Sustainability Research Institute
SCHOOL OF EARTH AND ENVIRONMENT

UNIVERSITY OF LEEDS

Quantifying the spatio-temporal evolution of energy poverty in China from 2010 to 2018 through a representative household survey

Lin Zhang, Lucie Middlemiss, Ian Philips

March 2023

No. 124

SRI PAPERS

SRI Papers (Online) ISSN 1753-1330

First published in 2023 by the Sustainability Research Institute (SRI)

Sustainability Research Institute (SRI), School of Earth and Environment,
The University of Leeds, Leeds, LS2 9JT, United Kingdom

Tel: +44 (0)113 3436461
Fax: +44 (0)113 3436716

Email: SRI-papers@see.leeds.ac.uk
Web-site: http://www.see.leeds.ac.uk/sri

About the Sustainability Research Institute

The Sustainability Research Institute conducts internationally recognized, academically excellent and problem-oriented interdisciplinary research and teaching on environmental, social, and economic aspects of sustainability. Our specialisms include Business and organizations for sustainable societies; Economics and policy for sustainability; Environmental change and sustainable development; Social and political dimensions of sustainability.

Disclaimer

Quantifying the spatio-temporal evolution of energy poverty in China from 2010 to 2018 through a representative household survey

Email: eelz@leeds.ac.uk

Contents

Abstract

Building an understanding of energy poverty (EP) in China is crucial to deliver the dual goals of SDG 7 and China's '3060' decarbonization[1]. This paper aims to understand the substantial inequalities that exist in domestic energy provision by using surveys from the China Family Panel Studies[2]. We investigated the spatio-temporal evolution of EP in China at household level in Gansu, Liaoning, Guangdong, Henan, and Shanghai covering urban and rural areas during 2010-2018. First, households' income and energy expenses were analysed, then, two EP indicators - '10%' and 'Low Income High Costs'(LIHC) - were applied to estimate EP in the study areas. Finally, the two indicators were compared in terms of their applicability, and the EP measurement implications for China were examined. Results show EP is most severe for the lowest 20% income group, especially in Northern provinces than the South. We describe the trend in EP rates in rural and urban areas in the provinces studied and rural areas have higher EP rates than urban areas under both indicators. The '10% indicator' revealed the rural-urban gap as more substantial than under the 'LIHC indicator'. Based on these findings, we suggest it is time for China to develop an EP policy which accounts for the heterogeneity of experiences in the country. Policy also needs to focus on underlying causes, such as poor building efficiency and poor maintenance of pipeline and infrastructure which will hinder long-term EP prevention and affordable and clean energy efforts in the residential sector.

Key words: Energy justice; energy poverty; China; urban; rural; spatio-temporal.

Submission date [22-11-2022]; Publication date [28-03-2023]

About the Author

Lin Zhang is a Postgraduate Researcher at Sustainability Research Institute at the University of Leeds. Her research interests are energy justice and low-carbon transition. She currently works on the evaluation, driving factors, and polices of energy poverty in China.

Lucie Middlemiss is a Professor of Environment and Society at Sustainability Research Institute at the University of Leeds. Her areas of expertise are sustainable consumption, energy poverty, and sustainable community.
Ian Philips is a Senior Research Fellow at Institute for Transport Studies at the University of Leeds. His research is focusing on GIS and spatial analysis of sustainable transport planning, especially on socially equitable aspect.

---

[1] China's '3060' decarbonization target: China's government is committed to hit emissions' peak by 2030 and carbon neutrality by 2060 which was announced in September in 2020 by the President Jinping Xi. China's carbon emissions should start declining in 2030. And by 2060, carbon emissions should reach net zero.
[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 Section 3.

1. Introduction

A dedicated and stand-alone goal on energy, SDG 7, to “ensure access to affordable, reliable, sustainable and modern energy for all" is included in Sustainable Development Goals (SDGs) of UN’s 2030 Sustainable Development Agenda, which highlights the disproportionate impact that injustice in the provision of, or access to, energy services is having upon marginalized groups of people (UN, 2015). Energy access is not universal, and SDG 7 raises questions of poverty and vulnerability caused by poor distribution, unaffordable supply, and unstable provision. These challenges lead to people failing to meet their daily needs, maintain good health, and live comfortably. The challenges of meeting people’s energy need under specific socio-spatial relations are echoed in SDG 7 of UN’s Sustainable Development Goals, recognizing a need for contextualized EP research which intended to explore where ‘individuals or households are not able to adequately heat/cool or provide other required energy services in their homes at affordable cost’ (Thomson and Bouzarovski, 2018).

Globally, EP is a well-established and persistent agenda in policy and academic research within many western countries and institutions: United Kingdom (Boardman, 1991; Middlemiss, 2016; Baker et al., 2018; Middlemiss et al., 2018; Robinson, 2019; Hargreaves and Middlemiss, 2020), Poland (Buzar, 2007), International Energy Agency (Birol, 2007; IEA, 2010), European Union (Thomson et al., 2017; Dobbins et al., 2019; Saheb et al., 2019; Bouzarovski et al., 2021), United Nations (Bouzarovski et al., 2012; UNDP, 2019), France (Isolde, 2015), Spain (Romero et al., 2018), United States (Bednar and Reames, 2020), Slovakia (Strakova, 2014; Koďouskov´a and Boˇruta, 2022). In contrast, China does not recognize EP and lacks a strategy that encompasses definitions, reduction objectives and periodic evaluation in policy agenda. Despite this, a limited amount of research into EP in China has been ongoing since 2000 (Li et al., 2011; Tang and Liao, 2014; Wang et al., 2014b; Wei et al., 2014; Wang et al., 2015; Wu and Zheng, 2016; Yang et al., 2017; Robinson et al., 2018b; Zhao et al., 2018; Jiang et al., 2020; Xia et al., 2022; Xie et al., 2022). Existing research tends to focus on either urban or rural areas (Wang et al., 2015; Zhang et al., 2019; Lin and Wang, 2020; Dong et al., 2021), highlighting the different effects of EP in one or the other.

More attention is paid to rural EP in China (Pachauri and Jiang, 2008; Xie, 2010; Démurger and Fournier, 2011; Li et al., 2011; Hao et al., 2014; Tang and Liao, 2014; Liao et al., 2016; Tang et al., 2016; Xie et al., 2022). There are few studies focusing on EP in single urban areas in China (Robinson et al., 2018b), or comparing research between urban and rural areas, relative to a larger number of explorations of EP in rural areas. Relatively little attention has been paid towards variation in EP arising from the district heating facilities in urban areas in northern China which are not available elsewhere (Robinson et al., 2018b; Xie et al., 2022). The temporal trends of EP in China and the policies behind these temporal trends have also been neglected among these limited existing studies. These gaps in the literature formed the inspiration for our study.

In this paper, we offer a detailed analysis of the problem of EP in China, articulating its specific nature and geographical diversity. We draw on data collected at the household level, which after considerable processing can be used to calculate two commonly used indicators: (the '10%' in which a household spend over 10% of their disposable household income (Boardman 1991) and the Low Income High Cost 'LIHC' indicator in which energy poor households have both below average income and above average energy costs (Hills 2012.). We then describe the development of EP in China geographically and temporally. We use these indicators to compare five regions of China, looking at the evolution of EP and its spatial distribution, regionally and in urban or rural areas. We comment on differences in the two methods of measuring EP as well as describing the rates of energy poverty in the provinces over time. In doing so, we show that it is possible to generate EP metrics even though China does not gather data explicitly for this purpose. We also describe the underpinning income and cost data used in the creation of these indicators. This offers a greater understanding of the problem of EP in China and offers new insights for researchers and policy makers. We conclude by making recommendations for an EP reduction strategy in China.

2. Literature review

2.1 Recognition of energy poverty

Various EP metrics have been configured, defined and experienced in different ways around world but there is no unanimously adopted definition of EP (Boardman, 1991; Pachauri et al., 2004; Nussbaumer et al., 2012; Bouzarovski and Petrova, 2015; Day et al., 2016; Thomson et al., 2017; Thomson and Bouzarovski, 2018; Middlemiss et al., 2019; Bednar and Reames, 2020; Robinson and Mattioli, 2020; Sareen et al., 2020; Bouzarovski et al., 2021). Table 1 gives a summary of the various ways of defining EP. The contemporary academic understanding of EP is that it is a multi-faceted and complex problem that has different characteristics in different places and for different people. Many nations and scholars have opted to have multiple indicators in order to reflect this complexity (Hills, 2011; Baker et al., 2018; Energy Poverty Action, 2019).

The UK is widely perceived to be a pioneer of the EP (also termed 'fuel poverty' in UK) agenda (Boardman, 2010; Hills, 2012). There are three indicators developed: the '10%' threshold adopted before 2011, for recognizing households that suffer EP issues which refers to the expenditure on energy as a percentage of disposable income exceeding 10% (Boardman, 1991); the 'Low Income High Cost (LIHC)' indicator adopted during 2011-2020, which defines a household as EP if it has a lower income and higher energy costs than average (Hills, 2012); and the most recent 'Low Income Low Energy Efficiency (LILEE)' metric, which is based on the new measurement of the Fuel Poverty Energy Efficiency Rating (FPEER) combined with disposable income data after housing costs and energy needs which is below the poverty line (National Statistics, 2022). Energy poverty knowledge in the rest of Europe is less developed, although a wider range of approaches has been used. Three main methods of measurement can be identified through these studies: 1) expenditure approach, where examinations of the energy costs faced by households against absolute or relative thresholds provide a proxy for estimating the extent of domestic energy deprivation; 2) consensual approach, based on self-reported assessments of indoor housing conditions, and the ability to attain certain basic necessities relative to the society in which a household resides; 3) direct measurement, where the level of energy services (such as heating) achieved in the home is compared to a set standard. Single country studies conducted in Ireland (Healy and Clinch, 2002), France (Dubois, 2012; Legendre and Ricci, 2015), Greece (Katsoulakos, 2011; Santamouris et al., 2013), Poland, the Czech Republic and Hungary (Bouzarovski et al., 2016), Spain (Phimister et al., 2015), Italy (Miniaci et al., 2014), Denmark (Nierop, 2014), adopted expenditure approach, direct measurement or a combination of these two metrics to evaluate energy poverty. Also, studies in Germany (Heindl, 2015), adopted a consensual approach. There is also an established body of comparative research, focusing on the EU specifically (Consortium, 2009; Dubois and Meier, 2016; Bouzarovski and Tirado Herrero, 2017a, b; Healy, 2017; Thomson et al., 2017), and on Central and Eastern Europe and Central Asia (Energy, 2003). These studies have resulted in a range of metrics and indicators (See Table 1). We can be aware from these various EP metrics across countries, that EP is sensitive to regional contexts, as well as to individual behaviour, climatic, and sociodemographic characteristics.

Globally, a growing body of literature addresses geographical differences in EP to varying degrees, at different scales. Research has produced national comparisons (Pachauri and Jiang, 2008; Thomson and Bouzarovski, 2018); regional comparisons within one nation (Gillard et al., 2017; Robinson and Mattioli, 2020); disaggregation of national policy to small areas, and area-based targeting to supplement national indicators (Walker et al., 2012; Simoes et al., 2016); bottom-up indicators that explore a wider range of spatial inequalities (Reames, 2016; Reames et al., 2018); and spatially-orientated indicators that account for the spatial variability in the importance of EP drivers (Robinson et al., 2019).

Table 1 Energy poverty indicators and metrics from previous work

Dimension	Source	Description	Deprivation issues	Research area
Accessibility	(Pachauri and Spreng, 2004; Bazilian et al., 2014)	Poor availability of energy carriers appropriates to meet household needs.	Access to modern energy infrastructure; Sufficient appliance to meet household energy needs	Developing countries
Affordability	(Boardman, 1991)	High ratio between cost of fuels and household incomes, including role of tax systems or assistance schemes. Inability to invest in the construction of new energy infrastructures.	High or rising energy prices; Low household incomes;	Developed countries

Efficiency	(Rudge, 2012)	Disproportionately high loss of useful energy during energy conversions in the home.	Inefficient building environment, Inefficient heating or cooling system, Other outdated appliance stocks	Developing and developed world
Flexibility	(Bates et al., 2012)	Inability to move to a form of energy service provision that is appropriate to household needs.	Limitation for adequate facilities for cooking, lighting, electricity, heating etc.	Developing and developed world
Practices	(Bates et al., 2012; Bouzarovski and Petrova, 2015)	Lack of knowledge about support programs or ways of using energy efficiently in the home.	Unfavorable education level, energy cognition and related government propaganda	Developed world
Relationships	(Middlemiss et al., 2019)	The connection between social relations and energy poverty is recursive: good social relations can both enable access to energy services and be a product of such access.	Relationships with family, friends, agencies, and distant others impact on people's ability to cope with energy poverty, such as access to a range of resources, membership of particular collectivities, the need to perform social roles, and the common reasons used to explain poverty and energy use	Developed world
Governance	(Bednar and Reames, 2020)	Governmental program eligibility requirements and congressional funding appropriations shape the national understanding and implementation of energy poverty assistance.	Measurement and evaluative metrics hinge on the distribution of government resources and the number of vulnerable households assisted, rather than improving household well-being and reducing overall energy poverty	In the United States at the federal level

2.2 Measuring energy poverty in China

The limited existing studies recognized EP in China predominantly used an expenditure approach (Zhang et al., 2019; Hong et al., 2022; Xie et al., 2022), a rate of solid fuels use (Tang and Liao, 2014; Zhang et al., 2019; Hong et al., 2022), and multidimensional measurement (Wang et al., 2015; Dong et al., 2021) by quantitatively analysing a combination of national statistical data and surveys.

Expenditure approach is one of the most commonly used methods under affordability aspect, in which the energy costs faced by households against absolute or relative thresholds provide a proxy for estimating energy poverty. Among the most enduring EP thresholds is the 10% which shaped by definitions from the UK. Using the rate of solid fuels use to examine EP foregrounds the accessibility aspects of modern energy services. The studies from Zhang et al. (Zhang et al., 2019) and Hong et al. (Zhang et al., 2019; Hong et al., 2022) both examined EP households by adopting a combination of expenditure threshold method and the proportion of solid fuels use for cooking, analysing

CFPS survey data. Zhang et al. generated a multidimensional proxy by combing the two dimensions of expenditure threshold and solid fuels proportion using an equal weighted method, they identified EP rate in China is 57.78% in 2012 which then fell to 48.98% in 2016. Hong et al. mainly used the two dimensions as substituted variables for EP and adopted the proportion of firewood use for cooking (at the proportion of 30.53%) rather than coal use for cooking (at the proportion of 5.41%) of 2018. Zhang et al. and Hong et al. (Zhang et al., 2019; Hong et al., 2022) both linked EP with concerned aspects of clean energy and health's impacts. Wang et al. (Wang et al., 2015) comprehensively evaluated EP in China from 2000 to 2011 by constructing an index consisting of energy service availability, energy consumption cleanliness, energy management completeness, and household energy affordability and energy efficiency including indices of electricity consumption, and ownership of air-conditioners etc.. They found Anhui, Henan, Hebei, Shanxi, and Jiangxi are provinces with severe EP in China from 2000 to 2011 and Anhui province ranked 1st among China's 30 provinces with average index value of 87 by applying multidimensional index approach on statistical data of Chinese provinces. The choice of indicator depends on the research question, the accessibility of the data and the spatial scale of data.

More recent work from Lin and Wang (Lin and Wang, 2020) observed EP in China by using electricity consumption data from the Chinese General Social Survey of 2014 at household level . They identified EP exists in China at the proportion of 18.9% by adopting the '10%' and 'LIHC' indicators from the UK. The temporal downward trend of EP in China has been observed during 2000-2011 at provincial level (Wang et al., 2015), and during 2012-2016 at national level (Zhang et al., 2019). There is room for further evaluation of EP from the spatial and temporal perspectives. In 2020, Yip et al. (Yip et al., 2020) criticized the applicability of '10% indicator' based on expenditure approach when looking at Hong Kong context and first qualitatively captured EP in Hong Kong by using data from five in-depth household case studies and 14 semi-structured interviews by taking the lived experience of households as their central lens. They point out the significant needs for space cooling, and health dangers of hot summer nights in Hong Kong due to the unusual legal-political factors arising from subdivided rental apartments, in combination with extreme hot weather conditions. Yet, to date, relatively few studies tried different approaches to capture EP emerging from different regions in China offering a need for comparing and contextualizing the suitable evaluation of Chinese EP more precisely at household level to formulate targeted polices for EP alleviation.

2.3 Gaps in the literature

In China most EP studies have been conducted using data aggregated to national and regional scale (Zhu, 2007; Li et al., 2011; Zhu and Ye, 2012; Wang et al., 2015; Wu and Zheng, 2016; Xue, 2017; Zhang et al., 2019). Zhang et al. (Zhang et al., 2019) narrowed down the spatial scale to provincial level by using CFPS household data, however, CFPS pointed that only 'large provinces' (Shanghai, Liaoning, Henan, Gansu, and Guangdong) have sufficient samples to support comparison and inference at provincial scale (CFPS, 2017). Thus, their analysis limited them to reporting a national level indicator. Wang et al. (Wang et al., 2015) investigated both the 30 provinces and 8 economic regions in China to show different characteristics of EP from 2000-2011 using statistic data. Very few EP studies in China have been conducted at a finer spatial resolution or using household data to derive provincial averages. Lin and Wang (Lin and Wang, 2020) measured EP by using a single annual household electricity survey to report EP at regional level.

Compared to the macro scales studies above, Xie et al. (Xie et al., 2022) 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 EP breadth, depth, and gap have all increased due to the clean heating program[3], in detail, households facing clean energy retrofit need to weigh budget versus availability of basic energy services. They found energy poverty is significantly increased by replacing coal with electricity and gas, while it is decreased by replacement with clean coal. In addition, energy poverty became severer amongst vulnerable households, especially those with lower income and no insulation for their houses are negatively affected to a larger degree of energy poverty. Robinson et al. (Robinson et al., 2018b) paid attention to EP research from a thermal comfort perspective based on household surveys including 800

[3] The main goal of the program in the studied areas is to transition household heating energy from coal to cleaner energy. This is because the studied areas are in Northern China, where heating by coal is one of the major sources of air pollutants and carbon emissions.

respondents across 12 districts in Beijing of China. They highlighted vulnerabilities such as inefficient networked infrastructures and low quality of built environment, that increase the likelihood of households being unable to access adequate heating in the home across urban areas. Zhang et al. (Zhang et al., 2019) also pointed out that EP remains a critical issue in urban areas. This revealed the deep inequalities in domestic energy provision that exist in more affluent city regions in China. There remains considerable need for micro level studies of household EP which can disaggregate between rural and urban contexts and between different provinces. We note as well that most EP studies are cross sectional rather than longitudinal revealing a further research gap.

Evaluating EP is a prerequisite of understanding and formulating suitable policies for alleviating EP. There are no statistical yearbooks or specific surveys in China which comprehensively investigate household energy consumption data. A multidimensional approach using macro scale data hides some of the spatial differences (e.g., the district heating division between northern and southern China). Household level data is usually used to report cross-sectional and national EP with a lack of understanding at a micro spatial scale across time. This paper aims to develop further understanding of evaluation and spatio-temporal variation of EP in China. We do this through processing the CFPS in a way which allows us to calculate the adapted '10%' and 'LIHC' indicators for rural and urban areas in different provinces and assess the longitudinal trend between 2010 and 2018.

3. Data and methods

3.1 Data source

In the section that follows we explain the use of a processed version of the 'China Family Panel Studies' (CFPS), a series of household questionnaire surveys containing domestic energy consumption data, and we also summarize our method of calculating the '10%' and 'LIHC' indicators using this dataset.

3.1.1 Scale of analysis

The CFPS has the largest spatio-temporal scope and comprehensive household information amongst existing surveys in China. CFPS tracked baseline survey (2010) respondents and their families (n = 14,960 households and 42,590 individuals per round) for subsequent survey waves in 2012, 2014, 2016, and 2018.

The CFPS dataset contains household level data from 25 provincial level places[4] 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. It has two sample frames, one is called ‘large provinces’ (Shanghai, Liaoning, Henan, Gansu, and Guangdong) that aims to recruit 8,000 households to provide provincial level analysis. The other is called ‘small provinces’ [5] surveying 8,000 households in total across other 20 provinces to provide national level analysis combined with data from ‘large provinces’.

We selected the data from the five ‘large provinces’ in our analysis. The reasons for only focusing on ‘large provinces’ sample frame are: (1) These provinces have sufficient sample size to facilitate analysis of household energy consumption and comparison at provincial scale, which can also bridge the gap of reporting a finer scale EP rather than just national EP by using this dataset through the work from Zhang et al. and Hong et al. (Zhang et al., 2019; Hong et al., 2022). (2) The geographical dispersion of these five provinces (shown in Fig. 1) provides a representative understanding of China’s EP problem by different climate zones. (3) The various geographical and socio-economic features of these five provinces are conducive to the study of spatial differences of EP.

[4] 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).
[5] 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.

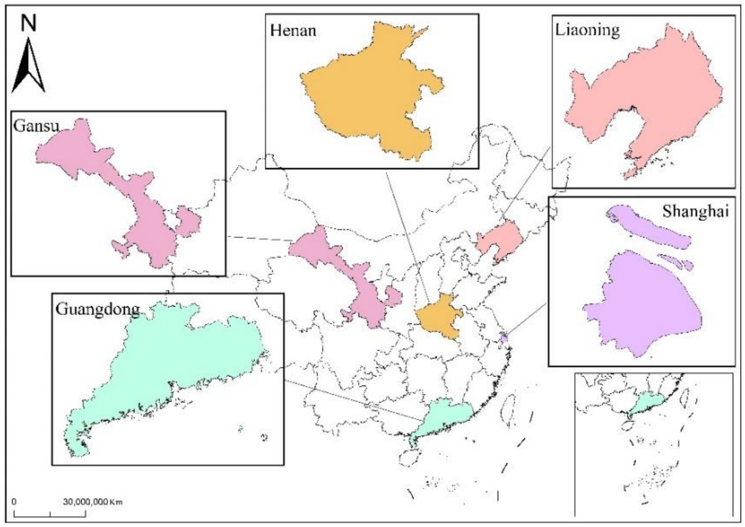


Fig. 1. Location maps of the five study provinces

3.1.2 Data description

Table 2 summarizes the data used. CFPS was not explicitly designed to collect information about household energy consumption, however, it still provides us with valuable information, for example, type of fuel used for cooking, family expenditures on energy use.

Table 3 lists the variables used in this paper to measure EP at household level. The precise collection of household energy expenditures was adjusted in each wave. Household's expenditure on electricity, fuel, and heating are all included in the five surveys from 2010 to 2018 which are key energy activities in household daily life despite the slight adjustment of statistical items (Day et al., 2016; Yip et al., 2020). In particular, we calculated annual energy expenditures per capita of each household, thus, the electricity and fuels expenditures have been adjusted to annual costs for data consistency.

Household income and housing cost data were also included since they play a vital role in affecting household energy choice and cost, and also in the calculation of 'LIHC' indicator (Robinson et al., 2018a). Two income types were investigated in these surveys, in the 2012 survey, variable 'Fincome1' indicates net family income from 2011 to 2012, and variable 'Fincome2' indicates net family income from 2011 to 2012 adjusting to a comparable price based on 2010. 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’s energy expenditures do not account for the comparable price calculations, so, this ensures the consistency of data for each survey year.

Table 2
Description of sample size in five provinces

Province	2010			2012			2014			2016			2018		
	Total	Urban	Rural	Total	Urban	Rural	Total	Urban	Rural	Total	Urban	Rural	Total	Urban	Rural
Guangdong	1394	784	610	1187	644	534	1293	715	574	1332	780	503	1462	874	539
Gansu	1537	297	1240	1494	285	1192	1490	357	1132	1527	408	1105	1599	496	1089
Henan	1506	612	894	1466	627	831	1544	679	853	1518	634	868	1511	676	819
Liaoning	1478	856	622	1378	715	635	1381	744	630	1361	692	613	1296	699	585
Shanghai	1405	1166	239	1039	814	205	1011	824	185	919	766	125	851	755	80

Table 3
Variables used in this paper

Year	Variables
2010	Expenditure on electricity last year (yuan) Expenditure on housing last year (community management, heating, etc.) (yuan) House costs (yuan)
2012	Expenditure on electricity last month(yuan) Expenditures of heating Housing costs (yuan)[6] Expenditure on fuel last month(yuan)[7]
2014-2018	Monthly expenditure on electricity (yuan) Payment for heating system (yuan) House costs (yuan) Monthly expenditure on fuels (yuan)

3.2 Methods

In this paper, we scrutinize the spatio-temporal distribution of EP yielded by the ‘10%’ and ‘LIHC’ indicators based on our dataset. We seek to understand whether the ‘10%’ and ‘LIHC’ indicators are applicable in representing EP in the Chinese case.

3.2.1 ‘10%’ energy poverty indicator

The ‘10% indicator’ of EP counts households who spend over 10% of their income on energy as energy poor. This indicator is an absolute measurement focusing on affordable warmth, and domestic energy needs including lighting, heating water,

[6] Household’ expenditure on ‘housing’ refers to any type of housing expenses in the year of the survey, including rent, loans, repairs, and maintenance, etc..
[7] Household’ expenditure on ‘fuels’ refers to self-heating and cooking fuel costs, including natural gas, liquefied gas, coal, firewood, charcoal, etc. Household’ expenditure on electricity, heating, fuels, and housing all unified as annual expenditure per capita of household.

appliance usage and cooking. A ratio of modelled fuel costs and income is calculated using a Before Housing Cost (BHC) definition of income. Modelled fuel costs are derived from energy price and a modelled figure of 'required' consumption that takes into account property size, the number of people in the household, energy efficiency and the mix of fuels used (Simcock et al., 2018). We applied this concept on the calculation of Chinese EP rate through the corresponding dataset. For the calculation of equivalised income, we consider the real household size rather than weight household regarding the number of children, adults, or old people to be consistent with the fuel costs' calculation. In our EP calculation based on CFPS surveys, the '10% indicator' should satisfy the two conditions as follows (Lin and Wang, 2020):

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

$$condition\ 2: Equivalized\ income < Middle\ income \quad (2)$$

Where the Equivalized income is calculated as:

$$Equivalized\ income = Income/Family\ size \quad (3)$$

3.2.2 'LIHC' energy poverty indicator

The UK government adopted a 'Low Income High Cost (LIHC) indicator' instead of '10% indicator' during 2011 to 2021, to provide a relative measure of EP (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). The income figure for each household is equivalized and combined with the equivalized fuel costs of the household. Therefore, the income threshold is higher for those households that require a greater level of income to meet larger fuel bills to avoid a situation of high income and high costs. EP under the 'LIHC indicator' should satisfy the two conditions as follows (Lin and Wang, 2020):

$$Equivalized\ net\ income \leq 60\%\ Equivalized\ median\ net\ income \quad (4)$$

$$Equivalized\ fuel\ costs \geq Required\ median\ fuel\ costs \quad (5)$$

Where the Equivalized net income is calculated as:

$$Equivalized\ net\ income = \frac{Disposable\ income - Housing\ cost - Domestic\ fuel\ costs}{Family\ size} \quad (6)$$

'10% indicator' has been critiqued for being too sensitive to fluctuations in energy price (Hills, 2012; Moore, 2012). Considerable examination and critique of both indicators exists (Boardman, 2012; Moore, 2012; Middlemiss, 2016), not least because the introduction of the 'LIHC indicator' led to a considerable reduction in the overall count of energy poor households in the UK. In practice, the 'LIHC indicator' was used by the UK government between 2011-2021 to fulfil its statutory targets, whilst the '10% indicator' is commonly referred to by practitioners as the more comprehensible of the two (Robinson and Mattioli, 2020). However, there is no existing EP research to comprehensively apply these two indicators in China comprehensively at household level and consider spatial and temporal context. We analysed the results and applicability of these two indicators in the following sections.

4. Income and energy expenses

Due to EP being highly related to households' income level and energy consumption, we start by getting an understanding of these variables' distributions among our household samples before generating the EP rate.

4.1 Household income level

Firstly, we referred to the income grouping method of the China Statistical Yearbook to avoid high-income high-consuming households being marked as energy poor under '10% indicator' and defined those learning less than 60% median income as low income. Fig. 2 compares the three lower quintile income groups (bounded by the 20%, 40% and 60% percentiles based on real income data of households in our dataset) which we use in the EP calculations. We used the descriptions of '1st quintile', '2nd quintile', '3rd quintile' below throughout the article to depict these three income groups.

Fig. 2 shows a generally rising trend of households' income from 2010 to 2018 in both rural and urban areas. In addition, differences in income can be seen between provinces; considerably higher income in eastern provinces (Shanghai, Guangdong, and Liaoning), less in central (Henan), and even less in western (Gansu). This is in line with the current pattern of economic development in China. Shanghai's per capita income is much higher than the other four provinces regardless of income quintile and the division of rural and urban. In the 1st quintile, rural households' income per capita in Shanghai is approximately four times than that in Gansu province, and 3.5 times higher in urban households. The geographical disparities of households' income exist between rural-urban and among the five provinces regardless of the improved economic situation during study years.

Fig. 3 and Fig. 4 show income disparities among different groups. We compared the 1st and 3rd quintiles. Income disparity is greater in urban than rural areas. The largest disparities are in Shanghai province. Fig. 3 shows the income gap between 3rd and 1st quintiles in rural households increased between 2010 and 2018. Fig. 4 shows an increasing income disparity trend from 2010 to 2018 also exists between the 1st and 3rd quintiles in urban households. The geographical differences (including rural-urban areas and different provinces) and differences among income quintile groups will impact household disposable income, and likely shape the differences in household energy consumption.

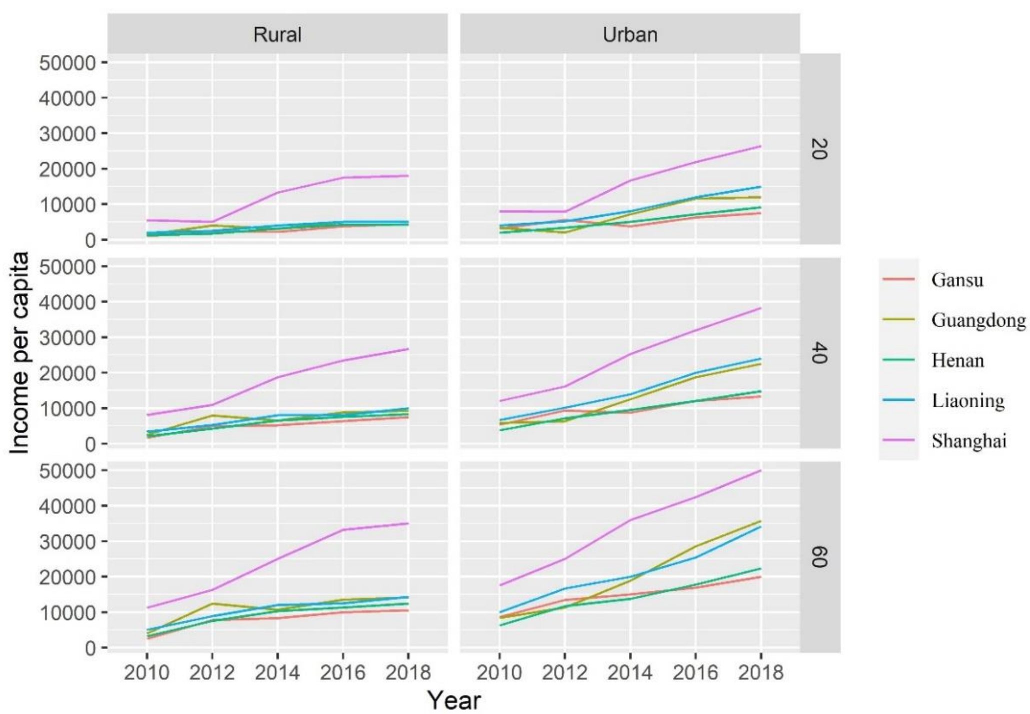


Fig. 2. Mean income per capita of the 1st, 2nd and 3rd income quintiles of household in five provinces from 2010 to 2018

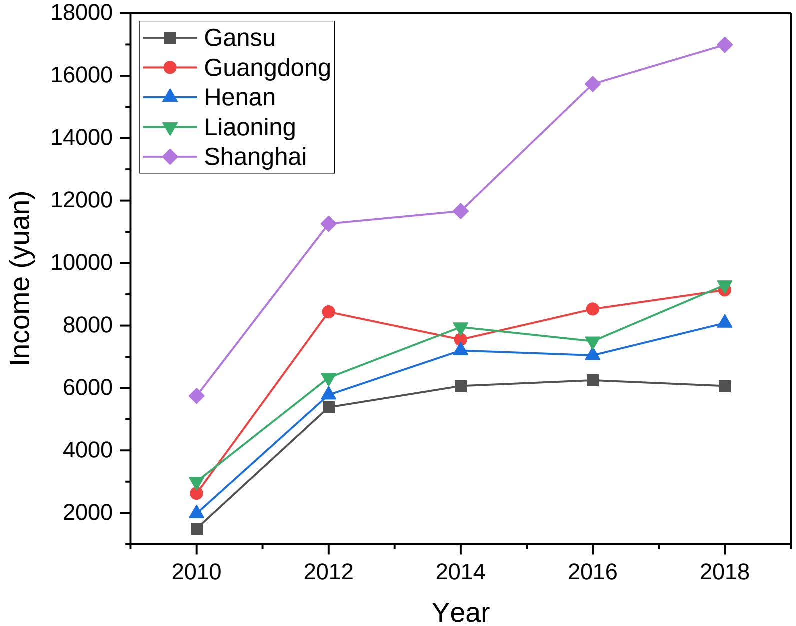


Fig. 3. Income gaps between the 3rd and 1st quintiles in rural area from 2010 to 2018

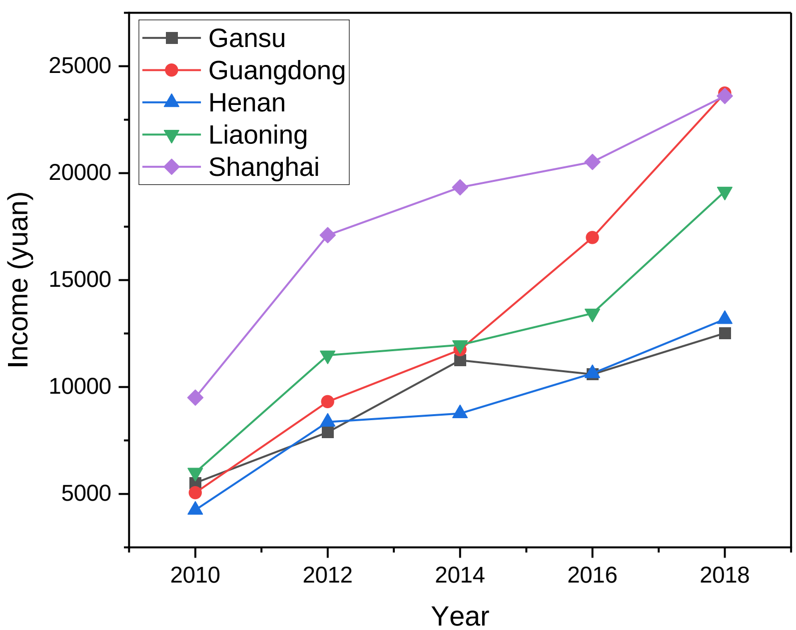


Fig. 4. Income gaps between the 3rd and 1st percentiles in urban area from 2010 to 2018

4.2 Household energy expenses

Disposable income per capita affects various household expenditures, including energy expenditure. We focus on four aspects of household energy consumption including electricity, heating, fuels, and housing as explained in 3.1.2. Here, we disaggregate these aspects by urban-rural and by province. This is to give us a sense of the actual energy consumption of households in our sample before we calculate the rate of EP.

1) Electricity

Fig. 5 shows the evolution of households' electricity cost per capita from 2010 to 2018 in each province. Firstly, the median value of the boxes in the plots reflects the average level of household electricity expenditure. In rural areas, households' electricity expenditure has been rising gradually during the eight-year study period except for in Shanghai where costs spiked in 2012. The length of the box in the plots reflects the range of electricity consumption costs for a specific sample group. We can observe an increase in disparity of electricity cost per capita through the length of the boxes during the study period. Also, the degree of disparity varies between the five provinces. The disparity of household electricity cost per capita is most obvious in rural Liaoning, in 2018. However, in rural Shanghai, the disparities of household electricity cost per capita changed only slightly between 2010 and 2018.

In urban Henan and Liaoning there is a gradual trend of increasing expenditure somewhat similar to the rural pattern in those provinces. In urban Gansu, the median expenditure decreases between 2010 and 2018. In the other urban areas, there has been more fluctuation. The possible reason of this fluctuation in 2012 may be due to the implementation of 'Multistep Electricity Prices'[8] in 2012 to promote social justice and conservation of resources, and some improved adjustments towards to this policy such as off-peak electricity price and rental housing electricity bill settlement in 2013 and 2014[9].

[8] China's National Development and Reform Commission promoted the 'Multistep Electricity Prices' system for residents which would cover most provinces in China except for Xinjiang and Tibet, specifically, the first tier of electricity amount has been raised, but the price has basically remained the same as the previous electricity price. the second and third tiers in most provinces raised prices by 0.05 yuan and 0.3 yuan respectively. As of the late July in 2012, 25 provinces have begun to fully implement this system except for Anhui, Guizhou, Hunan, and Shaanxi provinces, which are still under preparation.https://www.ndrc.gov.cn/fggz/tzgg/ggkx/201207/t20120709_1064623.html?code=&state=123

[9] China's National Development and Reform Commission informed to fully implement off-peak electricity price for residential sector and encourage residential users to participate in this policy making. Standardize

In urban areas, the disparity in electricity expenditure remained similar in each province over the study period. This suggests the overall electricity consumption in urban areas have developed equally, though unequal electricity consumption still exists, including ownership of electrical equipment, efficiency of appliances, and people's practice (Lin and Wang, 2020).

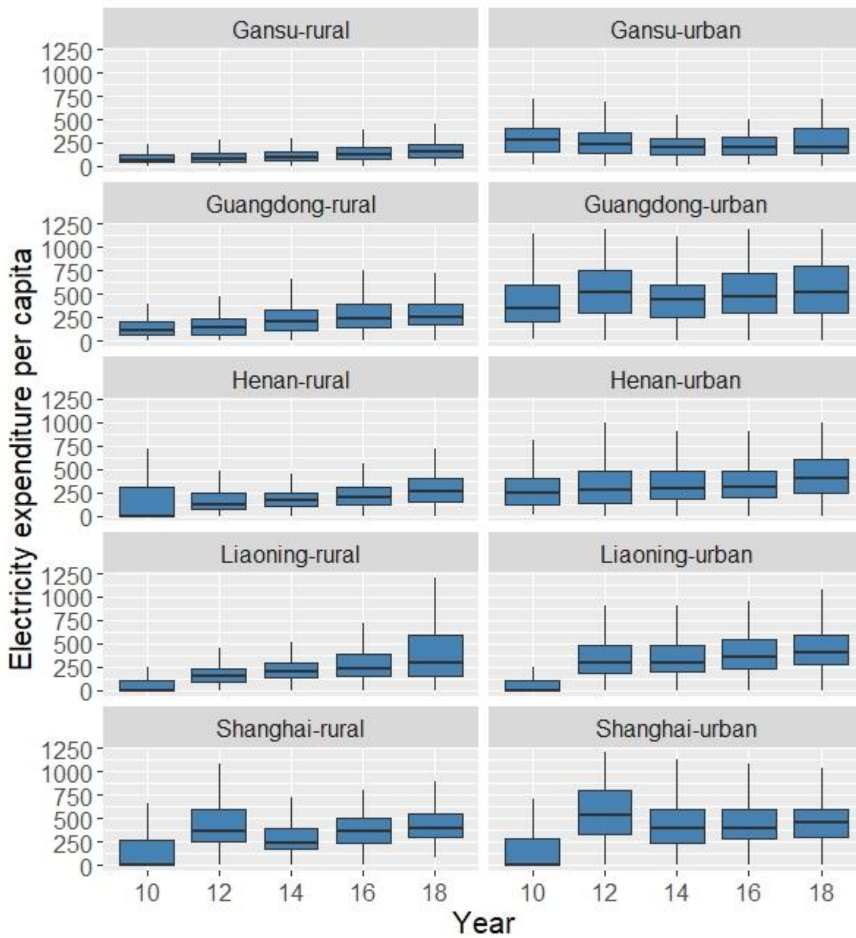


Fig. 5. Households' expenditure on electricity among five provinces from 2010 to 2018

2) Housing

Fig. 6 shows the evolution of households' housing cost per capita from 2010 to 2018 in each province, here the housing cost refers to any type of expenditure households paid on their housing including rent, loans, and purchase expenses annually. In rural areas,

---

the settlement of electricity bills for rental houses, and owners are not allowed to increase the price of electricity for tenants.
https://www.ndrc.gov.cn/xwdt/xwfb/201312/t20131225_956260.html?code=&state=123
https://www.ndrc.gov.cn/fggz/tzgg/ggkx/201401/t20140106_1072397.html?code=&state=123

the median housing cost in the Liaoning and Gansu provinces has fluctuated over these five years while the other three provinces have not changed substantially. However, although the median housing expenditure has changed very slightly, China's real estate boom during this period is reflected in the widening disparities in housing expenditure. In urban areas, the median housing cost has risen from 2010 to 2018 in Gansu, Henan and Liaoning provinces but has been almost steady in relatively developed Guangdong and Shanghai provinces. Stability in housing costs in Shanghai may be because the original households in developed Shanghai and Guangdong have a lower mobility than less developed Gansu. Housing expenditure almost doubled in urban Liaoning. In urban Shanghai and Guangdong province, the housing costs fell in 2012 compared to 2010, and remained at a low level since. However, the range of households' housing costs expanded from 2010 to 2018. In urban Henan, the maximum housing cost of 70% households reached to 1,125 yuan per capita in 2018, compared to 400 yuan per capita in 2010. Whether in rural or urban areas, households' housing cost per capita in this research are above average national levels in 2018 published in *China Statistic Yearbook 2019* (572 yuan including housing maintenance and management expenses). In this dataset, housing prices in the comparatively underdeveloped areas such as Gansu and Liaoning are growing together with households' housing expenditure. The housing price in the comparatively developed areas such as Shanghai and Guangdong province is already high, the income gap is reflected in the imbalance of housing expenditure, extremely high-value income increases the disparity in housing expenditures.

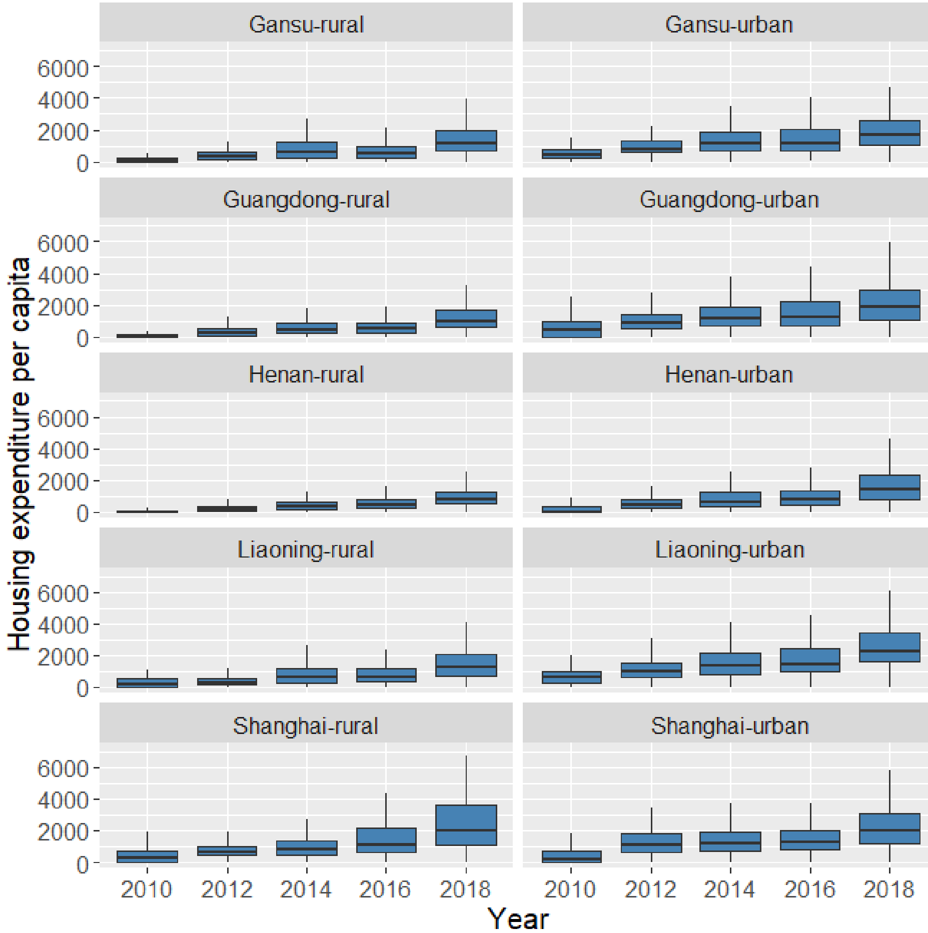


Fig. 6 Households' expenditure on housing among five provinces from 2010 to 2018

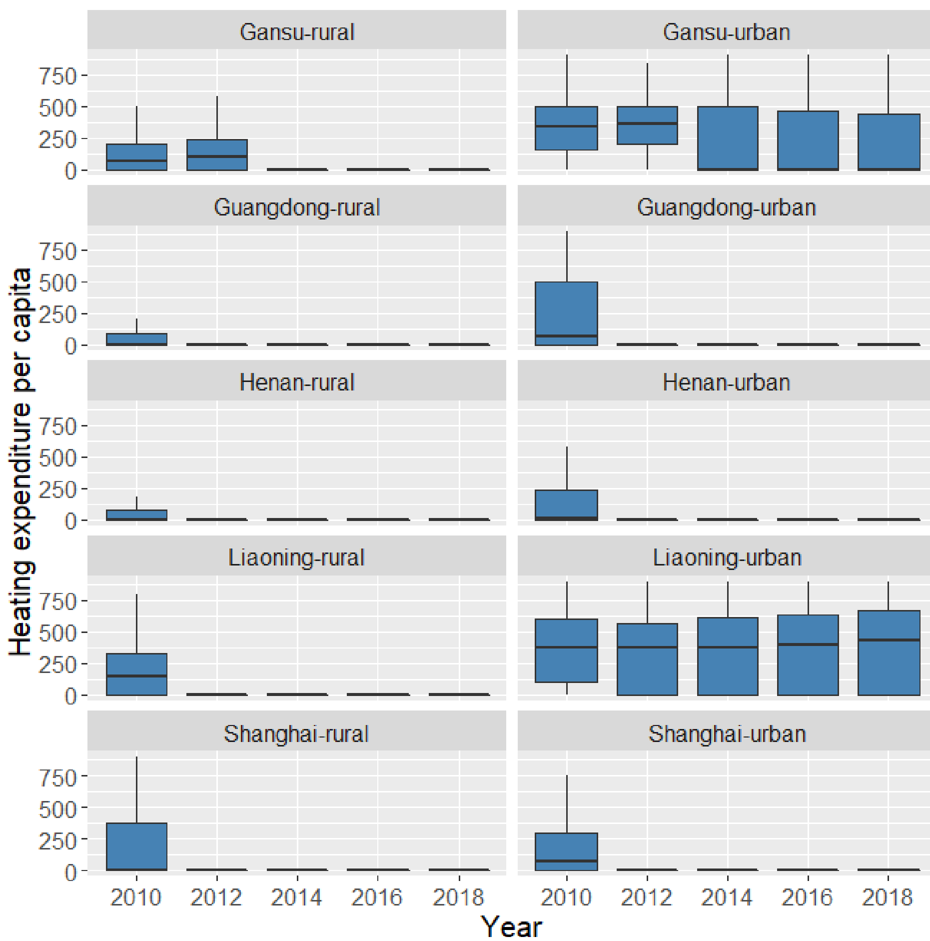
3) District Heating

Fig. 7 shows the evolution of households' heating expenditure per capita from 2010 to 2018 of each province. The Huai-river central heating policy in China, provides winter district central heating in the northern provinces such as Gansu and Liaoning in our dataset, southern provinces such as Guangdong, Henan and Shanghai do not have winter central heating. In Gansu, Heating costs dropped due to a range of policies: government subsidy from 2014 onwards, the coal-to-electricity heating policy, and introduction off-peak electricity tariffs as well as subsidies from employers to ensure that households are heated in winter [10]. We note though that many people who use electricity for heating lack separate

[10] For instance, Gansu Provincial Development and Reform Commission promotes Clean Heating Price Support Policy which indicates "one household, one meter" towards to urban and rural households (including schools and other non-residential categories that implement residential electricity prices) who would not be implemented the ladder electricity price policy for heating during the heating period. The off-peak policy is

heating statistics in this survey sample. The situation is similar in Liaoning due to the implementation of the electricity heating policy which sets 0.562 yuan per kilowatt-hour in peak time and 0.329 yuan per kilowatt-hour in off-peak time. Rural households in Gansu and Liaoning do not have district heating.

In urban areas, the median heating cost per capita in Liaoning is higher than that in Gansu. Liaoning province is further north and coastal in comparison to Gansu province which always experiences a cooler climate in winter; on the other hand, Liaoning has a higher disposable income level from 2010 to 2018 than Gansu province. Thus, in the Figure.5, the maximum heating cost per capita of 75% households is below 500 yuan in Gansu province which is always above 500 yuan in Liaoning province.



reducing electricity cost by 0.249 yuan per kilowatt-hour to further subsidize residential energy use. http://fzgg.gansu.gov.cn/fzgg/c106090/202108/1765285.shtml

Fig. 7 Households' expenditure on heating among five provinces from 2012 to 2018

4) Fuels (Self-heating and cooking fuel costs, including natural gas, liquefied gas, coal, firewood, charcoal, etc.)

Fig. 8 shows the evolution of households' fuel expenditure per capita from 2012 to 2018 of each province. Median fuel expenditure in urban areas shows minor fluctuation with the exception of Gansu which drops somewhat. In Rural areas fuel expenditure rises with the exception of Shanghai province. Guangdong Liaoning and Gansu have greater disparity than Henan and Shanghai which located more centrally. When comparing rural and urban areas in each province, the difference in disparity is smaller in Shanghai and Henan (the most economically developed provinces), and more pronounced in the economically less developed provinces.

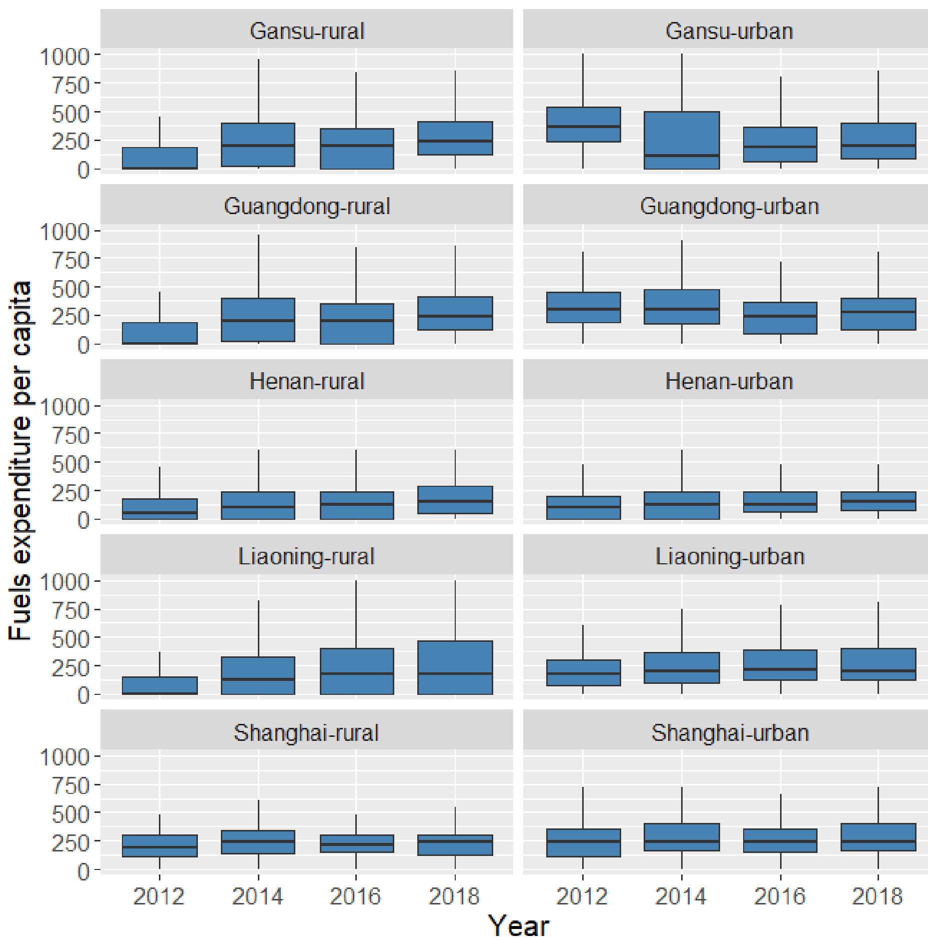


Fig. 8 Households' expenditure on fuels among five provinces from 2012 to 2018

5. Calculation results and discussion

Differences in households' income levels result in differing ability to pay for energy, however, other external factors such as the geographical location, the availability of infrastructure and local policy all affect households' energy consumption decisions, including the energy type, and the use of specific energy appliances. The multi-faceted nature of household energy needs can affect households' daily life. Here we applied the '10%' and 'LIHC' indicators to this dataset using the households' income and energy expenses data to identify energy poor households and their evolution during study period.

5.1 Energy poverty by using '10% indicator'

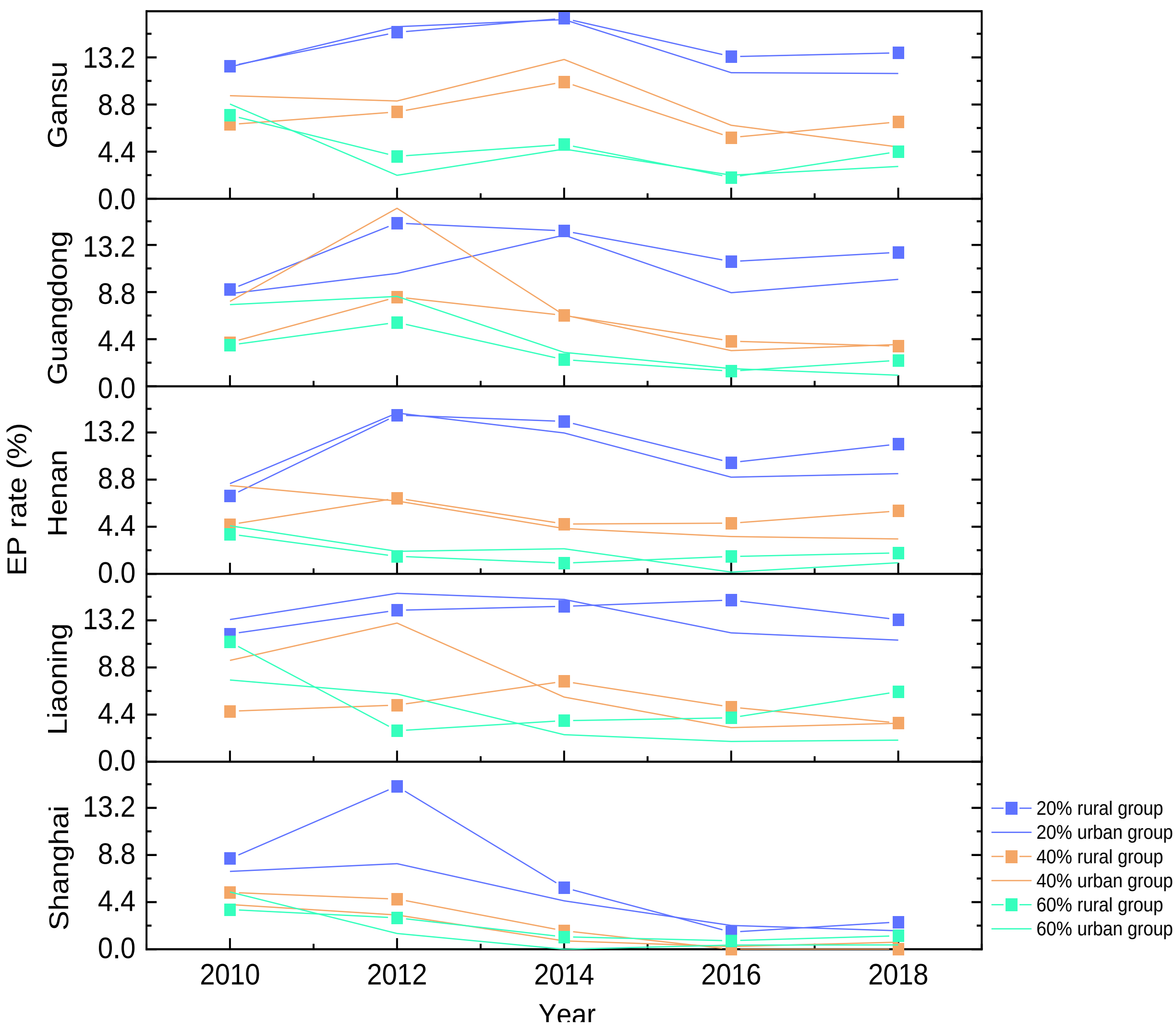


Fig. 9. Percentage of rural and urban EP ('10% indicator') of 1st, 2nd, 3rd income quintiles in five provinces from 2010 to 2018

1) By provinces

Fig. 9 shows the proportion of EP households in rural and urban areas using the '10% indicator'. We also show the rate of EP for each of the lowest three income quintiles. We can see the EP rate among Chinese households varies by income, rural / urban area type and among provinces. Whilst overall, there is a downward trend during 2010 to 2018, there are variations. In 2018, Gansu had the highest EP rate in rural or urban areas among these five provinces which was 13.62%, 11.69% respectively of the 1st quintile. By 2018, the 1st quintile group in developed Shanghai had the lowest EP rate: 2.53% and 1.73% respectively. Henan and Guangdong have similar EP rates in 2018 for both rural and urban areas. Different changes of EP rate during 2010 to 2018 can be found among income groups. In rural Gansu, for the 1st quintile, EP rate has slightly increased from 12.38% to 13.62% from 2010 to 2018, however, this rate has decreased from 7.79% to 4.42% for the 3rd quintile. In rural Liaoning, we also noticed the EP rate has increased in 1st quintile but has decreased in the 2nd and 3rd quintiles. In the 2nd quintile, the EP rate was 3.61% in 2018, which was originally 4.71% in 2010. The figure suggests that EP alleviation has occurred in the 2nd and 3rd income quintiles but not the lowest income quintile. This suggests that the poorest income group households should be paid more attention when formulating energy policies.

2) Urban-rural gap

It is notable here that households in urban areas do experience EP, sometimes at a similar level to rural areas, however, there remains a more pronounced rural-urban divide in EP amongst the 1st quintile than the 2nd and the 3rd quintiles. For example, in Gansu, EP rate was 4.42% in rural areas and was 3.02% in urban areas in the 3rd quintile in 2018. In addition, the difference between rural and urban areas is larger in the 1st quintile than the 2nd and 3rd quintile groups. Also, although the rural-urban income gap mentioned above is expanding, the gap between rural and urban EP ratios decreased mainly in the higher income groups during the study period. A relatively small difference between rural and urban areas can also be found in developed provinces such as Shanghai and Guangdong. The Chinese government has made progress in guaranteeing the basic energy provision to residents, also in alleviating the gap between urban and rural areas. However, our results show that there still are inequalities of energy costs and services between urban and rural: more effort should be made into the lowest income groups which would result in a more equal distribution of energy.

5.2 Energy poverty by using 'LIHC indicator'

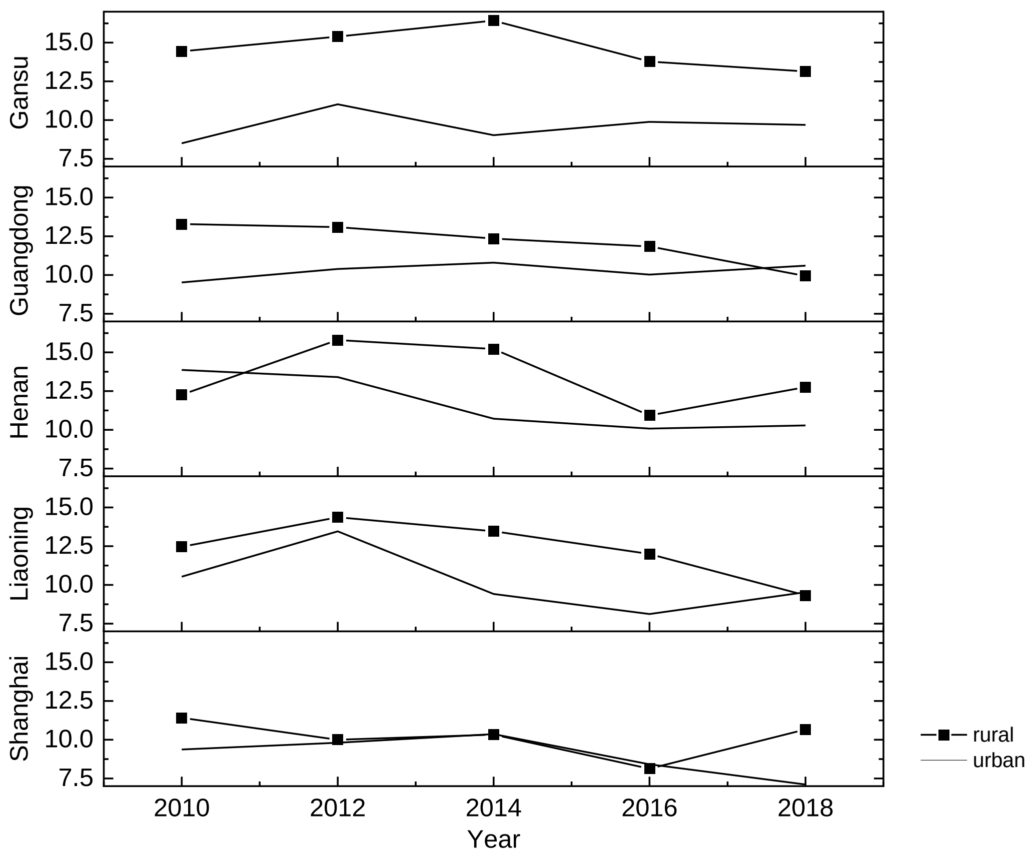


Fig. 10. Percentage of rural and urban EP ('LIHC indicator') of households in five provinces from 2010 to 2018

As we explained in 3.2.2, the 'LIHC indicator' set the 3rd of the weighted median for income After Housing Costs (AHC) as low income threshold which avoid a situation of high income and high costs, thus, we did not divide the income groups here like applied to the EP calculation under '10% indicator'. Fig. 10 shows the proportion of EP households by using 'LIHC indicator' for rural and urban areas in these five provinces from 2010 to 2018. In this figure, we can see that the EP rate under 'LIHC indicator' also shows heterogeneities among provinces across time, and a downward trend during 2010 to 2018 except urban Gansu and urban Guangdong. In 2018, Gansu had the highest EP rate in rural areas (13.14%), followed by rural Henan (12.76%). In urban areas, Guangdong, and Henan had the two highest EP rates in 2018 (10.60% and 10.28% respectively). Though central and western provinces report more severe EP under 'LIHC indicator', the EP trend is decreasing most years. The EP rate in rural areas also show a downward trend from 2010 to 2018 with the exception of Henan. For example, in rural Liaoning, the EP rate has changed from 12.47% in 2010 to 9.33% in 2018. In Guangdong, the EP rate has decreased from 13.29% in 2010 to 9.94% in 2018. Urban areas also have a decreasing trend in Shanghai, Henan, and Liaoning from 2010 to 2018. However, Gansu and Guangzhou have a slight increase of approximately 1.00% of EP rate in their urban areas. Thus, the households' EP rate has decreased during the study period among all these provinces under the 'LIHC indicator'. Decreases were similar between provinces although their EP rates varied finally in 2018.

As for the EP gap between rural and urban areas, this has decreased since 2010 in all five provinces, but Gansu, Henan, and Liaoning had a larger gap than Shanghai and Guangdong during the study period. In 2014, the EP gaps between rural and urban Gansu, Liaoning, and Henan are 7.40%, 4.50%, and 4.05% respectively. However, in relatively developed Shanghai and Guangdong, these figures are -0.04%, and 1.55%, which means in 2018, EP in rural Shanghai was only 0.04% higher than that in urban Shanghai. The differences between urban and rural EP are smaller in developed regions than undeveloped regions.

5.3 Comparison of '10%' and 'LIHC' indicators

The results of '10%' and 'LIHC' indicators give us insights into EP in urban and rural China from 2010 to 2018. Fig. 11-13 show us the statistical tests of differences between these two indicators' results after normality tests, we compared the results of '10% indicator' by three quintile groups with the results of 'LIHC indicator'. First, we note that EP does exist among Chinese households including rural and urban areas although the two indicators present different EP rates in provinces for specific years. The EP rates in these five Chinese provinces are all below 17.00% from either '10%' or 'LIHC' indicator.

The 'LIHC' result corresponds best to the 1st quintile under '10% indicator' rather than the 2nd and 3rd quintiles among these provinces, which can also be proved in the t-test results that the p-value are more significant in the 2nd and 3rd quintiles rather than 1st quintiles. Even in the 2nd, and 3rd quintiles, the results of '10% indicator' show that energy poor households exist, thus, to some extent, 'LIHC indicator' reduces the income sensitivity of EP rates and the estimation of EP household numbers in comparison to the '10% indicator'.

Second, spatial, and temporal analysis in the previous sections shows that the heterogeneities exist not only between rural and urban areas but also between developed regions and undeveloped regions. Both the '10%' and 'LIHC' indicators show that EP occurs in urban areas which rarely have been paid attention previously. Although the EP rates are generally more severe in rural areas, provinces such as Liaoning, Gansu and Henan show very little difference between rural and urban areas. The rural-urban gap is also not obvious under the 'LIHC indicator', for example, in Liaoning, the EP rates in rural and urban areas are 13.25% and 11.35% in 2018 under the '10% indicator', however, the rates are 9.33% and 9.53% in 2018 under 'LIHC indicator'. The '10% indicator' therefore reflects rural-urban disparities better than 'LIHC indicator'. While these two indicators have slight difference with regards to the disparities among provinces, the differences between these two indicators are less obvious at a macro spatial scale. The results of '10%' and 'LIHC indicators' both show that Gansu has suffered the most from EP among these five provinces, and that the relatively developed Shanghai has suffered the least from EP among households.

The results in these calculations illustrate the detailed spatio-temporal evolution of Chinese households' EP problem by applying '10%' and 'LIHC' indicators to the dataset, which are based on the income-expense perspective and have been widely used in western countries. The results show that this dataset and the two indicators can provide us with a lens on EP in China, which effectively captures the evolution features and geographical heterogeneities of EP among Chinese households. However, we need to critically think about the applicability of EP measurements in China due to the specific local context. We argue that the '10% indicator' is more suitable to capture this problem than the 'LIHC indicator' which may neglect some vulnerable households at a higher but below the median income level and may also hide the disparities among rural and urban areas.

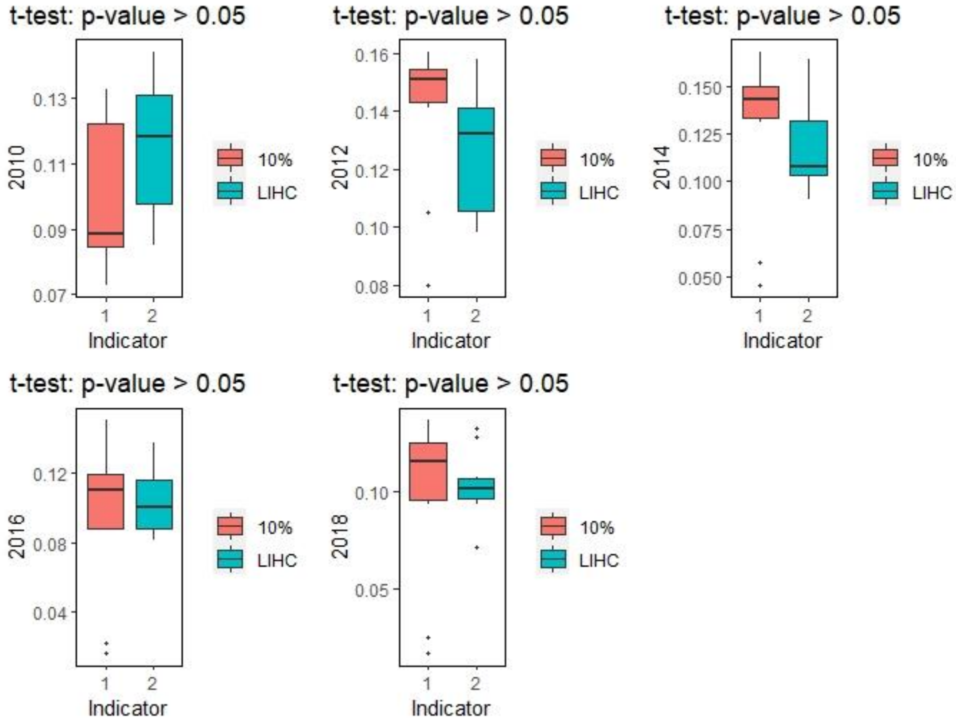


Fig. 11. Difference tests of EP results between the '10% indicator' (the 1st income quintile) and 'LIHC indicator'

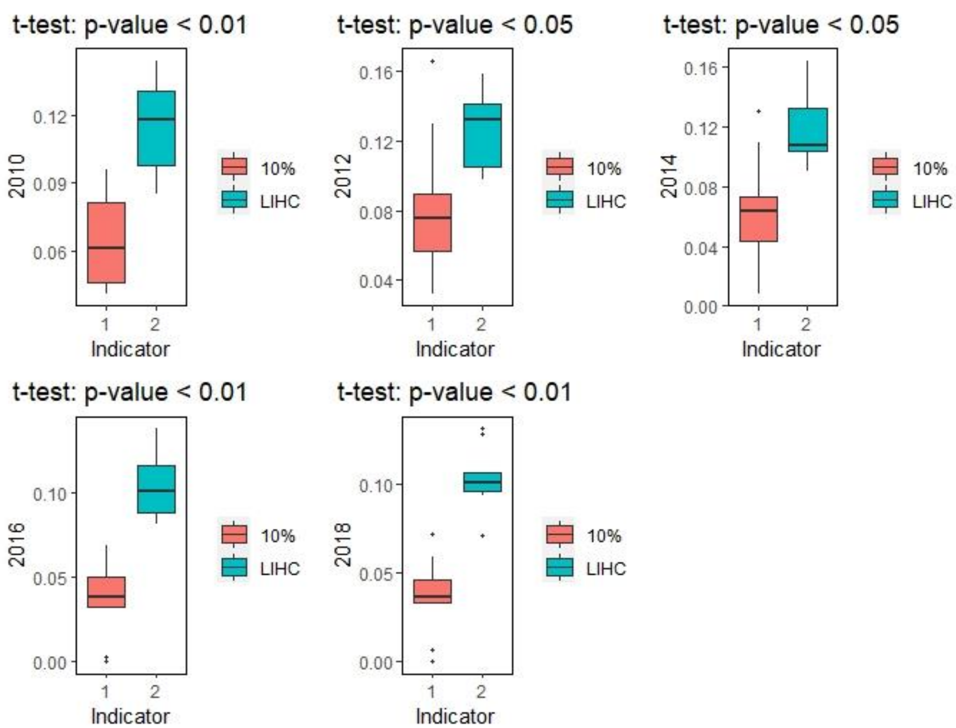


Fig. 12. Difference tests of EP results between the '10% indicator' (the 2nd income quintile) and 'LIHC indicator'

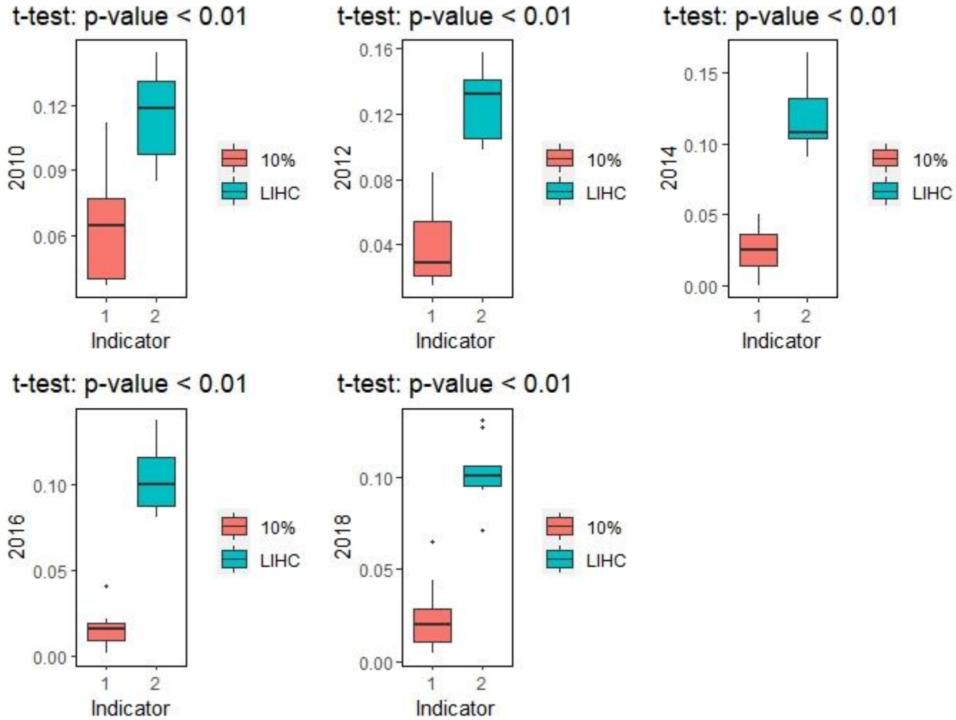


Fig. 13. Difference tests of EP results between the '10% indicator' (the 3rd income quintile) and 'LIHC indicator'

6. Conclusions and policy implications

6.1 Diversity of energy poverty in China

Based on the CFPS Survey waves (2010, 2012, 2014, 2016, 2018), this article uses the '10% indicator' and 'LIHC indicator' to describe China's EP spatially and temporally. The results highlight that there exists EP in Chinese households and it shows a downward trend across all areas in the study period, which is associated with rapid economic development, and gradual improvement of social infrastructure and household living standards. This is consistent with the IEA's evaluation and forecast for China (IEA, 2010). The reason for the alleviation of EP in China is mainly due to the improvement in energy access, subsidies, and efficiency, specifically, Chinese households can now get access to modern residential energy services like electricity and heating at a low price in both rural and urban areas with subsidies from government. However, in areas which have insufficient energy infrastructures to satisfy their daily energy consumption, households may have to balance disposable income and energy use. Some evidence was found by scholars who investigated rural households' energy use for cooking, that rural households may be artificially reducing their expenditures on modern energy use as a large number of households still use cheap solid fuel with associated indoor air pollution (Tang and Liao, 2014; Dong et al., 2021). Continued economic development in China suggests that EP will continue to fall but special efforts are needed to avoid leaving people and places behind.

Whilst EP is not exactly analogous to income poverty, EP rates are higher in western and northern China, which is consistent with the pattern of China's economic development and is reflected in the high rates according to the '10% indicator' and 'LIHC indicator' in Gansu and Liaoning provinces. Higher rates of EP are also found in rural areas, though urban EP does exist despite having received little attention in previous studies. This diversity is important to bear in mind in energy policy making.

6.2 Bundles of multiple disadvantages

Due to the gap between rich and poor, along with the differences in geographical location, climate conditions, and resource endowments, there is heterogeneity in household energy consumption in China. EP not just exists among rural households with lack of efficient modern energy services despite presence of basic energy access (Jiang et al., 2020). Our results also show that the mean EP rates of these five provinces are 10.80% in rural, and 8.81% in urban areas in 2018, according to '10% indicator' of the 1st quintile. Whilst EP rates are lower in urban areas than rural areas, expenditure is higher. This mainly because households in China have not reached the saturated stage in energy demand, and electricity consumption in developed urban areas is likely to increase with increasing income. Therefore, the policy of 'Multistep Electricity Prices' is reasonable in restricting the household electricity usage with high prices for higher income and higher consumption households (Lin and Wang, 2020). However, our results show that such subsidies are insufficient to shield from the cold or heat those households that have a lower income. These households likely struggle to afford heating or cooling or lack access to appropriate networked infrastructures and a high quality, energy efficient built environment. In undeveloped rural areas, the enhancement of access to modern energy has improved in the past decades in China, following interventions among rural households. For example, the 'Multistep Electricity Prices' policy which attempts to cross-subsidies between different living standards while ensuring that the basic electricity demand does not rise. To guarantee affordability of electricity, provincial governments have also introduced a policy of 10-15 kW*h per month of free use for each low-income household. In addition, heating subsidies are also provided to rural families, varying according to needs of rural families between 950-1,200 yuan. EP in rural areas is more severe than in urban areas suggesting more persistent income, infrastructure, and building problems among rural households (Li et al., 2011; Luo and Liu, 2013; Hao et al., 2014; Zhao et al., 2018; Hong et al., 2022).

Energy consumption is sensitive to tariff, income, and the efficiency of home appliances in poorer areas such as Gansu and Liaoning in western and northern China. As residents in these areas suffer from both income poverty and relatively high energy costs, who should be provided with extra support? Considering their low income and household appliance possession, economic subsidies in both power consumption and appliance purchasing could be effective, and the policy of '10-15 kW*h free use' already implemented represents a kind of universal basic service for these residents no doubt addressing poverty alleviation (National Development and Reform Commission). This is not enough for subsiding the basic usage of households' energy appliance to maintain daily life such as air conditioner, fridges, TV etc. and for China to pursue a clean and low-carbon economy, especially a household energy transition from coal to electricity and natural gas. A further policy, the clean heating program, launched in 2017, pays the costs of infrastructure construction and for the replacement of heating equipment. Under this scheme, households do not bear the cost of infrastructure construction, but bear a portion of heating equipment replacement.

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

Identifying the level of EP in a place is helpful when considering the synergy of climate and equality solutions, scholars have identified the inescapable correlations between energy poverty policies and climate policies (Ürge-Vorsatz and Tirado Herrero, 2012; Sawhney, 2013; Wang et al., 2014a). In Chinese case, basic realization of power grid coverage has a significant effect on reducing energy poverty, but the proportion of coal power in China is still high (Xie et al., 2022), which produces a large amount of greenhouse gas emissions. Increasing natural gas coverage in remote towns and rural areas and forming a fair and reasonable natural gas pricing mechanism will significantly reduce greenhouse gas emissions and improve the clean energy use in households. Improving home energy efficiency is mainly through improving cooking and heating equipment. Increased energy efficiency reduces the amount of energy consumption per unit of output, which in turn reduces emissions. Moreover, the development and utilization of renewable energy has the dual effect of alleviating energy poverty, saving energy and reducing emissions. Seek synergy between energy poverty and climate change policies is beneficial to collaboratively realize the dual goals of just and clean energy society.

6.3 Overcoming policy silos

The CFPS surveys used in this paper is one of the most complete public social surveys in China, and provides a basis for academic research and social policy analysis (CFPS, 2017). Household energy consumption data included in these surveys allow us to identify energy poor households in China spatially and temporally. Understanding the socio-demographic characteristics of these households could be one direction of future research, as it could shed light on ways to better understand EP in China and to improve households' welfare by improving the design and implementation of the clean heating and similar programs. The findings in this article call the attention of policy makers to low-income households when designing and implementing policies, specifically households that need special attention during the implementation of energy policies concerning the heterogeneous impacts across areas.

The dataset is not explicitly designed for EP evaluation, though we have shown that the data can be processed to derive '10%' and 'LIHC' measures. We suggest that as China-specific metrics are adopted, then some questions in the survey could be adapted to gather data explicitly for these metrics.

Further useful research would include utilizing the data processing and descriptive understanding provided in this paper for either statistical analysis or as a start point for evaluation of lived experience through mixed methods research. Data gathered at finer resolution may allow more detailed analysis of the variation within and between provinces over time.

Acknowledgements

My sincere thanks go to Lucie and Ian's professional contributions to this study. This work was supported by China Scholarship Council. The authors are grateful to the Institute of Social Science Survey of Peking University supporting the dataset used in this study. The authors would like to thank Alice Owen, Anne Owen, and Yim Ling Siu for their valuable comments during the review process.

References

Abbas, K., Butt, K.M., Xu, D., Ali, M., Baz, K., Kharl, S.H., Ahmed, M., 2022. Measurements and determinants of extreme multidimensional energy poverty using machine learning. Energy 251. https://doi.org/10.1016/j.energy.2022.123977

Bailey, I., Hopkins, R., Wilson, G., 2010. Some things old, some things new: The spatial representations and politics of change of the peak oil relocalisation movement. Geoforum 41, 595-605.

Baker, K.J., Mould, R., Restrick, S., 2018. Rethink fuel poverty as a complex problem. Nature Energy 3, 610-612. https://doi.org/10.1038/s41560-018-0204-2

Bednar, D.J., Reames, T.G., 2020. Recognition of and response to energy poverty in the united states. Nature Energy 5, 432-439. https://doi.org/10.1038/s41560-020-0582-0

Birol, F., 2007. Energy economics: A place for energy poverty in the agenda? The energy journal 28. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol28-No3-1

Boardman, B., 1991. Fuel poverty: From cold homes to affordable warmth. Pinter Pub Limited.

Boardman, B., 2010. <fixing fuel poverty.Pdf>.

Boardman, B., 2012. Fuel poverty synthesis: Lessons learnt, actions needed. Energy Policy 49, 143-148. https://doi.org/10.1016/j.enpol.2012.02.035

Bouzarovski, S., Bassin, M., 2013. Energy and identity: Imagining russia as a hydrocarbon superpower, The new geographies of energy. Routledge, pp. 94-105.
Bouzarovski, S., Petrova, S., 2015. A global perspective on domestic energy deprivation: Overcoming the energy poverty–fuel poverty binary. Energy Research & Social Science 10, 31-40. https://doi.org/10.1016/j.erss.2015.06.007
Bouzarovski, S., Petrova, S., Sarlamanov, R., 2012. Energy poverty policies in the eu: A critical perspective. Energy policy 49, 76-82.
Bouzarovski, S., Thomson, H., Cornelis, M., 2021. Confronting energy poverty in europe: A research and policy agenda. Energies 14. https://doi.org/10.3390/en14040858
Bouzarovski, S., Tirado Herrero, S., 2017a. The energy divide: Integrating energy transitions, regional inequalities and poverty trends in the european union. European Urban and Regional Studies 24, 69-86.
Bouzarovski, S., Tirado Herrero, S., 2017b. Geographies of injustice: The socio-spatial determinants of energy poverty in poland, the czech republic and hungary. Post-Communist Economies 29, 27-50.
Bouzarovski, S., Tirado Herrero, S., Petrova, S., Ürge-Vorsatz, D., 2016. Unpacking the spaces and politics of energy poverty: Path-dependencies, deprivation and fuel switching in post-communist hungary. Local Environment 21, 1151-1170.
Brunner, K.-M., Spitzer, M., Christanell, A., 2012. Experiencing fuel poverty. Coping strategies of low-income households in vienna/austria. Energy Policy 49, 53-59.
Buzar, S., 2007. Erratum to "the 'hidden' geographies of energy poverty in post-socialism: Between institutions and households" [geoforum 38 (2) (2007) 224–240]. Geoforum 38. https://doi.org/10.1016/j.geoforum.2007.03.001
Calvert, K., 2015. From 'energy geography' to 'energy geographies'. Progress in Human Geography 40, 105-125. https://doi.org/10.1177/0309132514566343
CFPS, 2017. Cfps user's manual (3rd+edition) (eng), in: Xie, Y., Zhang, X., Tu, P., Ren, Q., Sun, Y., Lv, P., Ding, H., Hu, J., Wu, Q. (Eds.). Institute of Social Science Survey,, Peking University.
Consortium, E., 2009. Tackling fuel poverty in europe. Recommendations guide for policy makers. Retrieved 28, 2019.
Day, R., Walker, G., Simcock, N., 2016. Conceptualising energy use and energy poverty using a capabilities framework. Energy Policy 93, 255-264. https://doi.org/10.1016/j.enpol.2016.03.019
Démurger, S., Fournier, M., 2011. Poverty and firewood consumption: A case study of rural households in northern china. China economic review 22, 512-523.
Devine-Wright, P., Wiersma, B., 2013. Opening up the "local" to analysis: Exploring the spatiality of uk urban decentralised energy initiatives. Local Environment 18, 1099-1116.
Dobbins, A., Fuso Nerini, F., Deane, P., Pye, S., 2019. Strengthening the eu response to energy poverty. Nature Energy 4, 2-5. https://doi.org/10.1038/s41560-018-0316-8
Dong, K., Ren, X., Zhao, J., 2021. How does low-carbon energy transition alleviate energy poverty in china? A nonparametric panel causality analysis. Energy Economics 103. https://doi.org/10.1016/j.eneco.2021.105620

Dorow, S., O'Shaughnessy, S., 2013. Fort mcmurray, wood buffalo, and the oil/tar sands: Revisiting the sociology of" community". Canadian Journal of Sociology 38, 121-140.
Dubois, U., 2012. From targeting to implementation: The role of identification of fuel poor households. Energy Policy 49, 107-115.
Dubois, U., Meier, H., 2016. Energy affordability and energy inequality in europe: Implications for policymaking. Energy Research & Social Science 18, 21-35.
Energy, I., 2003. Can the poor pay for power? The affordability of electricity in southeast europe. Available online at ww. ebrd. com/country/sector/energyef/about/powersee. pdf
Energy Poverty Action, W., 2019. Moving beyond the state of the art in energy poverty measurement, in: Sareen, S., Thomson, H. (Eds.), Working Group 2 - Implementation: Developing an operational energy poverty framework. http://www.engager-energy.net/new-report-on-the-moving-beyond-the-state-of-the-art-in-energy-poverty-measurement/
Gillard, R., Snell, C., Bevan, M., 2017. Advancing an energy justice perspective of fuel poverty: Household vulnerability and domestic retrofit policy in the united kingdom. Energy Research & Social Science 29, 53-61. https://doi.org/10.1016/j.erss.2017.05.012
Hao, Y., Yin, J., Yang, D., 2014. The study on energy poverty's regional differences in china. Research and Approach 36, 34-38. https://doi.org/10.3969/j
Hargreaves, T., Middlemiss, L., 2020. The importance of social relations in shaping energy demand. Nature Energy. https://doi.org/10.1038/s41560-020-0553-5
Harrison, C., 2013. The historical–geographical construction of power: Electricity in eastern north carolina. Local Environment 18, 469-486.
Healy, J.D., 2017. Housing, fuel poverty and health: A pan-european analysis. Routledge.
Healy, J.D., Clinch, J.P., 2002. Fuel poverty, thermal comfort and occupancy: Results of a national household-survey in ireland. Applied Energy 73, 329-343.
Heindl, P., 2015. Measuring fuel poverty: General considerations and application to german household data. FinanzArchiv/Public Finance Analysis, 178-215.
Hills, J., 2011. Fuel poverty: The problem and its measurement. http://eprints.lse.ac.uk/39270/
Hills, J., 2012. Getting the measure of fuel poverty. http://eprints.lse.ac.uk/43153/
Hong, X., Wu, S., Zhang, X., 2022. Clean energy powers energy poverty alleviation: Evidence from chinese micro-survey data. Technological Forecasting and Social Change 182https://doi.org/10.1016/j.techfore.2022.121737
IEA, 2010. World energy outlook 2010, Paris. https://www.iea.org/reports/world-energy-outlook-2010
Isolde, D., 2015. Définition de la précarité energétique. https://expertises.ademe.fr/batiment/quoi-parle-t/precarite-energetique-suivie-lonpe-sein-lademe
Jenkins, K., 2018. Energy poverty and vulnerability: A global perspective. Energy 147, 388-389. https://doi.org/10.1016/j.energy.2018.01.043
Jiang, L., Yu, L., Xue, B., Chen, X., Mi, Z., 2020. Who is energy poor? Evidence from the least developed regions in china. Energy Policy 137, 111122. https://doi.org/10.1016/j.enpol.2019.111122

Katsoulakos, N., 2011. Combating energy poverty in mountainous areas through energy-saving interventions. Mountain Research and Development 31, 284-292.
Koďouskov´a, H., Boˇruta, D., 2022. Energy poverty in slovakia officially defined but misrepresented in major policies. https://doi.org/10.1016/j.enpol.2022.113095
Legendre, B., Ricci, O., 2015. Measuring fuel poverty in france: Which households are the most fuel vulnerable? Energy Economics 49, 620-628.
Li, K., Liu, C., Wei, Y., 2011. Analysis of the current situation of energy poverty in china. Research and Approach 33, 32-35. https://doi.org/10.3969/
Liao, H., Tang, X., Wei, Y.-M., 2016. Solid fuel use in rural china and its health effects. Renewable and Sustainable Energy Reviews 60, 900-908. https://doi.org/10.1016/j.rser.2016.01.121
Lin, B., Wang, Y., 2020. Does energy poverty really exist in china? From the perspective of residential electricity consumption. Energy Policy 143https://doi.org/10.1016/j.enpol.2020.111557
Luo, G., Liu, T., 2013. The exposion of non-electricity customers, renewable energy, power poverty problems of the rural areas of western china Journal of North China Electric Power University (Social Sciences), 6-12.
Middlemiss, L., 2016. A critical analysis of the new politics of fuel poverty in england. Critical Social Policy 37, 425-443. https://doi.org/10.1177/0261018316674851
Middlemiss, L., Ambrosio-Albalá, P., Emmel, N., Gillard, R., Gilbertson, J., Hargreaves, T., Mullen, C., Ryan, T., Snell, C., Tod, A., 2019. Energy poverty and social relations: A capabilities approach. Energy Research & Social Science 55, 227-235. https://doi.org/10.1016/j.erss.2019.05.002
Middlemiss, L., Gillard, R., Pellicer, V., Straver, K., 2018. Plugging the gap between energy policy and the lived experience of energy poverty: Five principles for a multidisciplinary approach, Advancing energy policy, pp. 15-29.
Miniaci, R., Scarpa, C., Valbonesi, P., 2014. Energy affordability and the benefits system in italy. Energy Policy 75, 289-300.
Moore, R., 2012. Definitions of fuel poverty: Implications for policy. Energy Policy 49, 19-26. https://doi.org/10.1016/j.enpol.2012.01.057
National Statistics, U., 2022. Anuual fuel poverty statistics in england, in: Department for Business, E.I.S. (Ed.). UK Government, England
Nguyen, C.P., Su, T.D., 2022. The influences of government spending on energy poverty: Evidence from developing countries. Energy 238https://doi.org/10.1016/j.energy.2021.121785
Nierop, S., 2014. Energy poverty in denmark. Denmark: Aalborg University
Nussbaumer, P., Bazilian, M., Modi, V., 2012. Measuring energy poverty: Focusing on what matters. Renewable and Sustainable Energy Reviews 16, 231-243. https://doi.org/10.1016/j.rser.2011.07.150
Nye, D.E., 1999. Consuming power: A social history of american energies. 42, 137-138.
Pachauri, S., Jiang, L., 2008. The household energy transition in india and china. Energy Policy 36, 4022-4035. https://doi.org/10.1016/j.enpol.2008.06.016
Pachauri, S., Mueller, A., Kemmler, A., Spreng, D., 2004. On measuring energy poverty in indian households. World Development 32, 2083-2104. https://doi.org/10.1016/j.worlddev.2004.08.005
Perreault, T., Valdivia, G., 2010. Hydrocarbons, popular protest and national imaginaries: Ecuador and bolivia in comparative context. Geoforum 41, 689-699.

Phimister, E., Vera-Toscano, E., Roberts, D., 2015. The dynamics of energy poverty: Evidence from spain. Economics of Energy & Environmental Policy 4, 153-166.
Reames, T.G., 2016. Targeting energy justice: Exploring spatial, racial/ethnic and socioeconomic disparities in urban residential heating energy efficiency. Energy Policy 97, 549-558. https://doi.org/10.1016/j.enpol.2016.07.048
Reames, T.G., Reiner, M.A., Stacey, M.B., 2018. An incandescent truth: Disparities in energy-efficient lighting availability and prices in an urban u.S. County. Applied Energy 218, 95-103. https://doi.org/10.1016/j.apenergy.2018.02.143
Robinson, C., 2019. Energy poverty and gender in england: A spatial perspective. Geoforum 104, 222-233. https://doi.org/10.1016/j.geoforum.2019.05.001
Robinson, C., Bouzarovski, S., Lindley, S., 2018a. Multiple vulnerabilities? Interrogating the spatial distribution of energy poverty measures in england, Energy poverty and vulnerability a global perspective. Routledge.
Robinson, C., Lindley, S., Bouzarovski, S., 2019. The spatially varying components of vulnerability to energy poverty. Annals of the American Association of Geographers 109, 1188-1207. https://doi.org/10.1080/24694452.2018.1562872
Robinson, C., Mattioli, G., 2020. Double energy vulnerability: Spatial intersections of domestic and transport energy poverty in england. Energy Research & Social Science 70https://doi.org/10.1016/j.erss.2020.101699
Robinson, C., Yan, D., Bouzarovski, S., Zhang, Y., 2018b. Energy poverty and thermal comfort in northern urban china: A household-scale typology of infrastructural inequalities. Energy and Buildings 177, 363-374. https://doi.org/10.1016/j.enbuild.2018.07.047
Romero, J.C., Linares, P., López, X., 2018. The policy implications of energy poverty indicators. Energy Policy 115, 98-108. https://doi.org/10.1016/j.enpol.2017.12.054
Saheb, Y., Calcagno, S., Kostov, P., Bodis, K., Vondung, F., Thema, J., 2019. European energy poverty index (eepi).
Salman, M., Zha, D., Wang, G., 2022. Assessment of energy poverty convergence: A global analysis. Energy 255https://doi.org/10.1016/j.energy.2022.124579
Santamouris, M., Paravantis, J.A., Founda, D., Kolokotsa, D., Michalakakou, P., Papadopoulos, A.M., Kontoulis, N., Tzavali, A., Stigka, E.K., Ioannidis, Z., 2013. Financial crisis and energy consumption: A household survey in greece. Energy and Buildings 65, 477-487.
Sareen, S., Thomson, H., Tirado Herrero, S., Gouveia, J.P., Lippert, I., Lis, A., 2020. European energy poverty metrics: Scales, prospects and limits. Global Transitions 2, 26-36. https://doi.org/10.1016/j.glt.2020.01.003
Sawhney, A., 2013. Renewable energy policy in india: Addressing energy poverty and climate mitigation. Review of Environmental Economics and Policy 7, 296-312. https://doi.org/10.1093/reep/ret010
Shove, E., Walker, G., 2010. Governing transitions in the sustainability of everyday life. Research Policy 39, 471-476.
Simcock, N., Thomson, H., Petrova, S., Bouzarovski, S., 2018. Energy poverty and vulnerability a global perspective. Routledge.
Simoes, S.G., Gregório, V., Seixas, J., 2016. Mapping fuel poverty in portugal. Energy Procedia 106, 155-165. https://doi.org/10.1016/j.egypro.2016.12.112

Sovacool, B.K., 2015. Fuel poverty, affordability, and energy justice in england: Policy insights from the warm front program. Energy 93, 361-371. https://doi.org/10.1016/j.energy.2015.09.016
Spinney, J., Green, N., Burningham, K., Cooper, G., Uzzell, D., 2012. Are we sitting comfortably? Domestic imaginaries, laptop practices, and energy use. Environment and Planning A 44, 2629-2645.
Strakova, D., 2014. Energy poverty in slovakia. https://doi.org/10.2139/ssrn.2546758
Tang, X., Chen, X., Yang, C., 2016. A study on the system dilemma and countermeasures of energy poverty in constructing new agricultural and pastoral areas in tibet. Journal of Leshan Normal University 31, 93-100. https://doi.org/10.16069/j.cnki.51-1610/g4.2016.07.015
Tang, X., Liao, H., 2014. Energy poverty and solid fuels use in rural china: Analysis based on national population census. Energy for Sustainable Development 23, 122-129. https://doi.org/10.1016/j.esd.2014.08.006
Thomson, H., Bouzarovski, S., 2018. Addressing energy poverty in the european union: State of play and action, EU Energy Poverty Observatory. https://energy-poverty.ec.europa.eu/energy-poverty-observatory_en
Thomson, H., Bouzarovski, S., Snell, C., 2017. Rethinking the measurement of energy poverty in europe: A critical analysis of indicators and data. Indoor Built Environ 26, 879-901. https://doi.org/10.1177/1420326X17699260
UN, 2015. Sustainable development goals-7 affodable and clean energy https://www.undp.org/sustainable-development-goals#affordable-and-clean-energy
UNDP, 2019. Human development report 2019. Beyond income, beyond averages, beyond today: Inequalities in human development in the 21st century, New York. http://hdr.undp.org/en/content/human-development-report-2019
Ürge-Vorsatz, D., Tirado Herrero, S., 2012. Building synergies between climate change mitigation and energy poverty alleviation. Energy Policy 49, 83-90. https://doi.org/10.1016/j.enpol.2011.11.093
Vogel, E., 2016. Regional power and the power of the region: Resisting dam removal in the pacifi c northwest, Contentious geographies. Routledge, pp. 187-208.
Walker, R., McKenzie, P., Liddell, C., Morris, C., 2012. Area-based targeting of fuel poverty in northern ireland: An evidenced-based approach. Applied Geography 34, 639-649. https://doi.org/10.1016/j.apgeog.2012.04.002
Wang, B., Ke, R.-Y., Yuan, X.-C., Wei, Y.-M., 2014a. China׳s regional assessment of renewable energy vulnerability to climate change. Renewable and Sustainable Energy Reviews 40, 185-195. https://doi.org/10.1016/j.rser.2014.07.154
Wang, K., Wang, Y.-X., Li, K., Wei, Y.-M., 2015. Energy poverty in china: An index based comprehensive evaluation. Renewable and Sustainable Energy Reviews 47, 308-323. https://doi.org/10.1016/j.rser.2015.03.041
Wang, Q., Wang, L., Mi, Z., Li, K., 2014b. Impact of china's energy poverty eradication policy on climate change. Climate Change 36, 39-43. https://doi.org/10.3969/j
Wei, Y., Liao, H., Wang, K., Liang, Q., 2014. China energy report (2014): Energy poverty research. Science Press: Beijing, China.
Wu, S., Zheng, X., 2016. Elimination of rural energy poverty requires attention to systematic assessment. China Energy News, 1-2.

Xia, W., Murshed, M., Khan, Z., Chen, Z., Ferraz, D., 2022. Exploring the nexus between fiscal decentralization and energy poverty for china: Does country risk matter for energy poverty reduction? Energy 255. https://doi.org/10.1016/j.energy.2022.124541

Xie, L., Hu, X., Zhang, X., Zhang, X.-B., 2022. Who suffers from energy poverty in household energy transition? Evidence from clean heating program in rural china. Energy Economics 106. https://doi.org/10.1016/j.eneco.2021.105795

Xie, M., 2010. Research on the problem about energy poverty and rural energy build in the underdeveloped resource-rich region of china. Economic Research Guide, 29-31.

Xue, B., 2017. Cooperative prevention and control of air pollutants and greenhouse gases. Reform, 78-80.

Yang, Z., Yan, S., Zhang, H., Ma, M., 2017. Economic analysis of household energy poverty in inner mongolia pastoral areas based on differences in environmental endowments. Resources and Environment, 226-227. https://doi.org/10.13939/j.cnki.zgsc.2017.33.226

Yip, A.O.-n., Mah, D.N.-y., Barber, L.B., 2020. Revealing hidden energy poverty in hong kong: A multi-dimensional framework for examining and understanding energy poverty. Local Environment 25, 473-491. https://doi.org/10.1080/13549839.2020.1778661

Zhang, D., Li, J., Han, P., 2019. A multidimensional measure of energy poverty in china and its impacts on health: An empirical study based on the china family panel studies. Energy Policy 131, 72-81. https://doi.org/10.1016/j.enpol.2019.04.037

Zhao, X., Chen, H., Ma, Y., Gao, Z., Xue, B., 2018. Spatio-temporal variation and its influencing factors of rural energy poverty in china from 2000 to 2015. Geographical Research 37, 1115-1126. https://doi.org/10.11821/dlyj201806005

Zhu, C., 2007. Accelerate the construction of energy and electricity in rural china. Shanxi Energy and Conservation 44, 12-14.

Zhu, L., Ye, H., 2012. Analysis of emission reduction effect and cost benefit of rural biogas project. China population, resources and environment 22, 426-429.