Energy inequality under the toughest-ever clean air policy in China

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Abstract: Since 2013, with the implementation of the toughest-ever clean air policy in China, the residential energy transition has been remarkable. However, how this policy affects household energy costs and its associated inequality remains unclear. In this paper, we assessed trends in the clean energy uptake in household stoves and fuels based on data from a large nationwide household survey and evaluated the energy cost inequality. We find that, during 2013-2017, about two-fifth (39.3%) of households using traditional solid fuel switch to clean energy, however, 60.9% of them are extremely poor or poor households. As this rapid transition campaign, although the national inequality in energy cost has been redressed significantly, the growing disparity in household income has caused a deep concern for the inequality in energy burden. The results suggest that, the average household spends about 5% (the median) of its income on energy, which is higher than the 3.5% the US households. Moreover, more than 45% of participants spent more than 6% of income on energy in 2017, while this number is about 25% in US. In addition, our findings suggest that there is a stark disparity of energy burden between urban and rural households. During 2013-2017, the energy burden on rural households is not reduced but increased due to the dramatic rise of cost on clean energy, while urban households tend to pay a lower and decreasing proportion of their income on energy. In this regard, the impacts of rapid energy transition differ widely in terms of urban-rural settings. Meanwhile, difference in this impact of energy transition on the household energy burden among climate zones is also recognized. Planning efforts on narrowing inequality among different income groups that more closely examine energy burden may accelerate household energy transitions that benefit the climate and human health.

To address severe air pollution issues and protect public health, the State Council of China promulgated the toughest-ever Air Pollution Prevention and Control Action Plan (APCAP) in 2013[1]. In support of this plan, many aggressive emission control measures have been taken to reduce emissions from energy production[2-5], industry[5,6], transportation[7,8]. In addition, China also made a massive investment in the transition to clean energy in the residential sector[9,10,11]. A new campaign substituting residential solid fuels (coal, biomass) with clean fuels such as gas and electricity has been launched in Beijing, Tianjin, and 26 other municipalities in northern China[12,13]. It was planned that 60% of rural coal-using households will shift to clean fuels by 2021[12]. By the end of 2017, energy consumption in 6 million households in China switched from coal to electricity and natural gas[6]. Meanwhile, the implementation of the 'new-type urbanization' plan and 'rural revitalization' strategies that aim at 'human-centered', 'urban-rural balanced' and 'environmentally friendly' development pathways may accelerate nationwide energy transitions in the residential sector.

As expected, these plans and measures have achieved remarkable improvements in air quality[6,10,14] as the rapid promotion of clean fuels. Among different sectors, the residential sector was reported as one of the most effective measures in reducing $PM_{2.5}$ pollution and health burdens during 2013-2017, contributing to an 11.1% decrease in the national $PM_{2.5}$ concentration[6]. However, the magnitude of residential energy transition during this recent rapid promotion period has not been well quantified. Moreover, the abrupt transition to clean fuels requires not only stove and other equipment upgrades but also a marked increase in basic energy cost due to new energy infrastructure and relatively higher prices of modern clean fuels. Thus, a comprehensive evaluation of the influence of energy transition on the energy cost and its associated inequality is essential for policy-makers and planners to further accelerate the clean-energy transition. Prior studies that attempt to measure energy inequality mainly focused on energy consumption[15,16,17,18] and energy affordbility[19,20,21] defined as the percentage of household income spent on energy bills. However, for developing countries, the use of energy consumption and energy affordability data for measuring energy inequality has a major limitation and bias: energy consumption data might mask the inequality in fuel type. For instance, free or low-price solid fuels that largely dominate rural and poor household energy mix could cause a decrease in energy cost and a corresponding uncertainty of energy affordability.

To address these issues, leveraging data from the China Family Panel Studies (CFPS), we conducted the first study to quantify the short-term impact of recent, toughest-ever clean air policy on household energy cost and associated financial burden. CFPS is a nationally longitudinal survey of Chinese communities, families, and individuals launched in 2010 by the Institute of Social Science Survey (ISSS) of Peking University. In support of this survey, we also investigate the differences in the impact of energy transition on household energy cost and its burden between urban and rural settings, as well among different regions. The distribution of samples can be found in Supplementary Figure 1. In addition, determinants of energy burden during the rapid energy transition were revealed and discussed, with an emphasis on the impacts of clean-fuel uptake. Filling these knowledge gaps would inform the public of the magnitude of the strict implementation of large-scale energy transition and the associated changes in energy cost and energy affordability among different income groups, and provide in-depth insights into the multidimensional inequality in energy usage.

Results

Household energy transition. Figure 1 shows the rapid energy transition in the residential sector during 2013-2017. Overall, 1482 households made a switch from solid fuels to gas fuels or electricity, which accounted for about two-fifths of the survey participants using solid fuels in 2013. Meanwhile, the share of households using LPG/NG (Liquefied petroleum gas/natural gas) for cooking increased from 42.1% in 2013 to 50.0% in 2017 (Supplementary Figure 2), whereas the contribution of wood and crop residues dropped sharply with the strict implementation of promoting clean fuels in the residential sector, from 31.2% to 22.9%. This indicates the massive impact of the APCAP on the residential energy pattern mix in the short term. In addition, transition to clean energy (including electricity, LPG/NG, and biogas/solar energy) was more evident among rural households. There were 1042 (70.3%) households that underwent the transition to clean fuels during 2013-2017, including 160 households that migrated to urban areas. By 2017, rural households using LPG/NG for cooking increased from 23.3% in 2013 to 32.1%, while those using wood and crop residues decreased from 48.5% to 38.1%. However, free or low-price solid fuels still prevail in rural areas, and the wide urban-rural disparity in energy mix remained. That was particularly true considering the large urban-rural gap in both household income and the access to clean energy infrastructure.

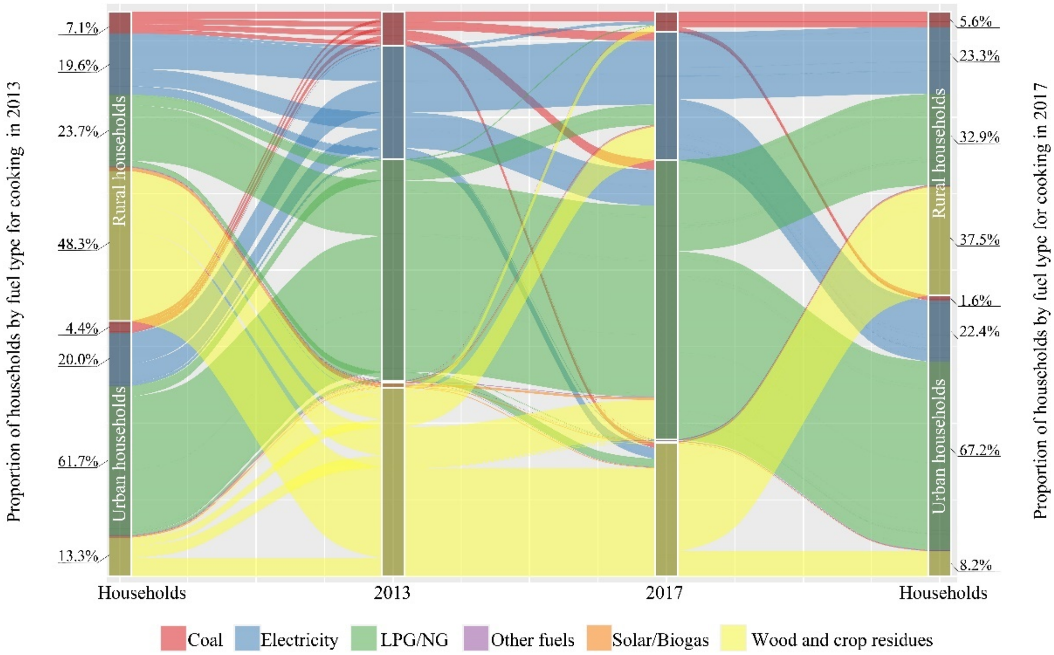


Fig. 1 | Fuel transitions from 2013 to 2017. The proportion of the households using different fuel types for cooking at baseline (2013) and at follow-up (2017) displays, indicating the great inequality in energy mix between urban and rural households.

Meanwhile, Figure 2 and Supplementary Figure 3 show the distribution of households that experienced the energy transition by income group during 2013-2017. Among the households involved in the energy transition, extremely poor and poor households dominated, and they account for 60.9% of the households that underwent energy transition. A complete switch from free or low-price solid fuels to relatively high-price clean fuels requires not only equipment and utility technology upgrades but also a shift in users' socioeconomic conditions, including income, behavior, and cultural preferences[22]. In this regard, a dramatic rise in energy cost with the adoption of clean fuels will impose a financial burden on these households and therefore leads to a partial switch to clean energy use and the combined use of traditional and clean fuels[11,15]. This is unlikely to lower air pollution levels to the extent that greatly reduces the adverse health impacts[23] and can even cause higher air pollution[24,25]. Assessing the impact of the energy transition on the inequality in energy cost and its associated economic burden seems essential to support policy and planning efforts that accelerate a more complete energy transition.

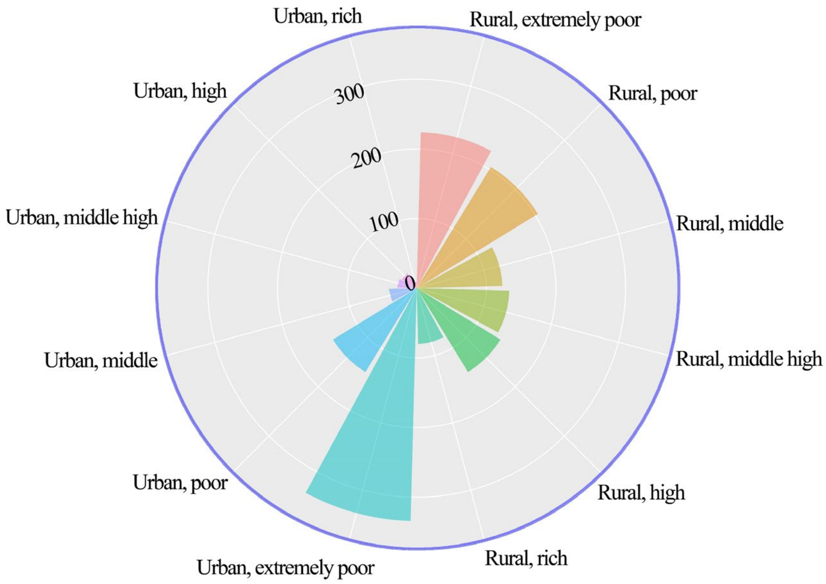
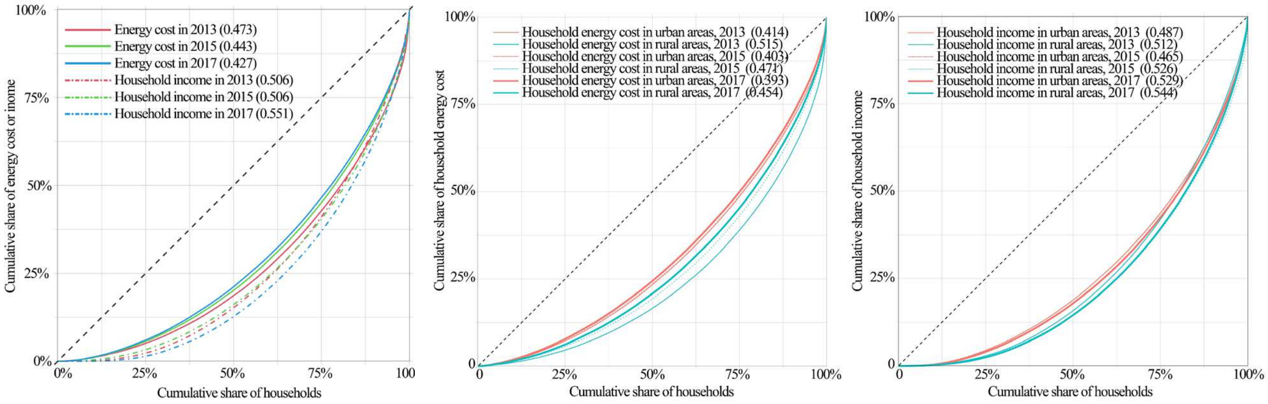


Fig. 2 | Number of households that energy transition occurs by income groups, 2013-2017. The number in the figure represent the number of households in each income group.

Inequality in energy cost. It is important to evaluate the impact of this rapid, large-scale energy transition on household energy costs and the associated inequality. Figure 3 shows the Lorenz curves for energy cost and household income in 2013, 2015, and 2017. The figure indicates that as the average household energy cost increased (Supplementary Figure 4), the inequality measured in terms of energy cost yields a Gini coefficient of 0.473, 0.443, and 0.427, respectively, which means the inequality in energy cost has declined in this rapid energy transition period. However, as shown in Figure 3-a, the curve of family income is lower than that of energy cost and skewed towards the 'perfect inequality', indicating the rise of income inequality in recent years. This finding is consistent with a previous study showing that China's latest Gini coefficient is in the range of 0.53-0.55 under the influence of rapid economic growth[26]. The rising inequality in household income will inevitably lead to the inequality in energy affordability.



a b c

Fig. 3 | Lorenz curves of energy cost and household income. a. For the whole samples; **b**. Energy cost by urban-rural settings. **c**. Household income by urban-rural settings. The diagonal is the line of perfect equality. The number presented in parentheses are the Gini coefficient.

Figure 4 shows great differences in cost inequality by fuel type. Specifically, inequality in central heating cost is the starkest, with a Gini coefficient of higher than 0.8, as more than 80% of households consume none. Followed by fuels cost, half of which is consumed by 12.5% of households, its Gini coefficients reach 0.648, 0.607, and 0.574, respectively. By comparison, the distribution of electricity cost is more equal, with a Gini coefficient decreasing from 0.462 in 2013 to 0.398 in 2017. These findings are consistent with Wu et al. (2017), who measured the energy inequality among rural households in China[17]. Meanwhile, our findings also reveal that the Gini coefficients present a decreasing trend, especially for other fuel cost (excluding electricity), as more and more households have access to modern and commercial fuels. As a result, from the perspectives of the Gini coefficient's composition, the contribution of other fuels cost to the overall energy inequality decreased from 47.1% in 2013 to 39.4% in 2017 (Figure 5-a), while electricity became prominent, with a share of the total energy inequality increasing from 35.5% to 42.7%.

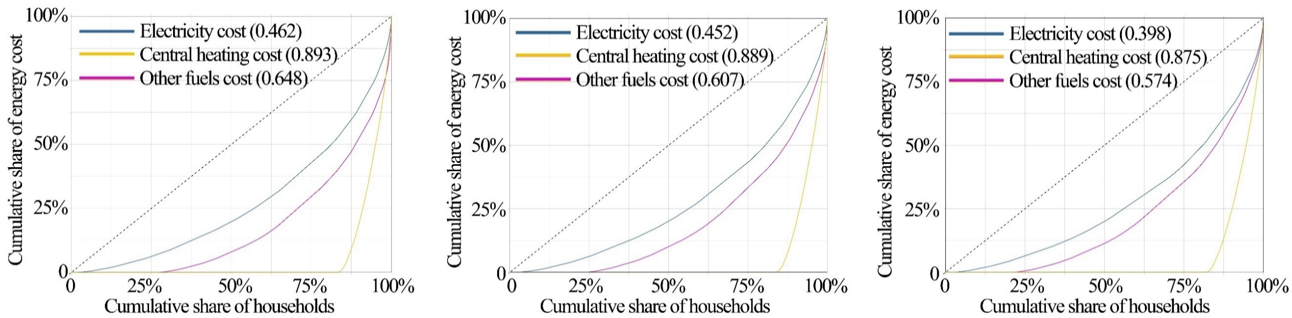


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Fig. 4 | Lorenz curve of energy cost by types. **a**, In 2013; **b**, In 2015; **c**, In 2017. The diagonal is the line of perfect equality. The first and second numbers presented in parentheses are the Gini coefficient.

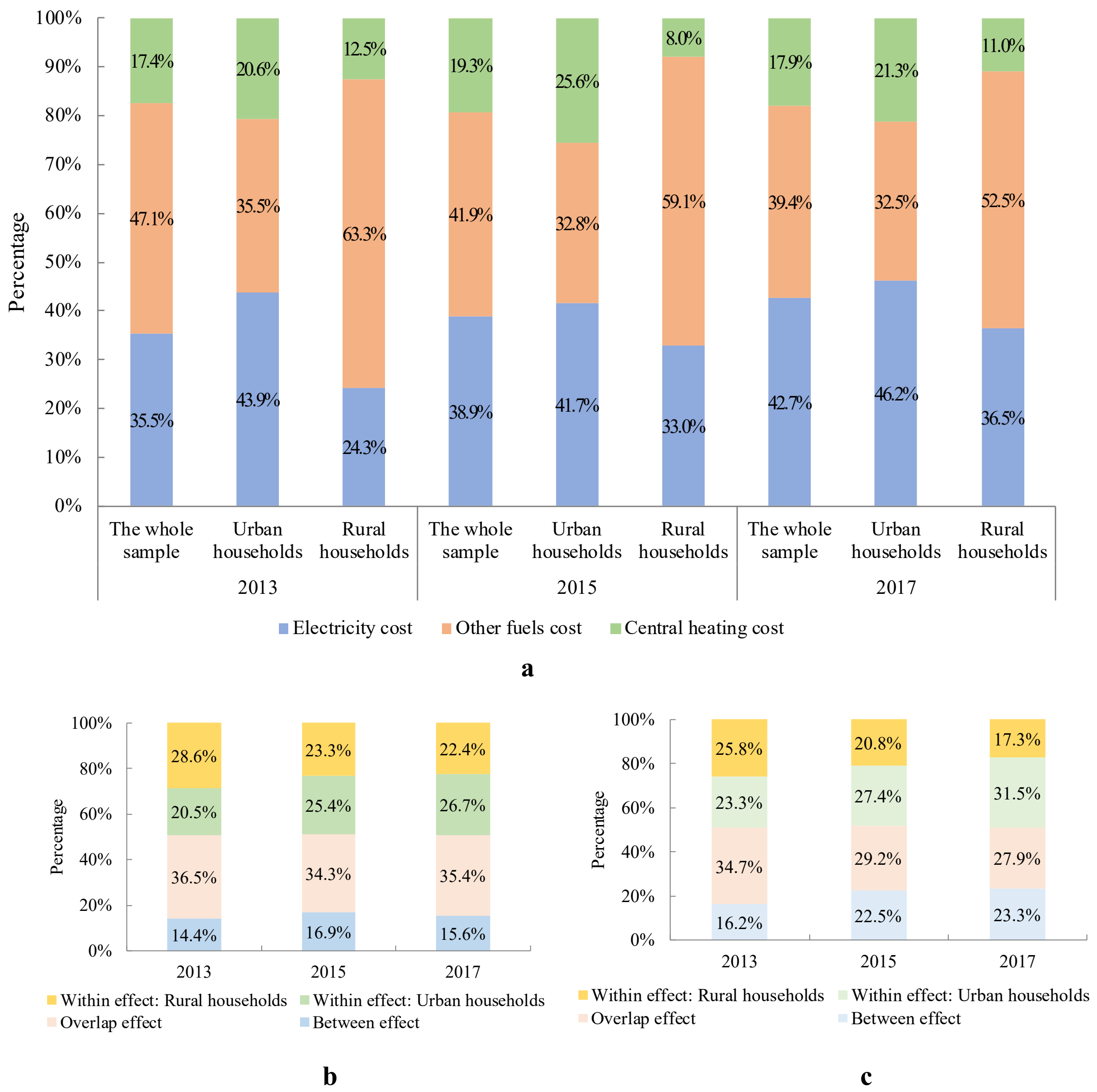


Fig. 5 | Decomposition of energy cost and income Gini coefficient by energy sources and urban-rural settings. a. Decomposing the energy cost Gini coefficient by fuel types and urban-rural settings; **b.** Decomposing the energy cost Gini coefficient by urban-rural settings; **c.** Decomposing the income Gini coefficient by urban-rural settings.

Energy inequality by urban-rural divide and regions. The urban-rural gap and regional disparity are two strong factors that shape China's income inequality in the past four decades[26,27]. To gain insights into these two structural differences in energy cost, we examine energy inequality by urban-rural settings and nine subregions.

As shown in Figure 3-b, the distribution curves of rural households' energy costs are lower than those of urban households, and the Gini coefficients for urban and rural households decreased from 0.414 and 0.515 in 2013 to 0.393 and 0.454 in 2017, respectively, indicating the higher energy inequality among rural households when compared to their urban counterparts. Meanwhile, the switch from low-price or free traditional solid fuels to relatively high-price clean fuels has led to a bigger reduction in the disparity of energy cost for rural households than that for the urban households (Supplementary Figure 5). Figure 3-b shows distinctly different patterns for both urban and rural household income that are skewed towards the 'perfect inequality' line.

Correspondingly, the Gini coefficients for both urban and rural household income reach the very high levels of 0.529 and 0.544, respectively. This observation reveals a growing disparity in household income in both urban and rural areas, leading to a deep concern for the inequality in energy affordability with the big push towards clean fuels.

Figure 5-b presents overall Gini coefficients of energy cost and their components by the urban-rural divide. The inequality within urban or rural areas accounts for half of the total energy cost inequality, in which urban areas contribute a growing share from 20.5% in 2013 to 26.7% in 2017. While the contribution of rural areas to overall inequality decreases from 28.6% to 22.4%. One reason for this change is that the improved access to commercial energy services in rural areas reduces the intra-group (i.e., within rural areas) inequality and its contribution to the total inequality. The urban-rural disparity constitutes approximately 15.6% of the overall inequality during 2013-2017, which is relatively small. We also observe the changes in the sources of income inequality. As shown in Figure 5-c, the sharp difference between income- and energy cost inequality lies in the contribution of urban-rural disparity that contributes to one-fifth of the total income inequality.

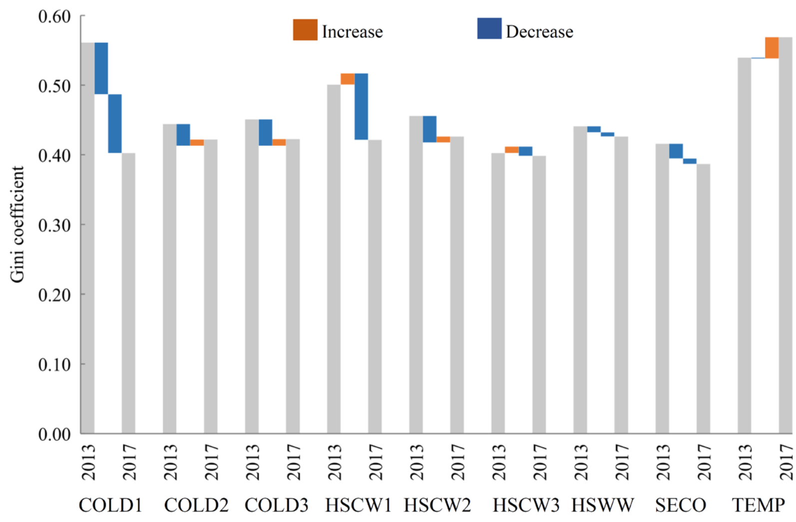
Besides the urban-rural disparity, climatic differences and socioeconomic conditions are expected to affect energy consumption and its cost. Therefore, we classify the survey participants into nine regions based on climatic and economic zones. Figure 6a reveals the great differences in inequality in energy cost across regions. The temperate region (TEMP) has the highest Gini coefficient and the inequality shows a significant increase from 0.539 to 0.569 during 2013-2017, while the hot summer and cold winter area in east China (HSCW3) and severely cold winter area (SECO) have the lowest inequality (less than 0.4 in 2017). The other six regions also have high Gini coefficients of greater than 0.4. Figure 6b shows the relationships between the Gini coefficients and economic development levels (per capita GDP) for nine regions in the three years, and the following non-linear function was derived where R^2 is the coefficient of determination of the regression:

$$G_c = 0.646 \times GDP_{cap}^{-0.237}$$

$$R^2 = 0.519$$

The regression results indicate that socioeconomic development level has a significant effect on energy inequality, which explains 51.9% of the total variation. As expected, in well-developed regions, residential energy services are better and the associated disparity is narrow.

To identify the contribution of each region, Supplementary Table 3 presents overall Gini coefficients' components by regions in 2013, 2015, and 2017. The result shows that the inequality within the nine regions accounts for one-tenth of the electricity inequality index, indicating that inequality in each region contributes a small share to the overall inequality. By contrast, about 70% share of the overall inequality comes from the overlap effect, followed by the between effect (near 20%) .



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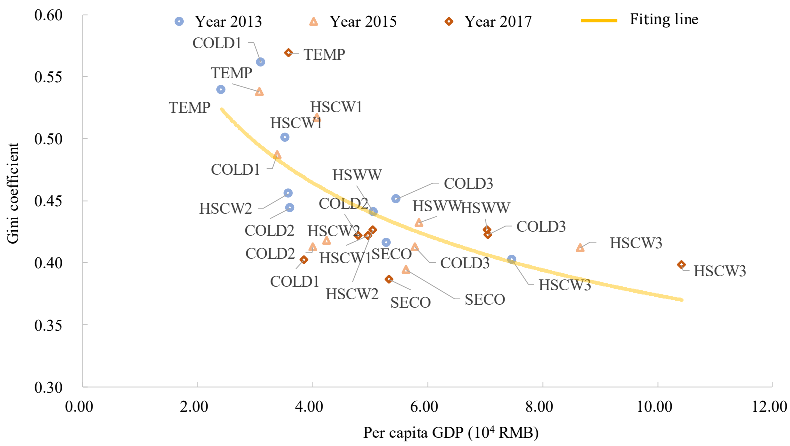
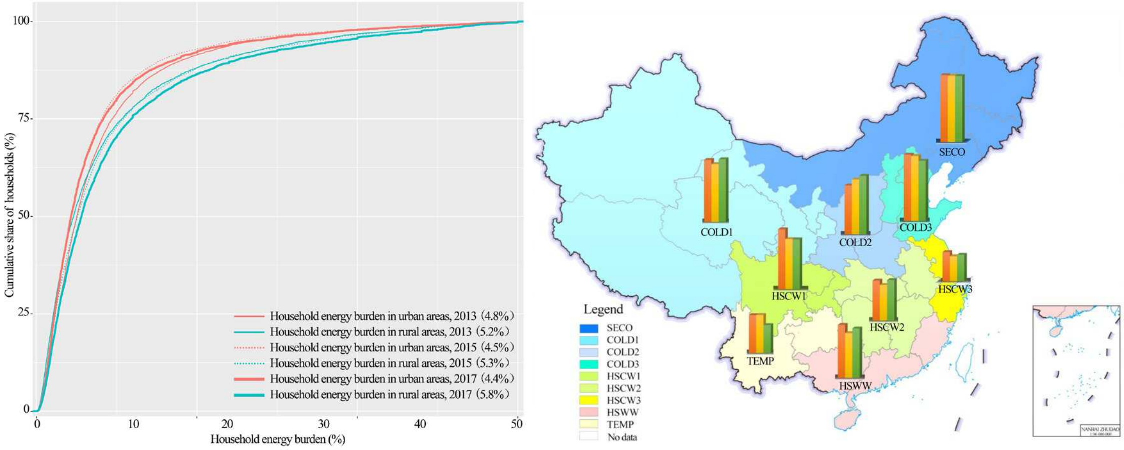


b

Fig. 6 | Changes in Gini coefficient by regions (a) and its relationship with regional economic development level(b).

Inequality in energy burden. Supplementary Figure 6 suggests that the average household spent about 5% (the median) of its income on energy during 2013-2017, significantly higher than that of U.S. households (about 3.3%)[28-30]. Meanwhile, stark disparities exist in energy burdens (i.e., the percentage of household income spent on energy bills) in China. Figure 7-a shows the change in the energy burden of urban/rural households. It indicates that rural households bear a significantly heavier energy burden than urban households. Moreover, with the rapid energy transition in recent years, this burden on rural households has not decreased but increased, the median of which grew from 5.2% in 2013 to 5.8% in 2017. By contrast, urban households tend to pay a lower and decreasing percentage of their income on energy; the median energy burden of urban households dropped from 4.8% in 2013 to 4.4% in 2017. In addition, inequalities of income led to even greater inequalities in energy burden (Supplementary Figure 6). For instance, the average and median energy burden for extremely poor rural households reached 30.5% and 22.3% in 2013, respectively, ten times higher than rich rural households, followed by extremely poor urban households (16.8% and 10%). With the abrupt switch in energy consumption, by 2017, extremely poor rural households still experienced the highest energy burden, whose median climbed to 27.0%.



a b

Fig. 7 | Changes in household energy burden by urban-rural settings(a) and regions (b). In **a**, the first and second numbers presented in parentheses are the median and mean household energy burden, respectively; In **b**, the orange, the yellow, and the green cuboid represents the mean household energy burden in 2013,2015, and 2017, respectively.

Besides urban-rural inequality in energy burden, we also observe considerable regional inequality in energy burden (Figure 7-b). As mentioned earlier, climate conditions affect household energy consumption patterns and the associated inequality through space heating and cooling demand[10,15,31]. Therefore, climate conditions will affect household energy burden. As shown in Supplementary Figure 7, on average, households in severely cold areas (SECO), experienced the greatest median energy burden, paying roughly 6.5 percent (median) of household income on energy consumption, more than twice as the median household energy burden of households in HSCW3, one of the most affluent regions in China. Meanwhile, households in the cold areas (COLD1, COLD2, and COLD3) have a high energy burden, spending roughly more than 5 percent of their income on energy cost, followed by the households in regions with hot summer and cold winter, HSCW1(approximately 5%). Households in regions with hot summer and warm winter have a median energy burden of 4.8% due to long-term cooling needs, higher than households in HSCW2 (4.0% in 2017). With less heating-cooling needs and inadequate access to modern energy, households in temperate areas bear a lower energy burden, with a median energy burden of less than 3%. In addition, urban-rural inequality in energy burden also exists in the nine regions. Compared with the reduction of energy burden among urban households, rural households spent an increasing percentage of their household income on energy consumption, which reached higher levels than those of the urban households. Particularly, the rural households in severely cold (SECO) and cold regions in eastern China (COLD3) paid more than 7 percent of their household income on energy consumption by 2017, and 1.20 and 1.49 times respectively than that of urban households. In addition, as shown in Supplementary Figure 8, for most of regions, the urban-rural disparity in household energy burden widens.

Impact of the energy transition on household energy burden. To quantify the driving forces that affect household energy burden, in particular the influence of the energy transition on households' financial burden, linear panel regression model with fixed effects is applied, and more information can be found in Supplementary Note 1. The results show that factors associated with energy burden include family members living in the same house, the age of the oldest living member in the house, access rate of fuel gas, and the share of wage or salary in household income (in model 1). In addition, a dummy variable *Tra* is included in Model 2, which is used to verify the impact of energy transition on household energy burden. The results indicate that energy transition significantly increases the share of household income spent on energy consumption. Further, adding the indicators of urban-rural settings, and climate conditions to Model 3, we identify their influences on household energy burden. The results show that urbanization does not influence household energy burden, indicating that under the APCAP, the energy transition mainly occurred in the rural areas. By contrast, the climate condition has a negative relationship with household energy burden, implying that households living in the warmer regions are likely to bear a lower energy burden.

In addition, to qualify the difference in the effect of energy transition between urban- and rural settings, we add two interaction term (*Tra_Rua* and *Tra_Urb*) to Model 4. As shown in Table 1, the coefficients of *Tra_Rua* and *Tra_Urb* are 1.067 and 1.021, respectively, meaning that energy transition happened in the urban area is likely to place a lighter energy burden on the household. Therefore, given the coefficient of *Tra*, the overall effect of the energy transition on average rural- and urban household's energy burden are 0.218 and 0.172, respectively. This finding is consistent with our observation of the urban-rural disparity in energy burden during 2013-2017. Meanwhile, taking TEMP as the reference region, we add four interaction terms (*Tra_SECO, Tra_COLD, Tra_HSCW, Tra_HSWW*) to Model 5. The regression results show that the effect of *Tra* is not significant ($P>0.100$), indicating that in temperate regions, energy transition seems to have a negligible impact on household energy burden during 2013-2017. However, except in HSCW, the other three climate zones show a positive influence on household energy burden, suggesting that both cold winter and hot summer climates impose a higher financial burden on household energy consumption when compared with those who live in regions with the temperate climate, or with a developed economy. Meanwhile, the presence of interactions implies that the effect of the energy transition on household energy burden is different under different climate conditions. Specifically, for regions with (severe) cold winter, energy transition seems to place a heavy financial burden on the households, and the coefficients of *Cli_SECO* and *Cli_COLD* reache at 0.295 and 0.299, respectively. This pattern is also consistent with the distribution of regional household energy burden, as shown in Supplementary Figure 7, namely, households in cold areas generally experience higher energy burden due to greater heating demand.

Table 1 | Driving forces of household energy burden.

Variable	Model 1	Model 2	Model 3	Model 4	Model5
Ln Fam_size	0.212***	0.219***	0.234***	0.235***	0.233***
	(11.72)	(12.09)	(12.92)	(12.96)	(12.86)
Ln Sha_health&education	0.046***	0.048***	0.046***	0.047***	0.0452***
	(8.05)	(8.52)	(8.21)	(8.28)	(7.98)
Ln Age_child	-0.006	-0.007	-0.008	-0.008	-0.004
	(-0.61)	(-0.70)	(-0.77)	(-0.77)	(-0.39)
Ln Age_adult	-0.108***	-0.100***	-0.102***	-0.101***	-0.096***
	(-6.48)	(-6.02)	(-6.14)	(-6.10)	(-5.81)
Ln Pen_gas	0.056***	0.0355***	0.025*	0.047***	0.041***
	(7.76)	(4.77)	(2.35)	(5.09)	(5.09)
Ln Sha_salary	-0.227***	-0.228***	-0.229***	-0.228***	-0.230***
	(-32.71)	(-32.91)	(-33.06)	(-33.04)	(-33.37)
Tra		0.187***	0.199***	-0.849***	0.001
		(9.37)	(9.99)	(-20.55)	(0.01)
Cli			-0.095***	-0.097***	
			(-11.05)	(-11.28)	
Urb			0.047		
			(1.83)		
Tra_Rur				1.067***	
				(26.05)	
Tra_Urb				1.021***	
				(22.98)	
Cli_SECO					0.295**
					(2.95)
Cli_COLD					0.299**
					(3.08)
Cli_HSCW					0.029
					(0.28)
Cli_HSWW					0.137
					(1.23)
Tra_SECO					0.211
					(1.93)
Tra_COLD					0.191
					(1.77)
Tra_HSCW					0.219
					(1.95)
Tra_HSWW					0.251*
					(2.08)
Constant	2.402***	2.305***	2.500***	2.456***	2.029***
	(31.04)	(29.80)	(31.26)	(30.76)	(17.03)
Number of obs	21924	21924	21924	21924	21924

Note: This table reports the modeled coefficients for each variable, and the dependable variable is *Ln Ene_burden*. The panel data is leveraged from the total sample, which tracked 7308 households from 2013 to 2017. *** $P<0.01$; ** $P<0.05$; * $P<0.1$

Discussion

Since 2013, along with the strict implementation of APCAP, China has taken a series of actions to promote residential energy transition widely in China. However, we find that extremely poor and poor households dominated the households that underwent energy transition during 2013-2017, with a share of 60.9%. Driven by the growing energy cost, this transition campaign seemed to pose an increasing economic burden on poor households, therefore the completeness of clean energy uptake and the suspension of solid-fuel usage is limited to some extent[11].

In this first evaluation of the inequality in household energy cost and the associated financial burden during the national energy transition campaign, we find that although inequality in energy cost has declined within either urban or rural areas, the latter maintain marked intra-group inequality. This finding suggests that the rural areas still deserve a constant policy attention to the access to clean energy in the future. Meanwhile, socioeconomic development is the primary driving force for such inequality at the regional scale. Accordingly, in the well-developed Yangtze River Delta Region (HSCW3), energy cost inequality looks narrow. Despite the increasing equality of energy costs between urban and rural households, the underlying impacts on households' financial burdens differ sharply. With the rapid transition, the energy burden on rural households is not reduced but reinforced, while urban households are more likely to pay a lower and decreasing percentage of their income on energy cost. Accordingly, the inequality in energy burden between rural and urban households increases.

Further, our study evaluates a comprehensive set of household-level factors and a number of environmental factors that may influence household energy burden. As reported by existing literature, household size has a positive effect on households' energy burden[11,31]. In addition, our findings suggest that households with elderly adults are more likely to bear a relatively low financial burden of energy consumption mainly because of higher income. Meanwhile, the share of household income spent on healthcare and education would increase the energy burden, while the percentage of wage or salary in household income exhibits a negative relationship with this burden. This finding reflects that the reliable source of income appears beneficial to reducing energy burden. The accessibility to gas fuels is positively associated with household energy burden, implying more equal access to clean fuels will increase the possible latent demand and associated cost. In addition to these variables, three dummy variables representing energy transition, urban-rural settings, and climate conditions are included to evaluate the influence of these environmental conditions on household energy burden. The results suggest that the energy transition not only significantly increases the share of household income spent on energy consumption, but its impacts also differ widely in terms of urban-rural settings and climate conditions. The rapid energy transition is more likely to impose an increasing energy burden on rural households in areas with cold winter or hot summer.

Our findings have important implications for public policies. For example, in the context of growing income inequality, complete energy transition requires not only improved energy infrastructure but also an affordable energy cost for average household. In this case, compared with the rise of residential energy cost during the rapid energy transition, energy affordability and its associated inequality concern individuals, taking into consideration of the relatively high cost of clean energy uptake. Therefore, alleviating urban-rural and regional income inequality rather than providing direct energy subsidies to households or communities is a more effective way for reducing energy inequality, considering that income inequality is more uneven. In order to accelerate the implementation of the Coal-to-Gas and Coal-to-Electricity Project, most governments in northern China are already providing subsidies to households[17,32]. But providing such high targeted subsidies is unbearable, for example, according to the Hebei provincial Clean Winter Heating Plan in 2018[33], the government cut the annual maximum subsidy on the gas cost for a household joining Coal-to-Gas project to 960 RMB (Ren Min Bi, Chinese currency, 1 RMB=0.16 US dollar) from 1200 RMB in 2017[34]. In addition, this subsidy to a participating household generally runs for three years. Therefore, phasing out coal use is prohibitively expensive for most of the targeted rural households. In this regard, a targeted solar photovoltaic power adoption program for poverty alleviation can provide a useful reference to the government. By the end of 2019, this program has assisted 4.18 million poor households in total[35], and each of them can benefit 3,000 RMB annually from power generation revenue. In the future, new industrial models such as ‘photovoltaic + agriculture’ and ‘photovoltaic + fishery’ should be carefully designed and implemented to effectively promote the energy transition and household income growth in concert.

Household energy transition not only can help improve people’s living conditions in developing countries but also can be an initiative for effectively fighting against climate change worldwide. In the future, a public monitoring and planning platform is needed to guide the transition towards Sustainable Development Goal (SDG) 7 for universal energy access. Researchers, planners and ministers must understand the determining factors that make a clean household energy transition project successful based on a monitoring and cataloging platform. This system can promote multidisciplinary research involving planning, management and engineering with the support of big-data analysis and simulations. In addition, initiating a global household energy transition plan would facilitate international exchange and inform more future policies and effective programs.

Unique strengths of our study include our ability to gather critical household-level information to evaluate the effectiveness of the implementation of APCAP and inequality in both energy cost and the associated energy burden. Further, we investigate differences in the effect of energy transition among urban-rural settings or different climate zones. This study will support the decision-making process in energy and environmental sectors in China and provide a reference to other developing countries in South and Southeast Asia and Africa.

Our study also has several limitations that need to be addressed in future studies. Transportation energy costs are also a significant household expense[36,37], but it was outside the scope of this study. Households using clean energy for cooking are regarded as those achieving energy transition in rural areas without considering the combined use or stacked use[11,15,38] of solid and clean fuels, which is a partial transition bias. Considering that the main purpose of this study is to examine energy cost inequality, the households with the combined use of solid and clean fuels generally pay low energy costs, which has a limited impact on this study. However, to some extent, this limitation masks the energy burden of households in rural areas. Finally, the impact of household energy use efficiency on energy cost is not considered in this study.

Methods

Household-level data. The household-level data source we use is the CFPS (China Family Panel Studies), which allows us to assess energy cost inequality during 2013-2017. These surveys are nationally representative panel surveys conducted by the Institute of Social Science Survey at Peking University every two years (more information can be found at www.isss.edu.edu.cn/cfps).

This survey focuses on the information covering such topics as economic activities, education outcomes, family dynamics and relationships, migration, and health, which has provided to the academic community the most comprehensive and highest-quality survey data on contemporary China. We derived the data on electricity cost, fuel cost, and central heating cost, and evaluated annual total energy cost. The 2014 CFPS survey covers 5955 urban and 6372 rural households in 28 provinces of China, allowing us to investigate household energy costs in 2013. In the 2016 and 2018 CFPS surveys that provide household-level information in 2015 and 2017, 31 provinces are covered, and the number of urban and rural households included is more than 6,000, which yields reliable data.

Meanwhile, in order to track the changes in household energy cost and associated financial burden and investigate the determinants of household energy burden, we leveraged the panel data of 7308 households in 2013, 2015, and 2017 from the CFPS dataset.

Classification of income groups and regions. To trace the households those underwent energy transition during 2013-2017 to various income groups, we used the grouped income data from the national average as proxies, and split the ungrouped data into 12 groups. The data was shown in Supplementary Table 1.

To explore the regional differences in household energy cost and associated energy burden, we defined 9 regions in terms of climate conditions and economic development level at the provincial level. The literature[15,17,27] usually classifies the mainland into seven regions (Northwest, Northeast, North, Central, Yangtze River Delta, Southwest, and Southeast) based on geographical proximity and development stage (see region definitions in Supplementary Table 2 and Supplementary Figure 1). In addition, it is common to classify the country into five climatic zones (severe cold winter, cold winter, hot summer and cold winter, hot summer and warm winter, and temperate wether) in accordance with the Standard of Climatic Regionalization for Architecture (GB 50178-1993)[39]. According to this standard, we divided seven regions into nine regions as shown in Supplementary Fig.1-2, including the northeast region with severely cold winter (SECO), the northwest region with cold winter (COLD1), the central region with cold winter (COLD2), the north region with cold winter (COLD3), the southwest region with hot summer and cold winter (HSCW1), the central region with hot summer and cold winter (HSCW2), the Yangtze River Delta with hot summer and cold winter (HSCW3), the southeast region with hot summer and warm winter (HSWW), and the southwest region with temperate weather (TEMP).

Measures of household energy cost and its associated inequality. We collect information on the cost of electricity and fuels per month and the annual central heating cost to evaluate the aggregate energy cost:

$$C_{all} = 12 \times (C_{elec} + C_{fuel}) + C_{heat} \tag{1}$$

where C_{all} is the aggregate household energy cost, C_{elec} and C_{fuel} represent electricity and other fuel cost per month, and C_{heat} means the annual cost of central heating.

This bottom-up cost-based accounting approach has several merits. First, it allows us to aggregate household energy cost by fuel type. Second, it can accommodate the estimation and aggregation of non-meterable energy, such as biomass. Third, to some extent, this indicator provides us a new and proper perspective into addressing the energy inequality issue, considering the inequality in the energy mix that is generally ignored in previous studies. However, it inevitably suffers from the common challenge of self-reporting bias in collecting microdata.

As the most widely used analytical tools in existing literature for measuring inequality, the Lorenz curve and the Gini coefficient are used in this study. Lorenz curve was developed by Lorenz in 1905 to represent the inequality of wealth distribution in a population[40]. In this study, the energy cost Lorenz curve is a ranked distribution of the cumulative percentage of the households on the horizontal axis versus the cumulative percentage of energy cost distributed along the vertical axis. In normal cases, a point on the energy cost Lorenz curve shows that y% of the overall energy cost is consumed by x% of the household samples.

The Gini coefficient proposed by Gini (1912)[41] is a numerical representation of the inequality in income or wealth. It is usually defined mathematically based on the Lorenz curve as follows:

$$G = 1 - \left|\sum_{i=1}^{N}(H_{i+1} - H_i)(C_{i+1} + C_i)\right| \tag{2}$$

where H is the cumulative share of households and C is the cumulative proportion of energy cost. H_i indicates the cumulated number of households from 1 to h with the basis of ranking list from lowest to highest cost on energy demand; C_i denotes the corresponding cumulated cost of energy consumption by household groups from 1 to i.

Gini coefficient by energy sources and regions. In order to investigate the influence of fuel types on energy inequality in energy cost, the Shapley approach[42] is applied to decompose Gini coefficients into a sum of contributions generated by electricity, fuel and central heating cost, which can be calculated as follows:

$$\phi_i(val) = \sum_{S \subseteq \{x_1,\dots,x_{n-1}\} \setminus \{x_i\}}^{n} \frac{|S|!(n-|S|-1)!}{n!}\big(val(S \cup \{x_i\})\big) - val(S)) \tag{3}$$

where n is the total number of players, $\phi_i(val)$ denotes the amount that player i gets given a coalitional game. $val_x(S)$ is the prediction for feature values in set S that are marginalized over features that are not included in set S, which is known as the coalition force or the worth of the coalitions.

Meanwhile, the Gini coefficient is decomposed into an urban component and a rural component, and nine regions, following a strategy similar to that suggested by Yang[43] and Wu etal[17].:

$$G = G_{within} + G_{between} + G_{overlap} \quad (4)$$

$$G_{within} = \sum_{i}^{N} \frac{n_i}{n} w_i G_i \quad (5)$$

$$G_{between} = 1 - \sum_{i}^{N} \frac{n_i}{n} \left(2 \sum_{k=1}^{i} w_k - w_{i_i}\right) \quad (6)$$

where G_{within} represents the inequality within group i, and the term $G_{between}$ measures the gap across the disparity across groups. Then, a residual, $G_{overlap}$, expresses the magnitude of overlaps between the urban and rural groups, or between the nine regions, which yields a zero value if the ranges of household energy cost do not overlap. n_i is the sample size in group i, and n is the total sample size. w_i is the *ith* group's proportion of energy cost or income, and G_i is *ith* group's Gini coefficient.

Relationship between household income and energy cost. To facilitate the comparisons of the results across different years, we applied the LOESS (locally estimated scatterplot smoothing) method to empirically fit the linear/nonlinear relationships of household income against energy cost. The primary advantage of the LOESS method is that it does not require a specification of a global function that would fit all the data. We implemented the LOESS method using the RStudio 1.2.1335[44]. In addition, the span parameter (ranging from 0 to 1) can be used to control the smoothness. In this study, we choose the default value (0.75) as the span value to control the size of the neighborhood and smooth the scatter plot.

Panel analysis. To quantify the driving forces that affect household energy burden, in particular the influence of the energy transition on households' financial burden, a cross-sectional time-series dataset of household- and regional-level variables is needed. In this study, the share of energy cost in a household's annual income is defined as the dependent variable (*BUR*). Independent variables were selected a priori on the basis of the energy consumption/cost and energy transition literature[11,15,17,29,45-56]. Household-level variables include household size (*Fam_size*) (the number of household members that live together), the proportion of household income spent on health care and education (*Pro_health&education*), the age of the youngest child (*Age_child*), the age of the oldest adult (*Age_adult*), urban-rural settings (*Urb*), and a dummy variable describing the status in the energy transition process (*Tra*). Regional-level variables include the market penetration of gas fuels *(Pen_gas*) and climate conditions (*Cli_condition*).

For the variables of *Age_child* and *Age_adult*, we first identify the households that have children or parents (other older family members) who live together at present; if so, the age of the youngest child and the age of the oldest adult are required. Otherwise, the variable of *Age_child* will be given a value of 18, and the variable of *Age_adult* will be assigned according to the self-reported oldest age.

For environmental condition variables, *Pen_gas* and *Cli_condition,* we downscale the provincial data to the household scale. Specifically, the value of *Pen_gas* for each household is set by the provincial statistical data which is evaluated at the urban (including the city-, county-, and town- scale) and rural scale. In addition, the sum of Heating Degree Days *(HHD*) and Cooling Degree Days (*CDD*) for each province is calculated to serve as the value of *Cli_condition*, which can be defined as follows[57-59]:

$$Cli_{-condition} = \frac{1}{n}\sum_{k=1}^{n}\sum_{i=1}^{I_t}\alpha(T_b - T_{kit}) + \frac{1}{n}\sum_{k=1}^{n}\sum_{i=1}^{I_t}(1-\alpha)(T_b - T_{kit}) \quad (7)$$

where n is the number of meteorological observation stations in a province, and I_t is the number of days in the t month; T_{kit} is defined as the daily average temperature in the k meteorological observation station in day i of month t. T_b denotes the reference temperature. In this study, we set T_b as 65°F referring to previous studies[57,60]. α is a characteristic function, which is 1 when T_{kit} is more than T_b, otherwise, it is 0. The daily average temperature data is obtained from 665 meteorological observation stations in 2013, 648 meteorological observation stations in 2015, and 563 meteorological observation stations in 2017, which can be downloaded from http://data.sheshiyuanyi.com/WeatherData/.

As the dummy variable, *Tra* takes the value 0 or 1 to indicate the absence or presence of clean energy in the residential sector. Similarly, the variable *Urb* is applied to distinguish the samples by urban (*Urb*=1) or rural (*Urb*=0) settings.

In addition, to verify whether energy transition has a different effect on the household energy burden depending on the urban-rural settings, we add two interaction terms *Tra_Urb* into the models. Moreover, taking the temperate regions as the reference, four interaction terms (*Tra_SECO, Tra_COLD, Tra_HSCW, Tra_HSWW*) are calculated and put into the models to examine the disparity in the influence of energy transition on household energy burden in different climate zones.

Data availability

The data that support the findings of this study are available from the corresponding author upon request.

Code availability

Requests for the code developed and annotated in Stata 15, Matlab R2019b and RStudio (version 4.0.2) to process and analyze the primary data collected in this study will be reviewed and made available upon reasonable request.

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