Humanities & Social Sciences Communications

ARTICLE

https://doi.org/10.1057/s41599-023-02573-2 OPEN

Low-carbon transition and energy poverty: quasi-natural experiment evidence from China's low-carbon city pilot policy

Yiming Xiao[1,2], Zhijun Feng[1✉], Xinying Li[3] & Shangrui Wang[4]

Low-carbon transition stands as a vital strategy for the global community to address the challenge of climate change, inevitably affecting residents' daily lives. However, there is a notable gap in the quantitative analysis of the low-carbon transition's impact on energy poverty in developing countries, limiting policymakers' understanding of the inherent mechanism and their ability to take informed actions. This study investigates the low-carbon city pilot (LCCP) policy, China's key low-carbon initiative, as a quasi-natural experiment, using the difference-in-differences (DID) method to examine its impact on residents' energy poverty conditions. Utilizing panel data from 4807 households in the CHARLS dataset, this study effectively integrated household-level and city-level data. Benchmark regression indicates that the LCCP policy exacerbates energy poverty among residents. Further analysis reveals the pivotal role of energy infrastructure and expenditure in bridging the nexus between the LCCP policy and energy poverty, providing crucial insights into the potential pathways through which this policy impacts energy poverty. Additionally, heterogeneity analysis indicates that the impacts of LCCP policy are more pronounced in eastern cities, non-resource cities, and high administrative-level cities, as well as in the communities suffering from subpar governance quality. By leveraging reliable survey data and robust quantitative methods, this study not only broadens the methodology of energy poverty studies but also offers valuable insights for developing countries to safeguard residents' energy welfare amid low-carbon transitions.

[1] School of Economics and Management, Dongguan University of Technology, 523808 Dongguan, China. [2] School of Management, University of Science and Technology of China, 230026 Hefei, China. [3] School of Data Science, City University of Hong Kong, 999077 Hong Kong, China. [4] School of Public Policy & Management, Tsinghua University, 100084 Beijing, China. ✉email: fengzj@dgut.edu.cn

Introduction

Low-carbon transition has been widely endorsed by the international community as a crucial lever to mitigate global warming (He et al., 2022; Olabi and Abdelkareem, 2022). Currently, global efforts in the low-carbon transition have transformed energy structure and bolstered the use of clean and renewable energy, thus aiding in achieving carbon reduction goals (Yu et al., 2022; Zhang et al., 2022). However, in light of the classic "energy trilemma" predicament, efforts toward low-carbon transition, at times, have unintentionally impacted energy security and energy equity in certain regions (Mišík, 2022; Xie et al., 2022). As countries implement these low-carbon strategies, their energy systems and even whole socioeconomic systems have become increasingly unstable and vulnerable (Frilingou et al., 2023; Magacho et al., 2023; Semieniuk et al., 2021; Sovacool et al., 2019). During the COVID-19 pandemic and the exacerbation of geopolitical tensions, various countries have witnessed energy supply threats and energy market fluctuations, further intensifying the energy accessibility challenges for numerous populations (Belaïd, 2022b; Carfora et al., 2022). Recent data reveals a startling 20% increase in the global population lacking sufficient energy service in daily life (Siksnelyte-Butkiene, 2022). Consequently, both scholars and policymakers must recognize the unforeseen repercussions of the low-carbon transition, particularly its implications for vulnerable groups in developing countries.

When residents grapple with challenges in getting enough energy services to sustain their daily lives, they are defined as trapped in an energy poverty condition (Liang and Asuka, 2022; Sy and Mokaddem, 2022). As the primary indicator assessing a resident's energy welfare, energy poverty encompasses the difficulties residents face in accessing or affording fundamental modern energy services (González-Eguino, 2015; Nussbaumer et al., 2012). According to previous studies, energy poverty, underscored by indoor air pollution and diminished thermal comfort, disrupts residents' daily activities, severely affecting their physical and psychological well-being (Xiao et al., 2021; Zhang et al., 2021). Furthermore, it also leads to a decline in productivity, thereby potentially exacerbating social inequities and hindering development in disadvantaged regions (Du et al., 2022; Liu et al., 2022; Shahzad et al., 2022). Recognizing the gravity of this issue, the United Nations (2012) considers universal access to modern energy services as a major goal by 2030.

Scholars have approached the tension between low-carbon transition and energy poverty from perspectives of equity and justice (Heffron, 2022). Since related policies were mainly formulated and executed by predominant governmental and corporate entities, the voice of the general populace is marginalized, further obstructing the realization of distributive, recognition, and procedural justice (Sovacool, 2021; Sovacool and Dworkin, 2015). During the low-carbon transition, on the one hand, the construction of wind/solar farms has encroached upon the arable lands that residents rely on for sustenance, exacerbating their impoverished conditions (Argenti and Knight, 2015; Gorayeb et al., 2018). On the other hand, such a transition has not only elevated the cost of energy production, transmission, and storage but also heightened the unpredictability of the energy system, inevitably increasing the risk of energy disruption and the economic burden of vulnerable groups (Geels et al., 2017; Mohseni et al., 2022; Tian et al., 2022). Recognizing the challenges the low-carbon transition posed, Belaïd (2022b) has probed into the new forms of inequalities birthed by transition policies, offering an integrated framework for harmonizing the low-carbon transition and energy poverty governance in developing countries. Existing research advises policymakers to ensure residents' welfare during the low-carbon transition, especially addressing the energy poverty issues confronted by vulnerable groups. Yet, current research still contains the following three gaps:

Firstly, previous studies on the impacts of the low-carbon transition on energy poverty often remain limited to qualitative discussions, lacking quantitative analysis. Secondly, academia primarily addresses the direct impact of the low-carbon transition, with a scant exploration into its underlying mechanisms or the heterogeneous effects under diverse governance scenarios. Thirdly, the focal point of most research predominantly rests on the developed countries, overlooking the specific challenges faced by vulnerable groups in developing countries. These research gaps hinder the governance implications of the pertinent conclusions, necessitating deeper exploration.

This study examines the relationship between low-carbon transition and energy poverty in developing countries, using China's low-carbon city pilot (LCCP) policy as a quasi-natural experiment. Specifically, employing the difference-in-differences (DID) method, we assess the LCCP policy's impact on residents' energy poverty conditions. We use panel data from 4807 households containing middle-aged or senior members in the China Health and Retirement Longitudinal Study (CHARLS) and match the data with the LCCP policy implementation in China's cities, shedding light on the macro-policy's micro-impacts. Moreover, we explore the underlying mechanisms by which the LCCP policy exerts its impacts, emphasizing the two mediating variables, including energy expenditure and infrastructure. Lastly, we conduct a heterogeneity analysis to understand the policy's impacts in cities and communities with different characteristics.

The study makes three significant contributions to existing literature. Firstly, this study offers a quantitative insight into the significant implications of low-carbon transitions on energy poverty in developing countries. With some cities in China adopting the LCCP policy and others yet to, China's LCCP initiative emerges as an ideal quasi-natural experiment to probe the effects of such transitions (NDRC, 2014). While earlier scholars predominantly embraced qualitative analysis or case studies, this study conducts a deeper and more reliable analysis, providing quantitative evidence for the relationship between low-carbon transition and energy poverty (Ravigné et al., 2022; Upham et al., 2022). Secondly, this study innovatively combines city-level pilot policies with household-level data, examining the micro-impacts of macro-policy. In previous research, scholars either pursued macro analysis using regional data or probed individual factors impacting energy poverty using household data (Dong et al., 2021; Zhao et al., 2022). Anchored by reliable survey data and robust methods, this study broadens the methodology for energy poverty research. Finally, the quantitative analysis not only aids China's policymakers in assessing the eventual impact of their LCCP policy on residents' welfare but also provides valuable reference for developing countries charting their future low-carbon transition pathways.

The remainder of this paper is structured as follows. Section "Literature review, theoretical basis, and research framework" reviews existing literature and proposes the theoretical basis and research hypotheses. Section "Methodology and data" introduces the methodology, including the model construction, variable selection, and data source. Section "Results and discussion" presents the results, as well as a discussion of the main findings. Section "Robustness test" presents the robustness tests. Section "Conclusion and policy recommendations" summarizes the main conclusions and offers relevant policy implications.

Literature review, theoretical basis, and research framework

Literature review

Determinants of energy poverty. Energy poverty, also called fuel poverty, is a central theme highlighting residents' welfare, which has attracted increasing scholarly interest. Since Boardman pioneered the 10% indicator for the energy poverty condition in the United Kingdom, various standards like the 2M indicator (double the median share of household expenditure on energy), low-income high cost (LIHC) indicator, and minimum living costs (MIS) indicator have emerged to determine whether residents are living in energy poverty or not (Boardman, 1991a; Castaño-Rosa et al., 2019; Hills, 2012; Moore, 2012). To fully cover residents' daily energy needs, Nussbaumer et al. (2012), drawing inspiration from the Oxford Poverty and Human Development Initiative, introduced the multidimensional energy poverty index (MEPI), encapsulating a range of daily energy necessities, from cooking, heating, entertainment to communication. Furthermore, based on the LIHC indicator, Belaïd and Flambard (2023) integrated three aspects, including income, energy, and housing costs, presenting a more holistic conceptual framework. Scholarly refinements in energy poverty indicators lay a solid foundation for further analysis.

The determinants of energy poverty have been studied from macro or micro perspectives. At the macro level, factors like regional economic development, resource allocations, and technological development played pivotal roles in determining the energy poverty of certain regions (Liang and Asuka, 2022; Wang and Hao, 2018; Xiao et al., 2023). At the micro level, factors such as household income, age, educational level, as well as societal belief were found to be associated with residents' energy poverty conditions (Awaworyi Churchill and Smyth, 2022; Belaïd, 2022a; Belaïd and Flambard, 2023; Fry et al., 2022; Hasanujzaman and Omar, 2022). Yet, current studies focus predominantly on general factors, neglecting the impacts of government-led policies represented by the low-carbon transition. Such oversights limit the depth and clarity of insights into fluctuations in residents' energy poverty conditions.

Challenges brought by low-carbon transition. Although the low-carbon transition has engendered numerous positive effects for the societal ecosystem, researchers have begun casting light upon the trade-off between such a transition and residents' welfare. As early as 1991, Boardman (1991b) argued that the introduction of carbon tax policy in the United Kingdom could cast a shadow upon the welfare of impoverished households. In the process of implementing a low-carbon policy, if stakeholders fail to simultaneously enhance energy efficiency, some households may be triggered into the predicament of high energy expenditure (Ürge-Vorsatz and Tirado Herrero, 2012). Nguyen et al. (2019) revealed that as Vietnamese households progressed from traditional to modern energy systems, there was a marked escalation in expenditure-based energy poverty. In the solar energy industry, the fabrication of thin-film solar panels, while advantageous for certain regions' low-carbon transition, also harbors potential health risks for manufacturing workers (Mulvaney, 2014). In fact, numerous endeavors aimed at energy transition, including architecture modifications, household solar panels, and electric vehicles, have precipitated varying degrees of discrimination and injustice among people, with a more conspicuous impact on vulnerable groups (Sovacool, 2021).

Diving deeper into the effects of the low-carbon transition on residents' welfare, researchers have pursued comprehensive studies from the perspective of energy justice. Setyowati (2021) examined the Indonesian government's efforts to achieve energy justice during the low-carbon transition and found that these endeavors inadvertently led to the further exclusion and disempowerment of energy-poor communities in energy-related decisions. In China's context, Wang and Lo (2022) investigated the country's journey toward justice during the energy transition, using the case of the environmental organization "Friends of Nature." They suggested that China's approach is distinctively different from the West, primarily based on Confucian self-cultivation. Sovacool et al. (2019) studied low-carbon initiatives in various countries, including France's nuclear power, the UK's smart meters, Norway's electric vehicles, and Germany's solar energy, and identified 120 energy injustices and introduced a strategic framework that includes distributive justice, procedural justice, cosmopolitan justice, and recognitional justice to ensure a fairer transition. While many scholars elucidate deprivation and inequity during the low-carbon transition by case studies, the lack of quantitative data makes it difficult to truly understand the degree to which certain low-carbon transition practices contribute to energy poverty.

China's low-carbon city pilot policy. As the world's most populous developing country, China's move toward a low-carbon transition might place a considerable burden on its residents (Bai et al., 2023). The "Coal-to-Gas" initiative launched in 2017 inadvertently resulted in a shortage of natural gas, leading to an inability for many households in northern China to heat their rooms (Luo et al., 2021; Wang and Ren, 2020). Furthermore, China's environmental protection law (Ma et al., 2022), as well as local environmental regulations (Xiao et al., 2023), have intensified energy poverty issues, particularly for households dependent on non-clean energy. However, a comprehensive quantitative analysis of the impact of China's low-carbon transition policy on residents' energy poverty is still lacking.

China's Low-Carbon City Pilot (LCCP) policy forms a critical part of the country's broader low-carbon transition strategy (Yang et al., 2023b). In pursuit of exploring efficient pathways towards carbon emission reduction, the National Development and Reform Commission selected cities to roll out the LCCP policy in 2011, 2013, and 2017. Directed by the central government, each pilot city, which reflected its own socio-economic characteristics, set individual carbon peaking objectives, established comprehensive greenhouse gas emission tracking systems, and employed both legal and economic mechanisms to encourage stakeholders to act accordingly (NDRC, 2014). The LCCP policy's overarching ambition is to overhaul the energy framework, augment energy efficiency, and achieve tangible reductions in greenhouse gas emissions.

The LCCP policy demands more in-depth exploration regarding its implications for residents. However, academic investigations have predominantly focused on the policy's broader outcomes, such as carbon emissions, ecological preservation, energy efficiency, innovation, and sustainable growth, highlighting its positive effects based on provincial or city-level data (Yang et al., 2023a; Zhang, Feng, et al. 2022; Zhu and Lee, 2022). Previous studies risk overlooking the intricate impacts on residents' energy welfare. Considering that residents utilize various forms of energy—like electricity, gasoline, and coal—accounting for around 20% of the overall societal energy usage (Shen and Shi, 2018), the implications of the LCCP policy on the energy system inevitably cascade down to residents, influencing their energy welfare.

Theoretical basis. Drawing upon existing research, this study centers on the theories of quasi-public goods and energy justice (Belaïd, 2022b; Belaïd and Flambard, 2023; Xiao et al., 2023). Both theories, grounded in human rights perspectives, offer a qualitative explanation for the latent correlation between governmental actions toward low-carbon transition and the energy poverty conditions of residents.

The theory of quasi-public goods concerns those goods that lie between the private and public domains (Buchanan, 1965; Savas, 1999). Unlike clear-cut public or private goods, quasi-public goods are partly non-rivalrous and non-excludable. Currently, utilities such as energy, water, and communication exhibit characteristics of quasi-public goods, with energy being a prime example (Zhao et al., 2015). Energy is vital for residential life, requiring residents to bear associated costs for their daily consumption. However, the energy sector is largely dominated by suppliers who possess inherent monopolistic characteristics (Wang and Chen, 2012). Given that the infrastructures of electricity and natural gas in specific regions serve a multitude of users and are irreplaceable in function, residents face stark limitations in choosing suppliers and struggle to find better suppliers based on free-market principles. As governments advocate for low-carbon transitions, energy suppliers might face increased costs, raising terminal energy prices. Due to the monopolistic nature of the energy sector, residents cannot easily switch to cheaper alternatives, thus risking increased energy costs, supply interruptions, and subsequent energy poverty.

Energy justice, viewed as the "ethical turn" in current energy policies and related research, aims to address the marginalization of vulnerable populations in policy formulation and implementation (Hartwig et al., 2023). Instead of viewing energy policies solely as technical solutions to climate issues, energy justice sees energy systems as a socially embedded phenomenon calling for a politically and morally informed response (McHarg, 2020). This perspective underscores the importance of prioritizing vulnerable groups during the low-carbon transition and addressing the inherent injustices and inequalities (Bouzarovski and Simcock, 2017; Jenkins et al., 2021; Sovacool et al., 2023). McCauley et al. (2013) and Jenkins et al. (2016) initially framed energy justice in terms of distribution, recognition, and procedure. Later scholars have added restorative and cosmopolitan justice to this framework (Heffron, 2022). Given the quasi-public nature of energy, the impact of low-carbon transition on residents' welfare is unavoidable. Energy justice enhances this argument, incorporating the justice dimension into the core values of governance, providing policymakers with a framework to identify and counter the ethical dilemma of low-carbon transition.

In summary, these theories provide an integrated consideration of climate, economy, and ethics for the formulation and implementation of energy policy. Quasi-public goods theory highlights the added burden residents face due to low-carbon transitions, while energy justice theory offers ethical benchmarks to address this issue. Using these theories as a foundation, this study investigates the nexus between low-carbon transitions and energy poverty in developing countries, utilizing quantitative analysis informed by China's LCCP policy.

Research hypotheses. To fill the research gap, this study treats LCCP policy as a quasi-natural experiment and employs the DID approach to delve deeper into the impacts of LCCP policy on the residents' energy poverty conditions, thereby advancing the understanding of the effects of low-carbon transition on energy poverty in developing countries.

Fundamentally, the LCCP policy is composed of a series of concrete emission reduction measures, forming a comprehensive policy system (Li et al., 2018; Wang et al., 2015). To meet stringent emission goals, local governments employ legal constraints and financial support to urge various stakeholders to reduce emissions, thereby driving the transformation of the societal energy structure (Feng and Chen, 2018; Khanna et al., 2014; Song et al., 2020). Although the main implementers of LCCP policy are the government and related enterprises, with few direct restrictions imposed on residents, residents will inevitably be affected by the aforementioned measures as the ultimate consumers of energy (Sovacool, 2021).

Primarily, the LCCP policy can exacerbate residents' energy poverty conditions by increasing necessary living energy expenditure. On the one hand, in a bid to optimize industrial and energy structure, the government propels solar power, natural gas, electricity, and other advanced energy to supplant outdated energy sources such as coal (Li et al., 2018). Some archaic enterprises may even face constraints or closures, inevitably leading to an energy supply shortage. In fact, inherent governance defects have further intensified this shortage resulting from energy structure upgrading (Luo et al., 2021). In China, the domestic natural gas shortage and electricity shortage that occurred in 2017 and 2021, respectively, are concrete manifestations of this predicament. On the other hand, energy enterprises, in order to comply with government emission reduction requirements and ensure normal operation, may invest more funds into technology upgrades and facility renovations, thereby escalating energy production costs (Amores-Salvadó et al., 2014; Sarkis and Cordeiro, 2001). Consequently, these enterprises pass on these costs to consumers when providing energy services, causing residents to bear the economic cost of cities' low-carbon transition (Zhang, 2018). In fact, energy prices have nearly doubled during some regions' low-carbon transition, leaving residents facing severe energy poverty issues (Frondel et al., 2015).

However, it is necessary to note that modern energy infrastructures established by the LCCP policy could potentially alleviate residents' energy poverty conditions. During policy implementation, governments encourage enterprises and other stakeholders to construct modern infrastructures for energy production, transmission, and distribution (Li et al., 2018). In China, as a result of the construction of large-scale power grids and natural gas networks, numerous residents have transitioned from using solid fuels such as coal or straw to modern energy (Yang et al., 2020). Previous research has demonstrated that well-developed energy infrastructures are crucial prerequisites for residents to get rid of energy poverty (Lippert and Sareen, 2023). Thus, energy infrastructure should also be taken into consideration when exploring the impact of LCCP policy on energy poverty.

Given the above analysis, the exact impacts of LCCP policy on energy poverty and the intermediary mechanisms still warrant further exploration. Therefore, we propose three hypotheses as follows, and the impact path is shown in Fig. 1.

Hypothesis 1: The LCCP policy exacerbates residents' energy poverty condition.

Hypothesis 2: The LCCP policy exacerbates residents' energy poverty condition through increasing energy expenditure.

Hypothesis 3: The LCCP policy alleviates residents' energy poverty conditions through energy infrastructure construction.

Methodology and data

Model construction

General form of difference-in-differences model. The implementation of specific public policies may impact certain groups while leaving other groups unaffected. Thus, it can be likened to a particular "treatment" administered to subjects in a medical experiment. Much like research in natural sciences, events in social science studies that alter the environment of individuals or cities in society are often referred to as quasi-natural experiments. If a specific public policy is seen as a quasi-natural experiment,

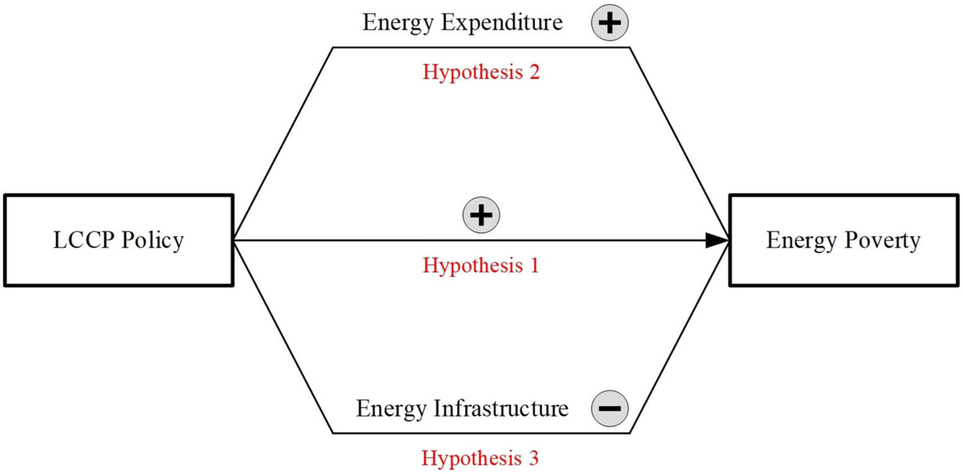

Fig. 1 Impact path of the LCCP policy on energy poverty.

then by comparing the individuals affected by the policy (treatment group) with the individuals unaffected (control group), one can discern the effects brought forth by the policy (Zhou and Chen, 2005).

The DID method is often employed to investigate the effects of public policy implementation from the perspective of quasi-natural experiments. Specifically, the DID method uses the dual differences in cross-sections and time series introduced by the public policy to identify the policy's "treatment effect" (Zhou and Chen, 2005). Its merit lies in circumventing the endogeneity issues when using policy as an explanatory variable and effectively controlling the interaction between dependent and independent variables. The DID model with panel data can account for unobservable individual heterogeneity among samples and control for unobservable factors that change over time, thereby achieving an unbiased estimation of policy effects (Fan et al., 2017). The general form of the DID model is shown in Eq. (1). Herein, y_{it} represents the dependent variable. The interaction term $\left(G_i \times D_t\right)$ indicates if the region of residence for individual i implemented a specific policy in year t. A value of 1 confirms this, while 0 negates it. X_{it} includes control variables that could impact the dependent variable. μ and ε, respectively, represent the fixed effect and the error term.

$$y_{it} = \alpha + \beta\left(G_i \times D_t\right) + \gamma X_{it} + \mu + \varepsilon \tag{1}$$

Difference-in-differences model for LCCP policy. The objective of this study is to delve into the impact of LCCP policy on residents' energy poverty conditions. Drawing from previous analysis, the effect of the LCCP policy can be perceived as a quasi-natural experiment. Given that selected pilot cities implemented the LCCP policy, their residents are inevitably under its sway. Conversely, residents of no-pilot cities remain unaffected. Thus, residents in pilot cities can be categorized as the treatment group, and those in non-pilot cities can be categorized as the control group. Utilizing the DID method, we can scrutinize the impact of LCCP policy by investigating differences before and after policy intervention, as well as differences between treatment and control groups at the same time point (Q. Shen et al., 2023). The benchmark DID model is shown in Eq. (2).

$$\mathrm{MEPI}_{it} = \beta_0 + \beta_1 \mathrm{LCCP}_{it} + \beta_2 C_{it} + \mu_i + \sigma_t + \varepsilon_{it} \tag{2}$$

Herein, i and t denote specific residents and years, respectively. MEPI_{it} signifies the energy poverty condition experienced by resident i in the year t. LCCP_{it} denotes whether the city where resident i lives implemented the LCCP policy in the year t, and a value of 1 indicates affirmation, whereas 0 indicates negation. C_{it} embodies control variables that could impact the residents' energy poverty. μ_i and σ_t correspondingly represent the fixed effects of residents and years, while ε_{it} constitutes the error term. In this model, the coefficient β_1 captures the shock of LCCP policy on energy poverty, with a positive value indicating an exacerbation effect, a negative value indicating an alleviation effect, and an insignificant value suggesting no substantial impact.

Regarding the intermediary effects of energy expenditure and energy infrastructure, we construct the following model, as depicted in Eqs. (3) and (4), to delve into the intermediary mechanisms.

$$\mathrm{Mediat}_{it} = \beta_0 + \beta_1 \mathrm{LCCP}_{it} + \beta_2 C_{it} + \mu_i + \sigma_t + \varepsilon_{it} \tag{3}$$

$$\mathrm{MEPI}_{it} = \beta_0 + \beta_3 \mathrm{LCCP}_{it} + \beta_4 \mathrm{Mediat}_{it} + \beta_5 C_{it} + \mu_i + \sigma_t + \varepsilon_{it} \tag{4}$$

In this model, Mediat_{it} represents the mediating variables. The coefficient β_1 captures the impact of LCCP policy on mediating variables, while the coefficient β_4 captures the impacts of mediating variables on residents' energy poverty. A statistically significant value for both coefficients indicates the existence of intermediary effects, while an insignificant value suggests no such effect.

The applicability of difference-in-differences model. When examining the impact of the LCCP policy on the energy poverty of residents, it is imperative to meet the following two fundamental prerequisites: (1) *Random City Selection for Pilots*: The process of selecting low-carbon pilot cities should be random, free from biases that might affect the dependent variable. Current literature and official statements suggest that policymakers have not considered residents during pilot city selection (Deng and Zhan, 2017). Our analysis of energy poverty conditions across low-carbon pilot cities shows varied values, indicating that city selection is random to some extent. (2) *Parallel trends*: Prior to the implementation of the LCCP policy, residents' energy poverty conditions in pilot cities should have a similar trend as those in no-pilot cities. This will be further elaborated upon in the section "Parallel trend test".

Variable selection

Dependent variable. Residents' energy poverty condition serves as the dependent variable in this model, referring to the challenges residents confront in accessing or affording modern energy services. We adopt the multidimensional energy poverty index (MEPI) framework, the widely accepted measurement proposed

Table 1 MEPI indicator system to measure residents' energy poverty condition.

Dimensions	Indicators	Measurement	Weight of dimensions	Weight of Indicators
Cooking	Q1. Cooking fuel	Modern fuel or not	0.2	1.0000
Room temperature	Q2. Air conditioner	Have or not	0.2	0.1483
	Q3. Thermal comfort	Comfortable or not		0.8517
Household appliances	Q4. Refrigerator	Have or not	0.2	0.3817
	Q5. Washing machine	Have or not		0.3661
	Q6. Hot water	Have or not		0.2522
Education/Entertainment	Q7. Television	Have or not	0.2	0.9127
	Q8. Computer	Have or not		0.0873
Communication	Q9. Mobile phone	Have or not	0.2	0.8522
	Q10. Internet	Have or not		0.1478

by Nussbaumer et al. (2012), to measure residents' energy poverty condition (Zhang, Appau et al., 2021). Specifically, we refine some indicators of MEPI to reflect China's unique circumstances more precisely. Finally, we developed a modified MEPI indicator system, including five dimensions (cooking, room temperature, household appliances, education/entertainment, and communication) and 10 specific indicators. Considering each dimension holds significant importance in household living, we assign each dimension an equal weight of 0.2 (Zhang et al., 2019). However, for indicators within each dimension, we employ the entropy method to assign weights, thereby avoiding subjective biases within specific dimensions (Feng et al., 2022; Zhang, Shu et al., 2021). The MEPI indicator system and corresponding weights of indicators are shown in Table 1.

According to the MEPI indicator system in this study, if a household's condition meets the criterion for residents' energy poverty, we will assign the indicator value to 1; otherwise, it will be assigned to 0. Specifically, if a household (1) uses non-modern energy sources (coal, straw, etc.) in cooking; (2) has no air conditioning; (3) has poor thermal comfort (too cold or hot); (4) has no refrigerator; (5) has no washing machine; (6) has no hot water supply; (7) has no television; (8) has no computer; (9) has no mobile phone; (10) has no internet, the corresponding indicator's value is assigned to 1. Finally, these values are aggregated according to their respective weights to calculate the final MEPI, as shown in Eq. (5). The higher the MEPI of the residents' households, the more severe their energy poverty condition.

$$\begin{aligned} MEPI_{it} = & (0.2*1.0000)Q1_{it} + (0.2*0.1483)Q2_{it} + (0.2*0.8517)Q3_{it} \\ & + (0.2*0.3817)Q4_{it} + (0.2*0.3661)Q5_{it} + (0.2*0.2522)Q6_{it} \\ & + (0.2*0.9127)Q7_{it} + (0.2*0.0873)Q8_{it} + (0.2*0.8522)Q9_{it} \\ & + (0.2*0.1478)Q10_{it} \end{aligned} \tag{5}$$

Independent variable. The LCCP policy serves as the independent variable within this model. As previously mentioned, when a specific city was chosen as an LCCP pilot in a certain year, the variable LCCP for that year and all subsequent years will be assigned to 1; otherwise, it will be assigned to 0. China's LCCP policy has undergone three batches: the first batch commencing in 2011, the second in 2013, and the final batch in 2017. The first batch was primarily aimed at provincial administrative regions, while the third batch had an excessively brief duration, both being unsuitable for this study (Zhao and Wang, 2021). Hence, this research selects the second batch of low-carbon pilot cities as a treatment group, while cities not identified as low-carbon pilot cities are utilized as a control group. In consideration of the availability of household-level data from the CHARLS database, 13 cities were finally chosen as the experimental group, and 85 cities as the control group.

Mediating variable. Energy expenditure is a mediating variable. Within China's economic situation, the price of transportation fuels, such as petrol, often fluctuates due to market dynamics (Ju et al., 2017). In contrast, residential electricity prices largely retain their stability, primarily due to governmental constraints (Li et al., 2023). Consequently, for a household, expenditures on domestic electricity can function as a reference benchmark, while expenditures on transportation might effectively serve as an indicator reflecting energy price fluctuations. Accordingly, we utilize the ratio between the transportation fee and the electricity fee of a household to measure energy expenditure.

Energy infrastructure is another mediating variable. Regarding infrastructural developments in China, natural gas, an innovative fuel advocated by governments in recent years, its pipeline construction can serve as a relatively precise barometer of the progress in energy infrastructure (Dong, Jiang et al., 2021; Dong et al., 2017). Thus, we utilize household natural gas supply as a measurement of energy infrastructure.

Control variable. Eight control variables are incorporated at the city level and household level, thereby enhancing the accuracy of our parameter estimates and alleviating biases derived from omitted variables. In light of previous research, at the city level, we incorporate variables including economic development, population, industrial structure, and societal consumption (Dong et al., 2021; Ren et al., 2022; Zhao et al., 2022). Specifically, we (1) use per capita GDP to denote economic development, (2) use the year-end total population as a measure of population, (3) use the ratio of the secondary industry's added value to GDP as a measure of industrial structure, and (4) use the total retail sales of consumer goods to represent societal consumption. At the household level, we include (5) household income, (6) household size, (7) marital status, and (8) the age of respondents (Abbas et al., 2020; Hong et al., 2022; Rahut et al., 2019).

Data source. This study utilizes household-level data from the China Health and Retirement Longitudinal Study (CHARLS) conducted by Peking University in collaboration with other institutions. This exhaustive survey employs a multistage stratified sampling methodology and rigorous survey process, guaranteeing regional representation and data quality (Peking University, 2023). CHARLS commenced its benchmark survey in 2011 and followed up in 2013, 2015, and 2018. The dataset encompasses households from 28 provinces, and more than 400 communities, offering rich information with a substantial sample size, fulfilling the requirements of this study.

CHARLS predominantly focuses on China's households containing middle-aged or elderly members and collects household-level data, including income, consumption, and other routine activities. Considering the traditional Chinese family structure where middle-aged or elderly individuals often

Table 2 Variable measurement.

Type	Variable	Symbol	Measurement
Dependent variable	Energy poverty	MEPI	Multidimensional Energy Poverty Index
Independent variable	LCCP policy	LCCP	Pilot Cities
Mediating variable	Energy expenditure	EXPEN	Ratio between the transportation fee and electricity fee of a household
	Energy infrastructure	INFRAS	Completeness of household natural gas supply
Control variable	Economic development	GDP	Per capita GDP
	Population	POP	Year-end total population of the city
	Industrial structure	IND	Ratio of secondary industry's added value to GDP
	Societal consumption	CONSUM	Total retail sales of consumer goods
	Household income	INCOM	Income per capita of a household in one year
	Household size	HOUSIZE	Total number of family members
	Marital status	MARRIAG	Married or not
	Age	AGE	Respondents' age

Table 3 Descriptive statistics of key variables.

Variable	Observations	Mean	Std. dev.	Min	Max	Median	60% of median
Energy poverty	19,228	0.330	0.231	0	1	0.323	0.194
LCCP policy	19,228	0.0894	0.285	0	1	0.000	0.000
Energy expenditure	14,556	0.730	4.680	0	250.0	0.000	0.000
Energy infrastructure	19,228	1.140	0.347	1	2	1.000	0.600
Economic development	19,228	10.49	0.566	8.842	12.20	10.50	6.300
Population	19,228	6.197	0.498	4.788	7.288	6.287	3.772
Industrial structure	19,228	47.66	10.31	18.63	74.78	48.04	28.82
Societal consumption	19,228	15.65	0.874	12.51	18.66	15.62	9.370
Household income	19,228	7.624	2.743	0	14.45	8.294	4.977
Household size	19,228	3.206	1.709	1	16	3.000	1.800
Marital status	19,228	1.209	0.407	1	2	1.000	0.600
Age	19,204	61.81	10.05	10	102	61.00	36.60

cohabitate with their offspring or kin, the CHARLS dataset aptly mirrors the typical Chinese household composition, portraying the evolving aging society in China (Wu, 2022; Yi and Wang, 2003). Therefore, if the energy poverty conditions of the households in CHARLS were confirmed to be impacted by LCCP policy, it would underscore the potential of low-carbon transition to alter energy poverty landscapes in developing countries. CHARLS publicly disclosed the cities where these households were located when starting the longitudinal survey. Leveraging this information, we can easily match these households with their respective cities, further establishing panel data to investigate the impact of the LCCP policy on residents' energy poverty conditions (Li et al., 2022).

Our study incorporates household-level data from four waves of CHARLS surveys (conducted in 2011, 2013, 2015, and 2018) that maintained continuous tracking of these households. We utilize the primary characteristics and energy consumption data of these households for the dependent variable MEPI, mediating variables, and household-level control variables. Additionally, we gather city-level control variables—including per capita GDP, population, industrial structure, and societal consumption—from national and city statistical yearbooks.

Utilizing DID regression on household-level panel data, we surpass the scope of previous region-based studies, enabling us to capture dynamic processes at the micro level and thus facilitating a deeper analysis. Table 2 illustrates the variable measurements. Tables 3 and 4 provide the descriptive statistics and characteristics of key variables. To reduce heteroskedasticity, we apply logarithmic transformations (Numan et al., 2023) for variables including per capita GDP, population, societal consumption, and household income. Finally, we have collected panel data from 4807 households from the years 2011, 2013, 2015, and 2018, yielding a total of 19,228 observations. The MEPI for these households ranges between 0 and 1, with a mean value of 0.330, thereby delineating a representative snapshot of energy poverty among Chinese residents. These households are distributed across a range of city types, including 13 pilot cities and 85 non-pilot cities, thus offering a wide-ranging representation of the manifold city types within China.

Result and discussion

Result

The evolution of residents' energy poverty condition. Using the previously outlined MEPI indicator system, we are able to calculate the MEPI index for households and trace the energy poverty condition of 4807 households from 2011 to 2018. As depicted in Fig. 2, the Sankey diagram illuminates the overall evolution of energy poverty within these sampled households, as well as the relative proportion of households experiencing varying degrees of poverty.

Upon a comprehensive overview in Fig. 2, the period from 2011 to 2018 witnessed a gradual decline in severe-energy-poverty households with an MEPI over 0.75, paralleled by an increasing trend of no-energy-poverty households with an MEPI below 0.25. This implies a gradual alleviation of the overall energy poverty situation in China. However, throughout the 8-year interval from 2011 to 2018, despite the increasing number of no-energy-poverty households, there persistently existed a segment of originally no-energy-poverty households transitioning into light, moderate, or severe energy poverty during 2011–2013, 2013–2015, or 2015–2018. Particularly during 2013–2015, around 20% of originally no-energy-poverty households transitioned into

Table 4 Data characteristics of key variables.

Variable	Categories	Frequency (in %)
Energy poverty	No poverty: 0.00 <MEPI ≤ 0.25	39.83
	Mild poverty: 0.25 <MEPI ≤ 0.50	39.05
	Moderate poverty: 0.50 <MEPI ≤ 0.75	15.49
	Severe poverty: 0.75 <MEPI ≤ 1.00	5.63
LCCP policy	0 no pilot city	91.06
	1 pilot city	8.94
Energy expenditure	<0.5	73.16
	From 0.5 to 1	12.77
	More than 1	14.07
Energy infrastructure	1 without natural gas supply	86.02
	2 with natural gas supply	13.98
Economic development	Less than 10.10	25.00
	From 10.10 to 10.50	25.00
	From 10.50 to 10.84	25.00
	More than 10.84	25.00
Population	<5.921	25.00
	From 5.921 to 6.287	25.00
	From 6.287 to 6.557	25.00
	More than 6.557	25.00
Industrial structure	Less than 41.57	25.00
	From 41.57 to 48.04	25.00
	From 48.04 to 54.34	25.00
	More than 54.34	25.00
Societal consumption	<15.15	25.00
	From 15.15 to 15.62	25.00
	From 15.62 to 16.13	25.00
	More than 16.13	25.00
Household income	<6.804	25.00
	From 6.804 to 8.294	25.00
	From 8.294 to 9.419	25.00
	More than 9.419	25.00
Household size	1 or 2 members	45.30
	3 or 4 members	33.45
	5 or 6 members	17.12
	More than 6	4.13
Marital status	1 Married	79.08
	2 Not married	20.92
Age	<54	22.31
	From 54 to 61	28.78
	From 61 to 68	24.13
	More than 68	24.78

light energy poverty, 7% into moderate, and 1% into severe energy poverty. The count of households transitioning into poverty during 2013–2015 exceeded that of any other interval before or after. This suggests a possible existence of an exogenous shock significantly impacting residents' energy poverty conditions, which could likely result from several cities being designated as low-carbon pilots since 2013.

In the following section, we will employ the DID approach to explore whether the LCCP policy can lead to a change in residents' energy poverty conditions.

Benchmark regression. Table 5 delineates the benchmark regression results of LCCP policy impact on energy poverty based on household-level panel data. Moving from column (1) to column (3), the coefficients of LCCP policy are significantly positive, irrespective of whether time-fixed or household-fixed effects are controlled. Furthermore, in column (4), when we simultaneously control both time-fixed and household-fixed effects, the coefficient of LCCP policy is 0.0218 at the 1% level. In other words, compared to the control group, the LCCP policy has exacerbated the energy poverty condition of residents in the pilot cities by 0.0218, thereby supporting Hypothesis 1. Sovacool et al. (2022) expound that the low-carbon transition is not a panacea devoid of detriments, and some actions towards low-carbon transition may indeed precipitate fresh inequities and risks. Our empirical analysis uncloaks the aggravating impact of the LCCP policy on residents' energy poverty, viewed from the perspective of inhabitants' welfare.

Control variables at both the city and household levels are incorporated into the DID model to mitigate omitted variable bias. The regression results in column (4) of Table 5 reveal that economic development (GDP), household income (INCOM), household size (HOUSIZE), and marital status (MARRIAG) exert significant influence on residents' energy poverty conditions. Among these, higher economic development, higher household income, and larger household size serve to alleviate energy poverty, consistent with previous studies (Ren et al., 2022; Zou and Luo, 2019). Intriguingly, the absence of marital relationships appears to alleviate energy poverty, which could be explained from a feminist perspective: within married households, women are typically tasked with energy consumption-related domestic labor (Amigo-Jorquera et al., 2019; Robinson, 2019). However, women's labor is often undervalued, leading to a lack of motivation within these households to upgrade their energy sources (Heltberg, 2005). In contrast, within unmarried or divorced households, women assume control of energy upgrades, thus effectively liberating themselves from energy poverty (Azhgaliyeva et al., 2021). In addition, the insignificance of other control variables might be attributed to complex nonlinear relationships (Yang et al., 2023a).

Intermediary mechanism. The aforementioned regression confirms that the LCCP policy can exacerbate residents' energy poverty conditions. Delving further, we elucidate the intermediary mechanism through the regression presented in Table 6. Columns (1) and (2) scrutinize the mediating effect of energy expenditure, columns (3) and (4) scrutinize the mediating effect of energy infrastructure, whereas column (5) gauges the joint impact of both on energy poverty. Results indicate that both energy expenditure and infrastructure play significant intermediary roles, while their effects are diametrically opposed. On one hand, the LCCP policy significantly enhances energy expenditure, subsequently exacerbating energy poverty. Hypothesis 2 is thus confirmed. On the other hand, the policy bolsters the construction of energy infrastructure, thereby alleviating energy poverty, and Hypothesis 3 is verified. Taken together, LCCP policy could exacerbate energy poverty, which is consistent with the previous benchmark regression.

Heterogeneity analysis based on city characteristics. This study encompasses 98 cities in China. Cities located at different geographical positions exhibit substantial variations in their resource endowment, scales, and administrative levels. To delve deeper into whether the LCCP policy's impacts differ across cities with distinct characteristics, we conduct a comprehensive heterogeneity analysis as follows.

Cities' natural conditions, including geographical location and resource endowment, are taken into consideration. Cities are categorized into eastern, central, and western regions, referenced from previous studies (State Council, 2000; Zheng and Shi, 2017). Subsequently, cities are bifurcated based on their resource endowments into non-resource and resource-dependent cities, in alignment with the National Resource-based City Sustainable Development Plan issued by the State Council (2013). The regression results are represented in columns (1)–(5) of Table 7.

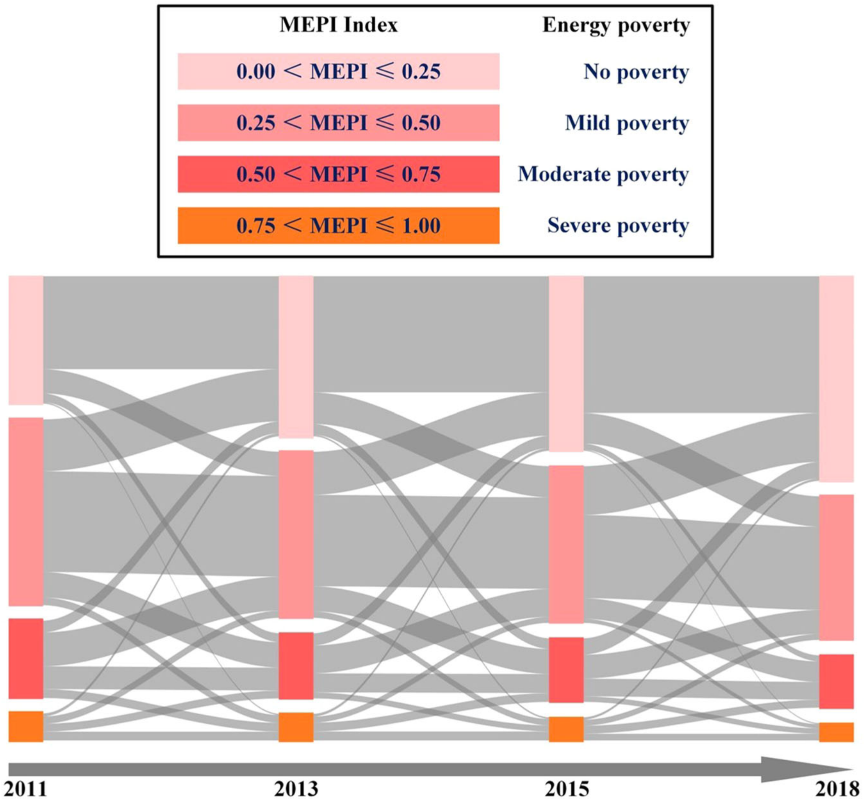

Fig. 2 The evolution of residents' energy poverty condition.

Table 5 Benchmark regression.

Variables	(1) No fix	(2) Time fix	(3) Household fix	(4) Both fix
LCCP	0.0219***	0.0163***	0.0135*	0.0218***
	(3.818)	(2.847)	(1.741)	(2.727)
GDP	−0.0444***	−0.0391***	−0.0195*	−0.0209**
	(−7.093)	(−6.268)	(−1.920)	(−2.031)
POP	0.0110*	−0.0025	0.0224	0.0148
	(1.789)	(−0.404)	(0.678)	(0.446)
IND	0.0014***	0.0004**	0.0002	0.0003
	(9.262)	(2.316)	(0.787)	(0.989)
CONSUM	−0.0402***	−0.0256***	−0.0163**	−0.0092
	(−7.932)	(−5.047)	(−2.267)	(−1.222)
INCOM	−0.0142***	−0.0143***	−0.0016***	−0.0015**
	(−25.446)	(−25.913)	(−2.603)	(−2.449)
HOUSIZE	−0.0139***	−0.0166***	−0.0083***	−0.0080***
	(−14.873)	(−17.693)	(−7.949)	(−7.569)
MARRIAG	0.0596***	0.0547***	0.0264***	0.0256***
	(14.849)	(13.749)	(3.031)	(2.943)
AGE	0.0055***	0.0062***	−0.0101***	−0.0078
	(33.553)	(37.578)	(−8.631)	(−1.017)
Constant	1.0282***	0.8506***	1.2697***	1.0746**
	(26.334)	(21.495)	(5.873)	(2.005)
Observations	19,204	19,204	19,204	19,204
R-squared	0.192	0.210	0.663	0.663
Time FE	No	Yes	No	Yes
Household FE	No	No	Yes	Yes

t-statistics in parentheses.
***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

Table 6 Regression for intermediary mechanism.

Variables	(1) EXPEN	(2) MEPI	(3) INFRAS	(4) MEPI	(5) MEPI
LCCP	0.5500*		0.0307**		0.0213**
	(1.953)		(2.371)		(2.458)
EXPEN		0.0007**			0.0007**
		(2.458)			(2.366)
INFRAS				−0.0350***	−0.0337***
				(−6.811)	(−6.127)
Constant	−27.1581	0.6624	1.0521	1.1484**	0.6888
	(−1.504)	(1.188)	(1.213)	(2.146)	(1.237)
Control variable	Control	Control	Control	Control	Control
Observations	14,540	14,540	19,204	19,204	14,540
R-squared	0.273	0.665	0.610	0.664	0.666
Time FE	Yes	Yes	Yes	Yes	Yes
Household FE	Yes	Yes	Yes	Yes	Yes

t-statistics in parentheses.
***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

Table 7 Regression for cities with different natural conditions.

Variables	(1) Eastern region	(2) Central region	(3) Western region	(4) Non-resource based	(5) Resource-dependent
LCCP	0.0425***	−0.0037	0.0082	0.0345***	0.0032
	(3.379)	(−0.221)	(0.589)	(3.167)	(0.265)
Constant	2.3971**	2.1905**	−0.5141	0.6539	1.7960**
	(1.982)	(2.436)	(−0.542)	(0.867)	(2.336)
Control variable	Control	Control	Control	Control	Control
Observations	6312	7012	5880	10,720	8484
R-squared	0.683	0.658	0.639	0.657	0.664
Time FE	Yes	Yes	Yes	Yes	Yes
Household FE	Yes	Yes	Yes	Yes	Yes

t-statistics in parentheses.
***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

The implementation of the LCCP policy in China's eastern region could markedly intensify energy poverty, with a significant increase of approximately 0.0425 at a 1% level. Yet, this policy's impacts on energy poverty in the central and western regions remain negligible. As the most economically vibrant region of China, the eastern region exhibits a keen response to supply-demand dynamics in energy pricing (Cai et al., 2023; He et al., 2016). Consequently, policy shifts have a swift and palpable impact on energy consumption at the household level. In contrast, the central and western regions with lower levels of economic development and marketization (Ren et al., 2018), exhibit a certain "inertia" in energy prices, and the energy poverty condition of residents in these regions also tends to remain unchanged during LCCP policy implementation.

In non-resource cities, the LCCP policy significantly exacerbates energy poverty, with a coefficient of 0.0345, whereas this impact is not significant in resource-dependent cities. Non-resource cities rely on imported energy from other cities or regions, which extends the energy supply chain and escalates acquisition costs (Qiu et al., 2021). Consequently, the disruption to their energy supply and household energy consumption by LCCP policy is more pronounced. On the other hand, resource-dependent cities usually satisfy their energy needs locally or nearby, ensuring shorter supply chains and swift demand response, further effectively mitigating the LCCP policy's impact on the entire energy system and residents' energy poverty. Interestingly, most resource-dependent cities are located in central and western China, while non-resource cities are chiefly located in the east, and the regression results for these two city types could offer mutual corroboration. Broadly speaking, non-resource cities, particularly those in the east, should be cautious when implementing the LCCP policy, paying keen attention to the energy welfare of their residents.

Heterogeneity analysis of cities' social conditions, including administrative level and city scale, is also conducted. Cities are classified by administrative levels: high-level (sub-provincial city or municipality) and low-level (prefecture-level city). Furthermore, we partitioned cities into small (populations under 5 million), medium (populations between 5 and 10 million), and large (populations over 10 million), and the corresponding regression results are presented in columns (1)–(5) of Table 8.

As shown in Table 8, the impact of LCCP policy is significant in high-level or big cities, in contrast to low-level or small cities. The above two regressions can be explained together: high-level city or large city tends to be more developed, leading its residents to adopt large amounts of modern energy (Liu et al., 2012; Ouyang and Hokao, 2009). However, the energy composition of these cities is relatively monolithic, largely relying on single sources such as electricity or natural gas, with limited options for energy substitution. Overdependence on single sources risks plunging these cities' residents into energy poverty during supply fluctuation caused by LCCP policy. Conversely, small cities with low administrative levels, despite some degree of energy poverty, exhibit a broader energy composition in residents' daily lives, including electricity, natural gas, liquefied petroleum gas, biogas, etc. (Cui et al., 2019; Peidong et al., 2009), thus these residents' energy poverty conditions are less sensitive to the LCCP policy targeted to the specific type of energy.

Table 8 Regression for cities with different social conditions.

Variables	(1) High-level city	(2) Low-level city	(3) Large city	(4) Medium city	(5) Small city
LCCP	0.0533**	0.0157	0.0895**	0.0456***	−0.0078
	(2.453)	(1.473)	(2.019)	(4.231)	(−0.576)
Constant	−4.5201	1.2461**	3.1474	0.4434	2.7884***
	(−1.586)	(2.249)	(1.146)	(0.559)	(3.180)
Control variable	Control	Control	Control	Control	Control
Observations	1744	17,460	1216	9564	8424
R-squared	0.579	0.665	0.707	0.660	0.662
Time FE	Yes	Yes	Yes	Yes	Yes
Household FE	Yes	Yes	Yes	Yes	Yes

t-statistics in parentheses.
***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

Table 9 Regression for communities under different governance.

Variables	(1) High quality	(2) Low quality	(3) High expenditure	(4) Low expenditure	(5) Urban	(6) Rural
LCCP	0.0082	0.0322**	0.0168*	0.0293*	0.0102	0.0215*
	(0.877)	(1.986)	(1.803)	(1.838)	(0.880)	(1.884)
Constant	1.1718	0.8376	1.0160	1.0121	0.7739	1.1124*
	(1.482)	(1.094)	(1.413)	(1.206)	(0.857)	(1.659)
Control variable	Control	Control	Control	Control	Control	Control
Observations	9572	9632	11,812	7392	6460	12,744
R-squared	0.650	0.664	0.673	0.641	0.638	0.644
Time FE	Yes	Yes	Yes	Yes	Yes	Yes
Household FE	Yes	Yes	Yes	Yes	Yes	Yes

t-statistics in parentheses.
***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

Heterogeneity analysis based on community characteristics. 349 distinct communities are included in this study. As the fundamental administrative unit in China's society, the community is linked to every resident's daily life. The LCCP policy's impact could vary significantly across communities with diverse characteristics. Initial surveys by CHARLS exhaustively charted the inherent features of communities, providing a complete dataset for community heterogeneity analysis.

From the perspective of community governance, communities are stratified based on public service quality (high or low, dependent on whether officials can speak Mandarin or not), and public expenditure (high or low, dependent on whether it exceeds the 20,000 Yuan threshold). The regression results are outlined in columns (1)–(4) of Table 9. The regression results show a significant impact of the LCCP policy, which amplifies residents' energy poverty in communities with low public service quality and low public expenditure. This suggests that the impacts of the LCCP policy vary with changes in community governance. In simpler terms, when grassroots governance is inadequate, the negative impacts of the LCCP policy become significantly more prominent. Grassroots governments, such as community administrators, serve as a 'shield' in mitigating potential energy poverty risks among residents during the low-carbon transition (Martiskainen et al., 2018).

In addition, the regression analysis presented in columns (5) and (6) of Table 9 reveals contrasting impacts of the LCCP policy on residents of urban and rural communities. Specifically, while the impact on urban residents' energy poverty proves insignificant, it is significant in rural communities. These findings align with previous heterogeneity analyses of public service quality and public expenditure. The significant urban-rural gap and governance practice in China give urban residents an advantage in accessing abundant resources and favorable energy policies, thereby enabling them to mitigate the potential deleterious effects of the LCCP policy (Lu et al., 2022; Yao and Jiang, 2021). Conversely, residents in rural areas, especially those in remote and sparsely populated regions, are often overlooked by energy policymakers, leaving them at the lower end of the energy ladder (Li and Ma, 2023; Tang and Liao, 2014). Despite China's recent progress made through "Targeted poverty alleviation" policy, which has lifted many rural residents out of absolute poverty, the existing rural energy infrastructure, including natural gas networks and power grids, is still inadequate for meeting residents' daily energy needs (Li et al., 2019; Liu and Mauzerall, 2020). Consequently, during the supply shortfalls caused by LCCP policy, rural residents are often forced to resort to outdated energy sources like coal, exacerbating their plunge into energy poverty.

Discussion. This research employs the DID method to delve into the impact of the LCCP policy on residents' energy poverty conditions and its underlying mechanisms. Our findings offer valuable insights into the delicate tension between low-carbon transitions and energy poverty in developing countries, enriching the understanding of both scholars and policymakers.

This study analyzes 4807 continuously tracked household samples from the CHARLS dataset, offering a snapshot of China's diverse households. Specifically, 79.08% of these households are married, and 78.75% have up to four members—a reflection of the smaller family units after China's one-child policy in the 1980s. Approximately 50% of households reported a per capita income above 4000 Yuan, a figure that rose between 2011 and 2018, echoing China's economic growth. However, the 8-year CHARLS survey reveals that, although there was an overall decrease in energy-poverty households from 2011 to 2018, some households transitioned into energy poverty. While broader studies suggest that China's recent socio-economic growth has

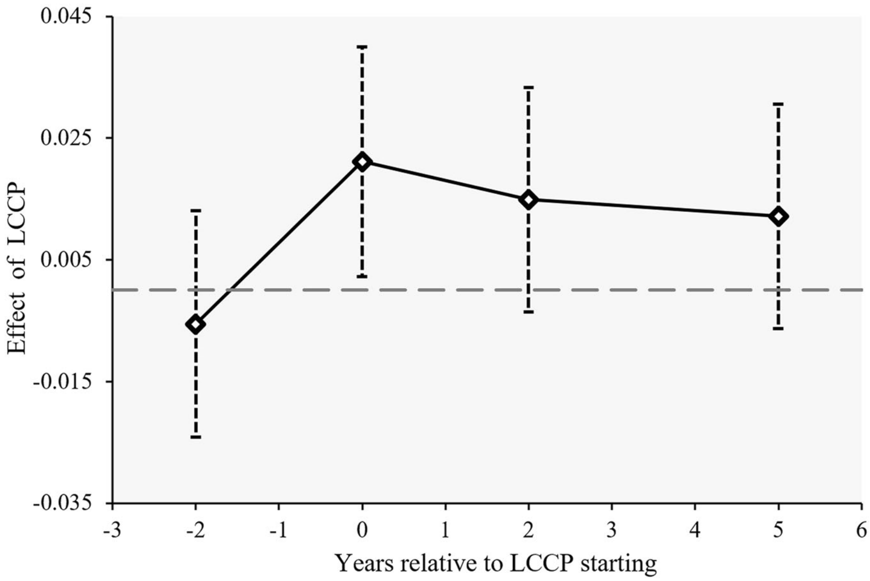

Fig. 3 Parallel trend test.

lessened its energy poverty issues (Liang and Asuka, 2022; Zhao et al., 2021), our analysis uncovers subtle 'shadows'—households at risk of returning to energy poverty—overlooked in regional data.

This study found that the LCCP policy significantly exacerbated residents' energy poverty condition, providing the first quantitative demonstration of the LCCP's negative impacts at the household level. Our findings contrast with previous studies (Dong et al., 2021; Dong, Ren et al., 2021). Employing province-level data and general regression methods, they deduced that low-carbon transition mitigated energy poverty (Dong, Jiang et al., 2021). However, such regional data inadequately captures the intricacies of residents' energy poverty. Additionally, gauging low-carbon transition via natural gas consumption fails to directly represent the overall implementation of the low-carbon transition policies, thus affecting the reliability of associated conclusions. Complementing earlier research, our study harnesses the LCCP—most representative low-carbon policy in China—to directly probe its consequences on residents' energy poverty, yielding more precise conclusions. This beckons policymakers to weigh the possible ramifications on residents' energy welfare in upcoming low-carbon endeavors and advises circumspection before embracing unreviewed low-carbon strategies.

This study experimentally identifies two potential mediating pathways in the relationship between LCCP policy and energy poverty: energy infrastructure and energy expenditure. Regression results reveal that LCCP policy can alleviate energy poverty through the enhancement of energy infrastructure, but exacerbate it by escalating energy expenditure. This can be explained as follows: To comply with government mandates regarding the LCCP policy, energy enterprises must augment their investments in infrastructure, refining energy production, and transportation, which subsequently elevates the cost of energy supply. These surging costs are then passed on to residents, subjecting households sensitive to energy price fluctuations to the energy poverty trap. Compared with previous research, this study delves into the relationship between variables utilizing household-level data, significantly augmenting scholars' preliminary qualitative analysis on the ramifications of low-carbon transition for resident welfare. Earlier investigations indicated that, with the rise in natural gas and oil prices, households previously affording these energy forms have resorted to coal as an alternative (Kapsalyamova et al., 2021; Turdaliev and Janda, 2023). This research further elucidates the trend of residents downgrading their daily energy source due to escalating prices, linking this argument to the broader issue of energy poverty.

However, some scholars, adopting a system dynamics perspective, underscore the dynamic feedback interplay between the aforementioned variables, including low-carbon transition, energy expenditure, and energy poverty (Che et al., 2023; Venkateswaran et al., 2018). Che et al. (2023) created causal loop diagrams to capture the interplay between energy poverty and various socio-economic factors, accentuating that energy poverty is influenced not merely by an array of factors and multifarious pathways but also exerts its own influence on the broader system. These perspectives highlight a limitation of this study: the path we identified from the LCCP policy through energy expenditure to energy poverty, perhaps reflects the associations among variables rather than the direct causality. Nonetheless, our study offers valuable insights for policymakers seeking to intervene in the adverse impacts of low-carbon transitions.

Heterogeneity analyses reveal that eastern cities, non-resource cities, high-level cities, and larger cities manifest a pronounced risk of residents descending into energy poverty after LCCP policy enforcement. These cities typically have a vibrant energy market where energy supply is predominantly market-driven. Consequently, this study supports the notion that an active energy market can enhance energy poverty risks since energy service for residents is considered a quasi-public good (Xiao et al., 2023). This finding aligns with scholars who warn against unchecked marketization of quasi-public goods like energy and highlight the importance of sustained government oversight to ensure residents' energy welfare (Luo, 2008; Zhao et al., 2015).

Robustness test

To ensure the reliability of DID regression, we conduct robustness tests, including parallel trends test, anticipation effects, placebo test, PSM-DID approach, outliers excluding, and variable substitution as follows.

Parallel trend test. The prerequisite for DID regression is the satisfaction of the parallel trend assumption (Liu et al., 2022; Zhao and Wang, 2021). In the context of our study, in the absence of the LCCP policy, the trend of energy poverty among residents in the pilot city should be similar to that of the non-pilot city. We employ Jacobson et al. (1993) method to perform the parallel trends test, as illustrated in Fig. 3. The results reveal that the coefficient prior to the policy shock is close to zero and statistically insignificant, indicating no divergence between the pilot and non-pilot cities before policy implementation. The coefficients significantly rise to positive values when the policy is implemented, suggesting that the LCCP policy initially exacerbates energy poverty. However, the coefficients gradually decrease in the second and fifth post-implementation years, signaling a diminishing impact of policy. Overall, this method validates the parallel trends assumption.

Anticipation effects. The absence of anticipation effects is another pivotal prerequisite for the DID method. If anticipation effects exist, they could cause estimation bias, making it difficult to determine whether the effects we observed in the treatment group are due to anticipation actions or actual policy implementation. Therefore, excluding anticipation effects is of utmost importance for our study. We will discuss the anticipation effects through two aspects: policy practice and data analysis.

Firstly, China's pilot city policy is a conventional approach to policy exploration and policy learning (Wang and Yang, 2021). In China's actual governance context, when selecting low-carbon pilot cities, the central government primarily considers regional representativeness (Fang, 2015), and the energy poverty condition does not fall into policymakers' consideration. In previous quantitative studies, scholars have confirmed that the selection of low-carbon city pilots is not related to the cities' own low-carbon development status before being selected (Deng and Zhan, 2017), indicating that the governments of pilot cities did not take relevant actions that may influence their conditions before LCCP policy implementation. Consequently, residents, at the furthest end of the policy impact scope, are even less likely to be prematurely affected. Therefore, based on the pilot-selection logic of the central government and previous studies, we have substantial grounds to confirm the absence of anticipation effects.

Secondly, we conduct a quantitative comparison, analyzing the average energy poverty condition in pilot cities and non-pilot cities before LCCP policy implementation. As shown in Fig. 4, there are no significant differences between pilot cities and no-pilot cities when the LCCP policy has not been implemented. Specifically, the average energy poverty condition of all cities included in the study was 0.3494 in 2011. In pilot cities like Guilin and Suzhou, levels were lower than 0.3494, while in Hulunbuir and Ganzhou, levels were higher, presenting a relatively uniform distribution, similar to that in non-pilot cities, indicating no anticipation effects before policy implementation. Therefore, we can confirm the absence of anticipation effects.

Placebo test. To mitigate the effects of random factors on energy poverty and substantiate the policy-driven impact, we conduct a placebo test through random sampling (Wang et al., 2023). We randomly select artificial pilot cities and policy implementation times from the samples, thereby randomizing the impact of the LCCP policy. We perform the corresponding DID regression and repeat the random process 500 and 1000 times, with the distribution of coefficients shown in Fig. 5. The coefficients cluster around zero, markedly less than the previously estimated value of 0.0218. Most regression coefficients have p-values exceeding 0.1, indicating insignificance at the 10% level. Therefore, the LCCP policy's impact on residents' energy poverty is not accidental and is not influenced by other random factors.

PSM-DID approach. PSM-DID approach is used to counter the selection bias of the treatment group and reduce endogeneity issues (Dong et al., 2022). Initially, we conduct logit regression using control variables as covariates to calculate propensity matching scores. We then use the scores to match the treatment group and control group via nearest neighbor, radius, and kernel method, respectively. Lastly, we execute three DID regressions, as shown in Table 10. The estimated values from all matching methods are similar to benchmark regression, confirming that the LCCP policy significantly exacerbates energy poverty, further reinforcing the robustness of our findings.

Outliers excluding and variable substitution. To mitigate the impact of outliers on the regression results, we apply a 1%, 5%, and 10% bilateral tail shrinkage treatment to the dependent variable. As shown in columns (1)–(3) of Table 11, the coefficients of the LCCP policy are significant at the 1% level after this treatment. Simultaneously, we replace the dependent variable MEPI with cooking fuel type, another indicator of household energy poverty. The coefficient of the LCCP policy, as shown in column (4), remains significant. These findings thus substantiate the robustness of our conclusions.

Conclusion and policy recommendations

Conclusion. To examine the relationship between low-carbon transition and energy poverty in developing countries, this study employs China's LCCP policy as a quasi-natural experiment. Drawing from 4-year household survey data from CHARLS, we leveraged DID models to examine the impact of the LCCP policy on residents' energy poverty conditions from a micro perspective.

The main conclusions are as follows: (1) The energy poverty conditions of the 4807 households involved in our study experienced notable shifts from 2011 to 2018, and a significant number of residents saw their energy poverty conditions worsen. (2) The DID regression underscores that the LCCP policy notably exacerbates residents' energy poverty. This conclusion holds true even after various robustness tests, including parallel trend test, placebo test, PSM-DID, and other methods. (3) According to intermediary mechanism analysis, energy infrastructure and energy expenditure play critical roles in the relationship between LCCP policy and energy poverty, offering valuable insight into the potential pathways of LCCP policy's impact. (4) City heterogeneity analysis shows that LCCP policy has stronger impacts in eastern, non-resource, larger, and high-level cities. In addition, community heterogeneity analysis underscores a more severe impact of the LCCP policy in communities with inadequate grassroots governance.

Policy implications. Considering the energy poverty issue brought about by the low-carbon transition in developing countries, this study illuminates the following policy implications for future low-carbon practices and energy poverty governance.

According to this study, there exists a delicate balance between advancing low-carbon transitions and ensuring residents' energy welfare. Developing countries' governments should adopt measured practices toward low-carbon transition, as well as assess the energy poverty risk of their residents. The empirical data presented in this study calls for a rethinking of current low-carbon strategies, represented by LCCP policy, and setting appropriate targets in light of local conditions. In practice, low-carbon policies that neglect residents' welfare might not only lead to resource misallocation but also incite public opposition. For instance, when China's "coal-to-gas" policy resulted in daily heating issues, the government was compelled to suggest a more

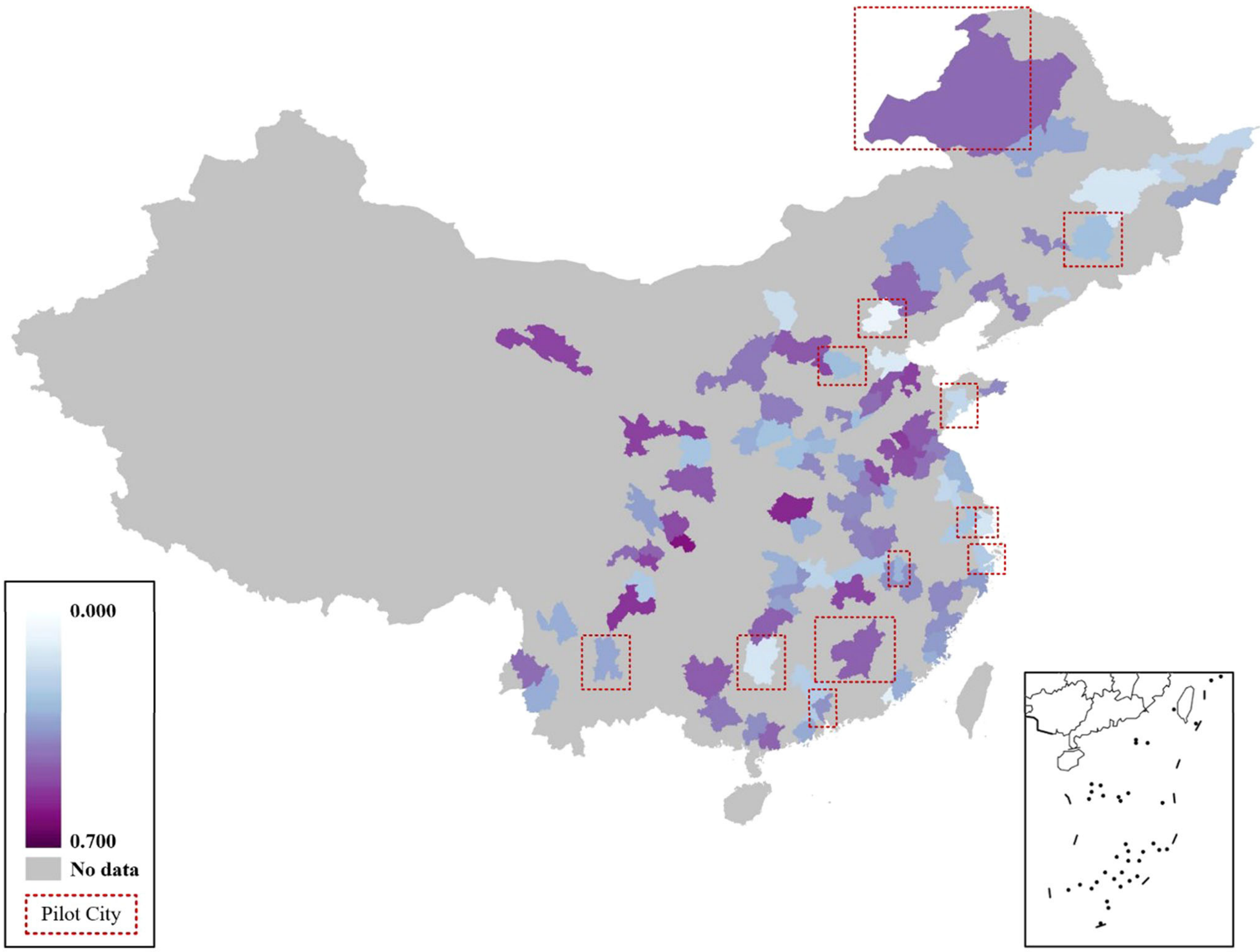

Fig. 4 Average energy poverty conditions of cities before policy implementation.

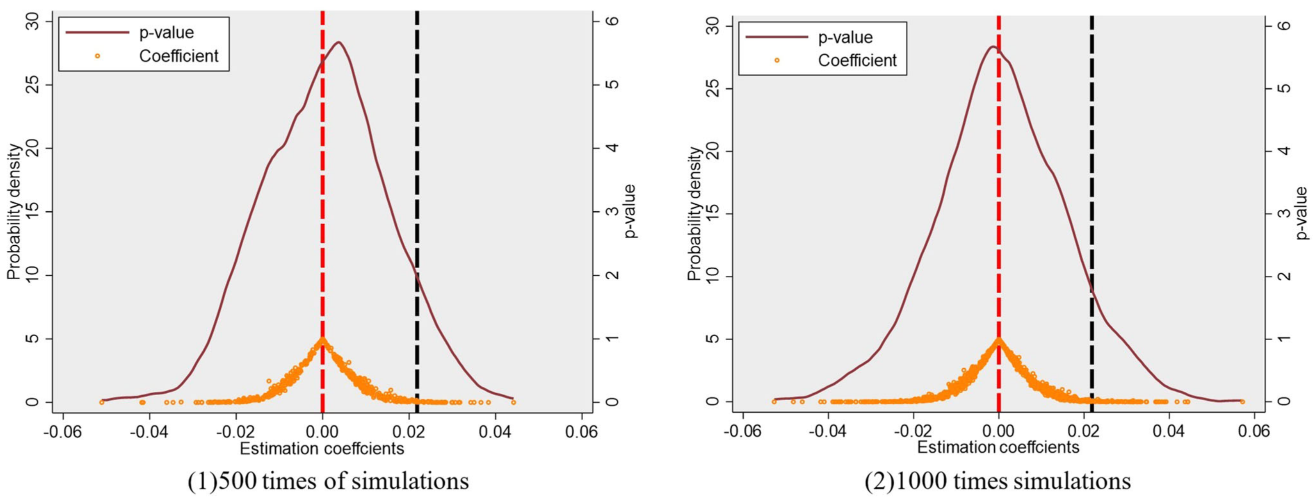

Fig. 5 Placebo test.

flexible approach, prioritizing coal, electricity, or gas based on regional suitability. Such frequent changes in policy resulted in substantial wastage of both administrative and financial resources. Therefore, before embarking on future low-carbon-related policies, it is imperative for governments to meticulously evaluate the potential impact on residents' energy welfare.

This study reveals the potential path of low-carbon transition impacting energy poverty: Regulations related to such transition invariably increase energy sector supply costs. These additional costs are transferred to final consumers, thereby increasing residents' economic burden, and even worsening their energy poverty conditions. Thus, governments should pay close attention

Table 10 Regression by PSM-DID approach.

Variables	(1) neighbor	(2) radius	(3) kernel
LCCP	0.0229***	0.0216***	0.0220***
	(2.763)	(2.691)	(2.747)
Constant	1.2290*	1.1269**	1.0758**
	(1.793)	(2.097)	(2.007)
Control variable	Control	Control	Control
Observations	15,228	19,160	19,172
R-squared	0.671	0.663	0.664
Time FE	Yes	Yes	Yes
Household FE	Yes	Yes	Yes

t-statistics in parentheses.
***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

Table 11 Regression for substitute variables and tail-shorting variables.

Variables	(1) 1–99	(2) 5–95	(3) 10–90	(4) Cooking fuel
LCCP	0.0219***	0.0218***	0.0206***	0.0645***
	(2.789)	(2.827)	(2.919)	(3.663)
Constant	1.0408**	1.0236**	0.9004*	2.2328*
	(1.977)	(1.982)	(1.905)	(1.894)
Control variable	Control	Control	Control	Control
Observations	19,204	19,204	19,204	19,204
R-squared	0.664	0.664	0.658	0.652
Time FE	Yes	Yes	Yes	Yes
Household FE	Yes	Yes	Yes	Yes

t-statistics in parentheses.
***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

to energy price fluctuations during policy implementation, set up early warning mechanisms for energy price increasing and supply disruption, and take effective actions to protect households from these situations. Additionally, it is imperative for the government to provide financial support to households, lessening the economic pressure associated with the low-carbon transition. Given the unique nature of energy as a quasi-public good, the government should maintain its role as a "gatekeeper" of residents' welfare, institutionalizing protections for the daily energy needs of residents, leveraging adaptive measures like universal service funds and housing renovation grants, thereby ensuring residents' energy welfare during the low-carbon transition.

Beyond direct financial support, information support can also safeguard against the risks of energy poverty during the low-carbon transition. According to Kyprianou et al. (2019), Spain has begun to offer residents advice about energy services, including whether their energy contracts are suitable for their own needs, and how to improve household energy efficiency. Compared to the financial measures, information support measures, aimed at enhancing public awareness and enriching energy-service knowledge, provide a more economical way to alleviate energy poverty. Drawing from Spain's policy, developing countries like China should also integrate such measures, which may yield long-term policy effects, into their policy frameworks. Additionally, our study reveals that well-governed communities can mitigate the potential impacts of low-carbon transition on residents' energy poverty, highlighting the importance of community support. Therefore, governments should recognize community officials as key participants in energy poverty governance, acting as a bridge for the government to provide information support to the residents. Moreover, community officials can also collect residents' feedback about their living conditions, and provide invaluable first-hand data for optimizing existing strategies.

Finally, this study also highlights the heterogeneous impacts of low-carbon transition across varied city characteristics, suggesting that governments should consider the specific socio-economic condition disparities of regions. Previous studies have shown that, compared with state-led governance for energy poverty, regional autonomy governance contained more measures directed at vulnerable consumer groups (Kyprianou et al., 2019). In other words, when regions have more administrative power to design their policies, they are more likely to implement diverse strategies that are better suited to local conditions. Therefore, considering the regional heterogeneity in China, it is necessary for the central governments to delegate the formulation of action plans to local governments. For instance, in bustling metropolises reliant on energy imports, local governments should establish mechanisms to monitor and regulate energy supply, ensuring its continuity and stabilizing energy prices for residents during market fluctuations. In less-developed yet resource-rich cities, local governments should focus on developing modern energy infrastructure accessible to vulnerable groups, ensuring they have access to efficient energy sources.

Data availability

Original data for this study are available in the China Health and Retirement Longitudinal Study: http://charls.pku.edu.cn/.

Received: 25 June 2023; Accepted: 18 December 2023;
Published online: 09 January 2024

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Acknowledgements
This work was supported by the Ministry of Education of Humanities and Social Science project (No. 21YJC630022), and the China Postdoctoral Science Foundation funded project (No. 2023M743362).

Author contributions
YX: conceptualization, methodology, and original draft writing. ZF: formal analysis, review, and supervision. XL: data curation and review. SW: review.

Competing interests
The authors declare no competing interests.

Ethical approval
This paper did not include any studies with human or animal participants conducted by all the authors.

Informed consent
This paper did not include any studies with human or animal participants conducted by all the authors.

Additional information
Correspondence and requests for materials should be addressed to Zhijun Feng.