



Who benefits from household energy transition? A cost-benefit analysis based on household survey data in China

Lunyu Xie^a, Chu Wei^a, Xinye Zheng^a, Yang Liu^{a,*}, Wanyi Wu^b, Ziru Feng^c

^a School of Applied Economics, Renmin University of China, China

^b National School of Development, Peking University, China

^c ICBC Credit Suisse Asset Management Co., Ltd, China

ARTICLE INFO

JEL codes:

Q48
Q53
Q58

Keywords:

Cost-benefit analysis
Energy transition
Inequity
Private benefit
Social benefit

ABSTRACT

Aiming to alleviate air pollution and carbon emissions from heating, Northern China mandatorily converted household heating energy from coal to electricity (*Coal to Electricity*), natural gas (*Coal to Gas*), and clean coal (*Clean Coal Replacement*). Based on large-scale household survey data in Beijing, this study provides a cost-benefit analysis of the transition program and distinguishes between social and private benefits. The results show that all three programs improve the welfare of society and households. Compared to the *Clean Coal Replacement* program, *Coal to Electricity* and *Coal to Gas* programs provide higher environmental benefits while bringing about larger costs, and thus the benefit-to-cost ratios are lower. We also find that private net benefits are lower than social net benefits, and household satisfaction with the programs is positively determined by private net benefits rather than social net benefits. Furthermore, households with lower income and larger housing areas are more likely to be harmed by the programs by a larger burden from the heating energy transition. These findings call attention to inequity issues during the household energy transition.

1. Introduction

As the largest coal consumer in the world and the largest contributor to global carbon dioxide, China has been suffering from severe air pollution and criticized for a large amount of greenhouse gas emissions. In 2019, China consumed 81.93 exajoules of coal, rocketing over half of the total coal consumption in the world (BP, 2020). Regarding carbon emissions, China emitted 9.83 billion tons in 2019, accounting for 28.8% of the world's emissions (BP, 2020). The large scale and rapid growth of China's carbon emissions have made China a global hot spot for carbon reduction and low-carbon development. Given the urgency of the issue, China has promised to achieve carbon neutrality before 2060, and one of the important strategies is energy transition to reduce the use of coal in the energy system (e.g. Cui et al., 2021; Dong, Qi, & Nemet, 2021; Zhang, Shi, Qian, Chen, & Nie, 2021).

A massive household heating energy transition (HET) policy is implemented in northern China, aiming to reduce household coal consumption by mandatorily replacing household heating coal with natural gas (*Coal to Gas*) or electricity (*Coal to Electricity*), or clean coal (*Clean Coal Replacement*, as a transitional program). The benefit of the programs, including fewer emissions of air pollutants and carbon dioxide, is jointly enjoyed by the participating households, and also the local environment. In contrast, the transition cost, including equipment upgrade expenditure and higher heating costs, is mainly burdened by household participants. Therefore,

* Corresponding author.

E-mail address: lyang0822@ruc.edu.cn (Y. Liu).

although the programs rolled out quickly with a high subsidy, it raised many complaints among the participants and put large challenges on governments' fiscal and administrative capacity. To address this issue and figure out the programs' efficiency and impact on household satisfaction, this paper provides a systematic cost-benefit analysis of the three HET programs from both the public and the household private perspectives, and proposes relevant policy suggestions.

There is a large body of literature evaluating government-led household energy transition programs. [Budy and Arofat \(2011\)](#) studied Indonesia's megaproject of converting cooking fuel from kerosene to LPG. The program is evaluated as a success since it alleviated the fiscal burden of kerosene subsidies, benefited the business community and the end-users, and reduced the emission of air pollutants and greenhouse gases. In contrast, many researchers demonstrated similar programs in other countries as less successful. For example, the [World Bank \(2003\)](#) and [Rao \(2012\)](#) explored the household cooking energy transition from wood and dung to kerosene and LPG in India, and found that price subsidies for kerosene and LPG were fiscally unsustainable and seriously mistargeted. [Michelsen and Madlener \(2016\)](#) analyzed the transition of fossil fuel heating systems to appliances based on renewable energy sources in Germany, and suggested that the perceived difficulty of getting used to the system and misunderstandings about its principal function made the transition difficult. [Nguyen, Nguyen, Hoang, Wilson, and Managi \(2019\)](#) used national household survey data in Vietnam, and concluded that the transition from traditional energy to modern energy led to an energy price increase and imposed a larger burden on the poor.

However, the HET policy in China differs in several aspects. First, the included programs are mandatory to promote coal reduction. Although the transition programs may benefit the public, the implementation process ignoring equity in allocating resources (e.g., subsidies and government expenditure among different groups) would harm participants and draw complaints about the transition ([Xie, Hu, Zhang, & Zhang, 2022](#)). Second, given the requirement of delivering two alternative energy sources – electricity and natural gas – the programs involve a large scale of infrastructure construction and are therefore very costly. Third, the programs put a large burden on government fiscal expenditures and household heating costs, because coal is abundant and cheap in China, while electricity and natural gas are expensive (e.g., [Lin & Mou, 2021](#)). Given the characteristics of the HET policy, the conclusions from previous studies may not apply.

The household heating energy transition in China has aroused attention with the evaluation of the health and environmental effects. [Barrington-Leigh et al. \(2019\)](#) evaluated the effects of the *Coal to Electricity* program on energy use and expenditure, indoor environmental quality, and household well-being. The findings suggested that households in the high and middle-income districts benefit from the program from a better indoor environment and higher satisfaction, while those in the low-income districts are not satisfied with the program and fewer benefit from the indoor environment. [Xu and Ge \(2020\)](#) found that household satisfaction with the *Coal to Gas* program is at a medium level based on survey data of Hebei Province. [Liang, He, and Qiu \(2021\)](#) employed posts from Sina Weibo to evaluate the *Coal to Gas* policy, and suggested that the public complaints are mainly from poor policy design, a shortage of energy, increased cost and safety. [Xie et al. \(2022\)](#) provided further evidence that the mandatory energy transition policy would harm low-income households, and increase energy poverty. Additionally, based on the cost-benefit analysis, [Zhang, Jin, Dai, Xie, and Zhang \(2019\)](#) investigated the *Coal to Electricity* program and found that the benefit of the program exceeds the cost in Beijing, Tianjin, and Hebei provinces. Although the HET program can realize positive net benefits for society, the program still leads to dissatisfaction in some households, as suggested above.

In the existing literature, however, the comparison of the benefit and cost directly associated with households and the distributional equity of cost burden among households have not been paid enough discussion. Energy transition programs need to address the energy equity among different groups to inform a more equitable distribution of environmental and economic costs and benefits, in order to reduce the disparities and complaints of households ([Chapman, McLellan, & Tezuka, 2016](#); [Tong et al., 2021](#)). In most cases, however, the poorest bear a disproportionate share of the costs of household energy transition ([United Nations \(UN\) Development Programme and University of Bergen, 2018](#)), which would aggravate energy inequity and bring about complaints ([Borenstein & Davis, 2016](#); [Carley & Konisky, 2020](#); [Rozenberg, Vogt-Schilb, & Hallegatte, 2020](#)). Household private benefits and costs brought by the HET policy would directly affect the satisfaction of households, leading to heterogeneous perceptions of the mandatory programs. To address this gap, our paper distinguishes the social and private benefits and costs of the HET policy, and assesses the distributional equity of allocating resources among households, which would affect household satisfaction.

This study contributes to the existing literature in three folds. First, based on large-scale household survey data in Beijing, we develop a cost-benefit analysis for all three main programs of the HET policy, including *Coal to Electricity*, *Coal to Gas*, and *Clean Coal Replacement* in Beijing, and compare the differences. Second, we distinguish between the social and private benefits and costs. Third, our paper considers energy equity based on a quadrant analysis applied to HET policy assessment, concerned with the distribution of the benefits and the cost burden.

Our estimations of three HET programs all exhibit positive net social benefits, which is consistent with positive net social benefits of most mandatory policies in China as suggested by [Zhang, Jin, et al. \(2019\)](#) and [Yu and Xin \(2020\)](#). Regarding the private effects, private benefits due to the improvement of indoor air quality are approximately two times higher than the cost borne by these households at the average level, which is lower than the social benefit-to-cost ratio of six. The positive net private benefits are based on households with relatively larger subsidies and higher income in Beijing. In contrast, households in the provinces with lower per capita income and lower subsidies, such as Hebei Province, households with lower income tend to benefit less while suffering more from the higher participant costs, and thus positive net private benefit would not hold for households in Hebei. These findings highlight the issue of energy inequity among households. We further find that household satisfaction with the programs is largely positively related to private benefit-to-cost ratios brought from the programs, while not decided by social benefits and costs. This finding shed light on the policy improvement that aims to increase public acceptance and satisfaction.

The remainder of the paper proceeds as follows. [Section 2](#) introduces the background, implementation, and subsidy scheme of the

programs. Section 3 describes the methodology, and Section 4 presents the data. Section 5 estimates the social and private benefits and costs of *Coal to Electricity*, *Coal to Gas*, and *Clean Coal Replacement* programs at the aggregate level, and Section 6 provides the relationship between benefit-to-cost ratios and subjective perceptions of the programs at the household level. Section 7 concludes.

2. Household heating energy transition in China

2.1. Background

The combustion of fossil energy, mainly coal, contributed 70% of smoke particulates, 85% of sulfur dioxide, and 67% of nitrogen oxide emissions in China (Ministry of Industry and Information Technology of the People's Republic of China (MIIT), 2015). Consequently, China has experienced large-scale and long-lasting poor air quality repeatedly in recent years (Ministry of Ecology and Environment of the People's Republic of China (MEE), 2018), and residents' health has been seriously harmed (National Health Commission of the People's Republic of China (NHC), 2013). The average concentration level of PM_{2.5}, one of the main airborne pollutants, was 39 µg/m³ in China in 2018 (Ministry of Ecology and Environment of the People's Republic of China (MEE), 2019). In addition to air pollution, China's carbon emissions amounted to 9.83 billion tons in 2019, accounting for 28.8% of global emissions (BP, 2020).

To cope with the problems of air pollution and carbon emissions, the State Council issued the "Air Pollution Prevention and Control Action Plan" in September 2013, setting the nationwide target concentration level of inhalable particulate in 2017 to be 10% less than that in 2012. In 2014, the National Development and Reform Commission (NDRC) published the "Interim Administrative Measures on Coal Reduction and Replacement in Key Regions", and confirmed the coal reduction targets in Beijing, Tianjin, Hebei and Shandong Provinces.

Industrial coal consumption was targeted first. Based on the "Beijing 2013-2017 Clean Air Action Plan" (Beijing Municipal Ecological Environment Bureau (BMEPB), 2013), all coal power and coal heating plants in Beijing had to be shut down, relocated, or transformed into natural gas plants. The "Beijing Action Plan for Industrial Air Pollution Control 2012–2020" (Beijing Municipal Committee of Economy and Information Technology, 2012) enhanced the standard on industrial coal quality and tightened pollution regulations (National Energy Administration (NEA), 2012). With all these measures, emissions from the industrial sector were reduced (Beijing Municipal Ecology and Environment Bureau, 2015). However, despite the reduction in industrial emissions, Beijing's air quality did not seem to improve (Beijing Municipal Ecological Environment Bureau (BMEPB), 2015).

The government, therefore, started to extend its attention to household coal, which is the main fuel for heating in northern China. Compared to industrial coal, household coal contains more sulfur and ash, and is usually combusted without washing (Zhi et al., 2015). In addition, due to the limitation of household heating devices, household coal combusts inefficiently and the emissions are not filtered before being discharged into the open air. Therefore, household coal emits five to ten times more airborne pollutants than industrial coal per ton.¹ The consequence is that, although household coal accounts for only approximately 10% of the total coal consumption in the area in question, the amount of pollutants emitted from the combustion of household coal accounts for more than half of the total emissions from coal combustion in this area.²

2.2. Implementation

The HET policy was piloted in Beijing in 2014, rolled out to the "2 + 4" cities in the Jing-Jin-Ji region in 2015, and extended to the "2 + 26" cities along the Jing-Jin-Ji pollution transmission channel, including Beijing, Tianjin, and another 26 cities in Hebei, Shandong, Shanxi, and Henan Provinces. Fig. 1 depicts the spatial distribution and the temporal trend in the number of households that were mandated to participate. The number increased from 194 thousand to 6889 thousand from 2015 to 2017, and Hebei stands out both in the total number and in the speed of increase of the number.

The transition is carried out from top to bottom. First, the task is proposed by the central government, and then is devolved to provinces and local governments. Then, the NDRC and the local government jointly create a plan based on local characteristics, such as the fiscal capacity of the local government, the household income of the village, the village's distance to the downtown city, and infrastructure conditions. Village leaders have the responsibility of ensuring participation through various measures, such as a ban on coal vendors in the village and penalties on coal consumption. Additionally, subsidies from various levels of government are provided, aiming to make the transition affordable to the mandated participants.

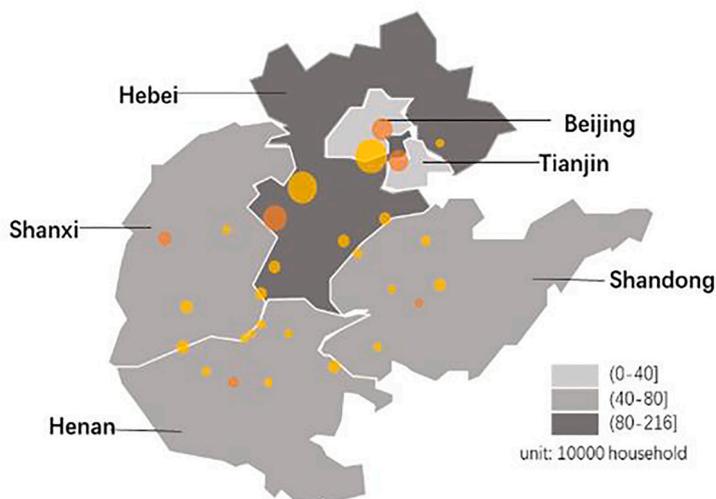
2.3. Subsidy scheme

The provincial governments generally cover the cost of infrastructure construction (e.g. electricity grid upgrade, pipeline extension, gas station construction) and provide subsidies to households on equipment replacement and fuel costs (e.g. discount on the price of electricity or gas).

The source and the amount of subsidy vary across villages. Generally, there are three levels of subsidies: municipal, district-level

¹ Xi, N., n.d. China's scattered coal consumption is approximately 750 million tons [WWW Document]. [Caijing.com.cn](http://news.163.com/17/0831/22/CT6TV2MC00018AOR.html). URL <http://news.163.com/17/0831/22/CT6TV2MC00018AOR.html>

² First Finance, n.d. Prescription:Coal to electricity [WWW Document]. [sohu.com](http://www.sohu.com/a/126100583_114986). URL http://www.sohu.com/a/126100583_114986



Panel A. Spatial Distribution

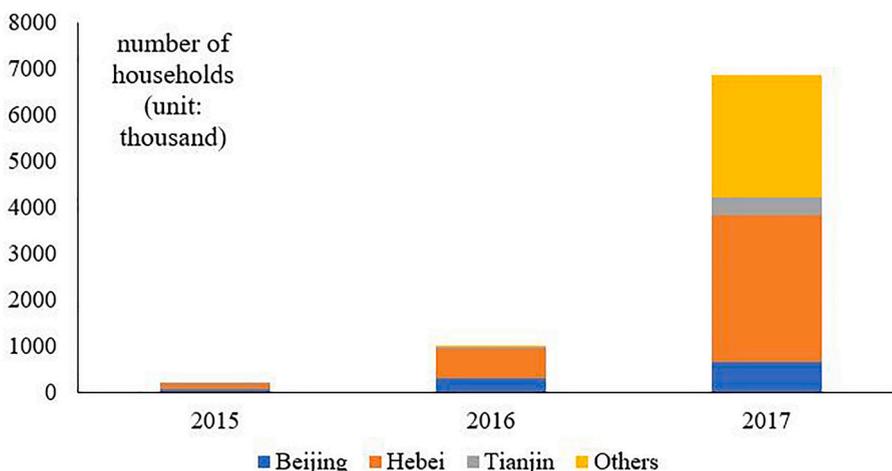


Fig. 1. Spatial distribution and temporal trend of the participated households.

Panel A. Spatial Distribution. Panel B. Temporal Trend.

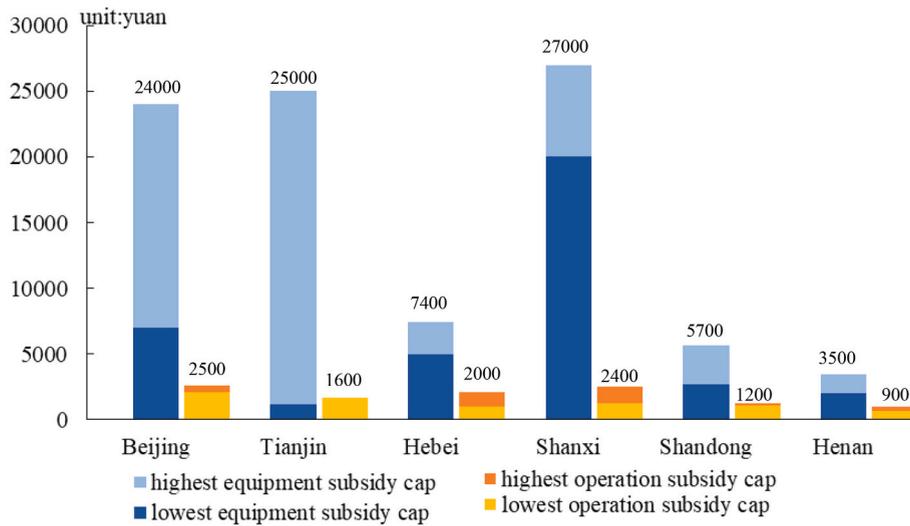
Notes: Dots in Panel A are the cities covered by the policy, and the size of the dots reflects the number of households covered in 2017.

and village-level³. Each level of subsidy is provided by a corresponding finance bureau. The municipal subsidy is uniform in a city, while district-level and village-level subsidies are based on the local government’s fiscal capacity. For example, the Beijing Municipal Finance Bureau provides a subsidy of 100 yuan/m³ for an air source heat pump with a maximum of 12 thousand yuan per household. The district finance bureau of the districts of Miyun, Tongzhou, and Chaoyang increase the subsidy to cover two-thirds of the equipment cost, and increase the maximum to 20 thousand yuan. In addition, both the municipal and district finance bureau provide a subsidy of 0.1 yuan/kWh for electricity consumed during “off-peak time” (9:00 pm to 6:00 am), with a maximum of 10,000 kWh per household per year.

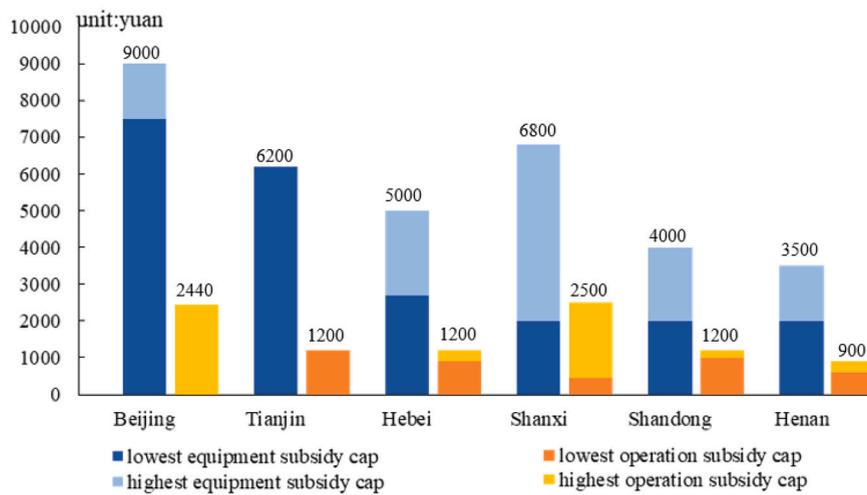
Fig. 2 compares the subsidies across provinces.⁴ Panel A summarizes the subsidies in the *Coal to Electricity* program. It shows that the equipment subsidy cap ranges from 3.5 to 27 thousand yuan. Shanxi, Tianjin and Beijing have the highest subsidy cap, which is eight times the lowest cap, in Henan. The variation in the cap on the subsidy of operational cost is much smaller across provinces. The

³ This scheme applies to municipalities (Beijing and Tianjin). Households in other areas generally have subsidies at the province level; some have subsidies at the municipal and district levels; very few of them have subsidies at the village level.

⁴ Since subsidies varied among different districts and equipment types, for Beijing we take the average of the survey data from village committees; for other provinces, we collect local policy document and take the weighted average of the collected subsidy information.



Panel A. *Coal to Electricity*



Panel B. *Coal to Gas*

Fig. 2. Subsidy cap across provinces.

range is between 0.9 and 2.5 thousand yuan. Beijing has the highest value, followed by Shanxi and Hebei. Panel B of Fig. 2 describes the subsidies in the *Coal to Gas* program. The equipment subsidy cap is much lower than that of *Coal to Electricity*. Beijing ranks the highest, with 9 thousand yuan per household, and is followed by Shanxi and Tianjin. The subsidy on the operational cost is similar to that of the *Coal to Electricity* program.

In sum, provinces with greater fiscal capacity tend to have larger subsidies. This contradicts the need, because households in the provinces with lower fiscal capacity have lower income, and therefore they are in more need of fiscal support in the energy transition.

3. Cost-benefit analysis framework

We calculate both the average and household individual level of social and private benefits and costs of the HET programs. As illustrated in Fig. 3, the social benefit occurs because the heating energy transition replaces high-polluting energy with less-polluting energy. Fewer pollutants and carbon emissions bring health and economic benefits to the population, including both the participants and the nonparticipants. For the household participants, the private benefit includes personal health benefits resulting from air quality improvement indoors and outdoors. The external impacts of emission reduction, such as climate change mitigation, are not considered by the participants. The total cost of the transition includes the cost of infrastructure construction and upgrade, equipment replacement, and the increase in fuel expenditure. The private cost is the part of the cost that is not covered by the government, such as the

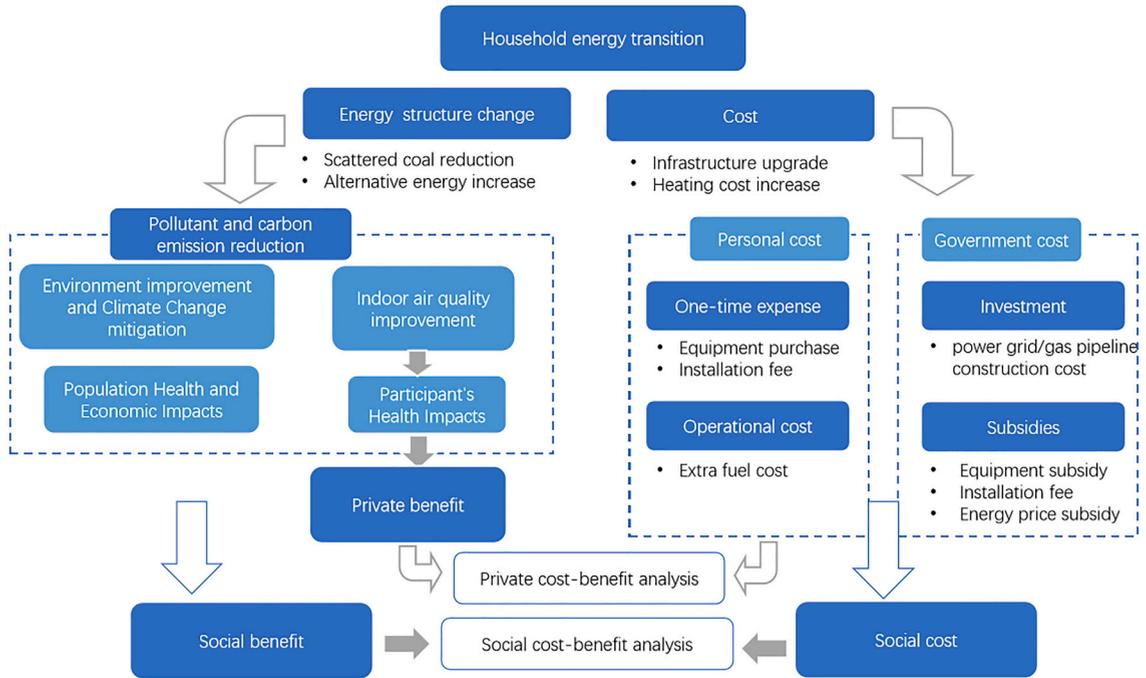


Fig. 3. A framework of the cost-benefit analysis.

additional fuel expenditure after subsidies. The following subsections elaborate the cost-benefit analysis.⁵

3.1. Social benefit

We first measure the energy consumption change caused by the transition using Eq. (1):

$$\Delta Q_j = Q'_j - Q_j \tag{1}$$

where j denotes the type of energy, including scattered coal, electricity, gas, or clean coal; Q_j and Q'_j are the per-household consumption of energy j before and after the program, respectively; and ΔQ_j is the change in the consumption of energy j (unit: ton for coal, MWh for electricity, thousand cubic meters for gas).

We next calculate the emission changes due to the energy change by Eq. (2):

$$\Delta E_{ij} = \Delta Q_j \times EF_{ij} \tag{2}$$

where ΔE_{ij} is the per household change in the amount of pollutant i emitted by energy j , and EF_{ij} is the emission factor (quantity of pollutant i per unit of energy j) in the following units: kg/ton for coal, kg/MWh for electricity, and kg/thousand m^3 for gas.

We then monetize the change in emissions by multiplying the emission change by the social cost of per unit emission as follows:

$$Sbenefit = - \sum_j \sum_{i=1}^n (\Delta E_{ij} \times SC_i) \tag{3}$$

where SC_i denotes the average social cost of pollutant i (unit: yuan/kg), and $Sbenefit$ is the social benefit gained from one household's heating energy transition (unit: thousand yuan/household). We summarize over i because the consumption of one type of energy emits more than one type of pollutant. For energy j , the *Coal to Electricity* program mainly involves coal and electricity; *Coal to Gas* mainly involves coal and natural gas; and *Clean Coal Replacement* involves different types of coal.

3.2. Participants' benefit

Because the participants benefit from the reduction of indoor air pollution through an increase in life expectancy, we adopt the human capital method (e.g. Yu, Cui, & Wang, 2008; Zhao, Fan, & Wang, 2013; Liu, Jia, & Song, 2016) to evaluate the health gain as the

⁵ Employed parameters for the cost to benefit analysis are shown in the Appendix A.

measurement of private benefit.

We first calculate the change in the indoor pollutant concentration level by Eq. (4):

$$\Delta C_{ij} = C'_{ij} - C_{ij} \tag{4}$$

where C_{ij} and C'_{ij} are the indoor concentrations of air pollutant i before and after program j , respectively (unit: $\mu\text{g}/\text{m}^3$).

We next calculate the life expectancy changes due to the changes in indoor pollutant concentration:

$$t_j = \Delta C_{ij} \times LF_i \tag{5}$$

where LF_i represents the change in life expectancy due to a one-unit increase in air pollutant i 's concentration (unit: $\text{year}/(\frac{\mu\text{g}}{\text{m}^3})$).

We then calculate the private benefit $Pbenefit$ using the value of statistical life LV (unit: thousand yuan) by Eq. (6):

$$Pbenefit_j = LV_j = Y + \frac{Y(1+\gamma)}{1+a} + \frac{Y(1+\gamma)^2}{(1+a)^2} + \dots + \frac{Y(1+\gamma)^{t_j}}{(1+a)^{t_j}} \tag{6}$$

where $j = 1,2,3$ denotes the energy transition from coal to electricity, gas and clean coal; Y is human capital, approximated by annual household income; a and γ are the social discount rate and expected growth rate in income⁶; and t_j is the life expectancy changes due to program j , which is the same as in Eq. (5).

3.3. Cost

The cost of the program mainly includes the cost paid by the household participants and the government's expenditure on the program. Household cost includes the cost of replacing heating equipment and the increased heating cost. We use the straight-line depreciation method to calculate the annualized cost. A household's annual cost $Cost_j$ is calculated as follows:

$$Cost_j = \left(EC_j \times \frac{(1-\beta_j)}{n_{j,year}} \right) + (HC_j - HC_{coal}) \tag{7}$$

where $j = 1,2,3$ correspond to the energy transition from coal to electricity, gas, and clean coal, respectively; EC_j is the equipment cost paid by households; $n_{j,year}$ indicates the expected life expectancy of the heating equipment; and β_j is the estimated salvage value rate of the equipment. Therefore, the first term denotes the annualized cost of replacing heating equipment. HC_j and HC_{coal} are the heating costs of using energy j and scattered coal before the program.

To compare the personal benefit and cost, we also estimate participants' cost of the transition during a lifetime as Eq. (8), where $Cost_j$ is the household annual cost, k is the average household size, and a is a discount rate.

$$Pcost_j = LC_j = \frac{Cost_j}{k} + \frac{Cost_j}{k(1+a)} + \frac{Cost_j}{k(1+a)^2} + \dots + \lim_{i \rightarrow \infty} \frac{Cost_j}{k(1+a)^i} \tag{8}$$

Government costs include subsidies on infrastructure construction, power grid upgrading, equipment replacement, and heating fuel, which are calculated as follows:

$$Subsidy_j = IS_j \times \frac{(1-\alpha_j)}{m_{j,year}} + ES_j \times \frac{(1-\beta_j)}{n_{j,year}} + OS_j \times Q'_j \tag{9}$$

where $j = 1,2,3$ corresponds to the energy transition from coal to electricity, gas and clean coal, respectively; IS_j represents the infrastructure investment subsidy, $m_{j,year}$ refers to the expected life expectancy of the newly built power grid and natural gas pipes; α_j is the estimated salvage value rate of infrastructure; ES_j is a subsidy on an equipment purchase, $n_{j,year}$ indicates the expected life of the equipment, β_j is the estimated salvage value rate of the equipment; OS_j is the per-unit subsidy for heating with energy j , and Q'_j is per household consumption of energy j after the program, the same as in Eq. (1). Therefore, the first term indicates the subsidy on infrastructure construction and upgrading; the second term denotes the subsidy on heating equipment; and the third term represents the subsidy on operational cost. The first two subsidies are one-time payments, so we annualize them using the straight-line depreciation method. The depreciation of the power grid is in accordance with the *Provincial power grid transmission and distribution price pricing method* (National Development and Reform Commission of the People's Republic of China (NDRC), 2016), which assumes an average life expectancy of 25 years and a salvage value rate of 5%. The depreciation of heating equipment is based on *Accounting Standards for Business Enterprises* (Ministry of Finance of the People's Republic of China, 2006), which assumes that the life expectancy of equipment is 10 years and the salvage value rate is 5%.

⁶ The value of income in Eq. (6) is calculated based on the information on household income and the number of household members collected in the survey. The calculated average per capita annual income is 22.94 thousand yuan. This is close to the 2016 rural Beijing residents' average income, which is 22 thousand yuan per capita (Beijing Bureau of Statistics, 2017). The expected growth rate of human capital is estimated to be 6.98%, which is the 2014–2018 rural resident per capita income compound growth rate in Beijing (Beijing Bureau of Statistics, 2018). For the social discount rate, we use 8%, which is recommended by national organizations and the NDRC of China.

4. Data

The data used in this paper are from the Chinese Residential Energy Consumption Survey 2016 Beijing (CRECS 2016 Beijing), conducted by the Department of Energy Economics at Renmin University of China. The survey randomly selected 183 villages in Beijing. In each village, the village committee and approximately 20 randomly selected households were interviewed in person. A total of 4000 questionnaires were distributed, and 3949 valid questionnaires were returned.

The main information collected by the village committee survey includes whether the village participated in the program, whether the household participated, participation year, type of subsidized heating equipment, subsidy scheme, and energy prices. Among the surveyed villages, 61 villages participated in *Coal to Electricity*, 17 in *Coal to Gas*, and 62 in *Clean Coal Replacement*. The survey also collected information about household social and economic characteristics, dwelling characteristics, heating equipment, household energy consumption behavior, and opinions about their experience in the program. Among the surveyed households, 1896 households were in participating villages, of which 796 participated in *Coal to Electricity* and 156 participated in *Coal to Gas*. After data processing, such as eliminating households with missing data and outliers, there remain 519 valid observations for *Coal to Electricity*, 79 for *Coal to Gas*, and 784 for *Clean Coal Replacement*.

4.1. Energy consumption changes

Based on the household-reported energy consumption before and after the program, we calculate the coal consumption change due to the implementation of the program. We distinguish between scattered coal and anthracite, and anthracite is further divided into briquette and honeycomb coal. Anthracite is regarded as clean coal, which is subsidized in the *Clean Coal Replacement* program. Table 1 summarizes the average energy consumption changes of the three programs. It shows that *Coal to Electricity* resulted in 2.68 tons of decrease in per-household coal consumption, which is an 80% decrease; *Coal to Gas* led to 1.61 tons of decrease in coal, which is a 69% decrease; *Clean Coal Replacement* led to a shift of coal consumption structure away from scattered coal and toward anthracite, the cleaner coal. The average increases in electricity and gas consumption per household are 5.48 MWh and 1.30 thousand m³ in the two programs, respectively.

Table 2 summarizes various costs of the program. Panel A presents household extra expenditure on equipment purchase and heating fuel. We calculate extra expenditure by multiplying household-reported energy usage change by the corresponding fuel price gained from the survey, and deducting government subsidy, which is also obtained from the survey. It shows that household extra expenditure for *Coal to Electricity* is higher, with an average of 4.97 thousand yuan of equipment expense and 1.41 thousand yuan of extra heating cost, compared with 2.50 thousand yuan of equipment expense and 1.24 thousand yuan of extra operational cost for *Coal to Gas*. The difference in household extra expenditure comes from the difference in equipment cost, heating efficiency, energy price, and the subsidy between the two programs. In contrast, in the program of *Clean Coal Replacement*, household heating costs decreased from 2.82 thousand yuan to 1.97 thousand yuan due to the heavy subsidy on clean coal. According to the 49 sampled villages that participated in *Clean Coal Replacement* in Beijing, the average price of clean coal is 427 yuan/ton after the subsidy, lower than the replaced scattered coal.

Panel B of Table 2 summarizes government expenditures and subsidies. This shows that *Coal to Electricity* has a slightly higher one-time subsidy on equipment and installation, but a lower subsidy on heating fuel, compared to *Coal to Gas*. *Clean Coal Replacement* has no subsidy on equipment or infrastructure construction since it does not involve such costs, but it has the highest subsidy on the operational cost, which is approximately 1.77 thousand yuan per household for a heating season. The infrastructure construction cost is estimated based on the field survey conducted in Beinianfeng Village and Fangezhuang Village, Beijing, as only these two villages provided this information during the survey. The overall investment in infrastructure is about 30 million yuan in a village, including government finance and village committee expenditure. For a medium-sized village (about 600 households), the per household cost is about 50 thousand yuan.⁷

4.2. Satisfaction of households

For our analysis of the distributional inequity of the implementation of HET policy among households, we compare the objective net benefits brought by the *Coal to Electricity* and *Coal to Gas* programs and satisfaction with the programs. Satisfaction scores of the programs are obtained from the answers to the following questions in the survey: "Compared with the previous coal-fired heating, after switching from *Coal to Electricity*/*Gas* in the heating season, how do you feel about the programs regarding comfort, convenience, indoor air quality, cleanliness, heating safety, respectively". The scores vary from 1 to 10 with satisfaction varying from totally unsatisfied to totally satisfied.

Fig. 4 shows the distribution of household satisfaction in the five dimensions with the programs of *Coal to Electricity* and *Coal to Gas*. The average value for *Coal to Electricity* is around 8.7, larger than that for *Coal to Gas* at around 8.45. The mean value of each satisfaction indicator is larger than 8, except for heating safety for the *Coal to Gas* program. Conventional coal heating emits carbon monoxide, which is not safe if the concentration is very high (Xie & Zhou, 2021). The *Coal to Electricity* and *Coal to Gas* programs could

⁷ According to the Chinese Academy of Environmental Planning (2017), the infrastructure investment per household is estimated to be 15,000 yuan for *Coal to electricity* and 4000 yuan for *Coal to gas*. The difference comes from that our estimation is the total investment including the cost of direct grid/pipeline expansion construction, the cost of indoor line remodeling, etc., while the planning only considered the construction cost.

Table 1
Changes in energy consumption.

Program	Obs.	Energy type	Quantity after Q_{coal}	Quantity before Q_{coal}	Change in quantity ΔQ_{coal}	
Panel A. Coal (ton)						
<i>Coal to Electricity</i>	519	Scattered coal	0.48	2.33	-1.85	
		Anthracite	Briquette	0.16	0.81	-0.65
		Honeycomb coal	0.03	0.22	-0.19	
<i>Coal to Gas</i>	79	Scattered coal	0.09	1.35	-1.27	
		Anthracite	Briquette	0.61	0.83	-0.21
		Honeycomb coal	0.19	0.15	-0.13	
<i>Clean Coal Replacement</i>	784	Scattered coal	0.57	3.13	-2.56	
		Anthracite	Briquette	3.34	0.8	2.54
		Honeycomb coal	0.49	0.241	0.25	
Panel B. Electricity (MWh)						
<i>Coal to Electricity</i>	519	Electricity	6.39	9.08	5.48	
Panel C. Gas (thousand m ³)						
<i>Coal to Gas</i>	79	Natural gas	1.34	0.04	1.3	

Notes: Energy consumption data are from CRECS 2016 Beijing. The heating energy consumption quantities in the heating season before and after the program are reported by households in the survey.

Table 2
Various costs of the program.

Panel A. Household's Extra Expenditure (thousand yuan per household)				
Program	Obs.	Average number of devices	Equipment expenses	Extra annual heating cost
<i>Coal to Electricity</i>	637	1.32	4.97	1.41
<i>Coal to Gas</i>	101	1.01	2.5	1.24
<i>Clean Coal Replacement</i>	49	/	0	-855
Panel B. Government Expenditure and Subsidy (thousand yuan per household)				
Program	Infrastructure cost	One-time subsidy		Annual subsidy on heating fuel
		Equipment subsidy	Installation subsidy	
<i>Coal to Electricity</i>	50	14.54	0.77	0.94
<i>Coal to Gas</i>	50	10	0.43	1.16
<i>Clean Coal Replacement</i>	0	0	0	1.77

Notes: Information on household equipment expenditure is collected in the household survey in CRECS 2016 Beijing. Extra annual heating costs are calculated based on the information of reported energy consumption change and corresponding energy prices. Infrastructure cost data are from field surveys conducted in Beinianfeng Village and Fangezhuang Village, Beijing. Subsidy data are from the village survey in CRECS 2016 Beijing.

both improve safety in energy use, but households may be more familiar with the safety issues in using gas. That is possibly why we find that some households are still worried about gas heating safety with relatively low safety scores. Additionally, households in the *Coal to Electricity* program think that the program has greatly improved the cleanliness and indoor environment.

5. Cost-benefit analysis results

Based on the cost-benefit analysis presented in Section 3 and the data described in Section 4, we evaluate the benefits and costs of the *Coal to Electricity*, *Coal to Gas*, and *Clean Coal Replacement* programs at the average level in this section.

5.1. Social benefits and costs

Table 3 summarizes the results of the social benefits and costs per household. The average social benefit resulting from one household transition is 32.04, 24.68, and 28.48 thousand yuan per heating season for *Coal to Electricity*, *Coal to Gas*, and *Clean Coal Replacement*, respectively. Surprisingly, *Clean Coal Replacement* has the highest environmental benefit. The reason is that *Clean Coal Replacement* was widely implemented in Beijing before *Coal to Electricity* and *Coal to Gas*. Therefore, *Clean Coal Replacement* replaced scattered coal, while the latter two programs replaced clean coal, which has much lower emission factors than scattered coal. Moreover, we find that the per household cost of *Coal to Electricity*, *Coal to Gas*, and *Clean Coal Replacement* is 5.85, 5.21, and 0.91 thousand yuan per heating season, respectively. In summary, the benefit-cost ratios are 5.47, 4.74 and 31.30 for the three programs, respectively. *Clean Coal Replacement* has the largest benefit-cost ratio because *Clean Coal Replacement* costs much less than the other two programs. *Coal to electricity* has a slightly higher ratio than *Coal to Gas*, because it has a similar social benefit but a lower cost.

To make the three programs more comparable, we standardize the initial coal quality and quantity. As shown in Fig. 5, the benefit

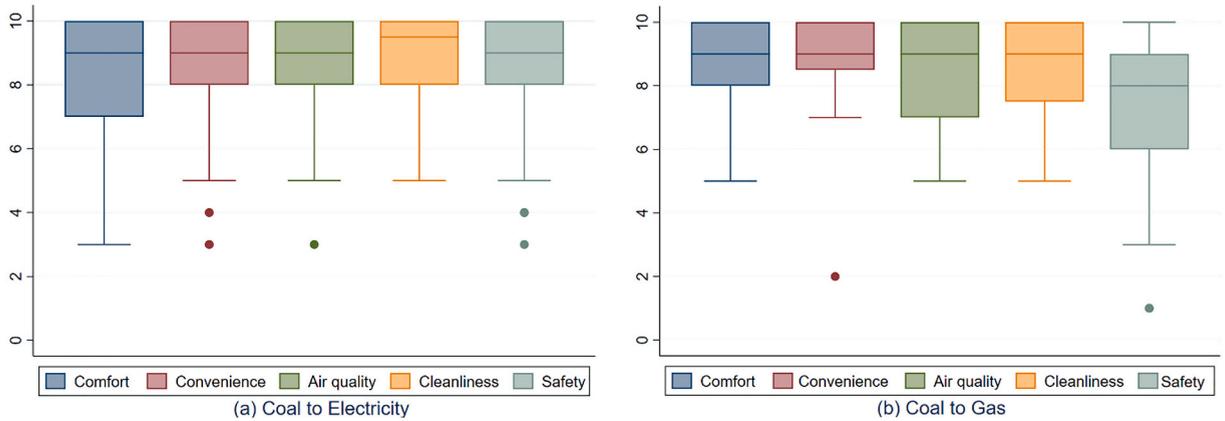


Fig. 4. Satisfaction of households.

Table 3
Social benefits and per household.

		Coal to electricity	Coal to gas	Clean coal replacement
Changes in energy use	ΔA_{coal} (ton)	-2.68	-1.61	0.23
	-Scattered coal	-1.85	-1.27	-2.56
	-Anthracite briquette	-0.65	-0.21	2.54
	-Anthracite honeycomb coal	-0.19	-0.13	0.25
	$\Delta A_{electricity}$ (MWh)	5.48	-	-
	ΔA_{gas} (thousand m ³)	-	1.30	-
Benefit per household (thousand yuan)		32.04	24.68	28.48
	Infrastructure expenditure	1.58	1.58	0
	Equipment subsidy	1.45	0.99	0
Cost items	Heating cost subsidy	0.94	1.16	1.77
	Household equipment extra expense	0.47	0.24	0
	Household heating extra cost	1.41	1.24	-0.86
Cost per household (thousand yuan)		5.85	5.21	0.91
Benefit-to-cost Ratio		5.47	4.74	31.30

Notes: The methodology for social benefit estimation is described in Section 3.1. The estimation of cost-benefit analysis per household is based on the original condition from the survey.

per ton of coal replacement for *Coal to Gas* is the highest (16.86 thousand yuan), followed by *Coal to Electricity* (15.61 thousand yuan); *Clean Coal Replacement* has the lowest benefit per ton of coal replacement (11.14 thousand yuan). This is expected because more than 60% of electricity in China is generated with coal, and coal has higher emission factors than gas. The fifth column of Fig. 5 shows that the replacement costs per ton of coal in the *Coal to Electricity*, *Coal to Gas*, and *Clean Coal Replacement* programs are 2.27, 2.61, and 0.36 thousand yuan, respectively. It is expected that *Clean Coal Replacement* has a much lower cost than the other two programs, because *Clean Coal Replacement* does not involve costly infrastructure construction and equipment replacement. Compared with the Cost-Benefit Analysis for each household, the estimations for per ton of scattered coal replacement share the same pattern: *Clean Coal Replacement* has the largest benefit-to-cost ratio of 31.30, followed by *Coal to Electricity* and *Coal to Gas* with magnitudes of 6.88 and 6.46, respectively.

We are aware that the benefit-to-cost ratio may vary across regions because coal consumption, social cost of emissions, and the cost of implementing the program are likely to be different from one region to another. As shown in Table 4, the social costs for Beijing could be more than ten times the average for China. Replacing the social costs for Beijing with those for the China average and assuming other conditions unchanged, we recalculate the benefit-cost ratios, and find that the ratios are 0.71, 0.75, and 3.10 for the three programs respectively. If further considering the quantity of coal that could be reduced by the programs, the ratio could be even lower, because regions to the south of Beijing consume less coal for heating than Beijing.

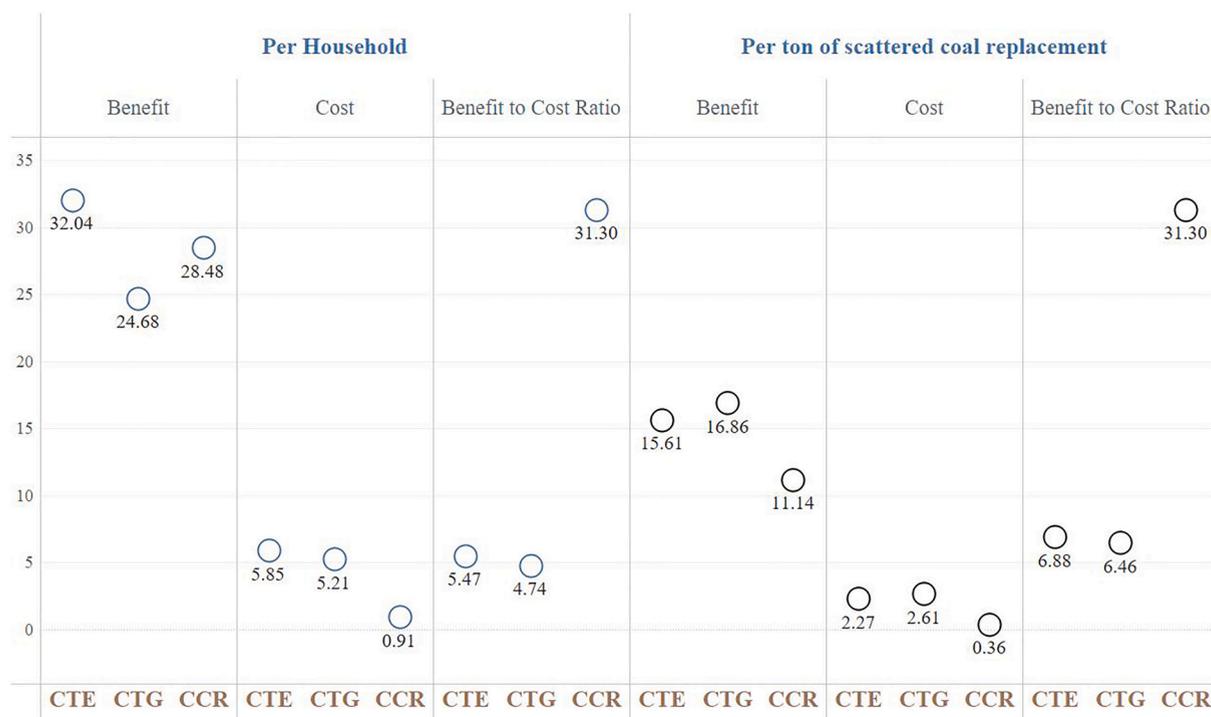


Fig. 5. The comparison of social benefit and cost per household and per ton of scattered coal replacement.

Notes: The methodology for social benefit estimation is described in Section 3.1. The estimation of Cost-Benefit Analysis per household is based on the original condition from the survey. The Cost-Benefit Analysis of per ton of scattered coal replacement is the result after standardizing the initial coal quality and quantity and scaling other energy consumption. The unit of benefit and cost should be thousand yuan. CCR, CTE and CTG represent Clean Coal Replacement, Coal to Electricity and Coal to Gas, respectively.

5.2. Benefits and costs of the participants

Table 4 presents participants' benefits and costs for the three programs. With the assumption that people stay half of the day in the same room with the coal heating device, the increases in life expectancy for Coal to Electricity, Coal to Gas, and Clean Coal Replacement are 4.81 years, 4.50 years and 3.58 years, respectively.⁸ Based on the increase in life expectancy, the individual benefits of Coal to Electricity and Coal to Gas are estimated to be 108.43 thousand yuan and 101.52 thousand yuan per person, respectively, higher than that of Clean Coal Replacement, which is 81.09 thousand yuan per person. For rural Beijing residents, as we explained in the previous section, since they do not usually install heating devices in living rooms or bedrooms, the private benefit of the heating energy transition is much lower. With the assumption that one individual spends two hours next to a heating device, the benefits are 18.41 thousand yuan, 17.23 thousand yuan, and 13.72 thousand yuan for the three programs, respectively.

To compare personal lifelong benefit to lifelong cost, we first calculate the personal annualized cost by dividing the calculated household cost by the sample average household size of 3.7. The personal annualized cost after standardization is estimated to be 500 yuan/year and 604 yuan/year for participating in Coal to Electricity and Coal to Gas, respectively. Using an 8% social discount rate, we calculate the mean individual lifelong cost and obtain 6.75 thousand yuan for Coal to Electricity and 8.15 thousand yuan for Coal to Gas. Those involved in Clean Coal Replacement do not have to pay an extra cost and can even save 237 yuan per person per year because of the heating subsidy; therefore, their lifelong savings are 3.12 thousand yuan.

In summary, the private benefit-to-cost ratio for Beijing rural households is 2.73 and 2.11 for Coal to Electricity and Coal to Gas, respectively. However, we should be aware that the ratio varies across regions for the following reasons. First, household income is different; therefore, the value of statistical life is different. Second, the dwelling characteristics are different, where the heating device is installed matters. Third, government fiscal capacity affects the subsidy scheme and therefore affects the cost paid out of household pockets. Take Coal to Gas in Hebei for example. The annual rural household income in Hebei was 14.03 thousand yuan in 2018, and the 2014–2018 compound growth rate for rural residents' income is 8.34%. Assuming the same dwelling characteristics and other conditions, the individual benefit of Hebei is 10.52 thousand yuan for the program, and the benefit-to-cost ratio is 1.29 if the individual

⁸ Chen (2013) found that air pollution during the winter heating period in northern China reduced the residents' average life expectancy by about 5.5 years, which is higher than our results. Considering that our comparison is about different heating fuel instead of whether or not to heat, our estimation is reasonably slightly lower than that.

Table 4
Benefits and costs of the participants.

		Coal to electricity	Coal to gas	Clean coal replacement
Environmental externality	$\Delta C_{PM2.5}$ ($\mu\text{g}/\text{m}^3$)	-96	-90	-72
	Δ life expectancy (year)	4.81	4.50	3.58
Benefit per person for duration factor = 1/2 (thousand yuan) for duration factor = 1/12		108.43	101.52	81.09
		18.41	17.23	13.72
Cost items	cost per year	0.50	0.60	-0.23
	- Annualized one-time cost	0.13	0.06	0
	- Heating cost	0.37	0.54	-0.23
Cost per person (thousand yuan)		6.75	8.15	-3.12
Benefit-to-cost for duration factor = 1/2		16.06	12.45	-
Ratio for duration factor = 1/12		2.73	2.11	-

Notes: The methodology for the benefit estimation is described in Section 3.2. The duration factor measures the portion of time a person spent in the same room with the coal heating device. The longer the time is, the greater the benefit of the energy transition. For comparison, benefits and costs are both measured in life-long. That is, we measure the total benefit and cost for the transition that lasts once it is made.

costs stay the same. Furthermore, Hebei's subsidies are lower than those in Beijing, as shown in Fig. 2. Hence, the individual cost would be higher than the cost faced by Beijing residents, which is 8.15 thousand yuan, as shown in Table 4. This indicates that the benefit-cost ratio of the program in Hebei would be even lower than 1.29. If it is lower than one, it indicates that households in Hebei would lose from participating in the HET policy. The income level of the population and the subsidies in Hebei Province is lower than those in Beijing. Combined with the above estimations, we can conclude that the poorer provinces benefit less but burden a higher cost due to the HET policy.

6. Assessment of distributional equity among households

As investigated in Section 5, the household heating transition programs of *Coal to Electricity* and *Coal to Gas* both have positive net social and private benefits, which indicates that both society and households can benefit greatly from these two programs. The puzzle is that many households were still not satisfied with the programs. To understand the puzzle and improve the public acceptance of the policy, this section explores the relationship between subjective satisfaction and monetary benefits and costs for households.

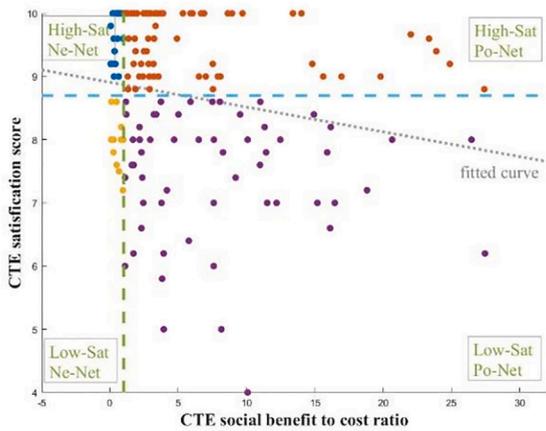
We first calculate the social and private benefit-to-cost ratios at the household level to explore the characteristics of different groups of households. We then consider the average value of five subjective perception scores of each household, including comfort, convenience, air quality, cleanliness, and safety, to represent the satisfaction of each household. Combined with perception scores and benefit-to-cost ratios in a quadrant analysis,⁹ we obtained the distributions of the households in four quadrants by overall average score and benefit-to-cost ratio as one, as shown in Fig. 6.

As shown in the fitted curve between satisfaction and the benefit-to-cost ratio in Fig. 6, households are inclined to perceive private benefits from the programs, and households with a higher private benefit-to-cost ratio tend to give a higher satisfaction score. However, the satisfaction of households is negatively associated with the social benefit-to-cost ratio. Table 5 further compares the households in four quadrants based on housing characteristics and household demographics, including income level and health status. Regarding the *Coal to Electricity* program, we find that the average housing area of households in the "High-Sat and Ne-Net" group is much lower than that of the "Low-Sat and Ne-Net" group, and the households in the "High-Sat and Ne-Net" group are healthier than those in the "Low-Sat and Ne-Net" group. The households in "Low-Sat and Ne-Net" group are faced with much higher costs with larger housing areas, and they are relatively healthy and not sensitive to the pollutants of scattered coal. Hence, the satisfaction of households in the "Low-Sat and Ne-Net" group is lower. Comparing households distributed in groups with positive net benefits, the lower scores in the "Low-Sat and Po-Net" group might be caused by lower income levels and larger housing areas. Considering the *Coal to Gas* program, households with higher satisfaction scores are accompanied by characteristics of smaller housing areas, higher income, and healthier status.¹⁰

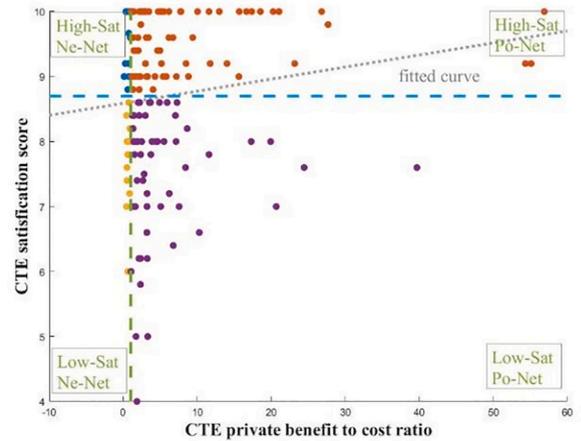
The difference in the health status between the *Coal to Electricity* and *Coal to Gas* programs might be largely attributed to the fact that healthier households are more inclined to highly rate the *Coal to Electricity* program, while lower rates for the *Coal to Gas* program, since that *Coal to Electricity* could largely improve the indoor environment and cleanliness, as discussed in Section 4.2.

⁹ There are some missing observations at the household level analysis, since we should obtain much information about the social and private benefits and costs, subjective perceptions of households. Appendix Fig. B. shows that whenever considering income and age, the sample of both *Coal to Electricity* and *Coal to Gas* programs used in this section could be representative of the whole sample used in the average level. Moreover, since the subjective perception data are only surveyed on the *Coal to Electricity* and *Coal to Gas* programs, this section we only consider these two programs.

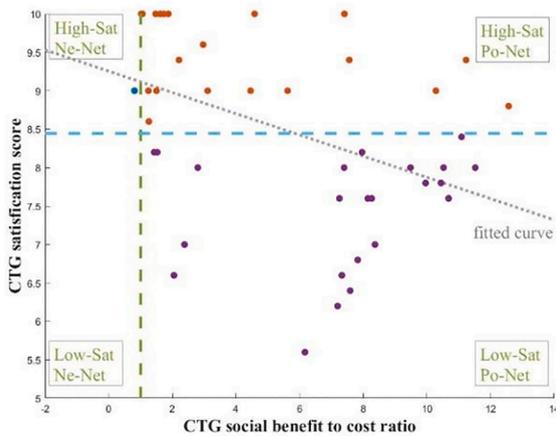
¹⁰ We also investigate the impact of social and private benefit-to-cost ratios, housing characteristics and household demographics on the satisfaction scores of households as shown in Appendix C. Households are inclined to perceive the private net benefits rather than social net benefits from the programs, and households with a higher private benefit-to-cost ratio would grade a higher score. The negative impact of housing area and poverty (an indicator variable equal to one if households obtain the minimum living guarantee due to lower income) on the satisfaction scores still hold. Moreover, households with the old tend to have higher scores on the programs, especially regarding the attitudes toward convenience and cleanliness. However, if the households have more children, the burden would be larger, and thus they are less likely to give a higher score.



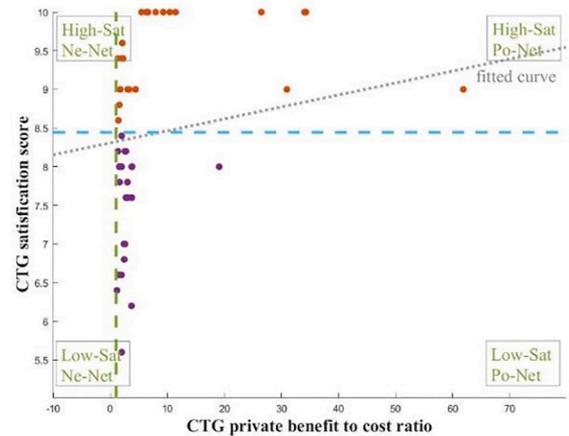
(a) Coal to Electricity-Social



(b) Coal to Electricity-Private



(c) Coal to Gas-Social



(d) Coal to Gas-Private

Fig. 6. The distributions of households combined with average perception scores and benefit-to-cost ratios.

Notes: (A) Households are distributed in the top-left quadrant with higher satisfaction scores and negative net benefits (High-Sat and Ne-Net). (B) Households distributed in the top-right quadrant with higher satisfaction scores and positive net benefits (High-Sat and Po-Net). (C) Households distributed in the bottom-left quadrant with lower satisfaction scores and negative net benefits (Low-Sat and Ne-Net). (D) Households distributed in the bottom-right quadrant with lower satisfaction scores and positive net benefits (Low-Sat and Po-Net).

Moreover, *Coal to Electricity* is the main HET policy in Beijing. From Table 5, we can find that the housing characteristics and household demographics vary much more in the *Coal to Electricity* program than in the *Coal to Gas* program. Additionally, there are many observations with ratios lower than one in the *Coal to Electricity* program and only one observation with social ratios lower than one in the *Coal to Gas* program, as shown in Fig. 6. Comparing the social and private effects, housing characteristics and household demographics among the four groups share the same patterns.

In summary, based on the assessment of the distribution of equity in terms of economic and environmental benefits and costs among households, the results provide the reason why households are still not satisfied with the programs with average social and private benefit-to-cost ratios larger than one. Households can perceive private benefits from the programs rather than social benefits. If the programs bring larger private benefits than costs, households are more satisfied with the energy transition programs. Additionally, households would be harmed by the programs by a larger burden from the heating energy transition with lower income and larger housing areas.

7. Conclusions and policy implications

Based on household-level survey data from CRECS 2016 Beijing, we investigate the benefits and costs of the implementation of the

Table 5
Differences in the sample mean between groups of households.

Groups	Social				Private			
	High-Sat	High-Sat	Low-Sat	Low-Sat	High-Sat	High-Sat	Low-Sat	Low-Sat
	Ne-Net	Po-Net	Ne-Net	Po-Net	Ne-Net	Po-Net	Ne-Net	Po-Net
Coal to electricity								
Housing area	123.981	172.265	231.250	241.483	147.222	161.678	198.421	253.382
Income level	3.115	2.926	3.125	2.741	2.667	3.053	2.632	2.891
Health	1.423	1.328	1.188	1.373	1.667	1.280	1.611	1.224
Coal to gas								
Housing area		135.870		139.565		132.708		139.565
Income level		3.174		3.000		3.167		3.000
Health		1.087		1.217		1.125		1.217

Note: The table reports the differences in means between groups corresponding to the four quarters in Fig. 6. The income level variables are discrete variables with 1 to 5, collected from the question- “Compared with other households in the village, the income situation of your family belongs to 1 Poor, 2 Lower to average, 3 Average, 4 Above average, 5 Very good”. The health status is 1 for healthy, 2 for chronic diseases, 3 for serious illness, 4 for physical disability, and 5 for mental and psychological disorders. Higher scores indicate that households are unhealthier.

HET policy in Beijing, including *Coal to Electricity*, *Coal to Gas*, and *Clean Coal Replacement*. We find that the social benefits of the three programs are approximately six- to thirty-fold the related costs, indicating that the transition largely improved social welfare. The results also show that the private benefits are larger than the costs paid by the participants, indicating that the participants also have positive net benefits from the programs.

When comparing the three programs, we find that *Coal to Gas* has a slightly larger social benefit-to-cost ratio than *Coal to Electricity*. This is as expected because more than 60% of electricity is generated using coal, and coal has larger emission factors than gas. According to the results in Beijing, there is only a small difference between electricity and gas in the social benefit per ton of coal substitution. Moreover, *Clean Coal Replacement* has the largest social benefit-cost ratio among the three programs. This is because, although the environmental benefit of *Clean Coal Replacement* is low, it is equipped with the lowest cost. If the government is fiscally constrained in the short term, *Clean Coal Replacement* is a good transitional measure. The choice among adopting electricity or gas and substituting for coal should take into account the specific characteristic of each area, since the infrastructure cost varies greatly across local conditions. In addition, program choice ought to take energy security and technology progress into consideration. The development of wind and solar power and clean technology in coal-fired power provides a larger potential to reduce the emission factors of electricity generation and thereby improve the social benefit-cost ratio of *Coal to Electricity*.

The study also investigates the impact of social and private benefit-to-cost ratios on the subjective perceptions of households, to explore the reason why some households complain about the HET policy. The results indicate that the satisfaction of households is largely and positively affected by private net benefits rather than social net benefits. As the benefit-to-cost ratios increase, the subjective perception scores of the programs increase. Moreover, households with lower scores in the *Coal to Electricity* and *Coal to Gas* programs are faced with a larger burden from the heating energy transition, accompanied by the characteristics of lower-income and larger housing areas.

The conclusions above are based on a Beijing survey. The social cost of pollution, household income, and the government’s fiscal capability in Beijing are all among the highest in the country. The HET policy has been carried out in more provinces in China. When applying the conclusion to other areas, we should adjust the parameters in the analysis accordingly. For instance, the estimation of social cost for pollution depends on the economic level and population density of the region; the value of statistical life is affected by income; and the calculation of subsidy is determined by the local government’s fiscal capacity. Consequently, our benefit-cost estimation model is more efficient to apply to the program of regions with high population density, high economic level, and large government capacity. The study also conducts benefit-cost explorations of other regions, and we further find the existence of energy inequality. When we replace the social costs for Beijing with the national average level, we find that the benefit-cost ratios of the three programs become much lower. Moreover, comparing the benefits and costs of the participants with Beijing and Hebei, the provinces with lower income suffer greatly from the higher participant cost. Therefore, it is essential to focus on the energy inequality of different income groups in the national household energy transition process.

The paper provides a reference for the social and private benefits and costs of household energy transition programs in achieving carbon neutrality. In particular, our results motivate the consideration of energy equity in terms of the allocation of benefits and costs among households across different income levels and cost burdens within policy evaluation. Mandatory policies would increase social welfare, whereas during the implementation, the government should consider the distribution of economic and environmental costs and benefits directly associated with households. For instance, policy-makers could provide more preferential and larger subsidies to low-income households in a more equitable manner.

Data availability

Data will be made available on request.

Acknowledgments

The authors gratefully thank the conference participants at the Beijing Energy Conference 2021-CO₂ Allocation and Equity Issues under China's Carbon Neutrality Targets for their helpful discussions and comments on this paper. All errors and omissions remain the sole responsibility of the authors. Financial supports from the National Natural Science Foundation of China (71703163, 72141308, 71774165 and 7210154), the Research Funds of Renmin University of China (22XNLG12, 17XNS001, 11XNL004), the Teaching and Research Funds of Renmin University of China (KCSZ202212), Major Innovation & Planning Interdisciplinary Platform for the "Double-First Class" Initiative, Renmin University of China are gratefully acknowledged.

Appendix A

A.1. Parameters for social benefit

The parameters for social benefit evaluation, including emission factors of air-borne pollutants from coal, electricity, and gas consumption, and the social cost of per unit emission. We do not directly estimate the parameters in this paper. We summarize the values estimated from relevant literature, and the details and the summary are as follows.

A.1.1. Emission factors

Table A1
Emission factors of main pollutants.

Panel A. Coal-fired Heating (kg/ton)								
Source	Research Object	Energy Type	SO ₂	NOx	CO	PM ₁₀	PM _{2.5}	CO ₂
Liang, Zhang, Lin, Ma, and Wu (2017)	Rural residents in Beijing, China	Scattered coal		2.2	86.3			
Xu, Wang, and Xu (2016)	Residents in Jing-Jin-Ji Area	Scattered coal	17.1	2.8	65.2			
Zhi et al. (2015)	Rural residents in Baoding	Scattered coal	20.7	1.6			7.0	
Kong, Bai, and Lu (2014)	Urban and rural residents in China	Scattered coal				11.9	9.9	
Shen et al. (2010)	Residents in Yulin/Taiyuan	Scattered coal			288			1288.5
Yu et al. (2008)	Rural residents in China	Scattered coal		1.9				
Chen et al. (2015)	Rural residents in Beijing	Scattered coal					4.3	
Zhang et al. (2008)	Rural residents in Beijing	Scattered coal					7.4	
Liu et al. (2007)	Rural residents in Beijing	Scattered coal					4.9	
Ma, Dong, Wu, and Pan (2015)	Residents in Shaanxi, China	Briquette				2.3		
		Honeycomb coal				1.3		
Liang et al. (2017)	Rural residents in China	Briquette	1.9	0.9	37.3			
		Honeycomb coal	1.5	0.4	22.4			
Kong et al. (2014)	Urban and rural residents in China	Honeycomb coal				0.9	0.8	
Chen et al. (2015)	Urban and rural residents in China	Briquette					1.0	
		Honeycomb coal					1.8	
Zhang et al. (2008)	Urban and rural residents in China	Briquette					5.2	
		Honeycomb coal					1.1	
Liu et al. (2007)	Urban and rural residents in China	Honeycomb coal					5.5	
IPCC (2006)	Urban and rural residents in China	Briquette						1550.4
	Urban and rural residents in China	Briquette/Honeycomb coal						2211
Summary			SO ₂	NOx	CO	PM ₁₀	PM _{2.5}	CO ₂
		Scattered coal	18.9	2.1	146.5	11.9	6.7	1288.5
		Briquette	1.9	0.9	37.3	2.3	3.1	1880.7
		Honeycomb coal	1.5	0.4	22.4	1.3	2.3	2211.0
Panel B. Electricity Generation (kg/MWh)								
Source	Research object	Energy type	SO ₂	NOx	CO	PM ₁₀	PM _{2.5}	CO ₂
Zhao et al. (2013)	Power sector in China	Electricity from power sector	2.2	2.3	0.3	0.3	0.2	773
Xing (2016)	Coal to Electricity in Beijing	North china power grid	1.1	1.1			0.2	478
Summary			SO ₂	NOx	CO	PM ₁₀	PM _{2.5}	CO ₂
			1.7	1.7	0.3	0.3	0.2	625.5

(continued on next page)

Table A1 (continued)

Panel B. Electricity Generation (kg/MWh)								
Source	Research object	Energy type	SO ₂	NO _x	CO	PM ₁₀	PM _{2.5}	CO ₂
Panel C. Natural Gas Combustion (kg/thousand m ³)								
Source	Research object	Energy type	SO ₂	NO _x	CO	PM ₁₀	PM _{2.5}	CO ₂
Wang, Xu, Xu, and Bai (2017)	Gas-fired boiler in China	Natural gas	0.6	1.8				
Chen, Ebenstein, Greenstone, and Li (2013)	Gas-based heating system in Jing-jin-ji area, China	Natural gas						1994
Summary		Natural gas	0.6	1.8	–	–	–	1994

Notes: Emissions factors are summarized from relevant literatures. We cite the literature that research object was mainly about rural household in China after 2006, especially in the Jing-Jin-Ji area of China. We take the average of the values from these literatures and use it as the parameters in the cost-benefit analysis.

Appendix Table A1 summarizes the findings in previous literature on emission factors of main air pollutants from coal combustion (Panel A), electricity generation (Panel B), and natural gas combustion (Panel C), and the average emissions factors for main pollutants.

The main air pollutants emitted from coal combustion include SO₂, NO_x, CO, PM₁₀, PM_{2.5} and CO₂. Emission factors of these pollutants are largely affected by coal's quality and combustion condition. Therefore, emission factors vary greatly across studies. To obtain emission factors for coal quality and combustion conditions that are similar to our study, we limit our literature review to research that studies coal used by rural households in China after 2006, especially the coal consumed in the Jing-Jin-Ji region of China. The average emission factors for scattered coal-fired heating are 18.9 kg/ton for SO₂, 2.1 kg/ton for NO_x, 146.5 kg/ton for CO, 11.9 kg/ton for PM₁₀, 6.7 kg/ton for PM_{2.5} and 1288.5 kg/ton for CO₂.

Heating with electricity does not produce air pollutants at the user end, but the generation of electricity produces pollutants, especially considering that in China about two-thirds of electricity is generated by coal (BP, 2020). We, therefore, use the average emission factors from the literature of electricity generation. The average emission factors for per kWh of electricity generation are 1.7 kg SO₂, 1.7 kg NO_x, 0.3 kg CO, 0.3 kg PM₁₀, 0.2 kg PM_{2.5} and 625.5 kg CO₂.

The main pollutants emitted from gas combustion include SO₂, NO_x and CO₂. We limit the literature review to household natural gas heating boilers. The average emission factors estimated by the literature are 0.6, 1.8 and 1994 kg/m³ for SO₂, NO_x and CO₂, respectively.

A.1.2. Social cost of pollution

Table A2 summarizes the findings in previous literature on the social cost of pollutants. The economic cost of social and environmental damage from pollution varies greatly across countries and estimation methods. For example, Yang, Teng, and Wang (2013) estimated the health impacts of pollution by multiplying the number of incidents of premature mortality and morbidity by the value of life expressed as a willingness to pay. They adjusted the value in the EU as the benchmark and adjusted it to the local conditions in Beijing. Su (2014) summarized related literature from developed countries and adjusted the findings to Shanghai's conditions. Both Kypreos and Krakowski (2005) and World Bank (2010) derived an ExternE method to estimate the environmental cost in China, adjusting the EU results to China's population density and income.

Given that social costs vary on regional population and income, and Beijing and Shanghai are similar in economic indicators, we use the average value of social costs estimated by Yang et al. (2013) and Su (2014), which are 113.53 yuan/kg, 100.55 yuan/kg, 7.91 yuan/kg, 810.03 yuan/kg, 591.69 yuan/kg and 0.20 yuan/kg for SO₂, NO_x, CO, PM₁₀, PM_{2.5} and CO₂, respectively.

If considering expanding the program to other provinces such as Hebei, the social costs per unit of the pollutant would take the average value of similar places or the average for China, as in Yang et al. (2013) Zhang, Mendelsohn, Cai, Cai, and Wang (2019), Wei and Zhou (2003), World Bank (2010) and Kypreos and Krakowski (2005). As shown in Table A2, the average value of social costs per unit of SO₂, NO_x, CO, PM₁₀, PM_{2.5} and CO₂ are 40.51 yuan/kg, 21.56 yuan/kg, 1.00 yuan/kg, 43.99 yuan/kg, 312.88 yuan/kg and 0.17 yuan/kg, respectively.

Table A2

Social costs of per unit of main pollutants (yuan/kg).

Source	Region	SO ₂	NO _x	CO	PM ₁₀	PM _{2.5}	CO ₂
Su (2014)	Shanghai, China	85.05	73.72	7.91	530.27	591.69	0.20
Yang et al. (2013)	Beijing, China	142.01	127.38		1089.80		
Zhang, Mendelsohn, et al. (2019)	BTH region, China	62.47	9.14			312.88	
Yang et al. (2013)	China average	6.94	6.22		53.26		
Wei and Zhou (2003)	China average	6.00	8.00	1.00			
World Bank (2010)	China average	78.46	52.84				0.21
Kypreos and Krakowski (2005)	Shandong, China	48.68	31.59		34.71		0.13

(continued on next page)

Table A2 (continued)

Source	Region	SO ₂	NOx	CO	PM10	PM2.5	CO ₂
Value used in this study		SO ₂	NOx	CO	PM10	PM2.5	CO ₂
	Beijing	113.53	100.55	7.91	810.03	591.69	0.20
	China	40.51	21.56	1.00	43.99	312.88	0.17

Notes: For the findings with original unit USD, we convert them into RMB with the average exchange rate of 6.8985:1 in 2019. The Beijing average social costs are from the first two pieces of literature, and the China average is from the other three pieces of literature.

A.2. Parameters for participants' benefit

The parameters for participants' benefit evaluation, as described in the previous section, including indoor air pollutant concentrations when heating with different energy sources, and change in life expectancy due to a one-unit increase in the concentration level of air pollutants. Again, we do not directly estimate the parameters, but summarize the values estimated from relevant literature. The details and the summary are as follows.

A.2.1. Indoor air pollutant concentration

We focus on the change in PM_{2.5} concentration as a result of using different types of heating fuel, because suspended particulates have the greatest impact on human health (Brunekreef & Holgate, 2002; Chen, Ebenstein, et al., 2013; Kampa & Castanas, 2008). The size of combustion-generated particles determines the harm to health, because smaller particulates can go deeper into the body (Liu, Wang, Ren, & Chen, 2018). Therefore, present research mostly considers PM_{2.5} or PM₁₀ when measuring the effects of indoor pollutant concentrations on longevity (e.g. Chen, Li, Tan, & Duan, 2013; Ebenstein, Fan, Greenstone, He, & Zhou, 2017; Pope III & Dockery, 2013; Zhang & Smith, 2005).

For the changes in pollutant concentration before and after the program, we use findings from studies comparing indoor air pollutant concentration between coal-fired and decentralized non-coal heating (e.g. electricity and natural gas). According to Fan, Cao, Zhang, Huang, and Dong (2014), the indoor PM_{2.5} concentration of using scattered coal, electricity and gas are 203 $\mu\text{g}/\text{m}^3$, 107 $\mu\text{g}/\text{m}^3$ and 114 $\mu\text{g}/\text{m}^3$ respectively. According to Liu et al. (2018) and Fan, Shao, Wang, Wang, and Li (2012), the indoor PM_{2.5} concentration expected when using anthracite briquettes is 132 $\mu\text{g}/\text{m}^3$. Therefore the changes in PM_{2.5} concentration from using coal to using electricity, gas, and clean coal are $-96 \mu\text{g}/\text{m}^3$, $-89 \mu\text{g}/\text{m}^3$, and $-72 \mu\text{g}/\text{m}^3$, respectively.

A.2.2. Impact of air pollutants on life expectancy

Extensive literature analyzes the impact of air pollutants on life expectancy per unit increase in PM_{2.5} concentration, as summarized in Table A3, which covers the estimations of China, the US, and Canada. These areas vary a lot in air pollutant concentration levels. Since the health effects of pollution may be non-linear in the initial pollution concentration level, we follow a study of Chen, Li, et al. (2013) based on China's air pollution and take the impact factor as $-0.1 \text{ year}/\frac{\mu\text{g}}{\text{m}^3}$.

Table A3

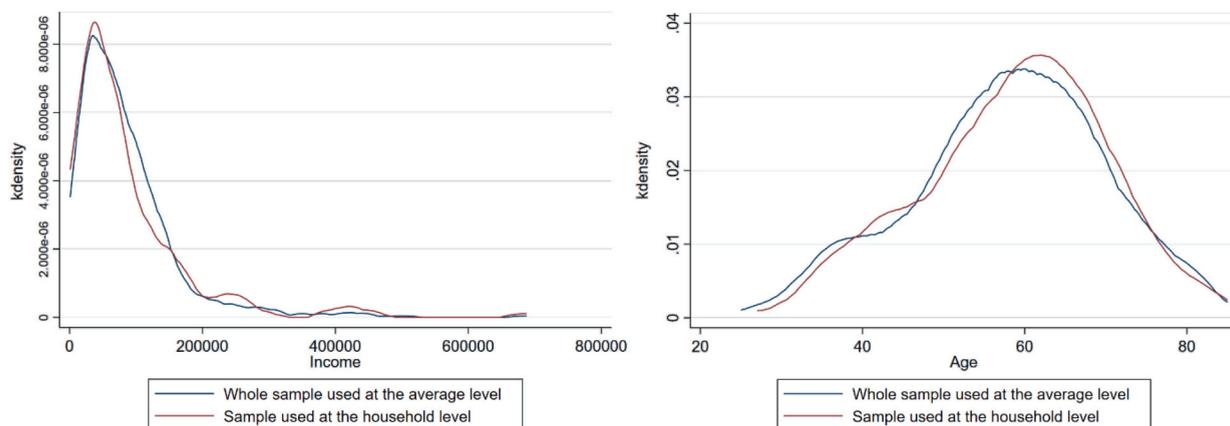
Impact of air pollutants on life expectancy.

Source	Method	Region	PM2.5 (year/ $\frac{\mu\text{g}}{\text{m}^3}$)
Chen, Li, et al. (2013)	Regression discontinuity study, North vs. South of Huai River	China	-0.10
Correia et al. (2013)	First difference analysis of county-level changes in life expectancy 2000–2007	U.S.	-0.04
Hoek et al. (2013)	Meta estimate of Cohort studies	U.S.	-0.07
Crouse et al. (2012)	Canadian Cohort study	Canada	-0.11
Pope III, Ezzati, and Dockery (2009)	First difference analysis of county-level changes in life expectancy 1980–2000	Metropolitan areas in U.S.	-0.06
Zeger, Dominici, Mcdermott, and Samet (2008)	Medicare Cohort study	Urban centers in U.S.	-0.04
Pope, III, Arden, & Richard (2002)	ACS CPS-II Cohort study	U.S.	-0.07
Value used in this study			-0.10

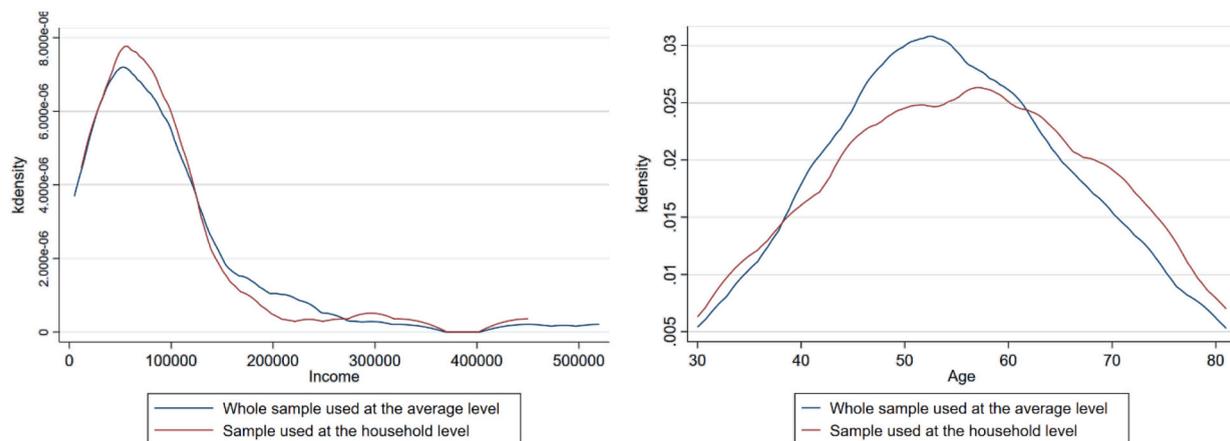
Notes: As the health effects of pollution are likely to be non-linear in the initial pollution concentrations level in different regions, we used the estimate in Chen, Li, et al. (2013), which focused on China, as the value of the parameter in the analysis.

One thing to notice is that the time a household spends on pollution affects the effect of the pollution on life expectancy, and the duration varies. It depends on where the heating device is installed. For the majority of rural Beijing households, the coal heating device is installed in the kitchen or a room in the yard, separated from living rooms and bedrooms. That is, most of the day, a household is not subjected to concentrated pollution. Consequently, we need to multiply the results calculated by Eq. (5) by a duration factor. If we assume that they spend two hours in the kitchen or the heating device room, the duration factor would be 1/12. In contrast, in places where households generally install heating devices in living rooms or bedrooms, the duration factor could be much larger, such as 1/2, indicating that the household spends half the day in the same room with the heating device.

Appendix B



(a) Coal to Electricity



(b) Coal to Gas

Fig. B. Representation of the household-level sample.

Appendix C

Table C

The impact of benefit-to-cost ratio on the subjective perceptions of households.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Full sample						CTE	CTG
Variables	Perception	Comfort	Convenience	Air quality	Cleanliness	Safety	Perception	Perception
Social ratio	-0.0451*** (0.0140)	-0.0418** (0.0203)	-0.0367** (0.0158)	-0.0712*** (0.0168)	-0.0426** (0.0165)	-0.0438** (0.0205)	-0.0359** (0.0145)	-0.1655*** (0.0532)
Private ratio	0.0204*** (0.0066)	0.0230** (0.0102)	0.0171*** (0.0065)	0.0173* (0.0091)	0.0107 (0.0065)	0.0340*** (0.0082)	0.0147* (0.0075)	0.0276* (0.0147)
Housing area	-0.0006*** (0.0001)	-0.0004* (0.0002)	-0.0005*** (0.0001)	-0.0008*** (0.0002)	-0.0007*** (0.0002)	-0.0003 (0.0002)	-0.0006*** (0.0001)	0.0032 (0.0026)
Income level	0.1046 (0.1026)	0.2771 (0.1786)	0.0593 (0.1373)	0.1094 (0.1360)	0.0686 (0.1128)	0.0296 (0.1590)	0.1276 (0.1086)	0.1244 (0.2782)

(continued on next page)

Table C (continued)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Full sample						CTE	CTG
Variables	Perception	Comfort	Convenience	Air quality	Cleanliness	Safety	Perception	Perception
Health	0.0504 (0.1288)	0.0722 (0.2016)	0.0808 (0.1248)	0.1197 (0.1779)	0.0203 (0.1386)	-0.0250 (0.1897)	0.0457 (0.1330)	-0.2475 (0.5388)
Poverty	-0.8147*** (0.1995)	-1.6741** (0.7974)	-0.9448*** (0.2699)	-0.6227** (0.2435)	-0.9229*** (0.2568)	0.1082 (0.4892)	-0.8686*** (0.2082)	
Child	-0.1995* (0.1085)	-0.2825 (0.1723)	-0.1944 (0.1290)	-0.1786 (0.1356)	-0.2407* (0.1328)	-0.0912 (0.1683)	-0.2516** (0.1217)	-0.1594 (0.2357)
Old	0.1369 (0.0893)	0.0221 (0.1482)	0.1629* (0.0981)	0.0837 (0.1113)	0.2026** (0.1018)	0.1994 (0.1292)	0.1135 (0.0963)	0.1117 (0.2827)
Constant	8.5381*** (0.4036)	7.7164*** (0.6601)	8.8712*** (0.5531)	8.6836*** (0.5382)	8.9845*** (0.4487)	8.4119*** (0.6138)	8.6002*** (0.4421)	8.6086*** (1.1038)
Observations	204	203	202	204	204	203	160	44
R-squared	0.1459	0.0936	0.0996	0.1422	0.1198	0.0666	0.1391	0.3338

Notes: the table reports the impact of social and private benefit-to-cost ratios on the subjective satisfaction of households. The income level variables are discrete variables with 1 to 5, collected from the question- "Compared with other households in the village, the income situation of your family belongs to 1 Poor, 2 Lower to average, 3 Average, 4 Above average, 5 Very good". The health status is 1 for healthy, 2 for chronic diseases, 3 for serious illness, 4 for physical disability, and 5 for Mental and psychological disorders. The higher scores indicate that households are unhealthier. The study also considers an indicator variable, poverty, that if households obtain the minimum living guarantee due to lower income, the variable equals one and otherwise zero. Child and Old represent the number of children and the old in a household, respectively. CTE and CTG represent Coal to Electricity and Coal to Gas, respectively.

References

- Barrington-Leigh, C., Baumgartner, J., Carter, E., Robinson, B. E., Tao, S., & Zhang, Y. (2019). An evaluation of air quality, home heating and well-being under Beijing's programme to eliminate household coal use. *Nature Energy*, 4(5), 416–423.
- Beijing Municipal Committee of Economy and Information Technology. (2012). *Beijing action plan for industrial air pollution control 2012–2020*.
- Beijing Municipal Ecological Environment Bureau (BMEPB). (2013). *Beijing 2013–2017 clean air action plan*.
- Beijing Municipal Ecological Environment Bureau (BMEPB). (2015). *Beijing environmental statement 2015*.
- Beijing Municipal Ecology and Environment Bureau. (2015). Environmental statistics annual report in 2014. <http://sthjj.beijing.gov.cn/bjhrb/xxgk/ywdt/zlkz/hjtj37/307481/index.html>.
- Borenstein, S., & Davis, L. W. (2016). The distributional effects of US clean energy tax credits. *Tax Policy and the Economy*, 30(1), 191–234.
- BP. (2020). *BP statistical review of world energy*.
- Brunekreef, B., & Holgate, S. T. (2002). Air pollution and health. *Lancet*, 360, 1233–1242.
- Budya, H., & Arofat, Y. M. (2011). Providing cleaner energy access in Indonesia through the megaproject of kerosene conversion to LPG. *Energy Policy*, 39, 7575–7586.
- Carley, S., & Konisky, D. M. (2020). The justice and equity implications of the clean energy transition. *Nature Energy*, 5(8), 569–577.
- Chapman, A. J., McLellan, B., & Tezuka, T. (2016). Proposing an evaluation framework for energy policy making incorporating equity: Applications in Australia. *Energy Research & Social Science*, 21, 54–69.
- Chen, L., Li, W. S., Tan, Z. G., & Duan, G. D. (2013). Impact of natural gas heat supply on carbon dioxide emission. *Gas Heat*, 33, 6–8.
- Chen, Y., Ebenstein, A., Greenstone, M., & Li, H. (2013). Evidence on the impact of sustained exposure to air pollution on life expectancy from China's Huai River policy. *Proceedings of the National Academy of Sciences*, 110(32), 12936–12941.
- Chen, Y., Tian, C., Feng, Y., Zhi, G., Li, J., & Zhang, G. (2015). Measurements of emission factors of PM_{2.5}, OC, EC, and BC for household stoves of coal combustion in China. *Atmospheric Environment*, 109, 190–196.
- Correia, A. W., Pope, C. A., III, Dockery, D. W., Wang, Y., Ezzati, M., & Dominici, F. (2013). The effect of air pollution control on life expectancy in the United States: An analysis of 545 US counties for the period 2000 to 2007. *Epidemiology*, 24, 23–31.
- Crouse, D. L., Peters, P. A., Van Donkelaar, A., Goldberg, M. S., Villeneuve, P. J., Brion, O., ... Brook, J. R. (2012). Risk of nonaccidental and cardiovascular mortality in relation to long-term exposure to low concentrations of fine particulate matter: A Canadian national-level cohort study. *Environmental Health Perspectives*, 120, 708–714.
- Cui, R. Y., Hultman, N., Cui, D., McJeon, H., Yu, S., Edwards, M. R., ... Zhu, M. (2021). A plant-by-plant strategy for high-ambition coal power phaseout in China. *Nature Communications*, 12(1), 1–10.
- Dong, C., Qi, Y., & Nemet, G. (2021). A government approach to address coal overcapacity in China. *Journal of Cleaner Production*, 278, Article 123417.
- Ebenstein, A., Fan, M., Greenstone, M., He, G., & Zhou, M. (2017). New evidence on the impact of sustained exposure to air pollution on life expectancy from China's Huai River policy. *Proceedings of the National Academy of Sciences*, 114(39), 10384–10389.
- Fan, D., Cao, S., Zhang, Y., Huang, N., & Dong, T. (2014). Preliminary study on indoor PM_{2.5} pollution levels of residents in Lanzhou during heating period. *Environmental Health*, 31, 232–234.
- Fan, J., Shao, L., Wang, J., Wang, J., & Li, Z. (2012). Variations in mass concentrations of indoor inhalable particulates in the coal-burning indoor air in Xuanwei County, Yunnan province. *China Environmental Science*, 32(8), 1379–1383.
- Hoek, G., Krishnan, R. M., Beelen, R., Peters, A., Ostro, B., Brunekreef, B., & Kaufman, J. D. (2013). Long-term air pollution exposure and cardio-respiratory mortality: A review. *Environmental Health*, 12(1), 1–16.
- IPCC. (2006). *IPCC Guidelines for national greenhouse gas inventories 2006*.
- Kampa, M., & Castanas, E. (2008). Human health effects of air pollution. *Environmental Pollution*, 151(2), 362–367.
- Kong, S., Bai, Z., & Lu, B. (2014). Comparative analysis on emission factors of carbonaceous components in PM_{2.5} and PM₁₀ from domestic fuels combustion. *China Environmental Science*, 34(11), 2749–2756.
- Kypreos, S., & Krakowski, R. (2005). An assessment of the power-generation sector of China. In *International Energy Agency (IEA/AIE) Annex IX Technical Conference*.
- Liang, J., He, P., & Qiu, Y. L. (2021). Energy transition, public expressions, and local officials' incentives: Social media evidence from the coal-to-gas transition in China. *Journal of Cleaner Production*, 298, Article 126771.
- Liang, Y., Zhang, D., Lin, A., Ma, Z., & Wu, X. (2017). Emission characteristics of residential coal combustion flue gas in Beijing. *Environmental Sciences*, 38, 1775–1782.

- Lin, J., & Mou, D. (2021). Analysis of the optimal spatial distribution of natural gas under 'transition from coal to gas' in China. *Resource and Energy Economics*, 66, Article 101259.
- Liu, J., Wang, B., Ren, Z., & Chen, R. (2018). The pollution characteristics of indoor and outdoor PM_{2.5} in the rural areas of Tangshan in winter. *Environmental Pollution & Control*, 40, 283–286. +290.
- Liu, S., Jia, Z., & Song, G. (2016). Application of human capital law in assessment of the loss value of life and health in air pollution. *Environ. Protect. Sci.*, 6, 48–52.
- Liu, Y., Zhang, Y. X., Wei, Y. J., Dou, H., Gu, D. S., Zeng, L. M., & Shao, M. (2007). Measurement of emission factors of carbonaceous aerosols from residential coal combustion. *Acta Scientiae Circumstantiae*, 27, 1409–1415.
- Ma, L. Y., Dong, Z. Q., Wu, K. J., & Pan, J. (2015). Indoor air quality and characteristics of fine particle for rural Guizhou. *J. Environ. Monit. China*, 1, 28–34.
- Michelsen, C. C., & Madlener, R. (2016). Switching from fossil fuel to renewables in residential heating systems : An empirical study of homeowners' decisions in Germany. *Energy Policy*, 89, 95–105.
- Ministry of Ecology and Environment of the People's Republic of China (MEE). (2018). *China ecological environment status bulletin 2017*.
- Ministry of Ecology and Environment of the People's Republic of China (MEE). (2019). *China ecological environment status bulletin 2018*.
- Ministry of Finance of the People's Republic of China. (2006). *Accounting standards for business enterprises*.
- Ministry of Industry and Information Technology of the People's Republic of China (MIIT). (2015). *Efficient clean utilization of coal in industry (2015–2020)*.
- National Development and Reform Commission of the People's Republic of China (NDRC). (2016). *Provincial power grid transmission and distribution price pricing method*.
- National Energy Administration (NEA). (2012). *The Beijing action plan for industrial air pollution control 2012–2020*.
- National Health Commission of the People's Republic of China (NHC). (2013). *Air pollution (haze) health impact monitoring work program 2013*.
- Nguyen, T. T., Nguyen, T. T., Hoang, V. N., Wilson, C., & Managi, S. (2019). Energy transition, poverty and inequality in Vietnam. *Energy Policy*, 132, 536–548.
- Pope, C. A., III, & Dockery, D. W. (2013). Air pollution and life expectancy in China and beyond. *Proceedings of the National Academy of Sciences*, 110, 12861–12862.
- Pope, C. A., III, Ezzati, M., & Dockery, D. W. (2009). Fine-particulate air pollution and life expectancy in the United States. *The New England Journal of Medicine*, 376–386.
- Pope, III, C., Arden, Burnett, Richard, et al. (2002). Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *JAMA: Journal of the American Medical Association*, 287(9), 1132–1132.
- Rao, N. D. (2012). Energy for sustainable Development kerosene subsidies in India : When energy policy fails as social policy. *Energy for Sustainable Development*, 16, 35–43.
- Rozenberg, J., Vogt-Schilb, A., & Hallegatte, S. (2020). Instrument choice and stranded assets in the transition to clean capital. *Journal of Environmental Economics and Management*, 100, Article 102183.
- Shen, G., Yang, Y., Wang, W., Tao, S., Zhu, C., Min, Y., ... Wang, R. (2010). Emission factors of particulate matter and elemental carbon for crop residues and coals burned in typical household stoves in China. *Environmental Science & Technology*, 44, 7157–7162.
- Su, S. (2014). Ship emissions inventory, social cost and eco-efficiency in Shanghai Yangshan port. *Atmospheric Environment*, 82, 288–297.
- Tong, K., Ramaswami, A., Xu, C., Feiock, R., Schmitz, P., & Ohlsen, M. (2021). Measuring social equity in urban energy use and interventions using fine-scale data. *Proceedings of the National Academy of Sciences*, 118(24), Article e2023554118.
- United Nations (UN) Development Programme, & University of Bergen. (2018). *Policy brief no. 8. Interlinkages among energy, poverty and inequalities*. New York.
- Wang, C., Xu, C., Xu, G., & Bai, P. (2017). Studies on replacing coal with natural gas and heat pump for heating in Jing-Jin-Ji region. *China Environmental Science*, 37, 4363–4370.
- Wei, X., & Zhou, H. (2003). Evaluating the environmental value schedule of pollutants mitigated in China thermal power industry. *Environmental Science and Pollution Research*, 16(1), 53–56.
- World Bank. (2003). *Access of the poor to clean household fuels in India*. Washington, DC.
- World Bank. (2010). *China's envisaged renewable energy target the green leap forward*.
- Xie, L., Hu, X., Zhang, X., & Zhang, X. B. (2022). Who suffers from energy poverty in household energy transition? Evidence from clean heating program in rural China. *Energy Economics*, 106, Article 105795.
- Xie, L., & Zhou, O. (2021). What improves subjective welfare during energy transition? Evidence from the clean heating program in China. *Energy and Buildings*, 253, Article 111500.
- Xing, Y. K. (2016). Calculation of the synergistic emission reduction of air pollutants and greenhouse gas in the coal to electricity project in Beijing. In *Proceedings of the Annual Conference of the Chinese Society of Environmental Sciences* (pp. 3186–3190).
- Xu, G., Wang, C., & Xu, C. (2016). Evaluation of air pollutant emissions from scattered coal burning and electric heating in Beijing-Tianjin-Hebei region. *Research of Environmental Sciences*, 29, 1735–1742.
- Xu, S., & Ge, J. (2020). Sustainable shifting from coal to gas in North China: An analysis of resident satisfaction. *Energy Policy*, 138, Article 111296.
- Yang, X., Teng, F., & Wang, G. (2013). Incorporating environmental co-benefits into climate policies : A regional study of the cement industry in China. *Applied Energy*, 112, 1446–1453.
- Yu, H., & Xin, X. (2020). Demand elasticity, Ramsey index and cross-subsidy scale estimation for electricity price in China. *Sustainable Production and Consumption*, 24, 39–47.
- Yu, J., Cui, P., & Wang, W. (2008). Estimation on SO₂, NO_x and TSP emissions from energy consumption for non-production purpose in rural areas of China. *Geographical Research*, 27, 547–555.
- Zeger, S. L., Dominici, F., McDermott, A., & Samet, J. M. (2008). Fine particulate air pollution in urban centers (2000–2005). *Environmental Health Perspectives*, 116, 1614–1619.
- Zhang, J., & Smith, K. R. (2005). Indoor air pollution from household fuel combustion in China: A review. In *9. The 10th International Conference on Indoor Air Quality and Climate*.
- Zhang, S., Mendelsohn, R., Cai, W., Cai, B., & Wang, C. (2019). Incorporating health impacts into a differentiated pollution tax rate system: A case study in the Beijing-Tianjin-Hebei region in China. *Journal of Environmental Management*, 250, Article 109527.
- Zhang, X., Jin, Y., Dai, H., Xie, Y., & Zhang, S. (2019). Health and economic benefits of cleaner residential heating in the Beijing-Tianjin-Hebei region in China. *Energy Policy*, 127, 165–178.
- Zhang, Y., Schauer, J. J., Zhang, Y., Zeng, L., Wei, Y., Liu, Y., & Shao, M. (2008). Characteristics of particulate carbon emissions from real-world Chinese coal combustion. *Environmental Science and Technology*, 42(14), 5068–5073.
- Zhang, Y., Shi, X., Qian, X., Chen, S., & Nie, R. (2021). Macroeconomic effect of energy transition to carbon neutrality: Evidence from China's coal capacity cut policy. *Energy Policy*, 155, Article 112374.
- Zhao, X., Fan, C., & Wang, Y. (2013). Evaluation of health losses by air pollution in Beijing: A study based on corrected human capital method. *China Population, Resources and Environment*, 24(3), 169–176.
- Zhi, G., Yang, J., Zhang, T., Guan, J., Xue, Z., & Meng, F. (2015). Rural household coal use survey, emission estimation and policy implications. *Research of Environmental Sciences*, 28, 1179–1185.