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Who suffers from energy poverty in household energy transition? Evidence from clean heating program in rural China

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ABSTRACT

It can be challenging to provide energy that is both clean and affordable. In northern rural China, a household clean heating program has been adopted, requiring households to transition from coal to electricity and natural gas. This program led to an unintended sharp increase in the burden of heating cost for enrolled households, even with large subsidies. To investigate this policy-induced increase in energy poverty, we conducted a large-scale household survey in northern China. We find that energy poverty, measured in multiple dimensions, is significantly increased by replacing coal with electricity and gas, while it is decreased by replacement with clean coal. Econometric analysis shows that the change in energy poverty is heterogeneous in several ways. It remains stable in Beijing, but increases by 70% in the much less developed neighboring province of Hebei. Households with lower income, less education, and smaller household size are more likely to experience energy poverty. Those with lower income and no insulation for their houses are negatively affected to a larger degree. These findings provide empirical evidence that a mandatory "one policy for all" is likely to hurt low-income households more. It calls the attention of policy makers to the distributional effect when designing energy transition policies for a clean and low-carbon economy.

1. Introduction

The world is undergoing an energy transition, aiming to balance the trilemma of energy security, energy equity (accessibility and affordability), and environmental sustainability (Council-WEC, 2019). However, the balance is difficult to achieve, especially for developing countries. To improve environmental sustainability, the Chinese government has spent 35.12 billion yuan on household energy transition, besides other energy policies. A total of 43 cities in Northern China[1] have been covered by a clean heating program.[2] Through mandates and subsidies, this program converts household heating fuel from coal to natural gas, electricity, or clean coal. Although this program has helped achieve environmental goals, one possible negative consequence could be energy poverty confronted by low-income households, due to the higher costs of heating after the transition (see, e.g., Barrington-Leigh et al., 2019).

Given the significant impact of energy poverty on life satisfaction (Biermann, 2016; Churchill et al., 2020; Welsch and Biermann, 2017),

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[1] Some households in Northern China are connected to "central heating." They are not affected by the household clean heating program studied in this paper, and therefore are excluded from this study. Central heating refers to a district system that generates and transports heated water or steam from boilers into households. Such a system serves hundreds or thousands of households; the households do not choose the energy type the boilers use. The households in this study have to heat their homes individually.

[2] The number of cities is cited from the "China Coal Consumption Cap Plan and Policy Research Project: China Coal Comprehensive Management Report 2019" (https://max.book118.com/html/2019/0831/8067022053002045.shtm). This program has various names such as household energy transition program, the program of coal to electricity and coal to gas, the program of household coal regulation, household clean heating program, and so on. Which name is used depends on the focus of the documents and the discussions. We use the term "clean heating program" in this paper, because the main goal of the program in the studied areas is to transition household heating energy from coal to cleaner energy. This is because the studied areas are in Northern China, where heating by coal is one of the major sources of air pollutants and carbon emissions.

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health (Kahouli, 2020; Llorca et al., 2020; Thomson et al., 2017), and many other socioeconomic outcomes, this policy-induced energy poverty should receive full attention from both researchers and policy makers. This paper investigates the distributional effects of China's household clean heating program on energy poverty by depicting the cohorts that are more likely to experience energy poverty and identifying those who are negatively affected to a larger degree by the program. Based on the findings, policy implications are proposed to alleviate the energy poverty problem caused by this program.

The household clean heating program of China was piloted in 2014 in its capital city, Beijing; expanded to "2 + 4" cities in the Jing-Jin-Ji air pollution prevention core area in 2015; and further extended to "2 + 26" cities along the Jing-Jin-Ji pollution transmission channel.[3] The program is mandatory and is implemented from the top down.[4] All households in the selected villages are required to participate, and participation is strictly supervised. Considering that the substitute energy (i.e., electricity, gas, and clean coal) is more expensive than the substituted energy (i.e., regular coal), the various levels of government aim to ensure participation through a combination of high subsidies. The transition cost involves either electricity grid upgrade (for the *coal to electricity* program) or gas pipeline extension and construction of gas distribution stations (for the *coal to gas* program), as well as the replacement of heating devices and higher fuel cost. The government covers the cost of infrastructure construction and provide subsidies for fuel cost and equipment replacement at the household level. Previous literature has shown that the social benefit of this transition program exceeds the cost (e.g. Yu and Xin, 2020; Zhang et al., 2019). However, how the costs are distributed, in terms of poverty and equity, has not been paid enough attention. Rural households, who tend to be poor, experienced sharp increases in heating expenditure after being enrolled in the program, even with the subsidy. Energy poverty is likely to be intensified among these households.

Energy poverty is defined in terms of availability and affordability of modern energy that meets a household's basic needs (Foster et al., 2000). Energy availability is measured by the accessibility of modern energy such as electricity, natural gas, and so on. Such access is often limited in rural areas of developing countries (Jian-ping, 2013; Li et al., 2011; Pachauri and Spreng, 2004). Affordability is usually measured by indicators such as the ratio of household energy expenditure to household income. Households that have difficulty affording energy are susceptible to changes in income, energy price, and energy efficiency. Energy affordability is not only an issue in developing countries but also poses serious problems in developed countries (Legendre and Ricci, 2015; Thomson et al., 2016). Given that China has expanded electricity coverage to 100% of households in the country as of 2017,[5] we focus on affordability rather than accessibility in this paper.

Energy poverty in terms of affordability is widely discussed in developed countries such as the UK, the US, Ireland, and other EU countries, mostly focusing on winter heating energy expenditures. Previous literature defined and measured energy poverty in various dimensions (Hills, 2012; Li et al., 2014), and investigated characteristics of energy-poor households. For example, Chaton and Lacroix (2018) found that households with high income and education are less likely to experience energy poverty. Mould and Baker (2017) found that households with older members or children are vulnerable to energy poverty. Legendre and Ricci (2015) showed that the probability of falling into energy poverty is higher for those who are retired and living alone in a rented place.

Some papers have studied the impact of low-carbon energy transition on energy poverty. For example, based on a provincial-level panel of data from 2004 to 2017, Dong et al. (2021) investigated the impact of natural gas consumption on energy poverty in China and found that increased natural gas consumption can effectively mitigate the problem. Others have focused on how household energy transition programs have achieved their environmental objectives, such as reducing CO_2 emissions and air pollutants and promoting energy conservation (see, e.g., Aydin and Brounen, 2019; Baiardi, 2020; Bellocchi et al., 2018; Bertoldi and Mosconi, 2020; Blesl et al., 2007).

Several recent papers have studied the program that we study in this paper, but from different perspectives. For example, Liu and Mauzerall (2020) calculated the annualized capital and operating costs of using clean heating technologies for rural households in the Beijing-Tianjin-Hebei region. By comparing the costs of different technologies, they highlighted the most energy efficient options. Barrington-Leigh et al. (2019) estimated the impact of the clean heating program in Beijing on household energy use and expenditure, well-being, and indoor environmental quality, by comparing treated and untreated villages that vary in socioeconomic conditions. They found that, in some low-income districts, the program had negative impacts on well-being, measured as overall satisfaction with life, because of the increase in expenditures after the transition from coal to electricity.

To the best of our knowledge, few studies have investigated the impact of an energy transition program on energy poverty. One possible reason is that energy transition programs generally aim to address both energy availability and affordability, with the expectation that energy poverty will be alleviated. The subsidy element of the household clean heating program in China was expected to address the affordability of the substitute energy. However, given the mandatory nature of the policy – and despite the subsidy – energy poverty seemed to increase. This paper measures this unexpected effect and its heterogeneity, especially with respect to household income.

This paper contributes to the literature in several respects. First, we collected survey data at a fine level and on a large scale. Second, we consider changes in energy consumption as households re-optimize their behavior in response to changes in prices and policies. Ignoring re-optimization behavior may lead to misleading conclusions (Davis et al., 2014). Third, we measure the breadth and depth of energy poverty, as well as the gap between actual expenditure and a threshold, before and after the program. Fourth, utilizing econometric models, we explore the characteristics of the cohorts that are more likely to be in energy poverty and those that are negatively affected by the program to a larger extent. By identifying which households are most vulnerable to energy poverty, policies can more precisely target the most vulnerable.

Although studying a specific program in China, this paper could be of interest to other countries as well. Household energy transition has been a focus of policy makers, especially out of concern for climate change. This paper calls attention to the energy poverty effect of a mandated energy transition program and suggests the balance that is needed between environmental gains enjoyed by the public and the cost burden on individuals.

The remainder of this paper is organized as follows. Section 2 describes the methods for measuring energy poverty; section 3 introduces the survey and the data; section 4 presents the energy poverty measurement results; section 5 describes the econometric models and presents the regression results; and section 6 concludes with policy

[3] The Jing-Jin-Ji region is the area of Beijing city (Jing), Tianjin city(Jin), and Hebei province (Ji). The "2 + 4" cities are Beijing, Tianjin, and four cities in Hebei province. The "2 + 24" cities are Beijing, Tianjin, and 24 cities in Hebei, Henan, Shanxi, and Shandong provinces, which are on the pollution transmission channel to Beijing.

[4] The central government first selects the cities and sets the annual target number of covered households in each province; the provincial government then decomposes the number of targeted households into lower levels of government, and finally to villages; then, a specific transition plan for the selected villages is jointly made by the National Development and Reform Commission (NDRC) and the local government, based on the village's characteristics, such as distance to downtown, infrastructure condition, financial capacity, villagers' income level and preferences, and so on.

[5] World Bank's Electricity Access Report: http://documents.worldbank.org/curated/en/364571494517675149/pdf/114841-REVISED-JUNE12-FINAL-SEAR-web-REV-optimized.pdf

implications.

2. Measurement of energy poverty

Earlier literature provides many different approaches to measure energy poverty, including both economics-based and engineering-based approaches (Pachauri and Spreng, 2004). The engineering-based approaches calculate the direct energy required to satisfy basic needs (see, e.g., Reddy and Goldemberg, 1990; Revelle, 1976) and the households with energy consumption below the estimates are considered to be in energy poverty. Though the engineering approaches are straightforward, basic needs may vary with subjective wants, climate, region, time, and other factors.

The economic approaches usually involve setting an energy poverty line, which is often defined in terms of the proportion of household income that the household spends on energy or fuel. Those households spending a share of their income higher than the energy poverty line are considered to be in energy poverty (see, e.g., Boardman, 1991; Churchill et al., 2020; Thomson et al., 2016). Boardman (1991) proposed that a household is in energy poverty if it needs to spend more than 10% of its total income to meet its necessary energy consumption. The threshold of 10% is based on survey data in Britain in 1988, when the poorest 30% of the population spent 10% of their income on average on energy. In that survey, the sample median ratio of energy expenditure to income ratio was 5%. Because twice the median was thought to be disproportionate (Isherwood and Hancock, 1979), Boardman (1991) used 10% to define energy poverty. The threshold of 10% was then widely used (Mohan et al., 2018), until Boardman (2010) himself pointed out that, as economic and social conditions had changed, using twice the median as the threshold would be more consistent and more informative than fixing the threshold at 10% of the household's income (Boardman, 1991).

There are two other ways in the literature to set the energy poverty line. Barnes et al. (2011) proposed setting the energy poverty line at the point from which households' energy consumption starts to rise with an increase in income. Healy and Clinch (2004) and Sovacool (2012) proposed to consider households to be in energy poverty if they report being unable to afford basic heating in winter.

There are also studies where energy poverty is defined in terms of access to energy services (see, e.g., Alam et al., 1991; Davis, 1998). However, as mentioned above, accessibility is not an important issue in China anymore, even in the rural areas.

In addition, there are recent studies that use subjective measures of energy poverty to capture the "feeling" of material deprivation felt by households unable to keep their homes warm during the cold season (see, e.g., Churchill et al., 2020; Thomson et al., 2017). The limitation of a subjective measure is that it may not be reliable if households feel ashamed to admit their inability to adequately heat their homes or their feeling of being uncomfortably cold.

In this paper, we use the most common economics-based approach to measure energy poverty, i.e., by setting an energy poverty line, given its wide acceptance in the literature and its objectivity in measurement. Following Boardman (2010), we take twice the median proportion of energy expenditure in household income as the energy poverty line. Because this is a relative measure, it may not be suitable for comparing the degree of energy poverty across groups with quite different distributions of energy expenditure and income. However, this is not a problem in this study, because we compare the change in energy poverty before and after the program for the same group.

Our measure of energy poverty is as follows. The energy poverty line is denoted as α. The proportion of energy expenditure is defined as:

$$\frac{E_i}{I_i} = \frac{\sum_{e=1}^{m} (X_{ie} \bullet P_e - R_{ie})}{I_i} \tag{1}$$

where E_i is the heating energy expenditure of household i; I_i is the annual income of household i; m is the number of types of energy; X_{ie} is the quantity of energy type e consumed by household i; P_e is the price of energy e; and R_{ie} is the subsidy for energy e received by household i. If $\frac{E_i}{I_i} > \alpha$, household i is defined to be in energy poverty. $I_i \times \alpha$ is the poverty threshold of expenditure on energy.

Based on the definition of energy expenditure and energy poverty line, we measure energy poverty in the following three dimensions: (1) energy poverty gap, which is defined as the gap between actual energy expenditure and some energy expenditure threshold; (2) the breadth of energy poverty, which is defined as the proportion of households whose energy expenditure ratio is below the energy poverty line; and (3) the depth of the energy gap, which is defined as the distance between a threshold energy expenditure and the average energy expenditure of households in energy poverty.

We adopt the Energy Affordability Gap (EAG) index proposed by Fisher, Sheehan and Colton (Hills, 2012) to capture the energy poverty gap. The EAG index is as follows:

$$EAG_i = E_i - I_i \times \alpha \tag{2}$$

EAG_i measures the energy poverty gap of household i. The total energy poverty gap of the society and the average energy poverty gap are defined accordingly, in Eqs. (3) and (4) respectively:

$$EAG = \sum_{E_i \geq I_i \times \alpha} (E_i - I_i \times \alpha) \tag{3}$$

$$\overline{EAG} = \sum_{E_i \geq I_i \times \alpha} (w_i/N)(E_i - I_i \times \alpha) \tag{4}$$

where w_i represents the weight of household i. In this paper, each household takes an equal weight, so $w_i = 1$.[6] N is the number of households. EAG and $\overline{EAG}$ measure respectively the total cost and the average cost to the society to eliminate energy poverty.

We use the FGT class, proposed by Foster, Green, and Thorbecke (Foster et al., 1984), to capture the breadth and the depth of energy poverty. The FGT class is as follows:

$$P_\theta = \sum_{E_i \geq I_i \times \alpha} (w_i/N) \left[\frac{E_i - I_i \times \alpha}{I_i}\right]^\theta \tag{5}$$

where θ is a parameter that takes a value of 0 or 1.

When $\theta = 0$,i

$$P_0 = \sum_{E_i \geq I_i \times \alpha} (w_i/N) \tag{6}$$

P_0measures the breadth of energy poverty.

When $\theta = 1$,

$$P_1 = \sum_{E_i \geq I_i \times \alpha} (w_i/N) \left[\frac{E_i - I_i \times \alpha}{I_i}\right] \tag{7}$$

P_1 calculates the average distance between the threshold expenditure and the expenditures of households that are in energy poverty. A greater distance indicates more serious energy poverty. So, P_1 measures the depth of energy poverty.

3. Survey and data

We conducted large-scale household- and village-level surveys to collect detailed information for the calculation of the indices of energy

[6] The weights are subjective, and reflect the priorities that are placed by researchers on different types of households. In this study, because the household is the smallest unit of observation, we would like to treat each household equally, so we assign them equal weights. For a robustness check, we also try out the weights of the number of household members, and it does not change our basic findings. The results are available upon request.

poverty, including the energy poverty gap (defined in Eq. 2), breadth (defined in Eq. 6) and depth (defined in Eq. 7).

The survey covered rural areas in Beijing and Hebei province. In Beijing, 183 villages out of 3918 villages were randomly selected through stratified sampling. The sampling ratio is based on the number of villages in each district. In each selected village, 20–22 households were randomly selected for in-person interviews. Therefore, we obtained a sample of 3949 households in total. In Hebei, 550 households were directly randomly selected for survey in person.[7]

The surveys collected (1) information at the village committee level, including village participation status, subsidy scheme, and energy price; (2) social and economic characteristics at the household level, including household size, age, income,[8] and education level; and (3) household heating behavior, including program participation status, energy consumption before and after the program, subjective evaluation of the program, and so on.

Because the transition mainly affects heating energy and cost, and because heating is the main energy cost for the areas studied in this paper, we focus on heating energy poverty.[9] To evaluate the effect of the program on heating energy poverty, we first calculate the participants' heating energy expenditure before and after the program. In the Hebei survey, this information was directly reported by the households. In the Beijing survey, such information is not reported, so we calculate it by multiplying heating energy consumption by price and deducting the subsidy received by the household. The information on energy consumption is reported by households. The prices of electricity and gas are obtained from the local price schedule issued by the Development and Reform Commission of Beijing. There is no official price schedule for coal and firewood, so we take the median of the reported prices from the village level survey. As for the subsidies, according to the policy documents, participating households receive a subsidy of 0.2 yuan per kWh for off-peak electricity consumption (two-thirds of the off-peak electricity price), up to 10,000 kWh per household; 0.38 yuan per m^3 for natural gas consumption (one-sixth of the first tier natural gas price), up to 820 m^3 per household; and 200 yuan per ton for clean coal (one-fourth of the clean coal price), up to 4.5 tons per household. Details on the subsidy scheme are presented in Appendix A, and details on prices with subsidies are presented in Appendix B. For non-participants in the programs, we assume that the heating expenditure remained unchanged after the program.

The sample included households[10] and villages that were and were not participating in the heating transition program. The number of households participating in *coal to electricity* and *clean coal replacement* in Beijing is relatively large, accounting for 23% and 42% of the sample respectively. In Hebei, 46% of households were participating in *coal to gas*, and the number of households participating in other programs was small. Therefore, in Hebei we focus only on the *coal to gas* program.

Considering that effects on energy poverty vary across programs and regions, we distinguish the three programs and the regions in the following analysis. In Fig. 1, we compare the three programs in Beijing and the *coal to gas* program in Hebei.[11] It shows that, in Beijing, the heating expenditure increases by 0.74 and 1.17 thousand yuan for *coal to electricity* and *coal to gas* respectively, while it decreases by 0.30 thousand yuan for *clean coal replacement*. The ratios of heating expenditure to income change by 0.98, 1.98, and − 0.69 percentage points, which are changes of 18.00, 50.90, and 9.55%. Fig. 1 also shows that heating expenditure in Hebei is similar to that in Beijing before the program, but increases more after the transition. As a result, the ratio of expenditure to income in Hebei increases by 4.31 percentage points, which is a 65.90% change.

Table 1 presents the summary statistics of the key variables for the energy poverty measurement, including income, heating energy expenditure, and the ratio of expenditure to income.

4. Graphic findings on energy poverty

Based on the formula and the survey data described above, in this section we measure the breadth and the depth of energy poverty and the energy poverty gap before and after the program in Beijing and Hebei. We also explore the reasons why the heating transition program worsened energy poverty.

4.1. Energy poverty breadth, depth, and gap

The energy poverty line is set at two times the median ratio of the household heating expenditure to income. As calculated in the previous section, the median of the ratio is 3.67% and 4.00% before the program for Beijing and Hebei respectively. Therefore, the energy poverty line in this paper is set at 7.34% and 8.00% for Beijing and Hebei respectively. The indicators of energy poverty are calculated based on this energy poverty line. The results are summarized in Fig. 2.

The overall energy poverty breadth, depth, and gap have all increased due to the clean heating program. By comparing Beijing and Hebei, we find that, although the energy poverty situation in Hebei was similar to Beijing before the program, the indicators of energy poverty

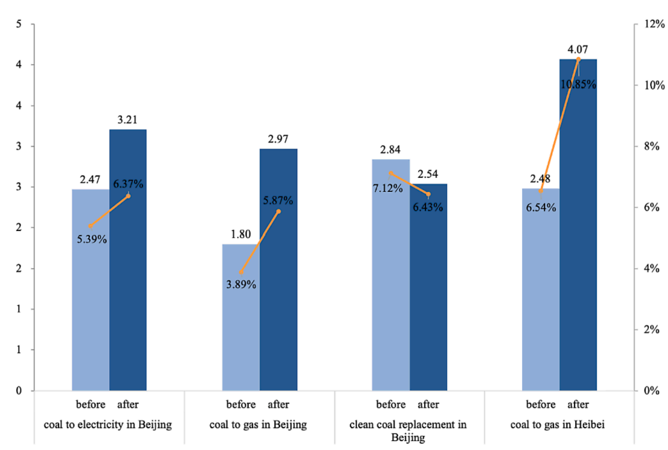


Fig. 1. Summary of Energy Expenditure and Income.

[7] The sampling strategies and sample sizes in Beijing and Hebei are different due to the differences in the funding sources and budget constraints. Some of the survey questions vary across Beijing and Hebei for the same reason. Compared to Hebei, Beijing's survey covers more households but with a shorter questionnaire for each household.

[8] To alleviate recall error in self-reported income, in the questionnaire we decomposed income into eleven categories and asked for information for each category, such as agricultural income, non-agricultural income, pension, asset income, government transfer, and more. These questions help the interview subjects recall income more carefully and therefore alleviate recall error. As for measurement error caused by under- or over-reporting, because income is part of the dependent variable (ratio of heating energy expenditure to income), as long as the measurement error is random, it will not cause estimation bias.

[9] Heating energy is part of total energy consumed by households. Therefore, the ratio of heating energy expenditure to income is smaller than the ratio of energy expenditure to income. Given that they are highly correlated and we use relative measures of energy poverty, the conclusions of this paper are expected to remain stable to the definition of energy as total energy or heating energy.

[10] While participation is mandatory for all households in participating villages, some households still make some use of traditional coal and firewood.

[11] In the Hebei sample, we have full information for only nine households in the coal to electricity program and two households in the clean coal replacement program, so we only investigate the coal to gas program in Hebei.

Table 1
Summary statistics of energy expenditure and income.

Panel A. Beijing							
		Participants			Non participants	Average
		Coal to electricity	Coal to gas	Clean coal replacement		
No. of Obs. (1585)		374	71	671	487	
Income (thousand yuan)		92.65	90.92	73.66	88.83	83.56
Before	Expenditure (thousand yuan)	2.47	1.80	2.84	2.27	2.53
	Ratio of expenditure to Income (%)	5.39	3.89	7.12	5.23	5.94
After	Expenditure (thousand yuan)	3.21	2.97	2.54	2.27	2.64
	Ratio of expenditure to Income (%)	6.37	5.87	6.43	5.23	5.98
Panel B. Hebei						
		Participants *coal to gas*			Non participants	Average
No. of Obs. (310)		143			156	
Income (thousand yuan)		61.07			54.36	58.93
Before	Expenditure (thousand yuan)	2.48			1.82	2.20
	Ratio of expenditure to Income (%)	6.54			6.50	6.55
After	Expenditure (thousand yuan)	4.07			1.82	2.95
	Ratio of expenditure to Income (%)	10.85			6.50	8.65

Notes: After dropping observations with missing values or outliers in key variables (e.g., total energy consumption and income), we have 1585 observations in Beijing and 310 observations in Hebei. Income and expenditure are both household annual values. The sum of participants and non-participants in Beijing exceeds the total number of observations, because some participants participate in more than one program.

became higher in Hebei than Beijing after the program. The possible reasons could be as follows. First, households in Hebei have much lower income than households in Beijing, as shown in the previous section. Therefore, an increase of energy expenditure has a larger effect on energy poverty for households in Hebei. Second, due to the differences in the local price and subsidy schemes, the price of clean energy in Hebei is higher than in Beijing. For example, in Hebei, the price of electricity is about 6% higher and natural gas is 5% higher than in Beijing. Third, the three programs have different effects on energy poverty, so the participation status may lead to different average effects. We therefore explore the heterogeneity of the effects across the programs in the next subsection.

By comparing participants and non-participants, we find that the energy poverty breadth, depth, and gap were all smaller for non-participants than for participants, even before the program, with the sole exception of energy poverty depth in Hebei. This suggests that the clean heating program's target households were those that were more likely to be in energy poverty even before the program. This does not mean that the program deliberately targeted households with lower income. But it is worth noting that households with lower income were more likely to be targeted, because they tend to live in regions that are too remote and/or in houses that are too old to have central heating. Because coal is the cheapest and most readily available heating energy, they tended to use coal for heating and therefore they became the target of the clean heating program.

4.2. Heterogeneous effects across programs

Given that *coal to electricity*, *coal to gas*, and *clean coal replacement* have different costs and subsidy schemes, they have different effects on energy poverty. As shown by Fig. 3, *coal to electricity* and *coal to gas* aggravate energy poverty, while *clean coal replacement* alleviates energy poverty. The *coal to gas* program has a larger negative impact than the *coal to electricity* program, in terms of the breadth, depth, and gap of energy poverty. For participants in the *coal to gas* program, the energy poverty breadth, depth, and gap in Beijing increased by 9.86 percentage points, 0.85 percentage points, and 162 yuan respectively. They increased by 14.68 percentage points, 3.04 percentage points and 721 yuan in Hebei. For *coal to electricity*, these three indicators increased by 5.88 percentage points, 0.56 percentage points and 258 yuan respectively, and for *clean coal replacement* these decreased by 3.43 percentage points, 0.39 percentage points and 76 yuan.

4.3. Reasons for the effects on energy poverty

The heating energy program worsens the energy poverty problem, because the household heating energy transition from coal to electricity and gas is costly and mandatory, and the supporting subsidy is not enough to cover the cost. In this section, we discuss these reasons in more detail.

Heating by electricity and gas costs more than heating by coal. Under the current energy prices and heating technologies, electricity and natural gas heating cost more than coal to achieve the same heating effect. According to the survey, Beijing households on average consumed 1.82 tons of coal per heating season, which cost 1.22 thousand yuan on average, before the program. After the program, households that participate in *coal to electricity* consume 6791 kWh of electricity for heating per heating season, which costs on average 3.70 thousand yuan without subsidy; households that participate in *coal to gas* consume 1409 m^3 of gas on average, which costs 3.32 thousand yuan without subsidy. Fig. 4 plots the distribution of household heating expenditures using different energy sources. From coal to electricity or gas, the heating expenditures shift to the right, indicating that heating with electricity and gas is more expensive than coal.

The subsidies for electricity and gas are not enough to cover the additional cost. According to the estimation results in Xie et al. (2019), the average subsidy received by a household that participates in *coal to electricity*, *coal to gas* and *clean coal replacement* is 0.93, 1.15 and 1.76 thousand yuan, accounting for 55.71%, 49.60% and 119.79% of the average additional expenditure. This indicates that the current subsidies for electricity and gas heating can only cover about half of the extra expenditure caused by the transition.

The mandatory implementation of the program leaves the covered households no option to participate or not. Because heating with electricity and gas are more expensive and the subsidies are insufficient, many households would have chosen not to participate if they had that option. However, all selected households are required to make the transition. Village leaders are responsible for ensuring participation, using means such as banning the sale of coal in the village. The mandatory feature means that energy poverty worsened more than it would have if households had a choice.

5. Regression analysis

The previous sections have shown that the clean heating program put more households into energy poverty. Because the effects vary across

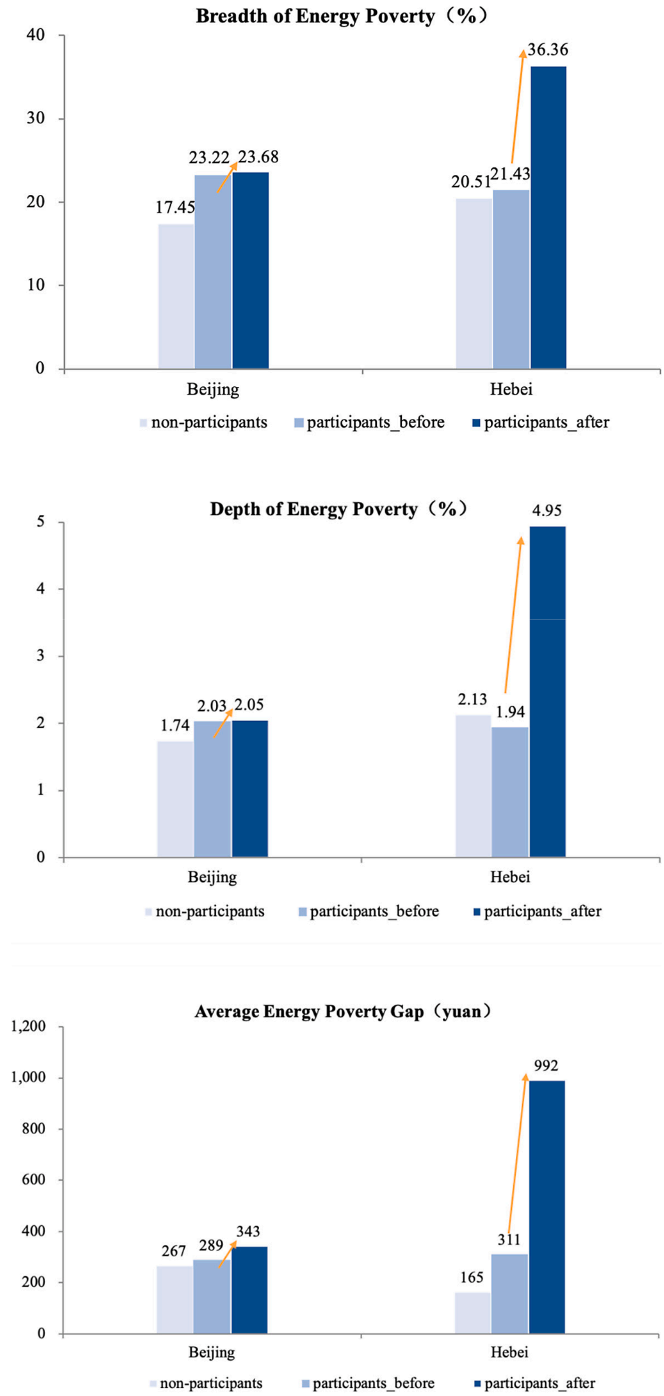


Fig. 2. Energy Poverty between Participants and Non-Participants.

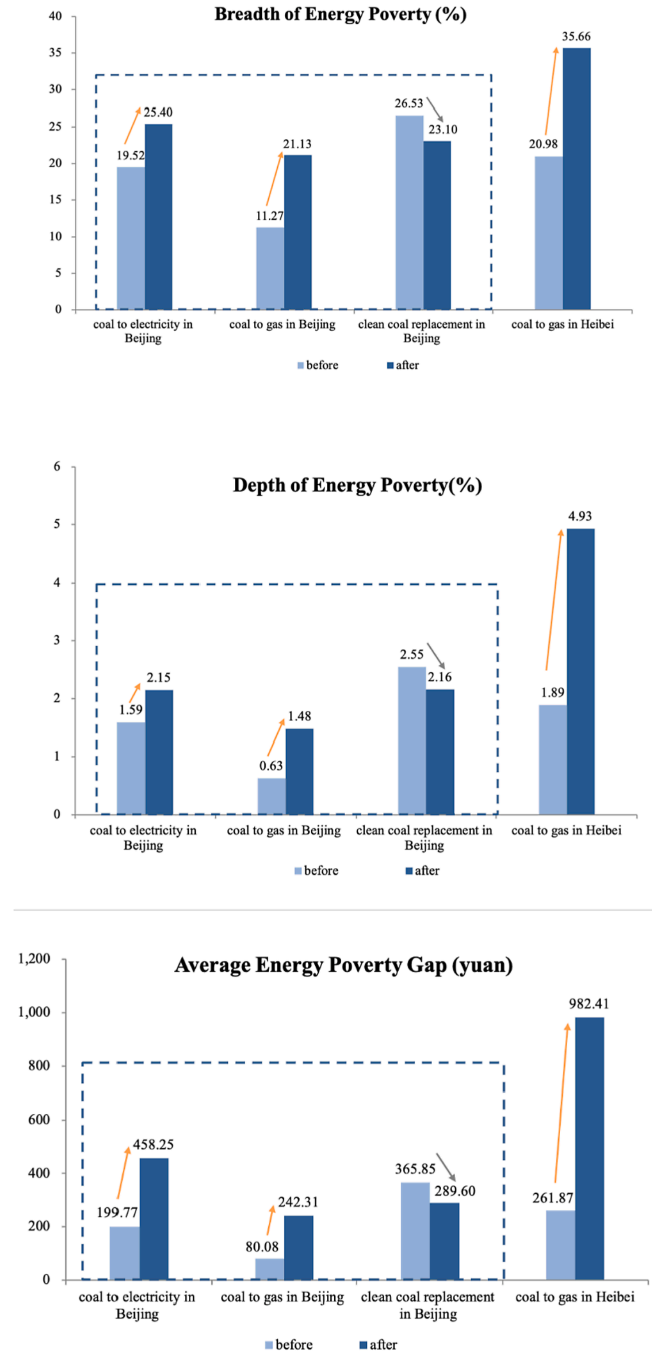


Fig. 3. Energy Poverty under Different Programs.

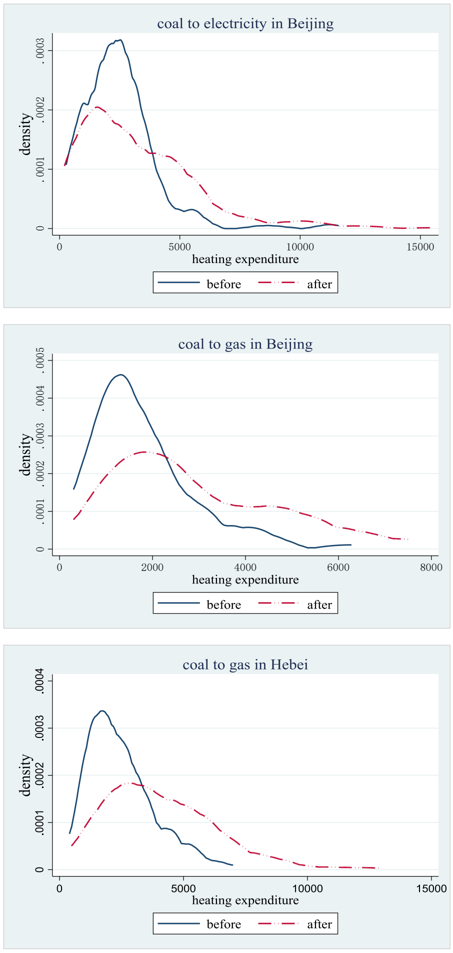
households, we further explore the characteristics of the cohorts that are more likely to be in energy poverty and those that are negatively affected by the program to a larger extent. We employ econometric models for the analysis, and the regression specification is as follows:

$$HEEratio_i = \beta_0 + \boldsymbol{HH}_i{}'\boldsymbol{\beta}_1 + \boldsymbol{HS}_i{}'\boldsymbol{\beta}_2 + \varepsilon_i \tag{7}$$

The explained variable $HEEratio_i$ is the ratio of heating energy expenditure to income of household *i*. We use this instead of the dummy variable for energy poverty, because the value of the energy poverty dummy is based on the comparison of the ratio and the energy poverty line. Using an energy poverty dummy would omit more detailed information on the ratio. As shown in Appendix C, the dummy variable yields similar findings, but with lower significance because there is less information in the dependent variable.

The explanatory variable vectors of $\boldsymbol{HH}_i$ and $\boldsymbol{HS}_i$ are household *i*'s characteristics and its housing characteristics. $\boldsymbol{HH}_i$ includes income, household size, household structure, and education. $\boldsymbol{HS}_i$ includes the size, age, and insulation of the house. The detailed definitions of the variables are presented in Table 2.

The summary statistics of these variables are presented in Table 3. In Panel A, the four columns respectively present the full sample and the samples of participants in Beijing in *coal to electricity*, *coal to gas*, and *clean coal replacement*. Panel B presents the Hebei *coal to electricity* program.



Notes: The plots depict the kernel density of heating expenditure in Beijing and Hebei before and after different programs. The solid line represents the distribution of the heating expenditure before the program, and the dotted line represents that after program.

Fig. 4. expenditure of heating with electricity and gas.
Notes: The plots depict the kernel density of heating expenditure in Beijing and Hebei before and after different programs. The solid line represents the distribution of the heating expenditure before the program, and the dotted line represents that after program.

5.1. Vulnerable households before the program

We first investigate the characteristics of households that were more likely to have a high ratio of heating expenditure to income before the program. We adopt a Multiple Linear Regression and include all the observed households in the regression. We run the regression separately for Beijing and Hebei and present the regression results in Table 4.

In terms of household characteristics, Table 4 shows that, before the initiation of the clean heating program, households in Beijing with lower income and education level and those who live in larger and older houses tended to have a larger heating expenditure to income ratio, and therefore were more likely to be in energy poverty. The regression results also show that households with more members tended to have a smaller ratio, indicating the existence of economy of scale in heating.

In terms of housing characteristics, the coefficient of insulation is positive and statistically significant, showing the positive correlation between houses with better insulation and a higher heating expenditure ratio. Insulation and heating expenditure ratio could be correlated in various ways: (1) insulation could save heating energy, which is a negative correlation; (2) households with high heating expenditure tend to add insulation and take other steps to save on heating expenditure (reverse causality), which is a positive correlation; (3) households with high heating expenditure are those who pursue comfort and therefore are more likely to improve the insulation of the house (simultaneous causality), which is also a positive correlation. Putting the three channels together, we see that the positive correlation dominated before the program.

In Hebei, the findings are similar to Beijing: households with lower income and those that have elderly members were more likely to be in energy poverty before the program.

Table 2
Definition of variables.

Variable	Definition
Explained variable	
Ratio of heating expenditure to income	Household annual heating expenditure divided by household annual income
Energy poverty	A dummy variable, which takes value of one if the household's ratio of heating expenditure to income is more than twice the median ratio, zero otherwise.
Explanatory variable	
Household characteristics	
income	household annual income (thousand yuan)
household size	number of household members
elderly	a dummy variable, which takes value of one if the household has a member over 60, zero otherwise.
children	a dummy variable, which takes value of one if the household has a child younger than 15, zero otherwise.
education	Education level of household head, which takes value of one if the education level of household head is illiteracy, uneducated or primary school; two if the education level is junior high school; three if the education level is high school (including vocational high school); four if the education level is college, university, master or doctor
Housing characteristics	
house size	housing area (100 m^2)
house age	Number of years from the construction of the house to the survey year
Insulation	a dummy variable, which takes value of one if the household has done warmth renovation or has double glazing, zero otherwise.

5.2. Vulnerable households after the program

We then investigate the characteristics of households that are more likely to have a high ratio after the program. We distinguish among the programs and summarize the regression results in Table 5. Each column in Table 5 includes the participants in one program.

Similarly to the findings before the program, the results after the program show that participants who have a high expenditure ratio are those with lower income, fewer members, lower education, and larger houses. One different finding is that the coefficient of insulation in the regression for *coal to gas* in Beijing is negative and statistically significant, while it is positive, small, and not statistically significant in other regressions after the reform. A possible reason is that the reverse causality and co-causality are alleviated in the after-program regressions, because the program brought a shock to heating expenditure and the response of improving insulation (e.g. adding or retrofitting insulation to old houses) takes time.

5.3. Households that suffered more due to the program

We further explore whether the clean heating program has heterogeneous effects across households with different characteristics. We run regressions of the change in the ratio before and after the program on characteristics of households and houses. Results are summarized in Table 6.

Similarly to previous findings, households with lower income are

Table 3
Summary statistics of regression variables.

Panel A. Beijing	Full sample	Coal to electricity participants	Coal to gas participants	Clean coal replacement participants
Explained Variables				
Before				
energy poverty	0.214	0.200	0.175	0.267
expenditure ratio	5.953	5.529	3.878	7.109
After				
energy poverty	0.216	0.254	0.221	0.231
expenditure ratio	5.990	6.502	5.948	6.426
Explanatory Variables				
income	82.743	93.416	90.853	72.646
household size	3.66	3.761	3.294	3.598
elderly	0.578	0.639	0.500	0.576
children	0.396	0.424	0.412	0.359
education	1.971	1.934	2.000	1.903
house size	1.638	1.757	1.369	1.742
house age	21.222	21.382	18.191	22.179
insulation	0.7	0.69	0.735	0.689
No. of observations	1483	335	68	637

Panel B. Hebei	Full sample	*Coal to gas* participants
Explained Variable		
Before		
energy poverty	0.232	0.228
expenditure ratio	7.052	6.856
After		
energy poverty	0.308	0.370
expenditure ratio	9.295	11.235
Explanatory Variables		
income	55.709	59.069
household size	3.323	3.543
elderly	0.335	0.346
children	0.285	0.339
education	2.167	2.220
house size	1.410	1.454
house age	21.209	21.087
insulation	0.502	0.543
No. of observations	263	127

Table 4
Heating expenditure ratio before the clean heating program.

	Beijing	Hebei
Household characteristics		
Income	−0.031***	−0.088***
	(0.005)	(0.015)
Household size	−0.681***	0.292
	(0.167)	(0.300)
Elderly	0.315	3.697**
	(0.467)	(1.529)
Children	0.297	0.177
	(0.407)	(1.338)
Education	−0.725***	−0.233
	(0.270)	(0.551)
Housing characteristics		
House size	0.480***	−0.994
	(0.170)	(1.001)
House age	0.038*	−0.008
	(0.020)	(0.072)
Insulation	0.704*	1.953*
	(0.405)	(1.011)
Constant	10.03***	10.77***
	(0.872)	(2.683)
Observations	1483	263
R-squared	0.160	0.226

Notes: OLS estimation. The explained variable is the ratio of heating energy expenditure to income before the program. *, ** and *** indicate significance levels of 10%, 5% and 1% respectively. Robust standard errors in parentheses.

more likely to be worse off due to the *coal to gas* program. These findings show that low-income households not only have a high expenditure ratio and easily fall into energy poverty, but also are burdened by a greater negative impact from these programs. For insulation, the coefficient in the regression for coal to gas in Beijing is negative and statistically significant, which provides support for results in Table 5.

For the other characteristics, the coefficients are not statistically significant, implying the universal influence of the program across households with different household characteristics and housing characteristics, except for income and insulation.

6. Conclusion

Heating is a necessity in northern winters. When heating expenditure accounts for a high proportion of energy expenditure, households need to pay a higher proportion of their income to meet this basic need, leading to energy poverty. After a household clean heating program was piloted in Beijing in 2013, the heating expenditures of participating households that switched to gas or electricity increased sharply, and the problem of energy poverty was intensified in the areas where the program was implemented.

Using household-level questionnaires in Beijing and Hebei, this paper studies the increase in energy poverty of rural households due to the clean heating program. The results show that the *coal to electricity* and *coal to gas* programs exacerbated energy poverty, and *clean coal replacement* alleviated energy poverty; households with lower income,

Table 5
Heating expenditure ratio after the clean heating program.

	Coal to electricity in Beijing	Coal to gas in Beijing	Clean coal replacement in Beijing	Coal to gas in Hebei
Household characteristics				
income	−0.023***	−0.014**	−0.054***	−0.162***
	(0.007)	(0.006)	(0.007)	(0.031)
household size	−0.828**	−1.908*	−0.581**	−0.202
	(0.395)	(1.016)	(0.248)	(0.567)
elder	−0.739	0.647	−1.024	1.510
	(1.078)	(1.808)	(0.876)	(2.899)
children	−0.132	2.147	0.938	−3.488**
	(0.791)	(1.711)	(0.658)	(1.342)
education	−1.212*	−2.670	−1.011**	0.579
	(0.695)	(1.613)	(0.472)	(1.311)
Housing characteristics				
house size	0.663	1.888*	0.832***	0.603
	(0.544)	(1.105)	(0.293)	(1.581)
house age	0.068	−0.130**	0.030	−0.053
	(0.053)	(0.057)	(0.036)	(0.102)
insulation	0.389	−3.241**	0.938	0.321
	(1.127)	(1.361)	(0.677)	(1.990)
Constant	11.72***	19.79***	11.86***	20.95***
	(2.431)	(6.023)	(1.314)	(5.541)
Observations	335	68	637	127
R-squared	0.152	0.412	0.175	0.317

Notes: OLS estimation. The explained variable is the ratio of heating energy expenditure to income after program. We distinguish the programs and the regions. Each column shows the results for participants in one program of one region. *, ** and *** indicate significance levels of 10%, 5% and 1% respectively. Robust standard errors in parentheses.

Table 6
Heating expenditure ratio change after the clean heating program.

	Coal to electricity in Beijing	Coal to gas in Beijing	Clean coal replacement in Beijing	Coal to gas in Hebei
Household characteristics				
income	−0.003	−0.008*	0.004	−0.068***
	(0.002)	(0.004)	(0.003)	(0.018)
household size	0.041	−0.052	0.104	−0.216
	(0.210)	(0.759)	(0.128)	(0.427)
elder	0.0145	1.937	−0.256	−2.301
	(0.762)	(1.285)	(0.494)	(2.140)
children	0.119	0.0275	−0.458*	−1.755
	(0.516)	(1.204)	(0.273)	(1.089)
education	−0.299	−0.118	0.060	−0.041
	(0.425)	(1.129)	(0.212)	(0.893)
Housing characteristics				
house size	0.529**	0.278	0.071	1.217
	(0.266)	(0.797)	(0.138)	(1.225)
house age	0.0153	−0.147***	−0.018	0.096
	(0.028)	(0.052)	(0.020)	(0.100)
insulation	−0.299	−3.008***	−0.166	−0.364
	(0.759)	(0.994)	(0.341)	(1.658)
Constant	0.581	6.704	−0.751	7.046
	(1.617)	(4.485)	(0.824)	(5.312)
Observations	335	68	637	127
R-squared	0.012	0.283	0.012	0.139

Notes: OLS estimation. The explained variable is the change of expenditure ratio after the programs. Each column is the results for each treatment group. *, ** and *** indicate significant levels of 10%, 5% and 1% respectively. Robust standard errors in parentheses.

smaller household size and lower education, and those with larger housing areas are more likely to fall into energy poverty; and low-income households and poorly insulated houses are negatively affected by the *coal to gas* program to a greater degree.

According to Beijing Municipal Bureau Statistics and the Hebei Government Report, at the end of 2017, there were 787,500 households in Beijing participating in the *coal to electricity* program and 137,000 in the *coal to gas* program, while 2,318,000 households in Hebei were participating in the *coal to gas* program. Based on our estimation, *coal to electricity* in Beijing increased the number of households in energy poverty by 46,300, and *coal to gas* in Beijing and Hebei increased the number of households in energy poverty by 13,000 and 340,300. These programs enlarged the energy poverty gap by 203.55 million, 22.23 million, and 1.67 billion yuan respectively, indicating that this mandatory energy transition has imposed a large cost on rural households.

In addition to fuel cost, the clean heating program also involves the costs of infrastructure construction and the replacement of heating equipment. Due to the subsidy scheme, households do not bear the cost of infrastructure construction, but bear a portion of heating equipment replacement. When the cost of equipment replacement is taken into consideration, the energy poverty problem is more serious.

The main reason for the increase in energy poverty is that the transition from coal to electricity or gas is both costly and mandatory, and the supporting subsidy is insufficient to cover the increased cost. Although the *clean coal replacement* program is also mandatory, clean coal is much cheaper than electricity and gas, and it does not involve the cost of infrastructure construction and heating equipment replacement. This implies that *clean coal replacement* would a good transitional measure before eventually achieving heating with gas or electricity, if the government is fiscally constrained in the short term.

These findings call the attention of policy makers to low-income households when designing and implementing policies. Without identifying the likely heterogeneous effects, a mandatory "one policy for all" is likely to hurt low-income households more. Low-income households need special attention during the implementation of energy transition policies. Increasing block pricing and decreasing block subsidy to electricity and gas may help address this problem. To design and utilize nonlinear pricing policy tools appropriately, it is critical to set the optimal number and optimal size of the blocks. Precisely estimating the price elasticities of households with different income levels and household characteristics would be helpful in identifying the optimal values of these parameters. Meanwhile, considering the heterogeneous impacts across areas, the subsidy should be negatively correlated with local income. The current subsidy comes from local governments and therefore is positively correlated with local income. To correct this, the central government need to further cross-subsidize the households in the areas with lower income. Such a subsidy could come from the increased electricity price faced by households whose electricity consumption is in the top blocks.

Furthermore, due to the huge financial pressure caused by the large-scale subsidies, it is foreseeable that the subsidy will not last long. When there is no subsidy in Beijing, the energy poverty breadth will further increase, by 2.8 percentage points. Considering the limited financial resources and the unsustainable subsidies, encouraging technological innovation to improve the efficiency of electricity and gas heating and to reduce the cost of clean heating would be the key to achieving affordable clean heating.

We should be aware that the focus of this paper is on the economic cost borne by households, which is only part of a household's welfare. Through the clean heating program, heating becomes not only cleaner, but also safer and more convenient. These improvements contribute positively to a household's welfare. For households that may value the non-economic attributes of clean heating more than the additional cost, it is possible that their welfare is improved. Identifying the characteristics of these households could be one direction of future research, as it could shed light on ways to improve households' welfare by improving the design and implementation of the clean heating program and similar programs.

We also would like to point out that this paper has not considered the general equilibrium effects of this program. The change of heating cost affects the relative price of other goods, so it may affect the consumption of other goods through substitution and income effects. The suppliers of coal, electricity, and gas are directly affected by this program, as the demand for coal is dramatically decreased and the demand for electricity and gas are significantly increased. In addition, all firms, not only energy suppliers, could be indirectly affected by this program, as they are charged a higher electricity price or tax to further cross-subsidize[12] the households in the program. A general equilibrium analysis taking all these stakeholders into consideration would be another interesting and important direction of future research.

CRediT author statement

Lunyu Xie: Conceptualization, Methodology, Writing (part). **Xian Hu**: Data Cleaning, Analysis, Writing (part), Validation. **Xinyi Zhang**: Data Cleaning, Analysis, Writing (part). **Xiao-Bing Zhang:** Validation, Writing- Reviewing and Editing.

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Appendix A

Subsidy scheme in Beijing

Coal to electricity – Time of Use pricing is implemented for the participating households and off-peak price is subsidized. During the off-peak period (21:00 to 6:00), the electricity price is 0.3 yuan per kWh without subsidy; the subsidy is 0.2 yuan/kWh, of which 0.1 yuan/kWh is from the municipal government and the other 0.1 yuan/kWh is from the district government. The cap is 10,000 kWh per household. In addition, there is a municipal equipment subsidy, which is 1/3 of the purchase cost for energy storage type electric heaters, with a cap of 2.2 thousand yuan; 100 yuan per square meter for air source heat pump and ground source heat pump, with a cap of 12 thousand yuan. The district government can increase the subsidies based on its financial capacity. Further, the government pays all outdoor electricity line expansion expenses, and subsidizes the indoor line expansion.

Coal to gas – Participating households enjoy a subsidy of 0.38 yuan per m^3 for natural gas, with a cap of 820 m^3. The government subsidizes 1/3 of the equipment price, with a maximum amount of 2.2 thousand yuan per household. For the gas pipeline, the government pays the construction cost and the village pays the renovation cost.

Clean coal replacement – The government subsidizes 200 yuan per ton for clean coal, with a maximum amount of 4.5 tons per household.

Subsidy scheme in Hebei

Coal to electricity – Electricity price and line subsidy schemes are the same as in Beijing. There is a small difference in the equipment subsidy scheme, which is that the government subsidizes 5 thousand yuan for participating households with direct electric heating or air energy heat pump heating.

Coal to gas – Participating households enjoy a subsidy of 1 yuan per m^3 for natural gas, with a cap of 1200 m^3. For pipeline transformation and equipment purchase, the government subsidizes 70% of the purchase and installation investment of gas equipment, with a maximum amount of 2.7 thousand yuan.

Clean coal replacement – The government subsidizes 300 yuan per ton for clean coal.

Appendix B

Table B1
Energy prices in rural areas of Beijing.

Energy type	Unit	Price before	Price after (with subsidy)
Electricity	yuan/kWh	Peak period: 0.4883 (first tier) 0.5883 (second tier) Off-peak period: 0.3	Subsidize 0.2 yuan per kWh for off-peak consumption, up to 10,000 kWh per household
Natural gas	yuan/m^3	2.28 (first tier) 3.5 (second tier) 3.9 (third tier)	Subsidize 0.38 yuan per m^3, up to 820 m^3 per household
Raw coal	yuan/ton	650	No subsidy
Bituminous coal: briquette	yuan/ton	675	No subsidy
Bituminous coal: honeycomb coal	yuan/ton	743	No subsidy
Anthracite: briquette	yuan/ton	750	Subsidize 200 yuan per ton, up to 4.5 ton per household
Anthracite: honeycomb coal	yuan/ton	800	Subsidize 200 yuan per ton, up to 4.5 ton per household
Firewood	yuan/ton	0.3	No subsidy

Notes: Information on prices of electricity and natural gas is from Beijing Municipal Commission of Development and Reform. Information on prices of coal and firewood is from the village survey of CRECS 2016 Beijing.

[12] Cross-subsidy is widely used in both developed and developing countries and is well-studied in the literature (e.g., Faulhaber, 1975; Abeberese, 2012; Deichmann and Zhang, 2013). China's electricity cross-subsidy comes from the differential electricity retail price, set by the State Grid Corporation of China (SGCC) and the China Southern Grid (CSG) for the purpose of providing universal service, which is one of the social responsibilities of state-owned companies. Based on the direction of the cross-subsidy, electricity cross-subsidy in China includes subsidy within residential sectors (urban households subsidize rural households), subsidy across sectors (industry sector subsidizes residential sector), and subsidy across regions (developed southeast region subsidizes less developed middle and west regions). Rural households, the ones studied in this paper, are cross-subsidized by urban households and firms, through a differential electricity price.

Appendix C

We rerun the regressions in Tables 4 through 6 with a new dependent variable: the energy poverty dummy. Given the dummy dependent variable, we adopt logit estimation. The estimated marginal effects of the explanatory variables are summarized in the following tables. The findings are similar to Tables 4 through 6, but the significance of the estimation is negatively affected. The reason is as explained in the main text: the energy poverty dummy is constructed from the expenditure ratio and contains less information than the continuous variable of the expenditure ratio.

Table C1
Energy poverty before the clean heating program.

	Beijing	Hebei
Household characteristics		
income	−0.007***	−0.011***
	(0.0004)	(0.001)
household size	−0.002	0.017
	(0.009)	(0.021)
elderly	0.004	0.037
	(0.018)	(0.036)
children	0.007	−0.040
	(0.025)	(0.052)
education	0.005	0.031
	(0.012)	(0.029)
Housing characteristics		
house size	0.039***	0.037
	(0.011)	(0.030)
house age	−0.0007	−0.001
	(0.0007)	(0.002)
insulation	0.008	0.041
	(0.017)	(0.037)
Constant	3.398***	2.659
PseudoR^2	(1.416)	(2.275)
	0.394	0.430
Wald *c*2	121.39***	24.35***
Observations	1483	263

Notes: Logit model. The explained variable is whether a household was in energy poverty before the program. The reported results are marginal effects. *, ** and *** indicate significance levels of 10%, 5% and 1% respectively. Robust standard errors in parentheses.

Table C2
Energy poverty after the clean heating program.

	Coal to electricity in Beijing	Coal to gas in Beijing	Clean coal replacement in Beijing	Coal to gas in Hebei
Household characteristics				
income	−0.005***	−0.007***	−0.007***	−0.011***
	(0.0005)	(0.001)	(0.001)	(0.002)
household size	0.0002	0.049	−0.018	0.026
	(0.020)	(0.053)	(0.013)	(0.029)
elderly	0.018	0.177**	−0.034	−0.044
	(0.046)	(0.073)	(0.027)	(0.065)
children	0.013	−0.005	0.062*	−0.057
	(0.063)	(0.155)	(0.037)	(0.076)
education	−0.014	0.029	−0.013	−0.013
	(0.029)	(0.058)	(0.020)	(0.041)
Housing characteristics				
house size	0.015	0.077	0.033*	−0.036
	(0.019)	(0.056)	(0.018)	(0.049)
house age	0.003	−0.004	3.34e-05	4.55e-06
	(0.002)	(0.004)	(0.001)	(0.003)
insulation	0.058	−0.183***	0.005	0.071
	(0.042)	(0.047)	(0.026)	(0.069)
Constant	1.370	1.823	5.828***	27.445**
	(1.057)	(5.762)	(3.572)	(40.251)
PseudoR^2	0.289	0.563	0.350	0.428
Wald *c*2	62.40***	21.64***	45.31***	21.98***
Observations	335	68	637	127

Notes: Logit model. The explained variable is whether a household is in energy poverty after the program. The reported results are marginal effects. Each column shows the results for participants in one program. *, ** and *** indicate significance levels of 10%, 5% and 1% respectively. Robust standard errors in parentheses.

Table C3
Energy poverty change after the program.

	Coal to electricity in Beijing	*Coal to gas* in Beijing	*Clean coal replacement* in Beijing	*Coal to gas* in Hebei
Household characteristics				
income	−0.003***	−0.004***	−0.001***	−0.001
	(0.0005)	(0.002)	(0.0004)	(0.0008)
household size	0.039**	0.057	0.009	−0.014
	(0.019)	(0.041)	(0.010)	(0.029)
elderly	0.069	0.162**	0.015	−0.174**
	(0.048)	(0.068)	(0.024)	(0.082)
children	−0.064	0.033	−0.052	−0.019
	(0.058)	(0.120)	(0.032)	(0.085)
education	0.024	0.073	−0.001	−0.087*
	(0.030)	(0.057)	(0.014)	(0.046)
Housing characteristics				
house size	−0.052**	−0.009	0.010*	−0.053
	(0.023)	(0.048)	(0.006)	(0.045)
house age	0.003	−0.0003	−0.001	0.003
	(0.002)	(0.004)	(0.001)	(0.003)
warmth condition	0.006	−0.105	0.003	0.061
	(0.042)	(0.066)	(0.023)	(0.0676)
Constant	0.279	0.049	0.177**	2.631
	(0.224)	(0.115)	(0.121)	(3.270)
PseudoR^2	0.199	0.313	0.075	0.101
Wald *c*2	44.67***	12.93	19.58**	12.75
Observations	335	68	637	127

Notes: Logit model. The explained variable is the change of household energy poverty state from before the program to after the program. The reported results are marginal effects. Each column shows the results for participants in one program. *, ** and *** indicate significance levels of 10%, 5% and 1% respectively. Robust standard errors in parentheses.

Appendix D. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2021.105795.

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