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Air pollution related externality of district heating – a case study of Changping, Beijing

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Abstract

Air pollution, caused by the use of fossil fuel, has been an environmental plague in China. It has a strong negative impact on human health. Since the costs of damage to health are not born by the pollution producers, these costs translate to social externality. Policies have an important role in optimizing resource allocation, such as penalizing the pollutant producers and incentivizing clean energy development. Among others, replacing coal with natural gas for heating represents an important example of air quality improvement measures. This paper presents a study that evaluates the health impacts from air pollution and the external cost of the “Coal-To-Gas” policy in district heating using Changping District (Beijing, China) as an example. Four scenarios were considered based on the historical and standard PM_{2.5} concentration. Results show that PM_{2.5} is responsible for causing an increase of 40% premature deaths in 2015 and that the monetary value of damage to health is higher than 1.2 billion CNY. In 2016 and 2017, the reported air quality was better than that in 2015. As a result, 13.3% and 26% premature deaths caused by air pollution were avoided in 2016 and 2017 compared to 2015 respectively. If the PM_{2.5} concentration level were to be reduced to national standard, the number of premature deaths attributed to PM_{2.5} could further decrease to 47.7% compared to 2015. Overall, the Coal-To-Gas policy in district heating reduces 0.017%–0.45% of premature death caused by air pollution each year. Air pollution reduction policies, which are expected to improve air quality together in the future, and the specific policy of Coal-To-Gas in district heating, could make great contribution to reducing the premature death caused by environmental problem and need more attention from the government and the public.

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1. Introduction

China faces a dire situation of combating air pollutions. Airborne pollutants can cause health diseases like chronic bronchitis, lung cancer, cardiovascular diseases, and stroke [1,2]. According to World Health Organization, three million premature deaths were reported worldwide in 2012 due to air pollution, and 88% of them were reported in low and middle income countries [1].

Replacing coal with natural gas is among the important plans and efforts to improve air quality in China. The share of natural gas in the primary energy mix was 6% in 2015 in China [3]. The country plans to further improve the share of natural gas to more than 10% by 2020 [4]. Particularly in Beijing, the policy is to promote Coal-to-Gas shift in space heating in the last ten years. According to Beijing's 12th five-year-plan, coal-fired boilers supplied 31.3% of energy for space heating in Beijing in 2010 [5] and 24% in 2012 [6] with a planned reduction to 17.6% in 2015 [5]. At the same time, natural gas-fired boilers and combined-heating-and-power was planned to have a larger share in 2015 than 2010 [5]. Studies have also been done about the energy saving potentials [7–10]. To improve air quality, the government has put in place subsidies for incentivizing the use of clean energy resources. According to a study by Shao [11], the natural gas boiler district heating (DH) would receive a higher subsidy than coal-fired boiler DH by 1.05 RMB per square meter. As planned, dust, SO₂ and NO_x emissions from the heating system in Beijing will be reduced by 4765 tons, 9754 tons and 4755 tons respectively through the Coal-to-Gas switching [5].

The physical impact of air pollution is usually evaluated through examining the pollutant discharge from a given system such as those seen in [12–14]. The socioeconomic impact of air pollution is usually examined through the analysis of external costs. The externality of energy systems generally refers to mortality or morbidity attributed to air pollution. The external costs are generally defined as those beyond costs internal to a given system, and imposed on to other people outside the system.

The health impact of air pollution has been evaluated in many studies, mainly focused on developed countries and urban areas [15,16]. In a Portuguese urban area, Grande Porto, if PM₁₀ emission were to be reduced by about 8%, the annual expected health benefit is 8.8 million Euro [16]. Due to the PM₁₀ air pollution in 113 cities in China, 299700 premature deaths were reported in 2006, and the total economic cost of damage to health was estimated to be 341.403 billion Chinese Yuan [15]. The health impact of air pollution attributed to heating energy use are also serious due to the long-term solid fuel combustion especially in Northern China. Zhang and Smith [17] found that 420,000 premature annual deaths in China are caused by indoor air pollution from solid fuel use, while 300,000 are attributed to urban outdoor air pollution. Wang and Luo [18] used spatial autocorrelation models to study the relations between life expectancy at birth and energy use in China, and found that domestic coal shows a negative effect on LEB, while other energy uses don't have significant effect. There are also some studies focused on specific sectors [19–21], especially sectors with high energy intensity.

There is a large gap between the environmental objectives of energy use between the 6-central-districts and suburb counties of Beijing. In 2015, the plan was to completely phase out the use of coal for space heating in 6-central-districts [5]. This plan has already been materialized by the heating season in 2017. However, the plan for suburb counties is less ambitious. Coal-fired boilers still accounted for 46.9% share of heating supply in 2015, which covered 150 million square meters building area [5]. Recent years saw suburb counties beginning to promote replacing coal with cleaner form of energy for heating. Changping district, located in the Northwestern part of Beijing, promoted the coal fired boiler reform by offering a large amount of subsidy financed by both district and municipal government [22,23]. The objective is to promote the use of natural gas in space heating so as to improve air quality in Beijing.

Existing studies on health effect of air pollution tend to focus primarily on urban areas. This paper focuses on the externality of Coal-to-Gas shift for district heating in suburb and rural areas in Beijing. Several air quality scenarios and the according air pollution reduction health effect under these scenarios are evaluated to show the impact of background air quality. This study combines the air quality model and Impact Pathway Methodology to evaluate the health impact of a specific group of emission sources. It is expected that this study could do some contribution for the externality studies in rural areas for developing countries, where air pollution problems are more serious than developed countries, and where the rural area are usually ignored in the beginning when dealing with environmental problems.

2. Methodology and models

Due to the impact on human health caused by air pollution, the ExternE project was commissioned in early 1990s and lasted for about 15 years in Europe to estimate the external costs of polluted air. And the Impact Pathway Methodology (IPM) was constructed to evaluate the monetary externality of air pollution [24,25]. The IPM model is applied in this study, including an air quality model called AERMOD to estimate the air pollutant dispersion and calculate PM_{2.5} concentration given emission data, and the health effect evaluation model to evaluate the premature mortality attributed to air pollution and its monetary value. This article has made some improvements to this model to study local issues. A generic model is constructed for the monetary evaluation of health impact caused by energy use in rural areas. Changping Beijing is taken as a case study in this paper. The model could also be adjusted to evaluate the externality of energy use in other districts, other developing countries and other energy consumption sectors.

2.1. PM_{2.5} concentration distribution

For the district heating emission reductions, an air quality model, AERMOD, is used to simulate the corresponding ambient PM_{2.5} concentration distribution. AERMOD is constructed by United States Environmental Protection Agency and recommended by the Ministry of Environmental Protection of China [26]. It assumes the smoke plume diffusion to follow Gaussian distribution.

The dispersion of air pollutants is affected by conditions of emission sources, like location, smoke temperature, emission rates and so on, also affected by meteorological conditions, like wind speed, wind direction, temperature and cloud cover. 11 DH plants are modeled as emission sources in the case study, and the emissions in each month are different according to heating demand. It is assumed that 341 tons of PM_{2.5} are emitted by these DH plants.

2.2. Health effect

The model for obtaining the correlation between PM_{2.5} concentration and health impact is a regression model called Cox proportional hazards survival model. Given other variables unchanged, when concentration is higher than threshold concentration, RR could be got from the formula below. The ERC value, exposure-response coefficient, used in this model is 5.37 from Fang Die [27]. Premature death is the product of basic premature death without exposure and the RR under real air quality. The monetary value of health effect is calculated by the formulas below,

$$RR = \exp(ERC * C_1) / \exp(ERC * C_0) = \exp(ERC * (C_1 - C_0)) \quad (1)$$

$$\Delta I = I - I_0 = I - I / RR = I * (I - I / RR) \quad (2)$$

$$HI = \Delta I * VSL \quad (3)$$

where I denotes the real mortality, I_0 is the ideal mortality without exposure, ΔI is the premature death due to air pollution, HI is the monetary value of health effect, VSL is the value of statistical life.

2.3. Initial and revised concentration

The health impact of air pollution is evaluated based on initial PM_{2.5} concentration, which contains the emission from space heating and all other sources. To evaluate the effect of space heating, the emissions from space heating is removed from the initial concentration to get the revised concentration, and the difference between the health effects from the two concentrations is attributed to space heating. Four scenarios on the air quality in Changping, Beijing, are set based on historical data [28] as shown in Table 1. The PM_{2.5} background concentrations are monitored from 2013, and 3-years' annual average concentration data of 2015, 2016 and 2017 and the standard concentration of 35 μ g/cm, form the basis of scenario settings. The historical average PM_{2.5} concentration is 70.6 μ g/cm in 2015,

61 $\mu\text{g}/\text{cm}$ in 2016, and 52 $\mu\text{g}/\text{cm}$ in 2017.

Table1 Historical data and scenarios of PM2.5 concentration, $\mu\text{g}/\text{cm}$

2015	2016	2017	C1	C2	C3-STND	C4
70.6	61.0	52.0	45.0	40.0	35.0	30.0

Generally, a higher concentration level of PM2.5 translates to greater harm to human health. There is a threshold concentration below which damage to human health can be ignored. The threshold concentration is set to be 7.5 $\mu\text{g}/\text{cm}$ in this paper, which is consistent with Fang [27]. Fig.2 shows the PM2.5 concentration levels in different scenarios.

2.4. Case study of Changping

Changping is a suburb district located in northwest of Beijing. Changping has 17 towns and about 594,903 people [29]. The PM2.5 concentrations and health effects for 17 towns are estimated separately using the IPM model. The name and population of each town are shown in table2.

Table2 Population of 17 towns of Changping

village	V1	V2	V3	V4	V5	V6	V7	V8	V9
name	Chengbei	Nankou	Machikou	Shahe	Chengnan	Huilongguan	Dongxiaokou	Yangfang	Xiaotangshan
population	93111	45026	35385	48789	20081	72746	60109	16047	33636
village	V10	V11	V12	V13	V14	V15	V16	V17	
name	Nanshao	Cuicun	Baishan	Beiqijia	Xingshou	Liucun	Shisanling	Yanshou	
population	19592	14359	16235	39897	23149	19369	26530	10842	

3. Results

3.1. Energy consumption of space heating in Beijing

According to Beijing Statistical Yearbook [30–32], the total energy consumption of space heating was 6.2 million tonnes of standard coal in 2016, about 9% of Beijing's total energy consumption. As shown in fig.1, the total energy consumption of space heating growth was slow, but the energy mix changed very quickly. The share of natural gas increased from 30% in 2013 to 64% in 2016. In effect, the dominance of coal in space heating was quickly replaced by natural gas in Beijing. The Coal-to-Gas project was implemented successfully in space heating, especially in district heating. Financial subsidies played an important role in the promotion of natural gas for space heating.

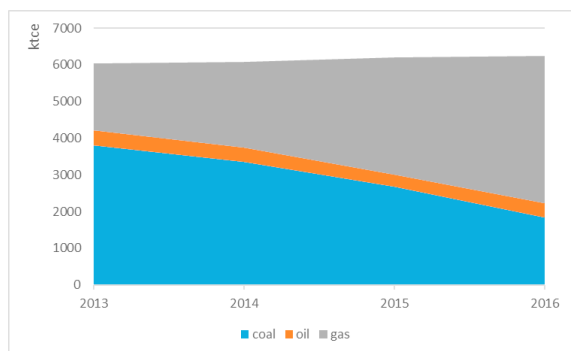


Fig.1 Total energy consumption of space heating in Beijing from 2013 to 2016

3.2. PM2.5 emissions and air pollution

Promoting natural gas in DH is mainly aimed at reducing air pollution. PM2.5 emissions from DH in Beijing were 2633 tonnes in 2015, 13% of total emission from energy use, and are expected to drop to 305 tons in 2020, while the share of PM2.5 emission drops to 3% [33]. In the case study of Changping, it is assumed that 341 tons of PM2.5 are reduced from Coal-to-Gas in DH. The PM2.5 concentration changes due to the Coal-to-Gas in district heating ranged from 0.01-0.11 μg/cm, as shown in Fig.3.

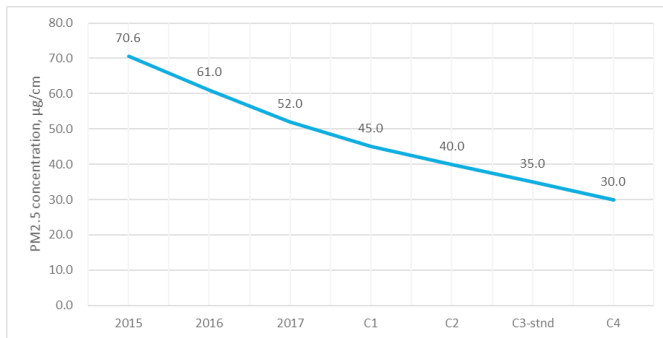


Fig.2 PM2.5 concentration levels in different scenarios

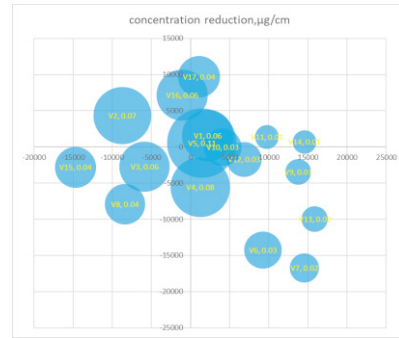


Fig.3 concentration reduction from Coal-To-Gas

3.3. Health impact

According to the modelling analysis results, the number of premature death attributed to air pollution was 308 in 2015, Changping, where the annual PM2.5 concentration was 70.6 μg/cm. When the air quality became better, a lot of premature deaths were avoided. Specifically speaking, when the PM2.5 concentration were to be reduced to the level of 2016 annual average, 41 premature deaths could be avoided. If the PM2.5 concentration were to be reduced to 2017 level and the standard level, the avoided premature deaths were 80 and 161, respectively. As shown in Fig.4, more premature deaths could be avoided in the four scenarios with lower PM2.5 concentrations.

The reduced premature death due Coal-To-Gas in district heating also varies in four scenarios. Among them, Scenario 4 has the highest value. As shown in Fig.5, the statistical value of reduced premature death each year is about 0.2 persons with PM2.5 concentration reduction about 0.01~0.11 μg/cm.

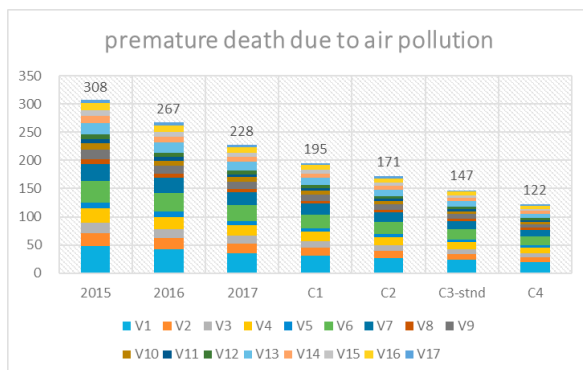


Fig.4 premature death in 4 scenarios

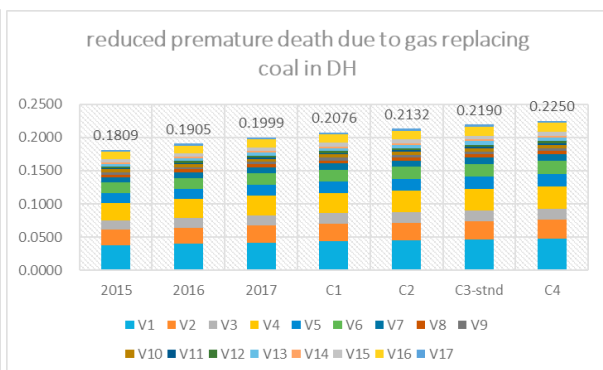


Fig.5 reduced premature death due to Coal-To-Gas in DH

The monetary value is calculated to evaluate the air pollution impact and policy effect. As shown in Fig.6, where OECD transferred VSL is 2,673,858 Chinese Yuan, while USA transferred VSL is 4,118,350 Chinese Yuan, the health damage is higher than 1.2 billion Chinese Yuan, in 2015, Changping, under the historical air quality condition. Health damage is reduced to 605 million in scenario C3, where the PM2.5 concentration is reduced to the standard

level.

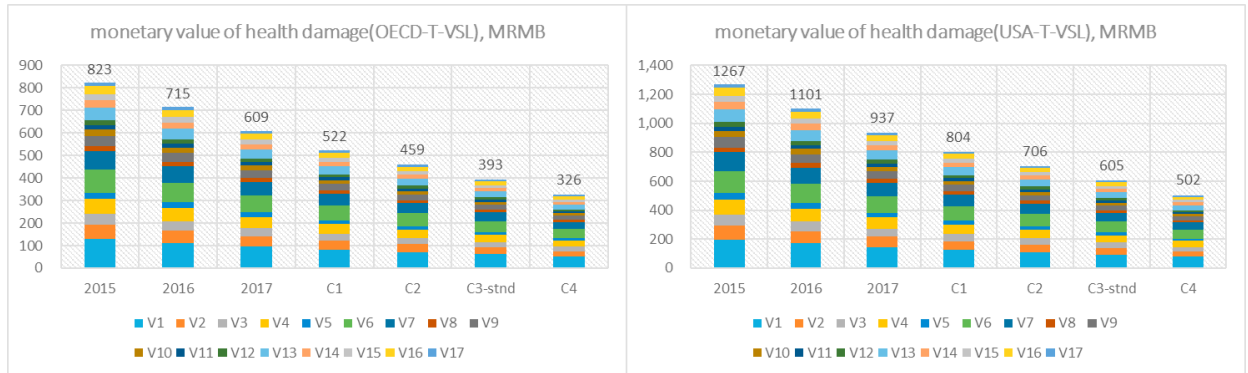


Fig.6 monetary value of health damage

The policy of Coal-to-Gas shift in district heating does have some contributions to reduce the air pollution health effect in Changping. As shown in Fig.7, the contribution of the DH policy ranged from 0.03%~0.26% in scenario C1, 0.04%~0.3% in scenario C2, 0.04%~0.36% in scenario C3-STND and 0.05%~0.45% in scenario C4. The Chengnan subdistrict, marking as village5, which is located in the central part of Changping, has the highest benefit from the DH policy, mainly because it has the highest concentration reduction impact. The comparison among villages shows that the distribution of population is also an important factor for the evaluation of policy environmental effects.

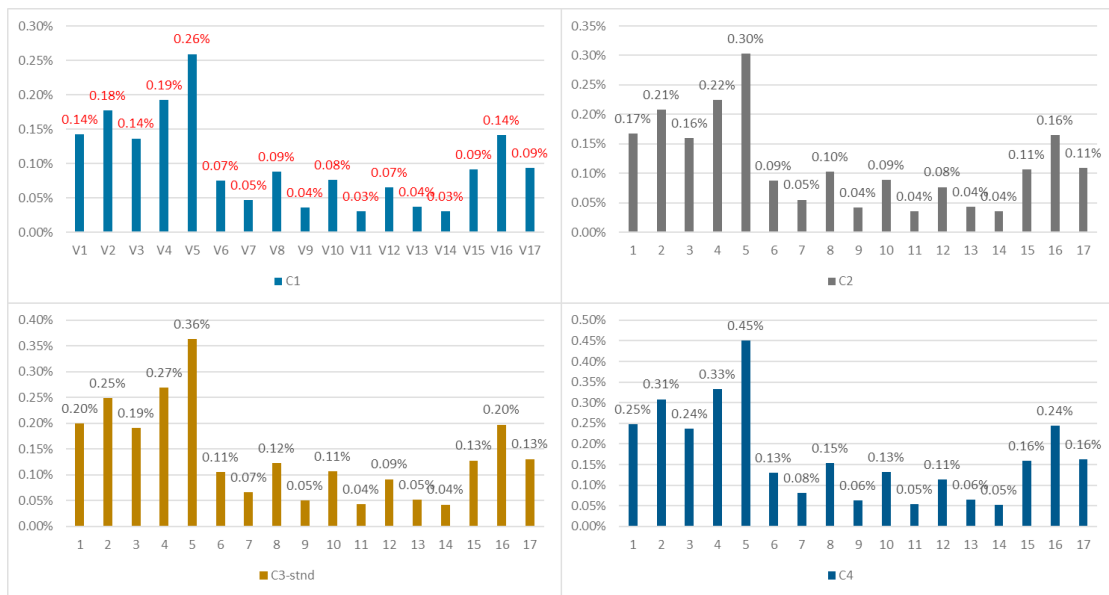


Fig.7 proportion reduction of monetary value of health damage due to Coal-To-Gas in DH

4. Conclusions

The results of this paper suggest a decreasing trend in air pollution-induced health impact in Changping, Beijing, from 2015 to 2017. The premature deaths due to PM_{2.5} are reduced from 308 to 228 from 2015 to 2017. Premature deaths are expected to further decrease to 147 when the annual average concentration is reduced to national standard level of 35µg/cm.

The Coal-to-Gas project in district heating contributed to 0.017%~0.45% of health damage each year. The health damage could be further reduced as the PM_{2.5} concentration continues to decrease. As such, it is important for consistent and continuously implementation of emission reduction policies to achieve the most desirable outcomes.

The model constructed in this paper is a generic model, which could also be applied to other districts, economic sectors, and countries to evaluate the health effect caused by energy use in rural areas.

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