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Energy Transition's Technical Pathways, Risks, and Equity—Article

Heterogeneous Household Responses and Indoor Temperature Inequality in the Clean Heating Transition

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ABSTRACT

The residential clean heating transition has proven effective in reducing air pollution and improving public health. However, most research to date has focused on its economic and environmental implications, with limited attention being paid to household behavioral responses and heating experiences. To address this gap, we conducted household surveys in Linfen, a city in northern China, and analyzed residents' self-reported indoor temperatures, heating costs, and heated areas before and after the transition. The results reveal substantial disparities across clean heating pathways. Compared with households that are continuing to use coal or biomass, those switching to gas experienced a 1.7 °C drop in indoor temperature and an annual cost increase of 1318.2 CNY, suggesting energy-limiting behaviors in response to higher expenses. In contrast, households adopting electric heating reported a 1.2 °C temperature increase without a significant rise in costs. Further analysis using the Gini coefficient and Oshima index shows that indoor temperature inequality increased among coal-to-gas households, while no such trend was observed among coal-to-electricity households. These findings highlight the importance of incorporating behavioral responses and thermal equity into the design of clean heating strategies.

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1. Introduction

The transition to clean energy for residential heating is a vital strategy for reducing air pollution, mitigating climate change, improving public health, and ensuring access to affordable, reliable, and sustainable energy [1–5]. This strategy is particularly essential in northern China, where the need to address both winter heating and air quality improvement persists [6]. In 2017, China issued the "Winter Clean Heating Plan for Northern Regions (2017–2021)," urging local governments to adopt clean energy solutions suited to local conditions. In the same year, the Ministry of Finance of the People's Republic of China, in collaboration with three other ministries, launched a pilot program to support winter clean heating across northern China. Pilot regions were selected through a competitive review process, accompanied by targeted subsidies and regulatory mandates to reduce residential coal use [7–9]. By the end of 2023, 88 cities and regions had been selected as pilot sites. In addition to the large-scale, government-led transitions in pilot regions, some residents, motivated by considerations of convenience and cleanliness, have also voluntarily engaged in the transition, thereby fostering the broader adoption of clean heating solutions.

As the clean heating transition progresses, its economic costs, along with its environmental and health benefits, have received widespread attention [10–16]. On the cost side, numerous studies have analyzed changes in household energy expenditures before and after the transition, highlighting a "green premium" associated with clean energy compared with coal-based heating [17,18]. Increasing attention has also been given to the unequal distribution of this energy burden across different population groups and the potential intensification of energy poverty [19]. For example, using the threshold where the ratio of heating expenditure to income exceeds twice the median ratio to define energy poverty, Xie et al. [20] reported that the energy poverty rate among rural

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households in Hebei Province (China) rose from 21% to 36% following the transition. On the benefit side, studies have highlighted the considerable environmental and health gains of clean heating. Chen et al. [21] assessed clean heating policies in northern China between 2014 and 2021, finding a 14% reduction in annual per capita carbon emissions and an 8% decrease in the air quality index. Zhou et al. [12] projected that, by 2030, the population-weighted average concentration of particulate matter with a diameter of 2.5 μm or less ($PM_{2.5}$) in cities along the Beijing–Tianjin–Hebei air pollution transmission corridor would fall by 13–15 $\mu g \cdot m^{-3}$ relative to 2015 levels, potentially preventing up to 81 400 premature deaths from non-communicable diseases (NCDs) and lower respiratory infections (LRIs). These cost–benefit assessments provide a critical foundation for local governments in shaping clean heating transition strategies, technology selection, and subsidy policy design [22–25].

However, a critical yet often overlooked aspect of the clean heating transition is how households respond behaviorally and how these responses shape their heating experiences. Households often balance the marginal costs and perceived benefits of heating, leading to substantial variation in winter thermostat settings [26]. This trade-off may shift after the transition, as households adjust to changes in energy prices, heating system efficiency, and subsidy policies [27,28]. For example, the green premium of clean energy relative to traditional coal or biomass in China can raise household energy expenditures, potentially exacerbating energy insecurity or prompting energy-limiting behaviors such as reducing consumption to ease financial strain [29–33]. Higher thermal efficiency in clean heating systems [34] may improve heating performance [35,36], while also increasing the potential for rebound effects in energy use [37]. These combined effects make post-transition heating experiences highly context-dependent. Moreover, the impacts are not evenly distributed [38]: Lower-income households may face greater energy insecurity and dissatisfaction, while wealthier households are more likely to enjoy warmer indoor temperatures and greater subjective well-being [25,39]. Understanding behavioral responses to the transition—and the uneven heating experiences across population groups—is critical for fostering a just transition and advancing energy equity [40–42].

We conducted household surveys targeting households with individual heating systems to collect firsthand data on behavioral responses and heating experiences in the context of the clean heating transition. Specifically, we compared self-reported winter indoor temperatures, heated areas, and heating costs before and after the transition, and examined differences across households adopting distinct technological pathways. Unlike households with centralized heating, those with individual systems have greater autonomy over indoor temperature and heating scope, enabling clearer insights into behavioral responses through these indicators. The analysis rests on two key assumptions. First, in the absence of economic constraints, individuals' preferences for indoor temperature remain stable before and after the transition. Second, when households have full control over their indoor climate and must weigh the marginal benefit of thermal comfort against the marginal cost of energy use, a higher indoor temperature serves as a proxy for a more comfortable thermal environment during winter.

The surveys were conducted in Linfen, a city in northern China selected for three main reasons. First, Linfen is located in a cold region where the minimum average outdoor temperatures during the winter range from −12 to 3 °C, making household heating essential for maintaining indoor thermal comfort. Second, in response to the urgent need to tackle air pollution [43], Linfen was included in the second batch of national clean heating pilot cities in 2018 and has actively promoted the transition ever since. Thus, it provides a useful case through which the broader implementation of the clean heating transition across China's pilot regions can be understood. Third, Linfen has implemented a variety of transition pathways, whereas some areas have yet to undergo transition [44]. This diversity provides a solid empirical foundation for comparative analysis.

Our findings show that, relative to households that continued using coal or biomass for heating, households transitioning from coal to gas in Linfen experienced a significant decrease in indoor temperature of approximately 1.7 °C, while their annual heating expenditures increased by about 1318.2 CNY, resulting in a "costlier and colder" outcome. This finding suggests that coal-to-gas households, particularly those facing financial constraints, may have sacrificed thermal comfort to manage higher energy costs. In contrast, households that switched from coal to electricity experienced a modest increase in indoor temperature of approximately 1.2 °C, without a significant rise in heating expenditures. This improvement may reflect a rebound effect, driven by subsidized electricity prices and the greater efficiency of electric heating systems. Further analysis using the Gini coefficient and the Oshima index reveals that indoor temperature inequality increased among coal-to-gas households, while no similar trend was observed among coal-to-electricity or non-transitioned households. These findings underscore the importance of accounting for heterogeneous household responses and thermal equity in clean heating transitions, offering critical insights for designing more equitable and effective clean heating policies and for optimizing transition pathways.

2. Material and methods

2.1. Survey design, sampling, and implementation

The household survey was conducted in May 2024, covering 1212 self-heating households in Linfen, Shanxi Province. After data cleaning and verification, a total of 1123 valid questionnaires were retained. A stratified sampling method was adopted for household sample selection. First, six areas in Linfen, including a district, a county-level city, and several counties—namely, Yaodu District, Huozhou City, Xiangning County, Xiangfen County, Hongtong County, and Quwo County—were selected as primary sampling units (PSUs), based on differences in the extent of clean heating adoption, transition pathways, and levels of economic development. Second, 30 townships and towns were selected from these areas, considering their geographic distance from the urban core, progress in the clean heating transition, and socioeconomic development levels. Finally, at least six households were selected from each township as sample households.

The survey combined face-to-face and online methods. For the face-to-face interviews, sample households were randomly selected from the townships and towns. A total of 129 valid interviews were conducted by trained surveyors, mostly graduate and PhD students from Tsinghua University and China University of Petroleum (Beijing), with each interview lasting around 30 min. While a standardized questionnaire was used, the surveyors had the flexibility to slightly adjust the wording in order to increase clarity and capture more detailed responses. The online survey was distributed via a quick response (QR) code, with support from township leaders and residents, yielding 994 valid responses. Participation in the online survey was voluntary, allowing for a broader, self-selected respondent pool.

To ensure data quality, we implemented several control measures. First, surveyors received intensive pre-survey training aimed at standardizing data-collection procedures and increasing accuracy. For example, when recording indoor temperature, surveyors were instructed to cross-check the self-reported values by inquiring about respondents' indoor clothing and thereby assessing the plausibility of the reported data. Second, data quality was moni-

tored daily by supervising faculty throughout the survey period. A rigorous post-survey validation process was also employed, including the screening and removal of invalid responses; 89 out of the 1212 collected questionnaires were excluded after verification. Additionally, continuous variables were winsorized at the 5th and 95th percentiles to reduce the influence of outliers. To encourage conscientious participation, respondents were informed that they would receive a 10-CNY incentive upon verification of a complete and valid questionnaire.

The survey questionnaire included four main sections: ① the heating energy types and transition statuses of sample households; ② attitudes toward the transition, including benefits and concerns; ③ self-reported indoor temperatures, heated areas, and heating costs before and after the transition; and ④ household and demographic characteristics, including household size, total floor area, year of house construction, income level, gender, household registration status (urban or rural), age group, health status, marital status, education level, and year of clean heating transition (for households that have undergone the transition). The full survey questionnaire is available in Appendix A. For households that had transitioned, indicator data were based on respondents' recall, capturing conditions before and after the transition. For households that had not transitioned, respondents were asked whether their heating fuel use had changed significantly compared with the previous year (Question 23). If no change was reported, we assumed that indoor temperature, heating expenditures, and heated area remained unchanged. If a change was reported, respondents were further asked to recall their heating conditions in the previous year, enabling a more accurate assessment of changes based on two consecutive heating seasons (Question 23A). As the data are self-reported, we acknowledge the possibility of discrepancies between subjective responses and actual conditions. For example, respondents may exaggerate or underestimate indoor temperature changes to align with their perceptions. However, our study focuses not on absolute temperature values but on household responses and perceived thermal experiences, which are more indicative of comfort and well-being.

2.2. Regression modeling

We used cross-sectional data to examine the effects of the clean heating transition on changes in household heating experiences. Ordinary least squares (OLS) regression was applied, as specified in Eq. (1):

$$\text{delta_}y_i = \alpha + \beta \text{Transition_status}_i + \gamma \text{Control}_i + \varepsilon_i \quad (1)$$

The dependent variable $\text{delta_}y_i$ captures changes in one of three household heating indicators: indoor temperature, annual heating costs, or heated area. For households that underwent a heating transition, from coal or biomass to either natural gas or electricity (i.e., coal-to-gas and coal-to-electricity households), these changes were calculated as the difference between post-transition and pre-transition values. For households that continued using coal or biomass for heating, changes were measured as the difference between values in the 2023 and 2022 heating seasons, in the absence of a clearly defined transition point. The key independent variable $\text{Transition_status}_i$ is a categorical indicator of household *i*'s transition status, comprising three categories: households continuing to use coal or biomass for heating (reference group), households that underwent a coal-to-gas transition, and households that underwent a coal-to-electricity transition. Control_i is a vector of household- and individual-level covariates. Household-level variables include household size, the logarithm of total floor area, year of house construction, household income level, and the time interval between the two observations. Individual-level variables for the respondent include interview type (face-to-face or online), gender, household registration status (urban or rural), age group, health status, marital status, and educational attainment. We also include district fixed effects to control for district-specific unobservables, such as climate conditions, social environments, and policy measures. Controlling for these variables, the changes in heating behaviors are measured as β, with γ being the coefficient for the control variables. α is the constant term and ε_i is the error term.

2.3. Measuring inequality

The Gini coefficient and the Oshima index are widely used in the economics literature to measure inequality [45,46]. We used these two metrics to assess trends in indoor temperature inequality across households. The calculation of the temperature Gini coefficient is shown in Eq. (2):

$$\text{Gini} = \frac{1}{n}\left(2\sum_{i=1}^{n-1}(P_i - T_i)\right) \quad (2)$$

where T_i represents the cumulative proportion of indoor temperature from household 1 to household *i*, ordered in ascending order, relative to the total sum of indoor temperature across all households, while P_i represents the cumulative proportion of households from household 1 to *i*, relative to the total number of households. *n* denotes the sample size. The temperature Gini coefficient ranges from 0 to 1, with higher values indicating greater inequality in indoor temperature.

Additionally, we used the temperature Oshima index, as shown in Eq. (3), to validate the robustness of our results:

$$\text{Oshima} = \frac{\text{AT}_{\text{top20\%}}}{\text{AT}_{\text{bottom20\%}}} \quad (3)$$

where $\text{AT}_{\text{top20\%}}$ is the average temperature of the top 20% of households with the highest indoor temperatures, and $\text{AT}_{\text{bottom20\%}}$ is the average temperature of the bottom 20% of households with the lowest indoor temperatures. A higher temperature Oshima index indicates greater disparities and higher temperature inequality.

3. Results

3.1. Heating cost as the primary concern, with thermal conditions close behind

The survey collects information on heating energy types and how they change in the context of the clean heating transition. Among the 1123 valid responses, 321 (29%) households continued to use coal or biomass for heating, 117 (10%) used natural gas, and 107 (10%) used electricity. Additionally, 293 households (26%) had transitioned from coal to gas, while 216 households (19%) had transitioned from coal to electricity. The remaining 6% used other fuels or reverted to coal from clean energy. Detailed descriptive statistics are provided in Tables S1 and S2 in Appendix A.

To assess attitudes toward the clean heating transition, participants were asked to select their top three concerns from a list of 10 options (see the Survey questionnaire in Appendix A, Questions 18 and 29) and to identify the three most significant perceived benefits from the transition (Questions 17 and 28). In terms of concerns, the most frequently mentioned were "high costs," "ineffective fuel heating," and "poorly insulated houses." High costs reflect the economic strain of the transition, while concerns about ineffective fuel heating and poorly insulated houses are directly related to thermal conditions—the former arising from dissatisfaction with heating sources and the latter from inadequate infrastructure. Other concerns, ranked lower, included poor equipment quality and delayed

maintenance, unstable energy supply, insufficient grid/pipeline infrastructure, improper regulatory enforcement, and inconvenient equipment operation. Regarding benefits, respondents most frequently acknowledged that clean heating provided cleanliness and convenience, with 84% and 46% of respondents selecting these options, respectively.

A comparison of the different transition pathways reveals that coal-to-electricity households provided more positive feedback on the clean heating transition than coal-to-gas households. As shown in Fig. 1, the primary negative feedback from coal-to-gas households was "costlier and colder." Among these households, 84% selected high heating costs as one of their top three concerns, and 42% chose ineffective fuel heating. In contrast, only 63% of coal-to-electricity households reported high costs, and just 14% expressed dissatisfaction with fuel heating. Another indicator of the relatively poorer feedback from coal-to-gas households is that only 10% reported no notable concerns, compared with 22% of coal-to-electricity households. Moreover, 42% of coal-to-electricity households reported feeling "warm and comfortable" after the clean heating transition, compared with just 18% of coal-to-gas households. When asked, "If winter heating were free of charge, by how many degrees Celsius would you raise your current indoor temperature?" 22% of coal-to-electricity households reported no need to increase the temperature, while only 8% of coal-to-gas households felt the same.

3.2. Impact of clean heating transition on heating costs and indoor temperature

Descriptive statistics illustrate the changes in heating experiences—measured by indoor temperatures, heating costs, and heated areas—before and after the transition among the sampled households. For coal-to-gas households, heating costs increased while indoor temperature declined. Average annual heating costs rose from 2385 CNY (N = 262, where N indicates the number of valid observations for each specific indicator) before the transition to 3749 CNY (N = 251) after, an increase of approximately 57.2% (Fig. 2(a)). Meanwhile, average indoor temperature dropped from 19.1 °C (N = 268) to 17.0 °C (N = 264) (Fig. 2(b)), and the average heated area decreased from 135.7 m^2 (N = 178) to 125.3 m^2 (N = 174) (Fig. 2(c)). In contrast, coal-to-electricity households experienced modest cost changes alongside improved thermal conditions. Average heating expenses declined slightly from 2544 CNY (N = 177) to 2519 CNY (N = 171), representing a 1% decrease (Fig. 2(d)); average indoor temperature increased from 19.0 °C (N = 188) to 20.0 °C (N = 185) (Fig. 2(e)); and the average heated area expanded from 115.2 m^2 (N = 135) to 118.3 m^2 (N = 130) (Fig. 2(f)). For households that continued using coal or biomass, comparisons across two consecutive heating seasons reveal a slight decline in annual heating costs from 2388 CNY (N = 276) to 2278 CNY (N = 226) (Fig. 2(g)). Average indoor

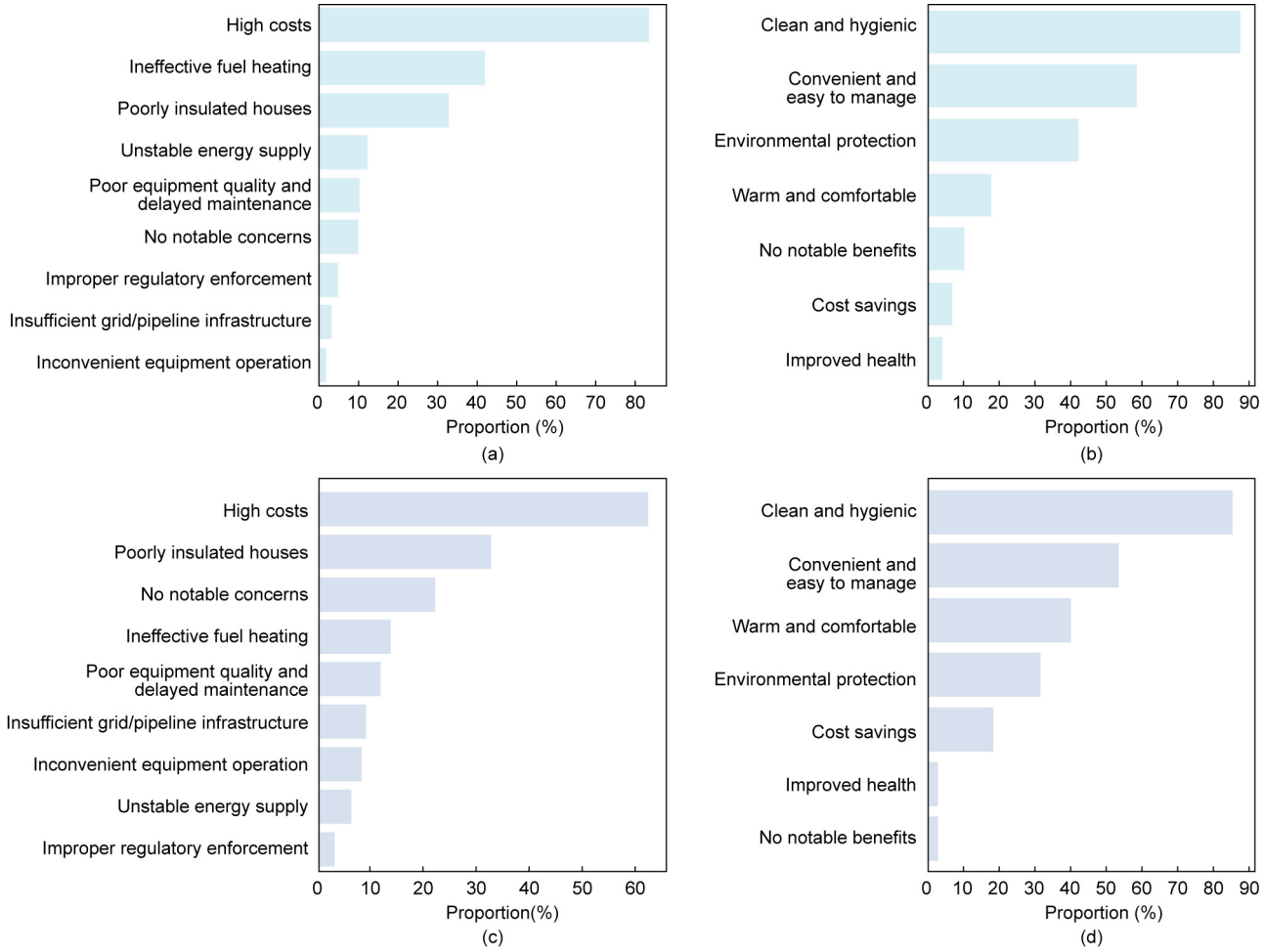

Fig. 1. Concerns and benefits of the clean heating transition as reported by residents. Proportion of (a) concerns and (b) benefits reported by coal-to-gas households; proportion of (c) concerns and (d) benefits reported by coal-to-electricity households.

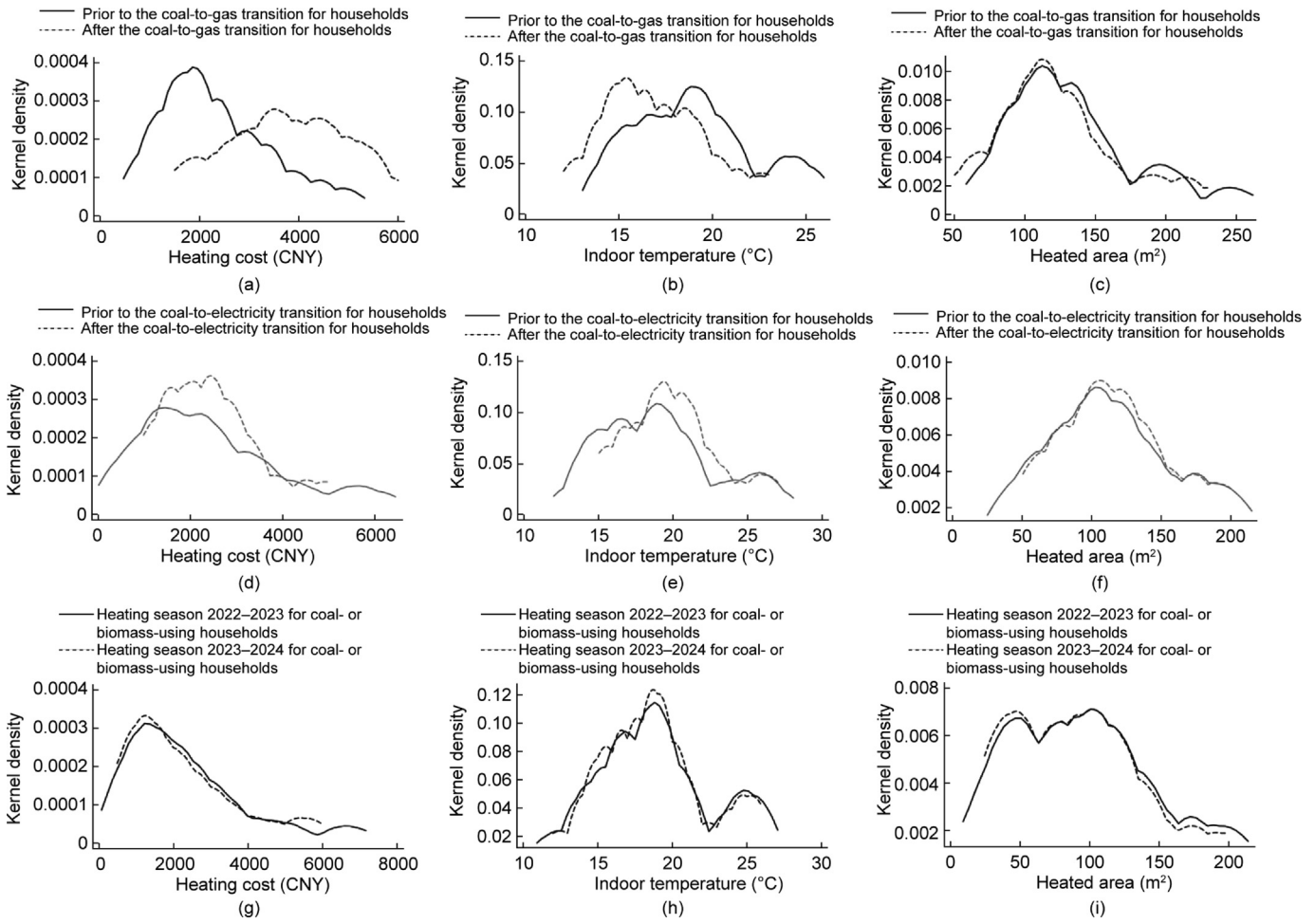

Fig. 2. Kernel density estimates of indoor temperature, heating cost, and heated area in sampled households. Kernel density estimates provide a non-parametric approach for estimating the probability distribution of a variable, offering a smoother and more continuous representation than histograms. The Epanechnikov kernel function and optimal bandwidth are used for estimation. This figure compares heating indicators across three groups of sampled households: (a–c) transitioning from coal to gas; (d–f) transitioning from coal to electricity; and (g–i) continuing to use coal or biomass for heating. (a, d, g) Changes in heating costs; (b, e, h) changes in indoor temperature; (c, f, i) changes in heated area.

temperature remained stable at approximately 19.0 °C (N = 284 for the 2022–2023 heating season; N = 230 for 2023–2024) (Fig. 2(h)), while the average heated area declined modestly from 97.1 m^2 (N = 226) to 93.2 m^2 (N = 182) (Fig. 2(i)).

A further regression analysis, incorporating household transition status as a categorical variable, reveals significant differences in the impacts of clean heating across transition types. As shown in Table 1, compared with households that consistently used coal or biomass for heating, coal-to-gas households experienced a significant increase in annual heating costs of 1318.2 CNY (p < 0.01); a 1.7 °C decrease in indoor temperature (p < 0.01); and a 10.4 m^2 reduction in heated area (p < 0.01). In contrast, coal-to-electricity households showed no statistically significant change in heating costs and heated area, while their average indoor temperature increased by 1.2 °C (p < 0.01). These differences help explain why evaluations of the coal-to-electricity transition were generally more favorable than those of coal-to-gas. They also suggest the presence of energy-limiting behaviors among coal-to-gas households and a potential rebound effect in energy consumption among coal-to-electricity households.

Table 1
Changes in heating behavior during the clean heating transition.

Transition_status	delta_cost (CNY)	delta_temp (°C)	delta_area (m^2)
Coal_to_gas	1318.2*** (206.0)	−1.7*** (0.4)	−10.4*** (3.7)
Coal_to_ele	−34.4 (155.3)	1.2*** (0.3)	3.6 (2.5)
N	605	640	457
r^2	0.3	0.3	0.2

The dependent variables are the changes in heating costs, indoor temperatures, and heated areas. The independent variable Transition_status is a categorical measure of household transition status. Specifically, coal_to_gas and coal_to_ele are dummy variables representing whether the household underwent a coal-to-gas or coal-to-electricity transition, respectively, with each taking the value of 1 and 0 otherwise. Households that continued to use coal or biomass for heating serve as the reference group. Control variables include interview type (face-to-face or online), household size, the logarithm of total floor area, year of house construction, household income level, district fixed effects, the time interval between the two observations, and respondent characteristics such as gender, household registration status (urban or rural), age group, health status, marital status, and educational attainment. Robust standard errors are in parentheses; ***p < 0.01, **p < 0.05, *p < 0.1.

Table 2
Income heterogeneity analysis of coal-to-gas and coal-to-electricity households.

Transition_status	delta_temp (°C)		delta_area (m^2)		delta_cost (CNY)	
	Lower income	Higher income	Lower income	Higher income	Lower income	Higher income
Coal_to_gas	−2.1*** (0.5)	−1.3*** (0.6)	−10.6** (5.1)	−11.0** (6.0)	1267.9*** (256.9)	1394.4*** (318.5)
Coal_to_ele	1.0*** (0.4)	1.4*** (0.4)	3.8 (3.3)	2.7 (4.0)	−39.5 (232.5)	−28.2 (216.3)
N	302	338	211	246	295	310
r^2	0.3	0.3	0.2	0.1	0.4	0.3

Households with an annual income below 25 000 CNY are classified as lower income, while those with an income above this threshold are considered higher income. Dependent variables are the changes in heating costs, indoor temperatures, and heated areas. The independent variable Transition_status is a categorical measure of household transition status. Specifically, coal_to_gas and coal_to_ele are dummy variables representing whether the household underwent a coal-to-gas or coal-to-electricity transition, respectively, with each taking the value of 1 and 0 otherwise. Households that continued to use coal or biomass for heating serve as the reference group. Control variables include interview type (face-to-face or online), household size, the logarithm of total floor area, year of house construction, household income level, district fixed effects, the time interval between the two observations, and respondent characteristics such as gender, household registration status (urban or rural), age group, health status, marital status, and educational attainment. Robust standard errors are in parentheses; ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

3.3. Indoor temperature inequality increases in coal-to-gas households

We further conducted a heterogeneity analysis by income group and found that the effects of heating transitions—relative to households that continued using coal or biomass—were broadly similar across income levels (Table 2). Specifically, among coal-to-gas households, both lower-income (annual household income < 25 000 CNY) and higher-income (≥ 25 000 CNY) groups experienced comparable changes: Indoor temperature declined by 2.1 °C ($p < 0.01$) and 1.3 °C ($p < 0.05$); the heated area decreased by 10.6 m^2 ($p < 0.05$) and 11.0 m^2 ($p < 0.10$); and annual heating costs increased by 1267.9 and 1394.4 CNY (both $p < 0.01$), respectively. In contrast, among coal-to-electricity households, no statistically significant changes in heating costs or heated area were observed across income groups. Notably, indoor temperature increased by 1.0 °C for lower-income households ($p < 0.05$) and 1.4 °C for higher-income households ($p < 0.01$). The results from the seemingly unrelated estimation (suest) test [47] indicated no statistically significant differences in the estimated coefficients between income groups. However, this should not be interpreted as evidence of no true difference, as the lack of statistical significance may be due to the relatively small sample size and the generally low income levels reported by the surveyed households. Taken together, these findings reinforce the result that the coal-to-gas transition led to comfort losses across income groups, while the coal-to-electricity transition did not compromise thermal comfort in either group.

We used the temperature Gini coefficient to assess changes in indoor temperature equality. Among households that continued using coal or biomass, the coefficient declined slightly from 0.116 to 0.111 between the two heating seasons. A more pronounced decline was observed among coal-to-electricity households, where the coefficient fell from 0.114 to 0.093. In contrast, the temperature Gini coefficient for coal-to-gas households increased from 0.097 to 0.101, indicating a slight worsening of temperature inequality. To validate these findings, we also calculated the temperature Oshima index as an alternative measure of inequality. Consistent with the Gini results, the Oshima index decreased slightly for both non-transitioned and coal-to-electricity households but increased for coal-to-gas households. These results suggest that, in addition to experiencing reduced indoor temperature, coal-to-gas households may face greater energy equity challenges.

4. Discussion

4.1. Multiple factors shaping household behavior in the clean heating transition

Our study revealed notable variations in indoor temperature changes across different clean heating transition pathways. Specifically, coal-to-gas households reported a decline in indoor temperature, while coal-to-electricity households experienced a modest increase. These differences can be attributed to a combination of factors, including energy costs, heating equipment efficiency, and behavioral responses.

In terms of energy costs, even with existing subsidy policies, heating expenses increased significantly for coal-to-gas households while remaining largely unchanged for coal-to-electricity households. For example, among the sampled coal-to-gas households using only wall-mounted gas boilers, average annual heating costs rose from 2385 CNY (pre-transition, coal or biomass) to 3749 CNY (post-transition, gas)—an increase of 57%. In contrast, among coal-to-electricity households using primarily air-source heat pumps, heating costs remained nearly the same: 2544 CNY (coal or biomass) versus 2519 CNY (electricity). This result is consistent with previous studies identifying heat pumps as cost-effective clean heating technologies that are competitive with traditional coal heating [11,12,24,48].

Regarding equipment efficiency, the transition from coal to gas or electricity led to substantial improvements, as households replaced traditional solid fuel systems (e.g., coal stoves and Kang) with modern clean heating technologies (e.g., wall-mounted gas boilers, air-source heat pumps, electric boilers, and direct-heat electric heaters). Among these, electric heating technologies demonstrated the highest efficiencies [35,49]. The existing literature estimates the heating efficiency of coal-fired boilers at 65%–75%, wall-mounted gas boilers at 85%–90%, and air-source heat pumps at 189%–337% [48–50]. Improved equipment efficiency is positively correlated with indoor temperature (Table S3 in Appendix A for further analysis).

The findings of this study suggest that, compared with households that continued using coal or biomass for heating, coal-to-gas households experienced a decrease in indoor temperature and an increase in heating costs after the transition. This result indicates that the higher energy costs associated with gas heating outweighed the benefits of improved equipment efficiency. Although gas heating systems are more efficient than coal-based systems, the higher cost of natural gas likely prompted energy-limiting behaviors such as reducing the indoor temperature to minimize energy expenses [31,40,41], reflecting hidden energy poverty and energy inequality [31–33,40]. In contrast, the subsidized electricity price, coupled with improvements in energy efficiency, likely triggered a rebound effect [37,51], encouraging modest gains in thermal comfort.

4.2. Integrating indoor temperature equality as an evaluation criterion

The central government's guidelines for selecting clean heating transition pathways emphasize a context-specific approach, urging local governments to adopt solutions tailored to local conditions

[52]. In line with this principle, policymakers in clean heating pilot areas consider a range of factors, including road infrastructure, economic costs, fiscal capacity, resident preferences, and energy prices [20,22,23]. Considering infrastructure investment requirements, many local governments promote a unified transition pathway within each village to reduce coordination and installation costs [53]. As supply–demand dynamics and energy costs evolve, transition strategies may also need to be adjusted accordingly.

Overall, electric heating generally entails higher initial capital investment but lower operating costs, while gas heating is associated with lower upfront costs and higher recurring expenses [10]. Due to upfront financial constraints, some regions initially prioritized coal-to-gas as their primary transition pathway [54]. However, as the natural gas supply–demand imbalance intensified and heat pump installation costs declined due to market competition, economies of scale, and policy incentives [55–57], more and more regions gradually shifted toward coal-to-electricity [24]. In some areas, households that had already transitioned to gas heating are now switching again to electricity [58].

The case of Linfen reflects this broader trend. After subsidies, the annualized capital cost for coal-to-gas households ranged from 634 to 684 CNY, while that for coal-to-electricity households ranged from 726 to 948 CNY [10]. According to our survey, the average annual operating cost is 3749 CNY for coal-to-gas and 2519 CNY for coal-to-electricity households. These figures are consistent with findings from previous studies [12,17,23] (more details are provided in Table S4 in Appendix A).

In addition to economic considerations, behavioral responses and heating experiences are critical for optimizing clean heating strategies. Our analysis contributes to this understanding by examining changes in indoor temperature before and after the transition. Among coal-to-gas households, declining indoor temperatures—along with rising disparities in thermal conditions—indicate the presence of energy-limiting behaviors and emerging energy inequalities. In contrast, the modest increase in temperature and the absence of increased inequality among coal-to-electricity households suggest more favorable outcomes.

These findings lend support to the prioritization of coal-to-electricity pathways, particularly in regions where improving indoor thermal comfort and equity are primary objectives. However, this should not be interpreted as suggesting that the coal-to-gas decisions were inappropriate. As noted, pathway selection is shaped by multiple technical, economic, geographic, and institutional factors, which may evolve over time. Thus the most suitable strategy may vary by context. The contribution of this study lies in its incorporation of behavioral responses and indoor temperature equality into the clean heating evaluation framework. This perspective complements traditional economic and technical assessments and is essential for safeguarding household well-being and ensuring a just and inclusive energy transition.

4.3. Optimizing subsidy policies to promote a just and inclusive transition

Our case study highlights significant heterogeneity in heating indicator changes before and after the clean heating transition across household groups, pointing to the potential for energy-limiting behaviors among coal-to-gas households and rebound effects among those transitioning to electricity. This heterogeneity underscores the need for more refined and targeted subsidy policies to promote thermal equity [59–61]. In the case of Linfen, for example, coal-to-gas households experienced more substantial comfort losses, suggesting that these households may require higher levels of support. Furthermore, subsidy schemes could be redesigned to prioritize end-use thermal comfort. Rather than focusing solely on infrastructure development, equipment investment, and operating cost coverage, the subsidy framework could place greater emphasis on enhancing indoor comfort—for example, through insulation retrofits [62,63].

Additionally, our analysis offers valuable insights for the design of subsidy phase-out strategies. Given the financial pressure and long-term sustainability of clean energy development, the gradual removal of subsidies is inevitable. Several cities have already implemented or are considering phase-out plans [50]. We propose that these phase-out policies be informed by a comprehensive assessment of indoor temperature equality. Households whose indoor temperature has remained stable or improved after the transition should be prioritized for subsidy reductions, while greater attention should be paid to groups exhibiting energy-limiting behaviors when designing phase-out plans.

4.4. Limitations

We acknowledge several limitations in this study. First, the household samples are primarily drawn from Linfen, Shanxi Province (China). While this case study is highly representative of coal-to-gas and coal-to-electricity pathways, caution is needed when interpreting and generalizing the results to other contexts. Second, the online surveys conducted in this study required initiative from respondents, which could introduce selective sampling and lead to concerns about nonresponse bias [64]. Third, while our analysis demonstrates that coal-to-electricity outperforms coal-to-gas in terms of both operating costs and indoor temperature, it is important to note that the initial equipment investment for coal-to-electricity households is likely to be higher [10]. The choice of transition pathways is inherently multifaceted, and our study provides one important dimension of this consideration rather than a full comparison.

Despite these limitations, the firsthand data from Linfen and our analytical approach offer valuable insights by evaluating energy transitions through the lens of household behaviors and heating experiences. This perspective provides essential decision-making support for designing local clean-heating-transition policies and serves as a model for post-transition assessments in other regions, complementing traditional cost-effectiveness analyses by incorporating indoor temperature equality.

5. Conclusions

For a long time, economic costs and environmental benefits have been the primary focus for decision-makers in promoting clean heating transitions. However, this study emphasizes the importance of incorporating residents' behavioral responses and the actual levels of energy service experienced under policy-driven transitions. Drawing on household survey data from Linfen, we found that different heating transition pathways—namely, coal-to-gas and coal-to-electricity—have divergent impacts on indoor temperature, heating costs, and heated area. Compared with households that continued using coal or biomass, those transitioning to gas experienced a significant decrease of 1.7 °C in average indoor temperature, along with an annual increase of 1318.2 CNY in heating costs. In contrast, households switching to electricity reported a 1.2 °C increase in indoor temperature without a corresponding rise in costs. This stark contrast in outcomes may be attributed to differences in behavioral responses, shaped by factors such as fuel prices and heating system efficiency. Despite improved equipment performance, the relatively higher operating costs associated with gas heating may have prompted energy-limiting behaviors among coal-to-gas households, such as reducing consumption due to economic constraints. Conversely, the subsidized electricity price in the study area is comparable to the fuel cost of

coal heating, and electric systems offer significantly higher efficiency. Together, these factors may have induced a rebound effect, motivating coal-to-electricity households to pursue higher levels of thermal comfort. Moreover, measures of indoor temperature inequality—including the Gini coefficient and the Oshima index—showed that inequality increased among coal-to-gas households but declined among both coal-to-electricity and non-transitioned households.

Observed disparities in heating experiences and behavioral responses provide valuable insights for decision-makers regarding the heterogeneous impacts of the clean energy transition. These findings underscore the need to integrate such heterogeneity into policy design, particularly in selecting transition pathways and designing subsidy schemes. Policymakers should move beyond conventional pre-transition cost–benefit analyses and place greater emphasis on post-transition policy evaluations. Conducting such evaluations in regions that have already implemented clean heating policies can generate critical lessons to guide future transitions in comparable areas. Moreover, identifying vulnerable groups exhibiting energy-limiting behaviors or experiencing hidden forms of energy poverty enables more targeted interventions, thereby contributing to reduced energy inequality and a more just energy transition.

CRediT authorship contribution statement

Xinzhu Zheng: Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Ling Zhang:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Yuxin Bai:** Writing – review & editing, Methodology, Investigation. **Jianhui Cong:** Writing – review & editing, Investigation. **Tianyi Zhang:** Writing – review & editing, Investigation. **Yue Ren:** Writing – review & editing, Investigation. **Jie Li:** Writing – review & editing, Investigation. **Yang Su:** Writing – review & editing, Investigation. **Junyuan Xu:** Writing – review & editing, Investigation. **Can Wang:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2025.07.034.

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