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Research article

Who is vulnerable to energy poverty in China?

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ABSTRACT

Energy poverty has been identified as a problem in China, but research to date does not discuss who experiences it, unlike in other countries. Here, we compared sociodemographic characteristics known to be linked to energy vulnerability in other nations between energy poor (EP) households and non-EP households, using the 2018 survey data from China Family Panel Studies (CFPS). We found that a range of sociodemographic characteristics associated with transport, education and employment, health, household structure, and social security, are disproportionately distributed among five provinces (Gansu, Liaoning, Henan, Shanghai, Guangdong) in our study. EP households are more likely to have low housing quality, low education, old people, poor mental/physical health, be mainly female, be rural-Hukou, be without pension, and lack clean cooking fuels. In addition, the logistic regression results further evidenced the increased likelihood of experiencing energy poverty given vulnerability related socio-demographic predictors in the full sample, in rural-urban areas, and in each single province. These results suggest that vulnerable groups should be considered specifically when formulating targeted policies for energy poverty alleviation to avoid exacerbating existing energy injustice or creating new ones.

1. Introduction

Recent work on energy poverty research argues for a more nuanced insight to policy, taking into account multiple vulnerabilities of households, when identifying and delivering interventions [1–6]. The triad of energy poverty drivers consisting of low incomes, high energy prices and domestic energy inefficiency [7,8] risks obscuring particular socio-spatial vulnerabilities. Vulnerabilities are understood as a set of conditions distributed across space inherent within an individual, household, or social group that renders them less likely to be able to access the socially and materially necessitated amount of affordable and reliable energy services [5]. More specifically, scholars use this framing to explain the differential access to energy services between societal groups [1,3]. It provides a means by which to identify and understand the characteristics of those most susceptible to harm from particular stressors and thus the opportunity to mitigate against these harms [9]. For Middlemiss and Gillard [4], this determines the sensitivity of a household to energy poverty and its capacity to cope with and adapt to the condition.

While energy poverty is not yet clearly on the political agenda in China, there is a limited amount of research into this topic. Research on energy poverty in China has emphasized contrasting rural and urban areas and comparing different regions [10–18], however, to date, there is no research to identify who is vulnerable to energy poverty in China. Existing research tends to focus on either urban or rural areas [11,19–21], highlighting the different effects of energy poverty in one or the other, with more attention paid

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to rural energy poverty [17,22–25]. Thus, existing work paints a picture of geographical heterogeneity in levels and effects of energy poverty in China. However, mapping the distribution of energy poverty geographically is insufficient to capture deeper drivers of vulnerability, which is likely to affect different households differently.

2. Literature review

2.1. Energy poverty in China

To date, China does not recognize energy poverty and lacks a strategy that encompasses definitions, reduction objectives and periodic evaluation in policy agenda. Despite this, a limited amount of research into energy poverty in China has been ongoing since 2000 [10–18,22,26,27]. Existing energy poverty research focusing on China tends to pay attention to either urban or rural areas [11,19–21], highlighting the different effects of energy poverty in one or the other. 1) From the latitude perspective, Northern China has colder winters than southern China due to the geography location.[1] District heating is available in some northern urban areas, because southern residents experience hotter summers and colder winters than northerners do, they frequently look for alternative methods of maintaining comfortable indoor temperatures. 2) While the energy poverty rates are greater in central and western China from a longitude perspective, this is consistent with the economic growth map of China [21,28]. Additionally, due to the benefits of accessibility and affordability for fossil fuels in the locations, northern and western rural residents use the most coal, whereas eastern rural residents use the most electricity and natural gas for cooking and heating [29]. Natural gas consumption in rural areas is remarkably low compared to urban areas, while per capita coal consumption in rural areas is noticeably greater [24]. Yet, for the Chinese Government, energy poverty is a nebulous term that does not exist in any statutory capacity. In other words, the national government has not formally recognized energy poverty as a distinct problem.

2.2. Energy vulnerability

Specific vulnerabilities are often associated with people who have particular sociodemographic characteristics which are associated with a particular need for energy [6]. This includes households with low-incomes [17,30–32], young children [33,34], older people [34–36], disabled people [1,4,37,38], or single parents [34,39]. During winter months with high heating bills, low-income households curtail energy use to thermally uncomfortable levels [30]. Old people require a narrower band of temperatures for health and are more likely to suffer exacerbated mortality during extreme heat or cold weather if unable to maintain the appropriate temperature [35,36]. Households with children bear additional costs associated with ensuring that children are well fed and healthy [33]. Compared to the general population, people with disabilities may need more energy to realize a range of essential capabilities [37]. Illness or disability can limit freedom of movement and employment, which raises energy costs due to people being at home more [1,4]. There is a strong connection between people with multiple vulnerabilities and energy poverty, these vulnerable groups reach beyond a need for greater levels of energy services, to accessibility and affordability.

The diversity of socio-demographic characteristics associated with vulnerability and subsequent losses of wellbeing to energy poverty also have a complex and uneven spatial distribution [5]. For instance, in England a higher proportion of pensioners live in rural communities, whilst families with young children are more concentrated in the suburbs of cities, those with a disability or illness are more likely to live in urban areas or coastal communities and lone parent families tend to concentrate in urban areas [40]. Also in England, households in the private rented sector, where properties are disproportionately inefficient and tenants often lack housing rights, tend to concentrate in inner-city areas [41,42]. Acknowledgement of these complex social-spatial vulnerabilities is a useful step in developing understanding and policy responses to energy poverty.

Given these experiences in other nations, we can expect that belonging to specific socio-demographic types will also increase the risk of a household falling into energy poverty in China. We ask: What are the sociodemographic factors of energy vulnerability drivers in Chinese context? Energy is not purchased for its own sake, but for the energy services that it delivers; some energy services are essential for wellbeing and survival as in the case of cooking, heating and access to clean water, and knowing who can and cannot access adequate energy is important [1,39]. This study explores vulnerability to energy poverty across various sociodemographic groups, and the spatial dynamics (covering five provinces and rural-urban differences) behind this, based on household surveys conducted in 2018 by the China Family Panel Studies (CFPS).[2] We consider household home energy use including heating, electricity, fuel expenditure and potential vulnerability factors including low education, mainly female households, households with young children, old people, disabled people, low quality housing. Based on the dataset, to map the potential vulnerability factors of domestic energy deprivation. Methodologically, we ran logistic regressions to further detect the influences of vulnerability factors on energy poverty. The results indicate that households without a car, with old people, and without pension have the strongest influence on likelihood of experiencing energy poverty, especially, the additional inequalities in social security would further exacerbate the domestic energy consumption difficulties faced by households with old people and households without pensions. This paper contributes

[1] North and south in China is divided by Qinling Mountains-Huai River Line - an important geographical concept in China, which was first described by geographer Xiangwen Zhang. The line is not only a division of the north and south, but also divisions of 0 °C isotherm in January, annual precipitation of 800 mm etc.

[2] CFPS: China Family Panel Studies is a national wide social investigation in China led by the Institute of Social Science Survey of Peking University, detailed information also introduced in Method.

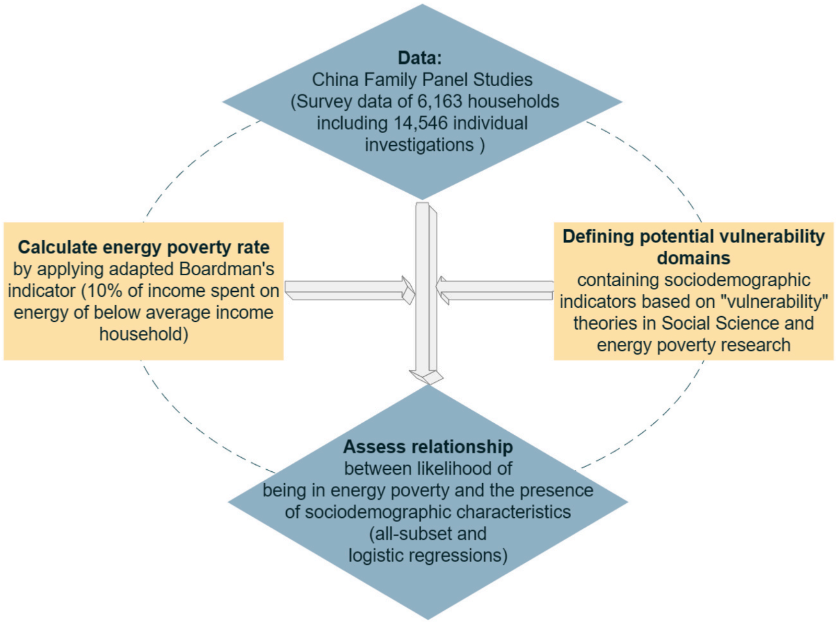

Fig. 1. Simple diagram of technical route and methods used in this paper.

by evaluating the importance of various sociodemographic characteristics on understanding energy poverty in China at household level, adding new insights to energy vulnerability research in the nation. We focus on the five potential vulnerability domains of housing and transport, education and employment, health, household structure, and social security, providing a comprehensive exploration of the links between household sociodemographic characteristics and energy poverty. This study is the first of its kind relating to the Chinese case.

3. Method

Fig. 1 shows the basic technical route and methods used in this study, we quantify the energy poverty rate by using the adapted Boardman “10%” indicator among Chinese provinces covering urban and rural areas based on comprehensive household survey data (CFPS). Then, we use socio-demographic information to identify potentially vulnerable groups, evidencing how the situation of different sociodemographic groups differs between EP households and non-EP households in the provinces studied. Through a logistic regression analysis, we estimate the relationship between likelihood of falling into energy poverty and various sociodemographic characteristics under five domains of potential vulnerability. We conclude by highlighting the need to take into account specific vulnerable groups when planning residential related energy policy and advocate targeted assistance to enhance energy poverty alleviation in this regard.

3.1. CFPS survey and case areas

The CFPS has the largest spatio-temporal scope and comprehensive household information amongst existing surveys in China which tracked baseline survey (2010) respondents and their families (n = 14,960 households and 42,590 individuals per survey round) for subsequent survey waves (2012, 2014, 2016, 2018). This study focuses on the most recent survey of 2018. The CFPS dataset contains household level data from 25 provincial level places[3] including 4 municipalities (Tianjin, Beijing, Chongqing, Shanghai), 1 autonomous region (Guangxi Zhuang Autonomous Region), and 16 provinces (Gansu, Guangdong, Henan, Jiangsu etc.), covering both urban and rural areas in China. The survey has two sample frames, one is called “large provinces” (Shanghai, Liaoning, Henan, Gansu, and Guangdong) that aims to recruit 8000 households to provide provincial level analysis. The other is called “small provinces”[4] surveying 8000 households in total across other 20 provinces to support national level analysis together with the “large provinces” data.

[3] China’s 34 provincial-level administrative regions including 23 provinces, 5 autonomous regions, 4 municipalities, 2 special administrative regions (Constitution of the People’s Republic of China).

[4] The ‘small provinces’ includes Jiangsu, Zhejiang, Fujian, Jiangxi, Anhui, Shandong, Hebei, Shanxi, Jilin, Heilongjiang, Guangxi Zhuang Autonomous Region, Hubei, Hunan, Sichuan, Guizhou, Yunnan, Tianjin, Beijing, Chongqing, Shaanxi.

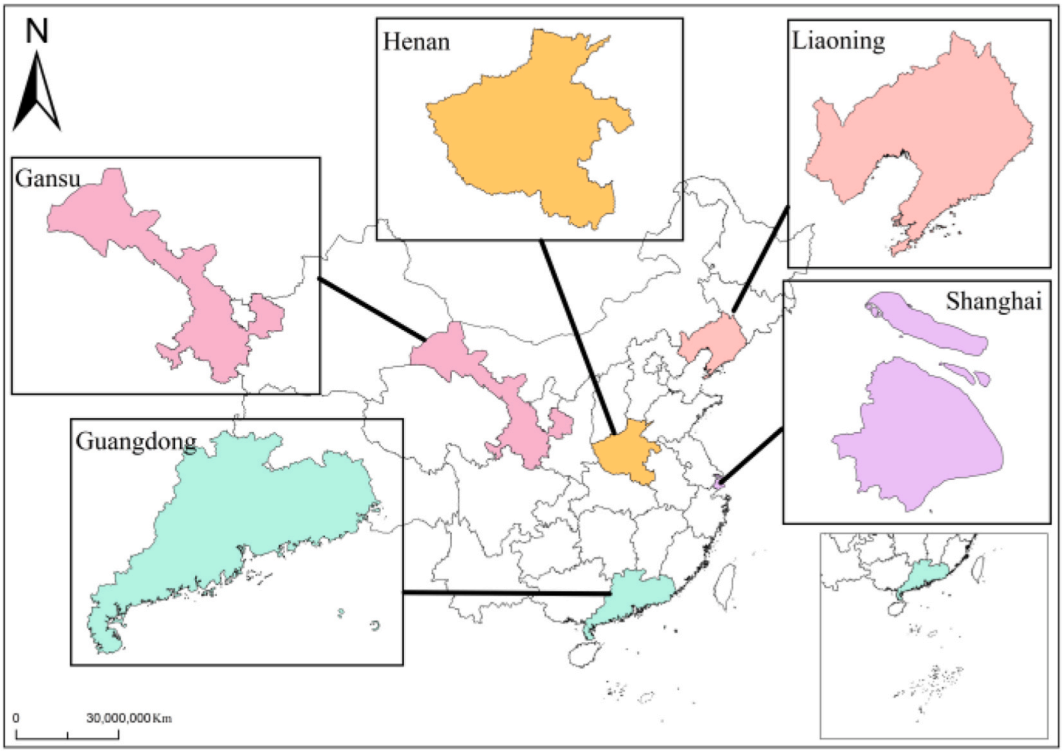

Fig. 2. Location maps of the five study provinces.

We used the data from the five 'large provinces' in our analysis. We did this because: (1) These provinces have sufficient sample size to facilitate analysis on household energy consumption and comparison at provincial scale, which can also bridge the gap of comprehensively reporting finer scale EP rather than national EP by using this dataset as in the work from Zhang et al. and Hong et al. [21,43]. (2) The geographical dispersion of these five provinces (shown in Fig. 2) provides a representative understanding of China's EP problem under different climates, especially the north and south.[5] (3) The geographical and socio-economic features of these five provinces also produce a diverse sample. (4) The sufficient data of these five provinces can support analysis on rural-urban division. In this study, we adopted the classification between rural and urban areas based on the statistics of administrative division from CFPS [44].

3.2. Energy expenditure, income, and energy poverty calculation

Table 1 summarizes the data used in this paper. Valid survey returns (6163 households including 14,546 individual surveys) are sufficient for the analysis we conduct. The CFPS was not explicitly designed to collect information about household energy consumption, however, it provides us with valuable information, for example, type of fuel used for cooking, house type, and family expenditures on energy use. We used household's expenditure data on electricity, fuels,[6] and heating in 2018 to measure the energy poverty rate at household level. We calculated annual energy expenditures per capita of each household for consistency. Two income types were investigated in the 2018 survey, variable 'Fincome1' indicates net family income in 2018, and variable 'Fincome2' indicates net family income in 2018 adjusting to a comparable price based on 2010 (The baseline survey year). Empirically, the use of income at comparable prices can reduce the impact of price changes over years. However, in this study, we choose to use variable 'Fincome1' as the household income in calculation since other household energy expenditures do not account for the comparable price calculations, so, this ensures the consistency of data used in this paper.

The "10% indicator" of EP counts households that spend over 10% of their income on energy as energy poor as proposed by Boardman [7] and widely used elsewhere among European countries [45]. This indicator is an absolute measurement focusing on affordable warmth, and domestic energy needs including lighting, heating water, appliance usage and cooking under various family

[5] The Chinese District Heating Policy provides winter district central heating from mid-November to mid-March in northern urban provinces located in cold climate zone which covers Gansu and Liaoning in our dataset.

[6] The fuels expenditure investigated among households in our sample refers to household-heating and cooking fuel costs, including natural gas, liquefied gas, coal, firewood, charcoal.

Table 1
Basic information of household samples from five provinces in 2018 used in this study.

Sample area	Guangdong	Gansu	Henan	Liaoning	Shanghai
Total	1462	1599	1511	1269	851
Urban	874	496	676	699	755
Rural	539	1089	819	585	80
Missing	49	14	16	12	16

size. A Before Housing Cost (BHC) definition of income is used to generate a ratio between fuel expenses and income. Practitioners often refer to the "10% indication" as the more understandable of the two classic energy poverty metrics (the other one is called "Low Income High Cost" indicator[7]), since the "LIHC indicator" significantly decreased the number of energy-poor families in the UK as a whole. While the "10% indicator" has drawn criticism for being overly susceptible to changes in the price of energy [8,46]. Thus, in our calculation, we adapted the "10% energy poverty indicator" by defining households that earn below the median level and spend over 10% on domestic energy as energy poor based on the real data in CFPS (thereby excluding wealthier households who are "over-consuming"). Wang et al. [11] point out that the commercial energy price is tightly controlled by the Chinese government through energy subsidies, which maintains commercial energy price relatively low compared with marked dominated of commercial energy price in some countries, such as UK. Thus, the measurement of EP in our work is based on the real costs in China. This means that we are likely to lose some of the 'under consumers' who are self-disconnecting and with abnormally low actual energy consumption: so, called 'Hidden Energy Poverty'[8] [47–49]. This is the best available indicator in the dataset we are working with here, although we recognize that it does not necessarily reflect the full picture of energy poverty in China.[9] Thus, the adapted 10% indicator should satisfy the two conditions as follows [19]:

$$condition\ 1: \frac{Domestic\ fuel\ costs/Family\ size}{Equivalized\ income\ (before\ housing\ costs)} \geq 0.1 \tag{1}$$

condition 2: Equivalized income < Median income (2)

where the Equivalized income is calculated as:

$$equivalized\ income = Disposable\ Income/Family\ size \tag{3}$$

3.3. Vulnerability domains and sociodemographic indicators

Vulnerabilities in households can result in the household falling into energy poverty, preventing them from accessing and affording the level of energy services needed for a decent life [5]. Chambers's definition of vulnerability (1989):

> Vulnerability thus has two sides: an external side of risks, shocks, and stress to which an individual or household is subject; and an internal side which is defencelessness, meaning a lack of means to cope without damaging loss. (Chambers, 1989: 33)

Emmel and Hughes' [50] developed this idea, showing that vulnerability involves relations between individuals and households and the institutions and services that address their basic needs. They conceptualize a longitudinal 'social space of vulnerability' with coordinates which relate to: (i) material shortages in households, characterized by 'making do' with limited resources for basic everyday needs; (ii) a lack of capacity to address needs in the present and plan for the future; and (iii) an uncertain reliance on welfare services acting to address crises when they happen.

Here, we categorize vulnerability domains and relevant sociodemographic characteristics to energy poverty by developing the above concepts in our dataset. The vulnerability notion in Social Science developed by Emmel and Hughes has identified three aspects consisting of material shortages, capabilities of household and uncertain welfares. Bouzarovski and Petrova theoretically constructed energy vulnerability framework which recognized six domains of energy vulnerability factors: Access, affordability, flexibility, energy efficiency, needs and practices [5]. Ongoing academic research on energy poverty has already empirically defined some of socio-demographic features (the old people, disability, single parent etc.) in contextualizing work (see Sections 1 and 2.2) [1,34,39,51,52]. Thus, based on the availability of the data in Chinese case, we identify five vulnerability domains: housing and transport, household structure, health, education and employment, and social security. These domains allow us to identify overlooked aspects in the Chinese context but are also constrained by the availability of the data in the CFPS. 20 sociodemographic characteristics are considered in this

[7] The UK government adopted a "Low Income High Cost (LIHC) indicator" instead of "10% indicator" during 2011–2021, to provide a relative measure of energy poverty (Hills, 2012). The fuel cost threshold is an equivalized, weighted median of the fuel costs of all households. The income threshold is calculated as 60% of the weighted median for income After Housing Costs (AHC).

[8] Hidden Energy Poverty (HEP) is specified by Herrero (2017) and Rademaekers et al. (2016), Chard and Walker (2016) and Yip et al. (2020) as households adopt under-consumption of energy as survival mechanism, that is, households interact with the built environment and rationing the needs of family members to consume less domestic energy. Thus, HEP tracks households with abnormally low actual energy consumption.

[9] Household' expenditure on 'housing' refers to any type of housing expenses in the year of the survey, including rent, loans, repairs, and maintenance, etc.

Table 2
Vulnerability domains and related sociodemographic categories to energy poverty identified in this study.

Vulnerability domain	Sociodemographic variable	Indicator
Housing and transport	Without car	Do you have cars?
	Lack clean cooking fuels	What type is your cooking fuel (Firewood, coal)?
	Without house ownership	Are you house owners (Employer real estate, public rental house, relatives and friends' houses)?
	Low house quality	What type is your house? (Bungalow, single-story house)
Education and employment	Poor own status	What extent is your satisfaction with your own status? (Low score)
	Poor life	What extent is your satisfaction with your life? (Low score)
	Poor job and income	What extent is your satisfaction with your job and income? (Low score)
	Unemployment	What is your current employment status?
	Low education	What is your latest and highest education qualifications? (Age $\geq$ 18 & no college/no school/illiteracy/half-illiteracy)
Health	Disability	Can you do outdoor activities independently? (50 > Age > 18 & cannot)[1]
		Can you eat independently? (50 > Age > 18 & cannot)
		Can you do kitchen activities independently? (50 > Age > 18 & can not)
		Can you take public transportation independently? (50 > Age > 18 & cannot)
		Can you go shopping independently? (50 > Age > 18 & cannot)
		Can you do cleaning activity independently? (50 > Age > 18 & cannot)
		Can you do laundry independently? (50 > Age > 18 & cannot)
		Can your hands reach the base of your neck? (50 > Age > 18 & cannot)
		Can your hands reach your lower back? (50 > Age>18 & cannot)
		Can you get up from your chair right away after sitting for a while? (50 > Age > 18 & cannot)
		Can you pick up the book on the floor? (50 > Age > 18 & cannot)
	Poor physical health	What is your physical health? (Unhealthy)
	Poor mental health	What is your mental health? (Most/often feel depressed)
Household structure	Mainly female	What is your gender? (Female > 1/2 family size)
	Large family size	How many people in your family? (Family size $\geq$ 5)
	Old people	What is your age? (Age $\geq$ 60)[2]
	Children	What is your age? (Age $\leq$ 15)[3]
	Single parent	What is your latest marriage status? (Widowed/divorced)
Social security	Rural Hukou[4]	What is your Hukou status? (Rural or urban)
	Without gov subsidies	Do you receive government subsidies?[5] (No)
	Without pension	Do you receive pensions? (Age $\geq$ 55 & no pension)

study which can be found in Table 2 below. The choice of these 20 sociodemographic variables is based on previous research on vulnerability, energy poverty [5], ongoing research on this topic [1,34,39,51,52], and the availability of data from CFPS.

50 > Age > 18[1]: we identified disabled people by two criteria: age range from 18 (legal age of adulthood in China) to 50 (the lowest threshold for retirement in China) and unable to do the activities in daily life. Age $\geq$ 60[2]: The statutory retirement age in China is 60 years old for male employees, 55 years old for female cadres, and 50 years old for female workers, thus, we defined people who are over 60 as old people here. Age $\leq$ 15[3]: China's Education Law stipulates nine-year compulsory education for school-age children and adolescents and exemption of related tuition fees and miscellaneous fees. This is the average age line for completing nine-year compulsory education. Hukou[4]: Refers to the legal documents produced by the Chinese administrative organs in charge of household administration of the state, which records and retain the basic information of the household population and is also a proof of identity for citizens. There have two divisions: Rural Hukou and Urban Hukou. Government subsiies[5]: Due to lack of specificity in original dataset, the subsidies here refer to any possible subsidies family receiving from the government, including subsidies of low-income, military, disability, coal-to-electricity, etc.

3.4. *The statistical model*

In order to assess the relationship between likelihood of being in energy poverty and households with sociodemographic characteristics, we perform a logistic regression analysis in this study and also add new of spatial insights by looking at the full sample, urban, rural, and each single province separately; we include whether a household is energy poor as the dependent variable in the regression model. Other sociodemographic variables under vulnerability domains are set as independent variables. This is the first such analysis on Chinese data. The unit of analysis is the household aggregating from 14,546 individual surveys, where we estimate the effects of various vulnerability factors on energy poverty at household level.

$$
\begin{aligned}
Logit(HH_{EP}) = \ln(HH_{EP} / (1-HH_{EP})) = \beta_0 + \beta_1 \bullet \textit{low house quality} + \beta_2 \bullet \textit{without car} + \beta_3 \bullet \textit{lack clean cooking fuels} + \beta_4 \\
\bullet \textit{mainly female} + \beta_5 \bullet \textit{old people} + \beta_6 \bullet \textit{poor physical health} + \beta_7 \\
\bullet \textit{poor mental health} + \beta_8 (\textit{low education}_i) + \beta_9 \bullet \textit{without pension} + \beta_{10} \bullet \textit{rural Hukou} \qquad (4)
\end{aligned}
$$

HH represents household unit, EP stands for whether a household is energy poor. Low house quality, without car, lack clean cooking fuels etc. represent significant sociodemographic variables in our model after significance tests of regressions. We found significant differences between EP households and non-EP households among these 10 variables in the total regression model. For regional models such as urban, rural, and each single province, the significances are at different levels.

4. Sociodemographic variations across space and between EP and non-EP households

4.1. Spatial distribution

Fig. 3 shows that sociodemographic characteristics that could potentially result in energy vulnerability are unevenly distributed among regions. Northern (Gansu and Liaoning) and central provinces (Henan) possess a greater proportion of the sociodemographic characteristics than eastern (Shanghai) and southern provinces (Guangdong). Table .3 categorizes the most different sociodemographic characteristics in each province in 2018. For example, households with old people, children, large family sizes, with rural Hukou, and with people of low education are more common in Henan (central China) and Gansu (western China) provinces in the sample. People in households with a disability represent 32.1% and 21.1% in Gansu and Henan. Central and western provinces have a higher proportion of old people and children in the household than eastern and southern provinces in the dataset. This is aligned with the result from The Sixth National Census[10]. Henan and Gansu have an average of 3.47 people in a household which is higher than the other three provinces we analyse. 6.8% old people in China (those over 60 years old) live in Henan. This distribution is somewhat influenced by the natural environmental conditions and historical factors that Henan province has the characteristics of a vast rural area, a large rural population, and a single industrial structure which resulted in the province including 38 'national-level poverty counties' and 15 'provincial-level poverty counties' [53]. Thus, the spatial distribution of specific household structure is related to levels of economic and cultural development.

For other provinces, households including someone with poor physical and mental health conditions are most prevalent in Guangdong and Gansu respectively. Gansu has the highest proportion of households with low housing quality. Liaoning has the highest proportion of households not receiving government subsidies or without pension. Aside from households without government subsidies and with old people, Shanghai presents the lowest proportion of other sociodemographic characteristics associated with vulnerability in these five provinces as the most developed province in our analysis. Thus, we can see, for vulnerability domain of housing and transport, Liaoning and Gansu have larger proportions of households; Liaoning also has a larger proportion of households vulnerable under the social security domain; Henan and Gansu have the highest proportion of households vulnerable under the household structure domain; however, variables in the health domain distribute across the 5 provinces. All these features may shape differences in domestic energy use.

4.2. EP and non-EP households

We found that households living at risk of energy poverty have a higher rate of most of the sociodemographic characteristics under the vulnerability domains in our dataset, especially households with low house quality, without pension, poor mental/physical health, and that lack clean cooking fuels. Firstly, based on income and energy expenditure data and according to Eqs. (1)–(3) (see Section 3.2), we can calculate the share of households living at risk of energy poverty (defined as households below the median income, spending more than 10% of household income on energy costs by using the adapted Boardman approach, see Fig. 4) is 16.4% in total. Urban areas show a more severe energy poverty situation (22.8%) than rural (10.7%) among these five provinces of 2018. This finding is interesting because, with some notable exceptions, previous studies have tended to neglect the urban aspect of energy poverty in China [10,19,20,54]. It is also useful to disaggregate the most important vulnerability factors that impact urban and rural energy poverty differently.

Fig. 5 shows differences of five potential vulnerability domains between energy poor and non-energy poor households. In Fig. 5, EP households have particularly high proportions of the characteristics in the and seem to have a stronger relationship with energy poverty than education and employment, heath, and household structure. Both energy poor and non-energy poor households have a high proportion of without car, low house quality, and rural Hukou in the surveys though these factors are higher among energy poor households. Additionally, energy poor households are also more likely to lack clean cooking fuels, not have pension, have old people and have low education level. In 2018, China's Ministry of Public Security announced that the rate of car ownership in China has reached 29.1%[11] which is roughly consistent with the data in our samples (31.9% of car ownership in non-energy poor household, and 13.8% of car ownership in energy poor households). 74.8% of energy poor households live in low quality houses where the building type is bungalow or single-/multi-storey house (Fig. 6) which are insufficiently equipped for very cold and very hot weather [10]. The majority of the sociodemographic characteristics we selected are higher among energy poor households, but some: household with unemployment, large family size, disability, without house rights and government subsidies are more common among non-energy poor households. 59.8% of non-energy poor households have not received government subsidies versus 40.5% of energy poor households. In contrast to existing research in neoliberal economies in the Global North, the price of energy is not a significant vulnerability factor

[10] The sixth National census is the sixth survey of the national population information in China. The State Council has decided to carry out the sixth national census in 2010. The standard time of the census is midnight on November 1. The census mainly surveys the basic situation of population and households including gender, age, education level. etc.

[11] The Ministry of Public Security of the People's Republic of China announced there were 409 million vehicle drivers in China of 2018 https://www.mps.gov.cn/, authors calculated the rate of car ownership based on this figure and national total population (1.405 billion people in China of 2018).

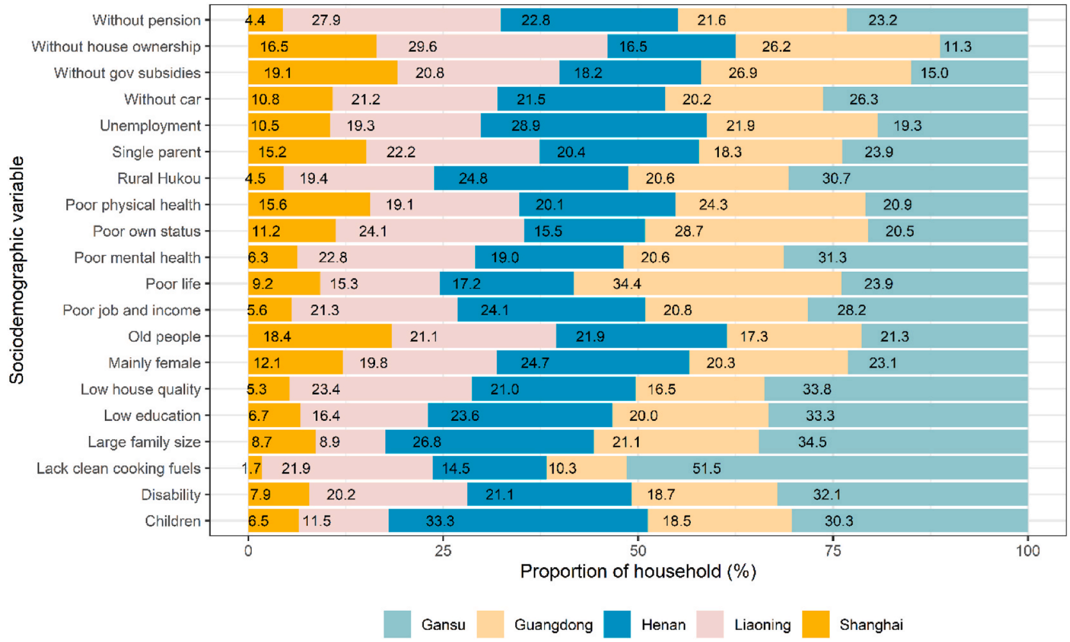

Fig. 3. Distribution of sociodemographic attributes associated with vulnerability among Chinese five provinces in 2018.

Table 3
Most common sociodemographic characteristics associated with vulnerability of five provinces in 2018.

Province	More likely to include	Less likely to include
Gansu	Lack clean cooking fuels; large family size; low house quality	Without house rights; without government subsidies; unemployment
Henan	Children; unemployment; large family size	Lack clean cooking fuels; poor own status; without house ownership;
Liaoning	Without house ownership; without pension; poor own status	Large family size; Children; poor life;
Guangdong	Poor life; poor own status; without government subsidies	Lack clean cooking fuels; low house quality; single parent
Shanghai	Without government subsidies; old people; without house ownership	Lack clean cooking fuels; without pension; rural Hukou

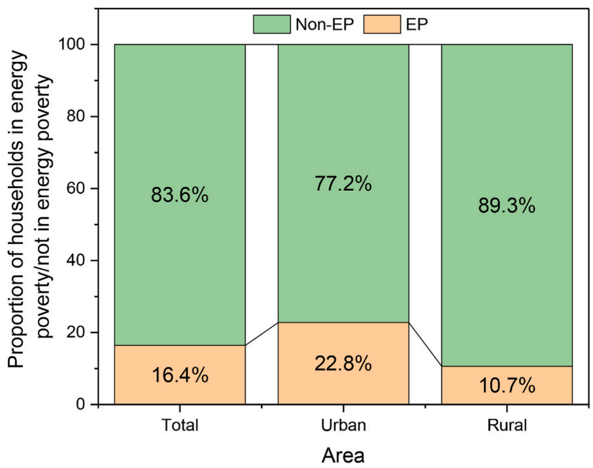

Fig. 4. Proportion of households in energy poverty in 2018.

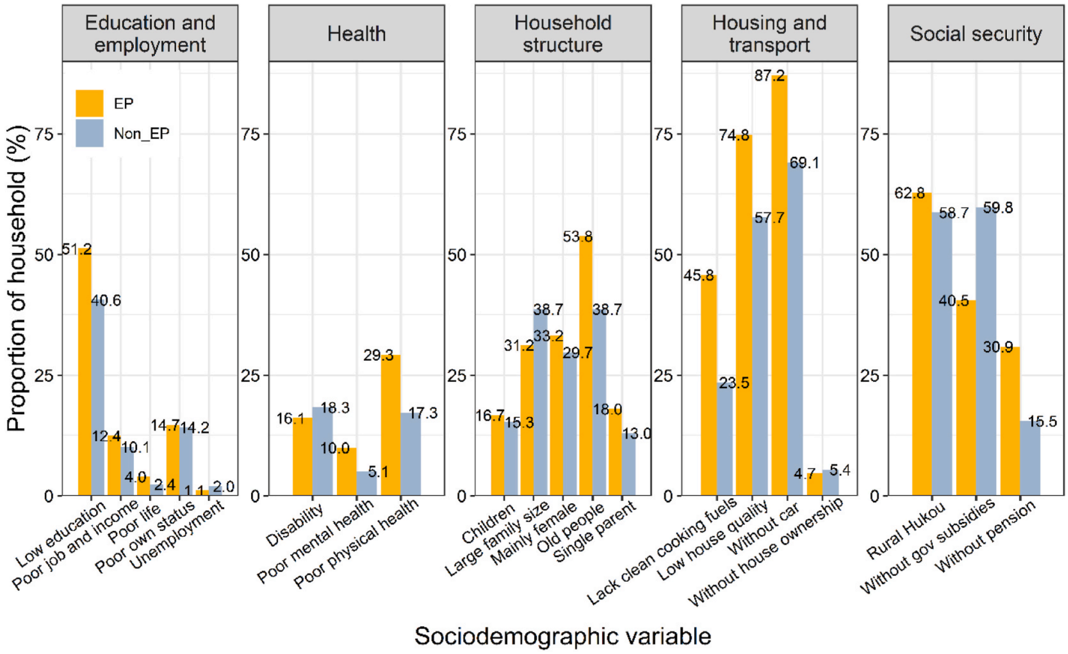

Fig. 5. Proportion of energy poor (EP) and non-energy poor (non-EP) households with a particular sociodemographic characteristic under vulnerability domains in Chinese five provinces of 2018.

Fig. 6. Examples of properties in Gansu categorized as bungalow/single-storey (the left) and multi-storey house (the right) (Source: Authors).

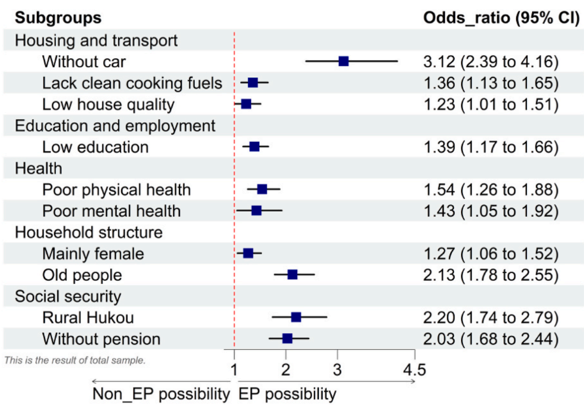

Fig. 7. Forest plot of logistic regression result for the total sample of five Chinese provinces in 2018.

with regards to energy poverty in China due to continued subsidies of domestic energy provision [10,17], however, energy deprivation still exists among energy poor households despite the fact that 59.5% of them received subsidies from government. Identifying the vulnerability factors which impact Chinese households suffering from energy poverty is vital to formulate related policies in an efficient way and to add novel insights to existing literature.

5. Statistical analysis

5.1. Significance test of variables

We ran the logistic regression according to Eq. (4) (see Section 3.4) and visualized the regression results for the five by plotting a Forest Plot (Fig. 7). We include the 10 sociodemographic variables that passed the significance test in the logistic regression model of the total sample. Variables right of the dashed red line in Fig. 7 to illustrate sociodemographic variables associated with an increased likelihood of experiencing energy poverty. We can see these 10 sociodemographic characteristics associated with increased likelihood of energy poverty; however, the intensity of the effect is varied. For example, households without a car, with old people, with rural-Hukou, and without pension have the strongest influence on likelihood of experiencing energy poverty. Low house quality and mainly female households have weaker effect on the likelihood of energy poverty compared to other sociodemographic characteristics. We can also find the accuracy of the estimation through the length/range of Confidence Interval on the plot of each variable. The variables lack clean cooking fuels, low education, mainly female have the most accurate estimation of the variables in the model since they have a narrower Confidence Interval than others. These statistically significant predictors of increased likelihood of EP can be regarded as vulnerability factors to household energy poverty we also tested the impacts of these factors on energy poverty in rural, urban areas, and each single province (see Section 4.2).

5.2. Logistic regressions

Detailed logistic regression results for the total sample, rural, urban, and each single province are included in Table .4. Fig. 8 depicts the coefficients plot of the sociodemographic influences on energy poverty likelihood for different sample areas of China in 2018 which we can find carless, old people, without pension households are more vulnerable to energy poverty than other sociodemographic characteristics in all samples. This is in line with the distribution of five vulnerability domains to energy poverty between energy poor and non-energy poor households (Fig. 5 in Section 3.2) that shows a larger gap of household without car, with old people, without pension between energy poor and non-energy poor households than other sociodemographic characteristics. For the total sample, household without car (coefficient 1.139) is the strongest predictors. Old people are vulnerable to energy poverty as many have fixed and often relatively low incomes based on superannuation or government pensions. Additional financial pressure can arise if old people have underlying health conditions that increase energy requirements [55]. In rural areas, households with old people have a greater effect on EP, with a higher coefficient of 0.891 than urban areas with a coefficient of 0.608. Though the Chinese government have implemented two types of endowment insurances[12] under the National Basic Pension Insurance System to realize social welfare and equity, there is a huge gap between the urban and rural endowment system regarding coverage and level. Yang and Yang indicate [56] the pensions of civil servants and intellectuals are almost 100 times higher than those of farmers: civil servants and intellectuals have a high retirement pension of up to 10,000 yuan per month, while farmers' pensions can be as low as 100 yuan and there are even some farmers who have no pension. These additional inequalities in social security would further exacerbate the domestic energy consumption difficulties faced by households with old people and definitely households without pensions. In addition, A lack of clean cooking fuels, poor physical health and rural-Hukou are other significant factors affecting likelihood of a household falling into energy poverty in both urban and rural areas. These findings give us novel understandings about urban and rural energy poverty.

Aside from the urban-rural division, different effects of vulnerability factors to energy poverty also exist among provinces. Henan and Gansu have more significant vulnerability factors than the other three provinces which is consistent with their spatial distribution of the majority of the sociodemographic characteristics as we analysed in Section 3.1. A lack of clean cooking fuels is an important factor influencing the energy poverty situation in Henan and Gansu with the coefficient of 0.417 and 0.257 respectively. This result partly aligns with the study from Hou et al. [57] that found that in 2011 rural households from Gansu, Liaoning, and Henan have a larger proportion of solid fuel use for cooking, (especially biomass and coal) than other provinces. Hou et al. indicate that the determining factors of the distance to the most commonly used farmer's market, education background, coal price and female labour participation to the high proportion of solid fuels use for cooking. While clean energy policy at national and local levels have been implemented since 2015, the use of solid fuel for cooking is still a limitation of energy poverty alleviation in western and central provinces in our sample. In Guangdong, there is a high proportion of mainly female household (20.3% see Fig. 3), Mainly female household is a stronger predictor of EP in Guangdong than elsewhere. Low education factor is more important in Gansu and Henan rather than other provinces. Shanghai has the least significant vulnerability factors to energy poverty as the most affluent region, however, the vulnerability factor of without pension is most significant here compared to other areas. In general, the social security vulnerability domain has significant effects on energy poverty among all these five provinces. Acknowledgement of these complex social-spatial vulnerabilities calls into question how energy poverty can be addressed more effectively among Chinese households?

[12] Till 2021, National Basic Pension Insurance System presents 65.76% in China's overall pension insurance system which includes two types: The Worker's Basis Endowment Insurance since 1991 and Social Endowment Insurance for Urban and Rural residents since 2009.

Table 4
Logistic regression estimates across sample areas.

Vulnerabilities	Variables	Total	Urban	Rural	Gansu	Liaoning	Henan	Shanghai	Guangdong
Housing and transport	Low house quality	0.206**	0.230	0.345**	0.244	0.054	0.154	0.591	−0.226
	Without car	1.139***	1.107***	1.205***	1.167***	1.575***	0.798***	1.776*	0.973***
	Lack clean cooking fuels	0.311***	0.312*	0.482***	0.257*	0.188	0.417**	−0.111	−0.056
Household structure	Mainly female	0.237**	0.243*	0.172	0.343*	0.275	−0.06	0.236	0.330*
	Old people	0.755***	0.608***	0.891***	0.872***	0.657***	0.968***	1.961**	0.353*
Health	Poor physical health	0.434***	0.620***	0.387***	0.827***	0.285	0.301	−1.189	0.610***
	Poor mental health	0.357**	0.604***	0.220	0.302	0.516	0.628*	1.010	−0.060
Education and employment	Low education	0.331***	0.169	0.480***	1.920***	−0.007	0.450**	−0.998	−0.036
Social security	Without pension	0.707***	1.188***	0.442***	0.518**	1.159***	0.284	2.378***	0.632***
	Rural Hukou	0.788***	1.066***	0.662***	0.317	0.982***	0.707***	0.585	0.331
	Constant	−4.794***	−4.797***	−5.135***	−5.725***	−5.169***	−3.924***	−7.284***	−3.526***
	Observations	6163	3229	2934	1518	1250	1407	781	1207
	Log Likelihood	−1838.02	−800.97	−1011.09	−484.764	−374.219	−426.177	−55.97	−404.345
	Akaike Inf. Crit.	3698.03	1623.94	2044.19	991.527	770.439	874.353	133.941	830.691

Note: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

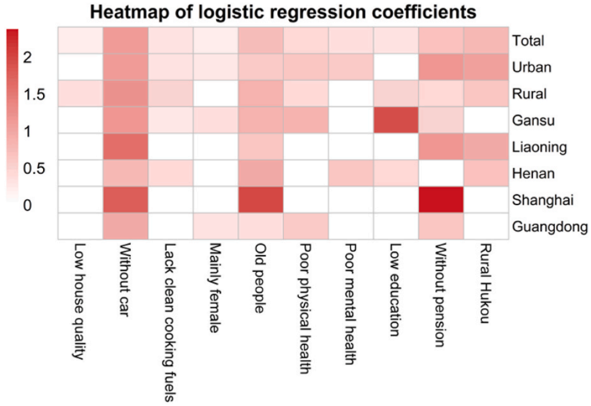

Fig. 8. Logistic regression coefficients visualization of the sociodemographic influences on energy poverty likelihood for different sample areas of China in 2018.

The significant positive influences of sociodemographic characteristics which significantly increase the likelihood of energy poverty are shaded red, the intensity of the colour indicates the magnitude of the coefficient, and the degree of influence. Sociodemographic characteristics with a negative or non-significant effect on the likelihood of energy poverty are white. Thus, the most obvious vulnerability factor of energy poverty across spaces can be found in this plot.

6. Conclusion and discussion

6.1. Conclusion: the vulnerability factors of energy poverty in China

This paper has begun to address an important gap in energy poverty and energy vulnerability research in China: the role that sociodemographic characteristics play in shaping and potentially ameliorating situations of energy poverty. Drawing on the CFPS survey data of 6163 households in five Chinese provinces, we have demonstrated how different sociodemographic characteristics affect vulnerability to energy poverty across different area types in China. Methodologically, we classified vulnerable domains to energy poverty by using 20 sociodemographic variables based on a vulnerability framework; identifying energy poverty rates by using the adapted Boardman's 10% energy poverty indicator and domestic energy expenditure and income data; and assessing the relationship between likelihood of being in energy poverty and households with sociodemographic characteristics using logistic regressions. In previous studies on Chinese energy poverty, scholars mainly concern about the measurement [17,21,43] and spatial differences of energy poverty [11,13,21,22,58–60], and rarely focus on the vulnerability factors of energy poverty. In this study, we found various sociodemographic features are disproportionately distributed across space and between energy poor and non-energy poor households. Spatially, Henan in central China, Gansu in western China have a larger proportion households with sociodemographic characteristics associated with vulnerability domains than other provinces, which is aligned to their lower levels of economic and social development in China. The socio-demographic characteristics in the vulnerability domains are more common amongst households experiencing energy poverty, illustrated through visualization of the data and logistic regression. This pattern of vulnerability factors increasing likelihood of energy poverty is observed at household level, when comparing rural and urban areas, as well as examining five provinces.

6.2. Policy implications

These findings point to a number of policy, practical and research implications which will allow a more nuanced understanding of who experiences energy poverty in what places as a result of which vulnerability factors. Double Energy Vulnerability (DEV) refers to the likelihood of experiencing negative impacts on wellbeing owing to the intersection of both Domestic Energy Poverty (DEP) and Transport Energy Poverty (TEP) has been found to be mostly a rural phenomenon in Europe by scholars [61–64], which uncovers households will experience trade-offs between whether to spend money on higher energy bills to sufficiently heat the home, or whether to fill the car with petrol, for example [61]. This is similar to the well-known 'heat-or-eat' phenomenon but has drawn less attention to date in the Chinese case. Our findings show carless households are found to be significantly vulnerable to energy poverty in China, while 31.9% of car ownership is in non-energy poor households, and only 13.8% of car ownership is in energy poor household in our sample (Section 3.2). This implies an indicative role of households without car in identifying who experiencing energy poverty in China. It is important to note that this is useful as an indicator, car ownership is indicative of relevant affluence. It would be a grave error to assume increased car ownership would cause a reduction in energy poverty. Energy poverty will not be solved by providing cars for such households, not least due to the potentially negative impacts on climate change commitments that this would represent.

There have been major achievements in energy poverty alleviation such as provision of electricity to all areas, and the pilot programme for clean heating implemented in some northern rural areas in 2017, which aims to replace coal with electricity and natural gas for heating in cold seasons. Xie et al. [17] explored heating energy poverty in northern rural areas of Beijing and Hebe regarding the implementation of a 'Clean heating program' in 2019. They found the overall energy poverty's breadth, depth, and gap have all increased due to the clean heating program,[13] especially, energy poverty is significantly increased by replacing coal with electricity and gas, while it is decreased by replacement with clean coal. In addition, those with lower income and no insulation for their houses are negatively affected to a larger degree of energy poverty. Our primary findings provide a more comprehensive analysis of the sociodemographic-energy poverty nexus regarding a household level distribution. Thus, "one policy for all" is likely to hurt vulnerable households in different places when helping to achieve sustainable goals. Our research contributes to developing more nuanced insights to energy poverty alleviation that calls the attention of policy makers to the most vulnerable households to energy poverty, especially with old people and those without pensions, and will also help policy makers to consider the distributional effects when designing energy transition and equality policies for a low-carbon and just economy and society.

6.3. Limitations and directions for further research

For further research, our findings point towards an important new research agenda to develop understanding of the socio-spatial vulnerability of energy poverty in China, and potentially a broader range of nations which lack political will to address this problem, or research on energy poverty. This paper reveals the influence of sociodemographic characteristics on the likelihood of energy poverty. Such an approach is useful to identify who is vulnerable to energy poverty, to consider how the different sociodemographic features impact on vulnerability to domestic energy use and energy poverty more broadly across spaces. The relationship between energy and society is co-productive; on the one hand energy availability and consumption establishes the parameters around the types of lifestyles that are possible, while on the other hand cultural and political-economic value systems guide the resources from which, and end-uses toward which, energy is expended. More to the point, physical energy flows and social energy demands are co-productive of socio-spatial relations [65–67]. The development of energy infrastructure has ethical implications which are not experienced evenly across space [5], and among society [34,64,68]. Decisions about which resources to prioritize and where to build new infrastructure (re)produce situations of energy poverty at more localized and household scales [69]. This research is applicable not only in China but in other nations which lack this kind of insight. Further research could explore how more detailed categories of each sociodemographic feature (e.g. people with different number/kind of disabilities, household receiving different kind of government subsidies) are distributed within and across households and spaces, and have access to policy and support. Future research can put an even stronger focus on how these socio-spatial effects on energy poverty, especially in the various local contexts where great differences can exist between and within nations. Additionally, the consequences of the energy crisis on domestic energy consumption since the COVID-19 epidemic should be taken into account in future studies [70].

Author contribution statement

Lin Zhang: Conceived and designed the experiments; performed the experiments; analysed and interpreted the data; contributed reagents, materials, analysis tools or data; wrote the paper.

Lucie Middlemiss: Conceived and designed the experiments; wrote the paper.

Ian Philips: Conceived and designed the experiments; wrote the paper.

Data availability statement

The authors do not have permission to share data.

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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