gas consumption, which limits the number of observations and the scope of quantitative analysis to the most recent, where further study could fill the gaps to improve the statistical significance of modeling.

Second, this article focuses on the development and effects of Beijing's coal-to-gas policy, but environmental issues cannot be addressed without considering surrounding areas; thus, further discussion could be done on a larger, integrated economic region with coordinated development, for instance, the Jingjinji Metropolitan Region, which is an economic zone surrounding the municipalities of Beijing and Tianjin.

Availability of data The $PM_{2.5}$ data analyzed during the current study are available in the Beijing Municipal Ecological and Environmental Monitoring Center repository, http://www.bjmemc.com.cn/. The CO_2 dataset analyzed during the current study are available in the Beijing Municipal Ecological and Environmental Monitoring Center repository, http://www.bjmemc.com.cn/. The CO_2 data analyzed during this study are included in this published article: *Long-term historical trends in air pollutant emissions in Asia: Regional Emission inventory in ASia (REAS) version 3.1*.

The daily consumption data that support the findings of this study are available from Beijing Gas Group Company Limited but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of Beijing Gas Group Company Limited.

Authors' contributions Conceptualization: JLW. Data curation: JLW, ZHL, HKY, YDM, JXF. Methodology: ZHL, HKY. Formal analysis and investigation: JLW, ZHL, HKY. Writing—original draft preparation: ZHL, HKY, QL. Writing—review and editing: JLW, YDM. Visualization: ZHL, HKY. Funding acquisition: JLW. Supervision: JLW, YDM.

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Declarations

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Competing interests The authors declare that they have no competing interests.

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