



Households' participation in energy transition and sustained use of clean energy: Evidence from China's clean heating program

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ABSTRACT

Household energy transition is a critical tool for air pollution mitigation and energy inequality reduction. The effectiveness of the transition largely relies on not only households' decision to participate but also their sustained use of clean energy after participation. However, the sustained use of clean energy has not yet received sufficient attention in policy making and in literature. This study examines China's Household Clean Heating program, which has switched millions of households' heating energy sources from coal to electricity and gas. We focus on both households' adoption and coal substitution behavior in the program. Based on the large-scale household survey conducted in rural areas of Northern China, we find that both high subsidies and compulsory measures effectively increased the household adoption rate; however, the latter did not guarantee sustained use of clean energy. We also find that In-person and repeated dissemination of program information had a better effect on involvement than passive announcements. Moreover, lower-income households were less likely to participate. Our findings suggest effective implementation approaches and supplementary measures to promote household energy transition, with fewer negative consequences for participants, particularly for the participants with lower income.

1. Introduction

Inequality has been increasing in most major countries since the 1980s and has been linked to seismic events ranging from environmental performance to domestic terrorism (Jorgenson, Schor, & Huang, 2017). International and intra-national energy inequalities are prominent between income groups, as energy is embodied in goods and services that people with different purchasing power have varying levels of ability to consume (Oswald, Owen, & Steinberger, 2020). Both inequality and energy inequality are associated with the energy transition process. Therefore, the provision of universal access to energy services to lower-income groups represents an urgent issue for governments worldwide at present (Lee, Miguel, & Wolfram, 2016).

To achieve an effective and fair energy transition, active participation and sustainable usage of clean energy are both critical. The existing evidence points out that many people do not use clean equipment, even though they have adopted it. For example, in India's cooking energy program (PMUY), nearly three-quarters of residents never or barely purchased liquefied petroleum gas (LPG) refills, and the participants' average annual LPG consumption was far less than half that of general customers (Kar, Pachauri, Bailis, & Zerriffi, 2019; Mani, Jain, Tripathi, & Gould, 2020). Carter et al. (2020) examined solid fuel suspensions (biomass and coal) after adopting clean fuels. The results indicated that two-thirds and four-fifths of participants continued to use solid fuel for cooking and heating,

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respectively, after the program. A large body of literature documented that households use multiple fuels simultaneously, termed fuel stacking. It indicated that increasing clean energy adoption alone cannot completely switch households away from traditional solid fuel (Kumar, Kaushalendra Rao, & Reddy, 2016).

Households in rural northern China consume approximately 200 million tons of dispersed coal during the heating season (He, 2017), most of which is of low quality and contributes disproportionately to air pollution and carbon emissions (Qin et al., 2017). Hence, to alleviate pollution and energy inequality problems, China has implemented a grand energy transition program for dispersed coal control since 2013, with Beijing piloting the Household Clean Heating (HCH) program in northern rural China. The nationwide HCH program aims to stimulate rural residents to replace dispersed coal with electricity or natural gas. Remote rural areas that do not have clean heating conditions have been provided with cleaner coal¹ as a transitional policy. By April 2021, the first three batches of the 43 pilot cities (see Appendix, Table A1) had completed the transition of a total of 35.26 million households (He, 2021).

As the program has been rolled out quickly through mandates and subsidies, households' adoption decisions and reduction in participants' coal consumption have varied across districts, and various challenges have emerged. The most prominent problem has been the reburning of the dispersed coal after participation. A survey conducted by the Ministry of Ecology and Environment found that the average rate of coal reburning in some villages reached 36%. Without the sustained use of clean energy, an energy transition program is likely to result in idle infrastructure (Liu & Mauzerall, 2020) and the failure of climate and clean air goals.

Therefore, it is critical to understand the determinants of the adoption and sustained use of substitute energy sources for an effective energy transition program. In this study, we identify implementation approaches that are effective in promoting clean energy usage and have fewer negative consequences for participants, especially those with lower income. Based on the Chinese Residential Energy Consumption Survey (CRECS) conducted in Beijing in 2017, we find that >60% of the households covered by the program chose to participate the program, and the participants reduced coal consumption by about 80%. We explore the determinates of the participation, and find that the high subsidies and compulsory measures effectively promoted the adoption of the program, but the latter did not work well in suspending coal and increasing electricity consumption. We also find that increasing publicity about the policy and improving homeowner satisfaction with clean heating significantly promoted the heating energy transition. Further, we find that although poor households have a lower participation rate, households' characteristics only have a limited impact on reducing the quantity of coal used, conditional on participation.

This study makes three contributions to the literature. First, it sheds light on China's experience with household energy transition policies. The HCH program is distinguished from previous practices by its large subsidies and mandatory enforcement. Therefore, this study also provides an opportunity to understand the effectiveness of controversial energy transition measures. Second, most previous studies on energy transition have focused on the penetration rate, whereas the analysis of sustained usage conditional on adoption has not yet received sufficient attention. We examine policy effectiveness from these two perspectives. Third, this study investigates energy transition in rural areas and explores the driving factors contributing to dissolving energy inequality. Our findings have important policy implications for improving the program's effectiveness and reducing energy inequality.

The remainder of this paper is organized as follows. Section 2 reviews the previous literature. Section 3 introduces the Household Clean Heating program in China. Section 4 describes the survey and summarizes the data. Section 5 presents the data analysis and findings. Section 6 concludes with policy implications.

2. Literature review

Energy transition affects energy inequality by changing energy affordability, efficiency, and the availability of energy services (Dong, Ren, & Zhao, 2021). In this regard, governments pursue the realization of an affordable, equitable, and fair energy transition. However, this pursuit is often confronted with many difficulties, including low benefits and large financing expenses (Gazull, Gautier, & Montagne, 2019), strong public opposition (Upreti & van der Horst, 2004), and the idling of equipment because of the unaffordable cost of clean energy or its inconsistency with living habits (Mani et al., 2020), etc.

Energy transition programs worldwide generally face problems in terms of participation and the sustained usage of substitute energy. For example, with the assistance of the World Bank, west African countries have designed an ambitious energy transition program encouraging residents to switch from conventional biomass to LPG since the 1990s. However, 25 years later, biomass still dominates residential energy sources in Sahelian countries, and its proportion has even increased in some countries (Gazull et al., 2019). India has implemented a cooking energy transition since 2016, with the aim of providing 95% of Indian households with access to LPG. However, most of the program's beneficiaries did not switch to clean energy as the primary fuel. The possible reasons include their easy access to free biomass and uncertain and irregular incomes (Mani et al., 2020).

Many studies have been conducted to explore households' selection of energy appliances and fuel types in developed countries (Ma, Yu, & Urban, 2018), such as Braun (2010) and Michelsen and Madlener (2013) in Germany; Gill et al. (2015) and Wasi and Carson (2013) in Australia; Goto, Goto, and Sueyoshi (2011) in Japan; Sopha, Klöckner, and Hertwich (2011) in Norway; and Dubin (1986) and Liao and Chang (2002) in the United States. The policy measures investigated included financial support, legislation, and renewable energy acts and certificates (Aydin & Brounen, 2019; Baiardi, 2020). The concerns typically pertained to energy efficiency and carbon emissions.

¹ Cleaner coal is clean briquette after washing and processing, with ash, sulfur, volatile, moisture, content being under 24%, 0.4%, 12%, and 4%, respectively, and calorific value being >5740 kcal. During combustion, the coal saving rate is over 20%, sulfide and toxic gases are reduced by 70%, and soot emission is reduced by over 80%.

In contrast, the energy transition literature in developing countries has focused on issues such as the welfare of lower-income groups (Kar et al., 2019), the well-being of women in rural areas (Shupler et al., 2021), climate change (Carter et al., 2020), pollution abatement, and energy conservation (Qin et al., 2017). Larger one-time subsidies and coercive measures are usually employed to ensure rapid project implementation, such as the conditional cash transfer program in Mexico (Gertler, Shelef, Wolfram, & Fuchs, 2016). With these measures, energy transition programs can be implemented rapidly in lower-income countries; however, there remain serious concerns about long-term sustainability.

Previous literature has pointed out that incentives (i.e., market-based tools, such as subsidies on new devices and taxes on disfavored energy) could be effective in promoting the adoption of energy transition programs; however, the effect has varied across cohorts and periods. For example, Chang, Lin, Leu, and Chung (2016) found that the Taiwanese government's subsidies for solar thermal systems since 2000 have effectively increased the total amount of installed solar power; however, these long-term subsidies have gradually lost their effectiveness. Mahapatra and Gustavsson (2008) found that government subsidies were significant factors for early adopters but had little effect on laggards. Dartanto (2013) suggested to gradually phase out energy subsidies because they are inefficient and worsen fiscal balances.

Regulations (i.e., command and control, such as administrative orders, standards, labeling, and bans) are controversial because of their high social costs, such as the welfare loss of the targeted group and other unintended consequences. Reyes, Schueftan, Ruiz, and González (2019) investigated the effects of the Air Pollution Management Plan in Chile, which required residents to replace old wood stoves and banned the use of firewood. They found that this policy aggravated energy poverty and social inequality, causing severe harm to low- and middle-income households. Wu, Zheng, Khanna, and Feng (2020) evaluated the effects of the mandatory coal replacement policies in northern China and found that the intervention contributed to an unintended shortage of gas in Hebei Province, reducing energy consumption and uncomfortably lowering indoor temperatures.

In addition to the energy transition policy itself, researchers have studied the implementation of policies, such as policy information dissemination and market strategies (Kumar et al., 2016; Orset, 2021), as well as the effects of equipment attributes (Kapoor & Dwivedi, 2020) and household characteristics (Li, Shan, Hernandez, Mallampalli, & Patiño-Echeverri, 2019; Mrówczyńska, Skiba, Bazan-Krzywoszańska, & Sztubecka, 2020) on promoting transitions.

Prior work on China's coal-to-gas or coal-to-electricity heating policy explored its environmental and economic impacts (Chen, Tan, & Xu, 2022), equipment and subsidy standards, spatial infrastructure distribution (Xu, Wang, Niu, & Ma, 2020; Yan et al., 2020), and household welfare and satisfaction (Liang, He, & Qiu, 2021; Xie & Zhou, 2021; Xu & Ge, 2020). However, limited by data availability, few studies have simultaneously conducted quantitative analyses of the enrolment rates and electricity use after adoption. In China's energy transition, considering the high cost of substitute energy, the low income of the targeted group, and the relatively low quality of rural houses, both coal substitution and the sustained use of clean energy could face challenges in the long term. Therefore, both of them need to be investigated to ensure the success of the energy transition.

3. China's household clean heating program

In Sep 2013, the State Council of China issued the *Air Pollution Prevention and Control Action Plan*, which proposed switching heating energy from dispersed coal to electricity and gas. It marked the launch of the HCH program in China, with Beijing being the first city to pilot it. In 2015, the program rolled out to the “2 + 4” cities in the Jing-Jin-Ji region, which includes Beijing (Jing), Tianjin (Jin), and four cities in Hebei province (Ji), the core area of air pollution prevention and control for Beijing. In December 2017, ten ministries and commissions issued the *Clean Heating Planning in Northern China (2017–2021)*, rolling out the project to the “2 + 26” cities along the Jing-Jin-Ji pollution transmission channel, including another 22 cities in Hebei, Shandong, Shanxi, and Henan provinces. In July 2018, the State Council issued and implemented the *Three-Year Action Plan for Winning the Blue Sky Defense War*. Afterwards, all provinces and local governments across the country issued comprehensive air pollution control plans. From 2017 to 2022, 63 pilot cities engaged in the HCH program (the four phases are shown in Appendix Table A1). The HCH program reduced dispersed coal consumption by approximately 10 million tons and eliminated over 56,000 small coal-fired boilers by the end of 2018 (China Power News, 2018). The average concentration of $PM_{2.5}$ in the Jing-Jin-Ji region during the heating season of 2019 was 33% lower than that in 2016, and the number of heavily polluted days was 52% lower (China Daily, 2020).

The HCH program was conducted through a top-to-bottom approach, one of its distinct features being its coercive nature. The central government initially proposed the program and its goals, which were then devolved to provinces and lower-level governments. When the task arrives at the county level, the National Development and Reform Commission and the local government jointly make a detailed implementation plan, considering local characteristics such as the fiscal capacity of the local government, household income in the villages, local infrastructure conditions, and the village's distance from downtown. The village leaders are responsible for ensuring the participation of villagers in the program through various measures. They announce and explain the program through village commission meetings, villager meetings, broadcasts, door-to-door visits, bulletin boards. They also ban coal vendors, impose penalties on coal consumption, and confiscate coal stoves.

Another distinct feature of the program is its large subsidies. The subsidies to households aim to make the transition affordable for villagers. Generally, local governments cover the cost of infrastructure construction (e.g., electricity grid upgrade, pipeline extension, and construction of facilities to dispense gas) and provide subsidies to households for equipment replacement and fuel costs (e.g.,

discounts on the price of electricity and gas). In this regard, support varies across villages in terms of source and amount. Generally, there are three levels of subsidies: municipal, district, and village,² provided by corresponding financial bureaus. Municipal support is uniform within a city, whereas district- and village-level offerings are based on the local government's fiscal capacity.

Based on the top-to-down approach, the HCH program achieved broad coverage. However, the effectiveness of coal reduction varied significantly across districts and villages. In some villages, a high proportion of residents refused to participate in the program. In some other villages, residents participated but still partially used coal for heating. It was reported that 15% of the households that adopted clean heating in four typical cities in the Jing-Jin-Ji region returned to using dispersed coal during the Spring Festival in 2020, and dispersed coal was still sold in some areas that banned household coal use (MEE, 2020). These phenomena highlight the importance of sustained usage of clean energy in energy transition programs.

4. Surveys and data

4.1. Village- and household-level surveys

The data used in this study were obtained from CRECS 2017 in Beijing, conducted by the Department of Energy Economics at Renmin University of China.³ CRECS-2017 Beijing focused on the HCH program and contained village- and household-level questionnaires. The village questionnaire collected information on (1) type of the HCH program implemented in the village (no program, coal-to-electricity, coal-to-gas, coal-to-cleaner coal); (2) if there was an HCH program, types and quantity of subsidies on heating equipment and substitute energy; and (3) channels of information dissemination, such as villager meetings, radio broadcasts, home visits, and bulletin boards. The household questionnaire collected information on (1) mandatory measures, such as the coal ban or stove confiscation; (2) household heating conditions, including equipment type, quantity, and fuel consumed; heating hours per day and heating months per household; and consumption of different types of energy before and after participating in the HCH program; and (3) household characteristics, including demographics (e.g., annual household income, number of household members, number of children, household head's age, education, occupation) and housing conditions (e.g., construction year, size of living area, insulation performance).

This study employed stratified sampling. First, according to Beijing Statistical Urban–Rural Classification Index, Beijing's villages were divided into six types, as shown in Table 1. Second, the sample sizes of these six village groups were determined, roughly following the ratio of the sample size to the total number of villages, which was 3918 to 200. Considering their representativeness, they were adjusted slightly to 40, 40, 20, 30, 20, and 50. Third, an isometric sampling method was used to sample the residents of the selected villages. On average, 20 households per village were randomly selected for the interviews. After excluding incomplete questionnaires, a sample of 3949 households from 200 villages was obtained.

For this study, we screened the full sample as follows. First, 395 households in the sample were connected to a central heating system, and 120 villages in the sample were not covered by the HCH program. As they did not have the choice of heating energy transition, they were excluded from the analysis. Second, Beijing's villages mainly chose *coal-to-electricity*, and very few chose *coal-to-gas* or *coal-to-cleaner coal*. Given the large differences between electricity and natural gas regarding equipment performance, energy price, and infrastructure requirements, we further excluded 78 households participating in the coal-to-gas transition. Consequently, we obtained a sample of 63 villages covered by the HCH program (hereinafter, this refers specifically to the *coal-to-electricity transition*) and 1172 households in these villages that were not connected to a central heating system.

4.2. Data

4.2.1. Participation and heating energy consumption

As both participation and sustained use of clean energy are essential for the program's success and the determinants of solid-fuel suspension differ from those of clean-fuel uptake (Carter et al., 2020), we investigated households' participation choice and the two-pronged energy transition (i.e., coal reduction and electricity increment).

Household interviewees reported their household-level participation choices. Although there were mandatory measures in the village, the participation rate, calculated as the number of households enrolled in the program divided by the total number of sampled households, was under 100%. Possible reasons include the fact that the enforcement of mandatory measures varied in villages, and that residents had different ways to avoid participating. The average participation rate of the full sample was 66%; only 38% of the villages enrolled all their residents; about 73% of the sampled villages had a participation rate above 50%; and 15% of the villages had no participants, even though the program was adopted at the village level. Details about the distribution of adoption rate see the Appendix Fig.A1.

² This scheme applies to municipalities (e.g., Beijing and Tianjin). Households in other areas generally receive subsidies at the province level; some receive subsidies at the municipal and district levels; and very few receive subsidies at the village level.

³ CRECS is an annual survey that has constructed a standardized, scientific, and demand-side-based micro database of household energy consumption in China since 2012. The first three topics covered by CRECS are committed to depicting the portrait of urban and rural household energy consumption nationwide. Then, it turns to investigate particular subjects such as the impact of the HCH program, climate change on the adaptive behavior of residents. The database includes over 56,000 samples as of February 2022. The shared online platform (<http://CRECS.ruc.edu.cn>) has supported researches from 15 countries, 182 institutions, and 1471 researchers worldwide.

Table 1
Administrative division of villages in Beijing.

First-order index	Urban					Rural	Total Number villages
Second-order index	Urban area		Town area			Rural area	
Third-order index	Main urban area	Urban-rural combined area	Township central area	Township-rural combined area	Special area	Rural village	
Number of villages	341	419	136	201	145	2676	3918

Coal reduction and electricity increment were calculated based on the information collected in the survey, wherein residents' heating energy consumption before and after the HCH program were obtained. Coal reduction (electricity increment) was calculated as the absolute amount of coal (electricity) consumption after the program minus the consumption before the program.⁴ For comparability across energy types, we converted the physical units of energy into units of standard kilogram coal equivalent (kgce) by multiplying by the corresponding conversion coefficient for heating.⁵ The average coal reduction amount was 0.78 tce (a ton of coal equivalent, which is one thousand kgce), accounting for 84% of coal consumption before the HCH program. Additionally, 45% of the households in the sample completely abandoned dispersed coal, while 5% reduced their use of coal by <20%. These households participated in the transition program and obtained electrical heating equipment but continued to use coal as the primary energy source for heating. This phenomenon indicates the importance of investigating the sustained use of substitute energy, in addition to the participation rate. From another perspective, how much electricity for heating is increased also illustrates the narratives of sustainability of the HCH program. On average, participants added 1.67 tce of electricity consumption to replace dispersed coal, which was nearly three times the electricity used for heating before the program. The distribution of the percent of coal reduction and electricity increment is shown in Appendix Fig.A2.

4.2.2. Influencing factors

The factors affecting household participation and energy-substitution decisions can be divided into three categories: policy implementation, energy and equipment attributes, and household characteristics. Table 2 summarizes and compares these factors between participants and non-participants.

4.2.2.1. Policy implementation. Policy variables included mandatory measures and channels for program information dissemination. In the sample, 97% (93%) of participants reported experiencing a coal ban (stove confiscation), whereas only 47% (26%) of non-participants reported the same experience. This implies that mandatory actions effectively increase the initial participation rate.

Policy dissemination methods in the HCH program included village meetings (*Meeting*), broadcasts (*Broadcast*), home visiting (*Visiting*), and bulletin boards (*Board*). According to interviews with village leaders, 43%, 29%, 40%, and 34% of the villages reported adopting the four information dissemination methods, respectively. Among the investigated villages, 97.3% used at least one method and 16.5% used two or more methods.

Subsidies are essential to policies. However, we did not explicitly include variables of subsidies because participants did not receive subsidies directly but faced price subsidies. Therefore, subsidies were included in the analysis as energy and equipment attributes, which are described as follows.

4.2.2.2. Energy and equipment attributes. Energy attributes included the change in households' heating cost (Δ energy cost) and coal price (Δ coal price). Δ energy cost was defined as the difference between energy cost (energy price multiplied by heating energy consumption) after and before the program. We found that the heating cost increased by an average of 2000 yuan. Meanwhile, 16% of households reported no change in heating costs after the program, while 2% said that the heating cost increased by over 5000 yuan, with electricity increment being triple that of the others. Δ coal price was calculated by weighting the different coal prices by the amount consumed by the household before the program. The household questionnaire collected information on the prices of various types of coal including bituminous coal balls, bituminous honeycomb coal, anthracite coal balls, anthracite honeycomb coal, and briquettes, which were 750, 800, 750, 800, and 700 yuan per ton in 2016; and 600, 685, 550, 600 and 600 yuan, respectively, in 2017.

⁴ To verify the reliability of the reported data, we compared the calculated actual energy consumption after the program with the reported data in Appendix Table A2. With data collected in the household questionnaire, actual energy consumption after the HCH program could be calculated according to the method introduced in the third chapter of the book "Household energy consumption in China: 2016 report." From Table A2, the reported and calculated heating energy consumption are similar. However, we did not have information to calculate energy consumption before the program, while the reported data could derive the desired variable (the change in households' heating energy). We therefore used the reported energy consumption rather than the calculated information.

⁵ The conversion coefficients (in a unit of kgce) for the heating energy of electricity, natural gas, bituminous coal ball, bituminous honeycomb coal, anthracite coal ball, anthracite honeycomb coal, and briquette are 0.294, 1.33, 0.357, 0.357, 0.4285, 0.4285, and 0.35715, respectively. The last five are represent coal of different qualities (NBS, 2017. China Energy Statistical Yearbook.

Table 2
Summary Statistics.

	Variables	Participants (n = 778) Mean(SD)	Non-participants (n = 394)	Difference
Dependent Variables				
Coal reduction	<i>Coal used before(tce)</i>	0.94(0.67)	1.10(0.62)	$p < 0.01^{***}$
	<i>Coal used after(tce)</i>	0.15(0.39)	0.98(0.58)	$p < 0.01^{***}$
Electricity increment	<i>Electricity used before (tce)</i>	0.85(0.75)	0.52(0.42)	$p < 0.01^{***}$
	<i>Electricity used after (tce)</i>	2.52(1.37)	0.54(0.77)	$p < 0.01^{***}$
Policy Implementation				
Mandatory measures	<i>Coal ban = 1 (%)</i>	0.97(0.17)	0.47(0.50)	$p < 0.01^{***}$
	<i>Stove confiscation = 1 (%)</i>	0.93(0.25)	0.26(0.44)	$p < 0.01^{***}$
	<i>Meeting = 1 (%)</i>	0.48(0.50)	0.32(0.47)	$p < 0.01^{***}$
Information dissemination	<i>Broadcast = 1 (%)</i>	0.39(0.49)	0.10(0.29)	$p < 0.01^{***}$
	<i>Visiting = 1 (%)</i>	0.44(0.49)	0.31(0.46)	$p < 0.01^{***}$
	<i>Board = 1 (%)</i>	0.38(0.49)	0.25(0.44)	$p < 0.01^{***}$
Energy and Equipment Attributes				
Cost	Δ <i>Energy cost(10³yuan)</i>	2.13(1.82)	–	–
	Δ <i>Coal price(10³yuan/t)</i>	–0.13 (0.05)	–0.14(0.03)	$p < 0.01^{***}$
	<i>Net equipment cost (10³yuan)</i>	3.73(1.90)	4.70(1.69)	$p < 0.01^{***}$
Use experience	<i>Clean = 1 (%)</i>	8.26(1.80)	–	–
	<i>Safe = 1 (%)</i>	7.50(1.72)	–	–
	<i>Convenient = 1 (%)</i>	7.58(1.74)	–	–
Household Characteristics				
Demographics	<i>Income (ten thousand yuan)</i>	7.32 (4.44)	6.30 (4.13)	$p < 0.01^{***}$
	<i>Members</i>	3.53(1.66)	3.64(1.81)	$p = 0.322$
	<i>Children</i>	0.48(0.67)	0.46(0.73)	$p = 0.795$
	<i>Age (year)</i>	58.00(12.50)	55.12(12.97)	$p < 0.01^{***}$
Housing	<i>House area(m²)</i>	157.80(66.56)	134.34(61.08)	$p < 0.01^{***}$
	<i>House age (year)</i>	17.3(10.77)	20.3(10.38)	$p < 0.01^{***}$

Each independent variable is compared between participants and non-participants. For the interval, nominal, and ordinal data types, we used the analysis of variance, Pearson's chi-square, and Mann-Whitney U methods, respectively to test the significance of within-group differences. Some variables are only reported by participants, such as energy cost changes and user experience.

It was found that the average cost decrease was 133 yuan.

Equipment attributes included net equipment costs incurred by households and households' experience of using clean heating devices. The net equipment cost is equal to the market price minus the equipment subsidy. Generally, households in the program had multiple choices of clean heating equipment, including direct electric heating, regenerative electric heating, and air-source heat pumps. Detailed information on the equipment market price and net equipment cost was obtained from a survey of village leaders. In the household survey, we asked participants about the type of clean heating equipment they use. For non-participants, we used the average price of the three equipment types in the village as their expected net equipment cost if they chose to participate. The average net equipment cost was 4053 yuan, which was approximately 19% of the market price. This highlights the provision of large subsidies in the clean heating program.

The participants' usage experience was measured on a 10-point scale of subjective evaluations of cleanliness, safety, and convenience of the clean heating device (*Clean, Safe, Convenient*). The three indices had a score of 7–8 points on average, indicating relatively high satisfaction with the clean heating devices.

4.2.2.3. Household characteristics. Household characteristics include demographics and housing characteristics. [Barrington-Leigh et al. \(2019\)](#) surveyed the implementation of the HCH program in the areas surrounding Beijing and found that coal substitution was significantly lower in less affluent districts. We found evidence that average income of participants is 1.02 ten thousand yuan higher than the non-participants, which means less affluent households are less likely to adopt clean transition program. This raises concerns regarding the affordability and satisfaction of lower-income groups during the cleaning-heating transition. Besides, the number of household members and children is not significant different between participants and non-participants, and age of household head is about 55–58 years old.

5. Empirical analysis and results

We conducted an econometric analysis of households' participation choices and the effectiveness of participation, as reflected through coal reduction and electricity increment one year after the implementation of the HCH program.

5.1. Participation

The empirical model is defined as follows:

$$p_{PARTI} = E(PARTI_i) = \Lambda(\beta_1 + \beta_2 \mathbf{MAND}_i + \beta_3 \mathbf{INFO}_i + \beta_4 \mathbf{EQUIP}_i + \beta_5 \mathbf{HH}_i + \varepsilon_i) \tag{1}$$

where $PARTI_i$ equals 1 if household i participates in the program, and 0 otherwise. Given that the dependent variable was a dummy, we chose the logit model over the linear probability model shown in Eq. (1). $\Lambda(\cdot)$ is a transformation function of the logit model. \mathbf{MAND}_i is the vector of mandatory measure variables, including coal bans and stove confiscation. \mathbf{INFO}_i is the vector of policy dissemination variables, including villagers' meetings, broadcasts, home visits, and bulletin boards. \mathbf{EQUIP}_i is the variable of net equipment costs. \mathbf{HH}_i is the vector of demographic and housing characteristics.

The marginal effect of a one-unit change in the explanatory variable on the probability of participation is:

$$\frac{\partial p}{\partial x_j} = \frac{\partial \Lambda(\mathbf{x}\boldsymbol{\beta})}{\partial \mathbf{x}\boldsymbol{\beta}} \bullet \frac{\partial \mathbf{x}\boldsymbol{\beta}}{\partial x_j} = \Lambda'(\mathbf{x}\boldsymbol{\beta}) \bullet \beta_j \tag{2}$$

Table 3 summarizes the estimated marginal effects. In the first three columns, we add three categories of explanatory variables, one for each column. Village dummies are added in Column 4 to control for the unobservable village characteristics that influence program penetration, such as local governance and culture background. As mandatory measures and policy dissemination methods are the same for all residents in the village, their effects are absorbed in the village dummies; therefore, we consider Column 4 as a robustness check and Column 3 as the main results.

The regression results show that mandates and interactive information dissemination promote adoption of the HCH program. Additionally, coal bans and stove confiscation increase participation by 7.0 and 30.1 percentage points, respectively. These two

Table 3
Regression results of participation.

	(1)	(2)	(3)	(4)
	Logit	Logit	Logit	Logit
Coal bans	0.073** (0.033)	0.069** (0.030)	0.070** (0.030)	
Stove confiscation	0.340*** (0.023)	0.321*** (0.019)	0.301*** (0.020)	
Meetings	0.145*** (0.026)	0.125*** (0.021)	0.095*** (0.021)	
Broadcast	0.161*** (0.030)	0.169*** (0.029)	0.165*** (0.029)	
Visits	0.113*** (0.026)	0.083*** (0.023)	0.072*** (0.021)	
Boards	0.055** (0.028)	0.072*** (0.023)	0.058*** (0.022)	
Net equipment cost		-0.038*** (0.006)	-0.038*** (0.006)	-0.043*** (0.013)
Income			0.005** (0.002)	0.009** (0.004)
Members			-0.001 (0.008)	0.011 (0.012)
Children			0.003 (0.019)	0.009 (0.025)
Head age			0.003*** (0.001)	0.006*** (0.001)
House area			0.000** (0.000)	0.000* (0.000)
House age			-0.012 (0.008)	-0.059*** (0.017)
N	1172	1172	1172	547
p_correctly classified	88.14%	89.59%	89.25%	83.00%
Log Likelihood	-398	-370.1	-348.1	-193.7
LR Chi2	325.4	316.8	311.6	178.4
Pseudo R-squared	0.468	0.505	0.535	0.473

A logit model was adopted, and the marginal effect is reported in the table. Robust standard errors are shown in parentheses. *, **, and *** indicate $p < 0.1$, $p < 0.05$, and $p < 0.01$, respectively.

measures are imposed on suppliers and users, respectively, with the latter having a greater effect. Moreover, delivering policy information through village meetings, broadcasts, home visits, and bulletin boards improves adoption by 9.5, 16.5, 7.2, and 5.8 percentage points, respectively. Compared with posting policies on bulletin boards, increasing information interaction and information exposure have a more significant effect on improving policy penetration.

The results also show that net equipment costs inhibit participation significantly; however, the magnitude is not economically significant. For every 1000 yuan increase (24.7%) in the equipment price, participation decreases by 3.8 percentage points. By contrast, Hesselink and Chappin (2019) identified the initial installation cost as a significant innovation barrier. The low magnitude in our study is probably attributable to the large subsidies, which cover 80.6% of the market price, and the relatively low net equipment cost, which greatly reduces entry obstacles.

Household demographics and characteristics are the inner forces driving heating fuel transition (Chen et al., 2016). Prior research has found that household income positively affects the adoption of high-efficiency technologies (Baldini, Trivella, & Wentz, 2018; Ma et al., 2018; Wang, Li, Cui, Liu, & Cai, 2019). Similarly, our results show that the participation of the lower income households is 0.5 percentage lower than wealthier group. Pachauri (2019) argued that policies encouraging the adoption of alternative energy faces significant difficulties in targeting lower-income groups; thus, focusing more on lower-income groups in rural energy transition is essential for a just and sustainable transition.

Table 4
Regression results of coal suspension and electricity increment.

	Coal reduction amount				Electricity increment amount			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
<i>Coal ban</i>	0.439*** (0.114)	0.115 (0.085)	0.108 (0.087)		0.326 (0.281)	-0.114 (0.255)	-0.060 (0.257)	
<i>Stove confiscation</i>	0.017 (0.076)	0.020 (0.057)	0.016 (0.057)		0.244 (0.188)	0.249 (0.170)	0.235 (0.170)	
Δ heating cost		-0.037*** (0.008)	-0.037*** (0.008)	-0.006 (0.007)		-0.040* (0.023)	-0.042* (0.022)	-0.042** (0.021)
Δ coal price		0.553*** (0.045)	0.567*** (0.045)	0.706*** (0.075)		0.384*** (0.135)	0.443*** (0.135)	0.565** (0.222)
<i>Net equipment cost</i>		0.015 (0.016)	0.014 (0.016)	0.003 (0.006)		0.010 (0.018)	0.009 (0.018)	0.026 (0.019)
<i>Clean</i>		0.059*** (0.009)	0.058*** (0.009)	0.059*** (0.008)		0.103*** (0.026)	0.099*** (0.026)	0.072*** (0.024)
<i>Safe</i>		0.016 (0.011)	0.016 (0.011)	0.019** (0.009)		0.038 (0.032)	0.039 (0.032)	0.044 (0.027)
<i>Convenient</i>		0.021** (0.011)	0.020* (0.011)	0.009 (0.009)		0.153*** (0.033)	0.150*** (0.032)	0.118*** (0.027)
<i>Income</i>			0.002 (0.003)	0.001 (0.002)			0.010 (0.008)	0.007 (0.007)
<i>Members</i>			0.026*** (0.009)	0.005 (0.008)			0.117*** (0.027)	0.070*** (0.023)
<i>Children</i>			-0.032 (0.022)	-0.011 (0.019)			-0.138** (0.066)	-0.087 (0.055)
<i>Head age</i>			0.0004 (0.001)	0.0002 (0.001)			0.003 (0.003)	0.0003 (0.002)
<i>House area</i>			0.0001 (0.0002)	-0.00003 (0.0002)			-0.0003 (0.001)	0.001 (0.0005)
<i>House age</i>			-0.001 (0.001)	-0.001 (0.001)			-0.002 (0.003)	-0.003 (0.003)
<i>Constant</i>	-0.015 (0.096)	-0.466*** (0.100)	-0.550*** (0.118)	0.119 (0.127)	0.845*** (0.231)	-1.319*** (0.307)	-1.735*** (0.357)	-0.981** (0.386)
<i>Coal used before</i>	Control	Control	Control	Control	Control	Control	Control	Control
<i>Village Dummies</i>	Control	Control	Control	Control	Control	Control	Control	Control
Observations	778	778	778	778	778	778	778	778
R ²	0.397	0.674	0.679	0.812	0.060	0.251	0.272	0.573

A multiple linear regression model was used. Robust standard errors are shown in parentheses. *, **, and *** indicate $p < 0.1$, $p < 0.05$, and $p < 0.01$, respectively.

5.2. Sustainability

We further analyzed the suspension of solid coal and the sustainable use of electricity, conditional on participation. We employed a multiple linear regression, defined as follows:

$$Energy_i = \gamma_0 + \gamma_1 MAND_i + \gamma_2 ENER_i + \gamma_3 EQUIP_i + \gamma_4 FEEL_i + \gamma_5 HH_i + \varepsilon_i \quad (3)$$

where $Energy_i$ denotes the amount and rate of coal reduction and electricity increment, and $ENER_i$ is the energy attribute that includes the change in household heating cost and the change in coal price. $FEEL_i$ represents a subjective evaluation of cleanliness, including cleanliness, safety, and convenience of a clean heating device.

As shown in Eqs. (1) and (3), the factors affecting participation and sustainability differ. Information dissemination methods $INFO_i$ are expected to have an effect on program participation but not on the sustained use of clean energy conditional on participation. Meanwhile, $ENER_i$ and $FEEL_i$ are expected to affect energy consumption conditional on participation (Hirst & Brown, 1990; Xie & Zhou, 2021), but not the participation decision because energy cost and use experience are only observed after participation.

The regression results are shown in Table 4. The rate of change was also examined, and the results are summarized in Table A3. Based on the estimation results, the mandates do not promote the sustained use of clean energy. Additionally, neither the coal ban nor stove confiscation increases coal reduction or electricity consumption. This finding rationalizes the concerns about the effectiveness of coercive measures. There is strong evidence in the literature that mandatory standards perform poorly in the long term (Abrahamse, Steg, Vlek, & Rothengatter, 2005).

We also find that the higher cost of clean heating and unexpected decrease in coal prices weaken the transition progress.⁶ As shown in Table 4, a 1000 yuan (1.7-fold) increase in energy cost reduces the amount of coal reduction by 37 kgce (equivalent to 87–104 kg) while reducing the electricity increment by 42 kgce (equivalent to 142 kWh). Moreover, for every 100 yuan (17%) decrease in the price of coal per ton, coal consumption decreases by 56.7 kgce, and electricity increases by 44.3 kgce. Furthermore, the effect of net equipment costs is not significant. One possible reason is that after participating in the program, equipment costs become sunk costs that no longer influence residents' later decisions.

In addition, the findings show that a better experience with clean heating mitigate the aforementioned negative impacts and increase coal reduction. Specifically, a good experience with clean heating increases the coal reduction by about 1.6 kgce (*Safe*) to 5.8 kgce (*Clean*) or increases the electricity consumption by 3.9 kgce (*Safe*) to 15 kgce (*Convenient*). This is consistent with the findings of Fujimi, Kajitani, and Chang (2016), who studied household energy-saving behaviors after natural disasters and electricity shortages in Japan and highlighted that only measures that did not require frequent efforts or could be implemented with slight discomfort tended to be persistent.

Regarding household characteristics, we found that income does not have a significant impact on promoting energy transition. We observed no significant difference between households with different income in terms of coal reduction or electricity increment. It highlights the fact that equipment purchasing is the main obstacle to energy inequality. Therefore, the starting point for reducing energy inequality should be to increase access to high-efficient equipment. In addition, the results show that the larger the family size and the more the number of children, the more coal consumption is reduced, both in terms of quantity and rate. A possible explanation is that clean equipment dramatically reduces the hassle of coal balls and removes ash, which is more pronounced in households with more members.

6. Conclusions and policy implications

Household energy transition is crucial for reducing inequality, decreasing air pollutant, and increasing household welfare. In this regard, the success of a program that aims to promote household energy transition depends not only on household participation but also on the sustained use of substitute energy. However, the policy has faced challenges including reburning coal for heating and the high cost of electricity compared to coal. This study investigated the factors that affect participation and energy use in the HCH program in rural areas of Northern China.

Our findings indicate that policy measures and effective dissemination of policy information significantly improve the likelihood of participation in the HCH program. However, lower-income households are less likely to participate, highlighting the need to address the affordability of clean energy. We also found that mandatory measures can help with the adoption of clean heating but cannot reduce coal consumption or promote the sustained use of clean energy. Instead, improving the user experience of using clean heating is essential for ensuring coal reduction and clean energy transition.

The long-term effects of compulsory and economic measures are also a concern. Residents who did not benefit from the program were more likely to return to burning coal after regulations were relaxed. Furthermore, depending on subsidies is not a sustainable solution, as providing large subsidies imposes tremendous financial pressures on local governments. Therefore, it is necessary to provide incentives to improve the sustainability of policy effects. Providing appropriate information dissemination channels, especially active communication, has been shown to improve consumer acceptance of high-efficiency equipment.

⁶ As households may have a more intuitive impression about the price of the largest consumed coal type, we reconstructed the measurement of Δ coal price with the price change of the largest consumed coal type before the program and used it as a robustness check. Results are shown in Appendix Table A4.

To improve the sustainability of clean energy transition program, it is essential to reduce the cost of energy transition, particularly for lower-income households. Gradual implementation of clean heating programs can be effective, with higher-income areas being the first to implement such programs. In areas with lower incomes and greater heating needs, clean coal can be used as transitional program until transition costs decrease as technology advances. Finally, improving user satisfaction is essential for the sustained use of clean energy. Therefore, strengthening market supervision to ensure a positive user experience of clean energy could be helpful.

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CRedit authorship contribution statement

Manyu Wang: Methodology, Software, Data curation, Visualization, Writing – original draft. **Lunyu Xie:** Conceptualization, Investigation, Supervision, Writing – review & editing.

Declaration of Competing Interest

This manuscript has not been published or presented elsewhere in part or in its entirety and is not under consideration by another journal. All study participants provided informed consent, and the study design was approved by the appropriate ethics review board. We have read and understood your journal's policies, and we believe that neither the manuscript nor the study violates any of these.

Data availability

Data will be made available on request.

Appendix A. Appendix

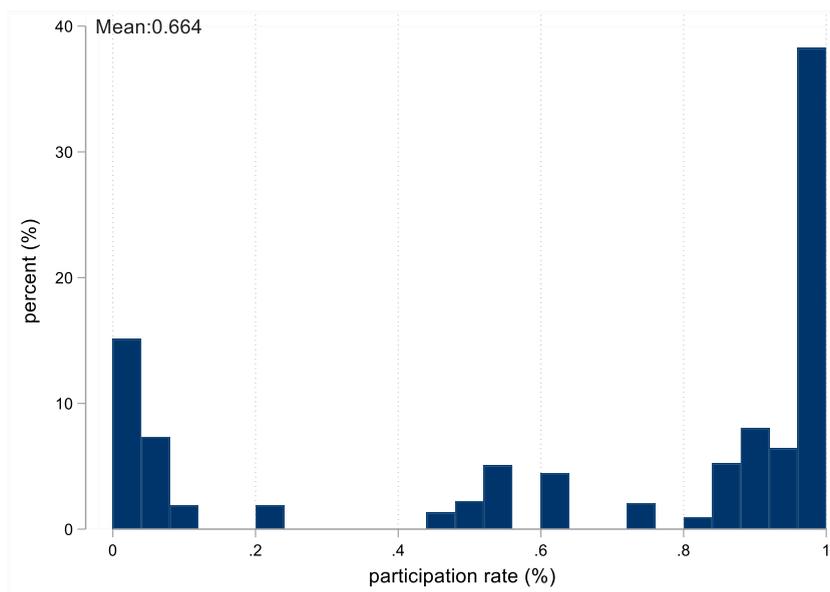


Fig. A1 Distribution of participation rate at the village level.

The village-level participation rate was calculated as the number of participating households in the sample divided by the total number of sampled households in the village.

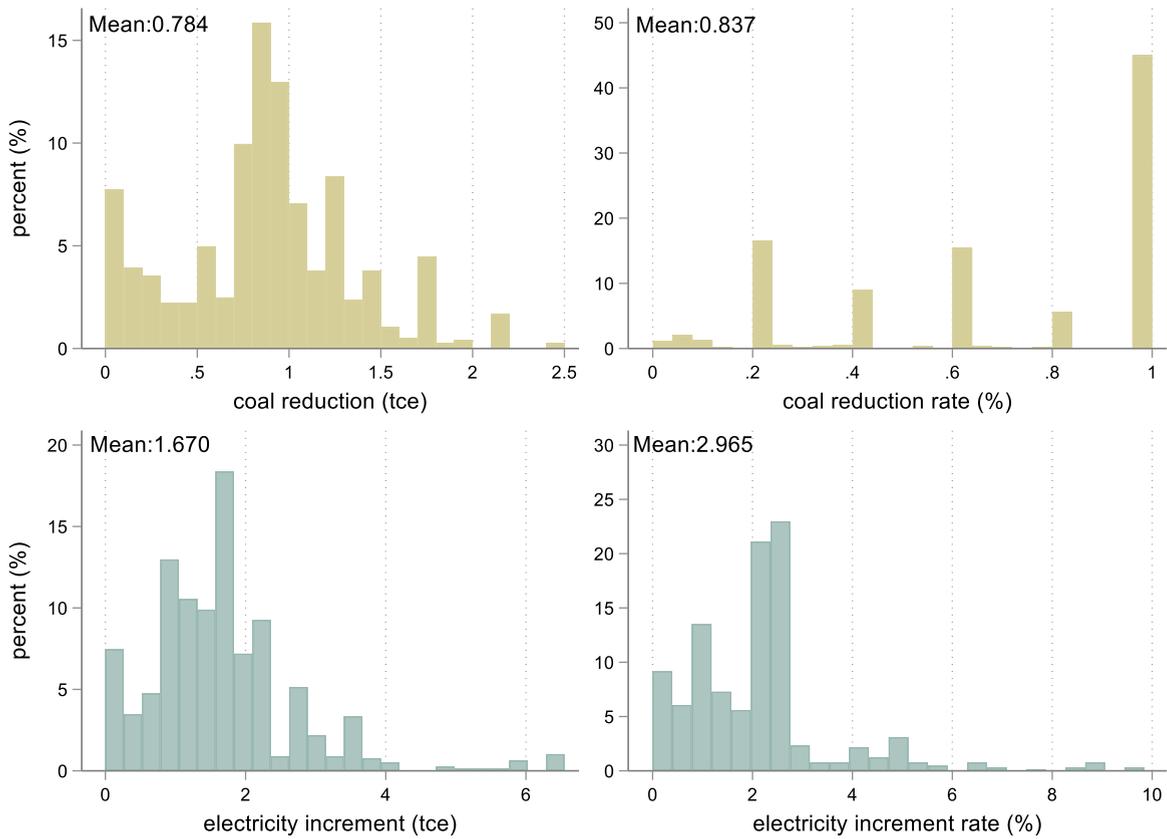


Fig. A2 Distribution of coal reduction and electricity increment for participants. The coal reduction rate was estimated as post-program coal consumption divided by previous consumption. The electricity increment rate was calculated similarly. The sample size of the first three plots was 778, and that of the fourth plot was 688 because 90 households did not consume electricity for heating before the program.

Table A1. Process of China's household clean heating program.

The first pilot: 12 cities (2017.4–2020.4)	The second pilot: 23 cities (2019.4–2021.4)	The third pilot: 8 cities (2020.4–2022.4)	The fourth pilot: 20 cities (2021.-)
Tianjin*	Hebei: Handan*, Xingtai*, Zhangjiakou, Cangzhou*	Hebei: Dingzhou, Xinji	Shandong: Yantai, Taian, Weifang
Hebei: Shijiazhuang*, Tangshan*, Baoding*, Langfang*, Hengshui*	Shanxi: Yangquan*, Changzhi*, Jincheng*, Yuncheng, Linfen, Lvliang	Henan: Sanmenxia, Jiyuan	Shanxi: Yizhou, Datong, Shuozhou
Shanxi: Taiyuan*	Shandong: Zibo*, Jining*, Dezhou*, Liaocheng*, Binzhou*, Heze*	Shaanxi: Tongchuan, Weinan, Baoji, Yangling	Hebei: Chengde, Qinhuangdao
Shandong: Jinan*	Henan: Luoyang*, Anyang*, Jiaozuo*, Puyang*		Henan: Xuchang
Henan: Zhengzhou*, Kaifeng*, Hebi*, Xinxiang*	Shaanxi: Xian, Xianyang		Shaanxi: Yunlin, Yan'an
			Beijing
			Liaoning: Fuxin
			Heilongjiang: Jiamusi
			Neimenggu: Baotou
			Qinghai: Haixi
			Xinjiang: Urumchi
			Jilin: Liaoyuan
			Gansu: Lanzhou
			Ningxia: Wuzhong

By 2017, Beijing had achieved coal-free development in the districts of Chaoyang, Haidian, Fengtai, Shijingshan, Tongzhou, Fangshan, and Daxing. In 2022, Beijing launched the second round of reform, proposing to “steadily and orderly promote the transition of coal to electricity in mountainous areas.” * indicates cities that belong to the “2 + 26” cities along the Jing-Jin-Ji pollution transmission channel.

Table A2. Comparisons of post-program reported and calculated energy consumption.

	Calculated (n = 778)	Reported (n = 778)	P-value
	mean(SD)	mean(SD)	
Coal (kgce)	0.11 (0.56)	0.15 (0.39)	0.058
Electricity (kgce)	2.38 (1.18)	2.52 (1.37)	0.112

Table A3. Regression results for coal suspension rate and electricity increment rate.

	Coal reduction rate				Electricity increment rate			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
<i>Coal ban</i>	0.267*** (0.084)	0.011 (0.052)	-0.001 (0.052)		0.294 (1.346)	-1.556 (1.231)	-1.108 (1.242)	
<i>Stove confiscation</i>	-0.007 (0.056)	0.039 (0.035)	0.044 (0.035)		1.374 (0.968)	1.582* (0.885)	1.557* (0.886)	
Δ heating cost		-0.047*** (0.005)	-0.047*** (0.005)	-0.039*** (0.005)		-0.034 (0.108)	-0.025 (0.107)	-0.044 (0.113)
Δ coal price		0.230*** (0.027)	0.237*** (0.027)	0.403*** (0.047)		1.269** (0.645)	1.453** (0.650)	0.181 (1.236)
<i>Net equipment cost</i>		0.005 (0.004)	0.006 (0.004)	0.006 (0.004)		-0.075 (0.089)	-0.075 (0.090)	0.005 (0.103)
<i>Clean</i>		0.097*** (0.006)	0.097*** (0.006)	0.086*** (0.005)		0.079 (0.130)	0.045 (0.131)	0.127 (0.132)
<i>Safe</i>		0.016** (0.007)	0.016** (0.007)	0.009 (0.006)		0.585*** (0.166)	0.598*** (0.167)	0.625*** (0.155)
<i>Convenient</i>		0.009 (0.007)	0.010 (0.007)	0.005 (0.006)		0.531*** (0.168)	0.538*** (0.169)	0.490*** (0.156)
<i>Income</i>			0.003 (0.002)	0.004** (0.002)			0.036 (0.040)	0.032 (0.039)
<i>Members</i>			0.022*** (0.006)	0.010* (0.005)			0.433*** (0.132)	0.148 (0.124)
<i>Children</i>			-0.036*** (0.013)	-0.014 (0.012)			-0.124 (0.320)	0.345 (0.295)
<i>Head age</i>			0.00000 (0.001)	-0.001 (0.0005)			0.0004 (0.014)	-0.012 (0.013)
<i>House area</i>			0.0001 (0.0001)	0.0001 (0.0001)			-0.002 (0.003)	0.001 (0.003)
<i>House age</i>			-0.001** (0.001)	-0.001** (0.001)			0.004 (0.016)	0.003 (0.015)
<i>Constant</i>	0.264*** (0.071)	-0.111* (0.061)	-0.141** (0.071)	-0.006 (0.080)	3.885*** (1.064)	-4.307*** (1.459)	-5.689*** (1.739)	-5.566*** (2.062)
<i>Coal used before</i>	Control	Control	Control	Control	Control	Control	Control	Control
<i>Village Dummies</i>				Control				Control
<i>Observations</i>	778	778	778	778	688	688	688	688
<i>R²</i>	0.124	0.678	0.688	0.802	0.111	0.277	0.293	0.501

A multiple linear regression model is employed. Robust standard errors are shown in parentheses. *, **, and *** indicate $p < 0.1$, $p < 0.05$, and $p < 0.01$, respectively. For households that did not use electricity for heating before the HCH program, the electricity increment rate is missing; therefore, we have 688 observations rather than 778 for the rate regressions.

Table A4 Robustness check by substituting the coal price variable.

	Coal reduction amount	Coal reduction rate	Electricity increment amount	Electricity increment rate
	(1)	(2)	(3)	(4)
<i>Coal ban</i>	0.163 (0.193)	0.030 (0.054)	0.060 (0.254)	-0.576 (1.230)
<i>Stove confiscation</i>	0.126 (0.161)	0.072 (0.136)	0.244 (0.168)	1.426 (0.875)
Δ heating cost	-0.061*** (0.008)	-0.055*** (0.005)	0.029 (0.022)	-0.050 (0.104)
Δ coal price	2.235*** (0.384)	0.821*** (0.225)	4.919*** (1.025)	22.401*** (5.217)
<i>Net equipment cost</i>	0.0003 (0.007)	0.006 (0.004)	0.002 (0.018)	-0.032 (0.089)
<i>Clean</i>	0.107*** (0.009)	0.111*** (0.005)	0.100*** (0.025)	0.035 (0.126)
<i>Safe</i>	0.020* (0.012)	0.016** (0.007)	0.045 (0.032)	0.636*** (0.166)
<i>Convenient</i>	0.028** (0.012)	0.003 (0.007)	0.174*** (0.032)	0.606*** (0.166)
<i>Income</i>	0.0002	0.003*	0.010	0.029

(continued on next page)

(continued)

	Coal reduction amount	Coal reduction rate	Electricity increment amount	Electricity increment rate
	(1)	(2)	(3)	(4)
<i>Members</i>	(0.003) 0.015	(0.002) 0.018***	(0.008) 0.103***	(0.039) 0.379***
<i>Children</i>	(0.010) 0.001	(0.006) −0.028**	(0.027) −0.128*	(0.130) −0.125
<i>Head age</i>	(0.024) 0.0003	(0.014) −0.0002	(0.065) 0.003	(0.316) −0.003
<i>House area</i>	(0.001) −0.0001	(0.001) 0.0001	(0.003) −0.0003	(0.013) −0.002
<i>House age</i>	(0.0002) −0.002*	(0.0001) −0.002***	(0.001) −0.003	(0.003) 0.002
<i>Constant</i>	(0.001) −0.336**	(0.001) −0.264***	(0.003) −2.425***	(0.016) −8.626***
	(0.135)	(0.079)	(0.376)	(1.821)
<i>Coal used before</i>	Control	Control	Control	Control
<i>Village fixed effect</i>				
<i>Observations</i>	778	778	778	688
<i>R²</i>	0.629	0.662	0.284	0.307

A multiple linear regression model is employed. Δ coal price is now defined as the price change of the household' largest consumed coal type before the program instead of the weighted price. Robust standard errors are shown in parentheses. *, **, and *** indicate $p < 0.1$, $p < 0.05$, and $p < 0.01$, respectively.

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