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业绩成果材料

（申报人的业绩成果材料包括论文、科研项目、获奖以及其他成果等）

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姓　名　　肖一鸣

材料核对人：　　　　　　　　　　　单位盖章：

核对时间：

华南农业大学制

目　录

一、科研项目

二、论文、著作等

关于中国博士后科学基金第 74 批面上资助项目的立项通知（合同）及有关佐证材料

资助证书

中国科学技术大学　肖一鸣　（博士后编号：343227　）获得中国博士后科学基金第74批面上资助。资助编号：2023M743362

特颁此证。

This certificate verifies that its holder has been awarded a fellowship from the China Postdoctoral Science Foundation(Certificate Number:　2023M743362　).

中国博士后科学基金会

2023 年 11 月 27 日

关于广东省哲学社会科学规划 2024 年度青年项目的立项通知（合同）及有关佐证材料

广东省哲学社会科学规划专项小组

粤社科规专通〔2024〕7 号

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广东省哲学社会科学规划专项小组

2024 年 2 月 27 日

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检索证明

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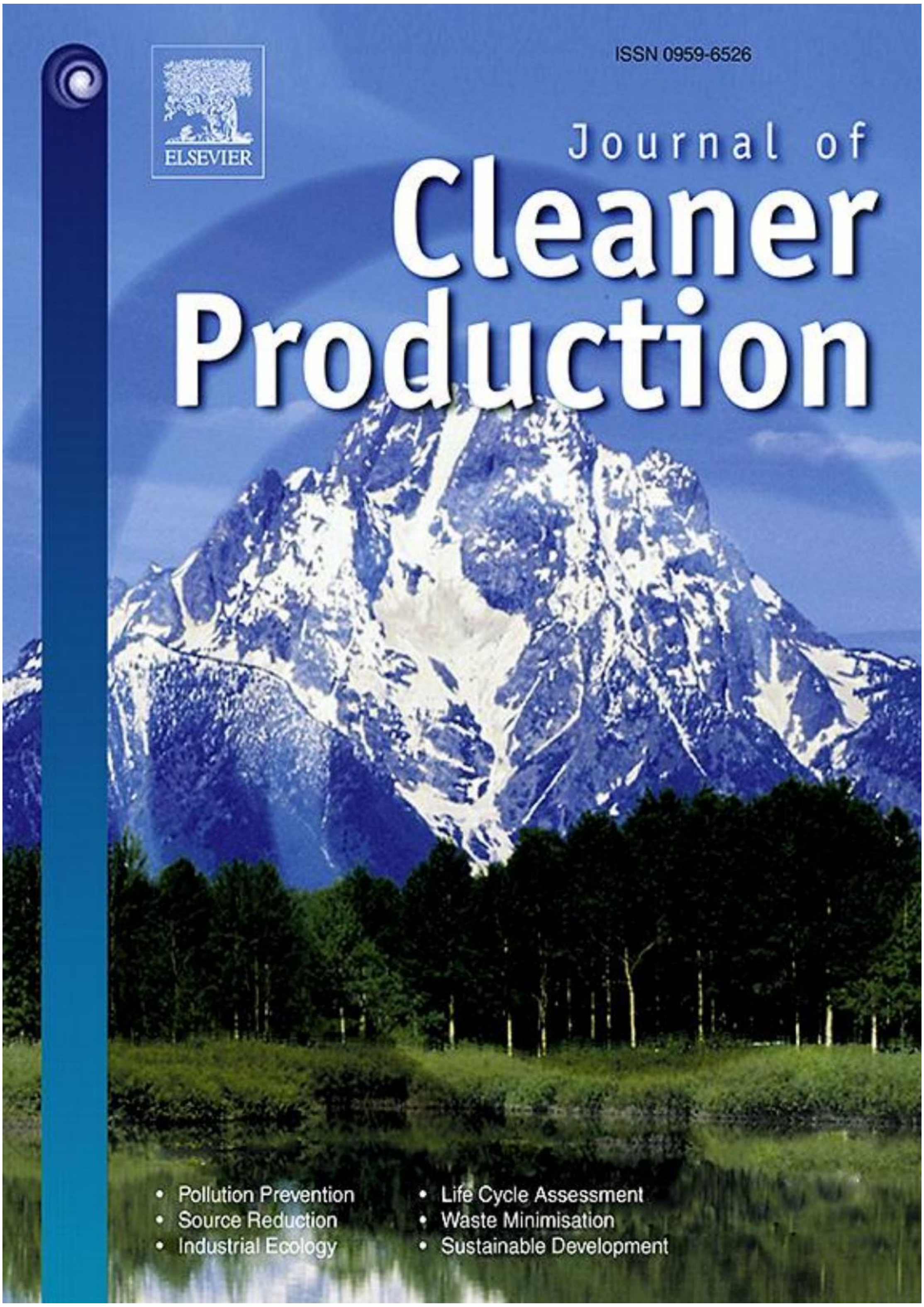

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Every rose has its thorn: Do environmental regulations exacerbate regional energy poverty?

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ABSTRACT

Environmental regulations play a critical role in shaping the energy welfare of residents, thus potentially impacting regional energy poverty. Nevertheless, limited quantitative research has investigated these effects from a regional perspective. This study constructs a comprehensive analytical framework to examine the impact of environmental regulations on regional energy poverty using Chinese provincial panel data from 2000 to 2018. It utilizes the spatial Durbin model (SDM) to investigate the direct effect and spatial spillover effect of environmental regulations on regional energy poverty and the interaction between environmental and pro-poor regulations. The main findings are as follows. Since 2000, China has significantly reduced energy poverty. Directly administered municipalities have shown the lowest energy poverty levels, whereas the western and northern regions have experienced limited energy poverty alleviation. Environmental regulations are positively correlated with regional energy poverty, whereas pro-poor regulations are negatively correlated. Moreover, the interaction effect and spatial spillover effect of the regulations are significant. The SDM regression indicates that environmental regulations may exacerbate regional energy poverty and counteract the benefits of pro-poor regulations. Stringent environmental regulations in one region intensify its energy poverty and aggravate that of its neighboring areas. Moreover, heterogeneity analysis shows that regulations primarily influence the accessibility dimension of energy poverty, with more pronounced effects in the first decade of the 21st century. This research highlights the challenges of balancing residents' energy welfare and environmental protection, and offers valuable insights for researchers and policymakers in the governance of the environment and energy poverty.

1. Introduction

Energy poverty signifies the insufficiency of modern energy services and residents face challenges in accessing and affording them. This condition has far-reaching consequences for health, well-being (Churchill et al., 2020), and social development (González-Eguino, 2015). The issue is pervasive in developed and developing regions (Niu et al., 2023). In Europe, energy poverty affects an estimated 50–125 million people (Charlier et al., 2019), whereas, in some developing countries, it affects over half of the population (Adusah-Poku and Takeuchi, 2019). As the largest developing country, China is no exception. Although modern energy has gradually become more accessible in China, many residents continue to experience energy poverty, which leads to indoor air pollution (Huang et al., 2022), illnesses, and depression (Zhang et al., 2021).

However, addressing energy poverty is not without challenges. As the International Energy Agency (2022) points out, there is often a trade-off between residents' energy access and environmental protection. While the Chinese government has implemented strict environmental regulations to address severe pollution and greenhouse gas emissions, these measures have created new challenges for residents' energy poverty. For instance, the "Action Plan for Air Pollution Prevention and Control" in 2013 significantly alleviated smog problems nationwide but limited the energy access of some residents (Liu, 2015). Similarly, the "Coal-to-Gas Plan" implemented in 2017 was beneficial in upgrading the energy structure but triggered a natural gas shortage,

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leaving some residents unable to access heating and sustain their daily lives (Wang and Ren, 2020). These examples highlight the trade-off between energy welfare and environmental protection.

The relationship between environmental protection and energy poverty alleviation is of the utmost importance. Effective approaches to environmental regulation—output restrictions, infrastructure renovation, and technological upgrades—often lead to increased costs in energy production (Dechezleprêtre and Sato, 2017). This situation intensifies the difficulties for disadvantaged groups in accessing or affording essential energy services, thereby exacerbating energy poverty conditions (Nguyen et al., 2019). In other words, environmental protection often comes at the expense of energy welfare. The literature is limited to specific regulations such as the Coal-to-Gas Plan or the new Chinese Environmental Protection Law (Ma et al., 2022), and rarely conducts a comprehensive quantitative investigation of the overall impact of the entire regulatory system on energy poverty from a regional perspective. Therefore, a holistic investigation of this issue is necessary. It could provide academia and governmental bodies with a complete understanding of the "dark side" of environmental regulations, help mitigate the unexpected consequences of such regulations on residents' energy poverty in future policy implementations, and eventually realize a harmonious relationship between environmental protection and energy poverty alleviation.

This study explores whether and how environmental regulations impact regional energy poverty in China's governance context. Unlike previous investigations that focus on limited regulations or household perspectives, this study utilizes provincial panel data from 2000 to 2018 and conducts regression analysis using the spatial Durbin model (SDM) to investigate the impact of environmental regulations on energy poverty from a regional perspective. The SDM can determine the direct effect of environmental regulations and their interaction with other regions and regulations. Furthermore, a heterogeneity analysis is conducted to examine the impacts of environmental regulations on different dimensions of energy poverty and the impacts in different periods. This analysis offers a comprehensive understanding of environmental regulations and draws attention to their adverse effects on the energy welfare of residents. According to the adage, "Every rose has its thorn." Similarly, this study delves into the frequently overlooked adverse outcomes of environmental regulations to answer the following questions. First, do environmental regulations impact regional energy poverty in China? Second, do environmental regulations have spatial spillover effects on energy poverty in the context of China's governance? Third, do environmental regulations have different effects in various conditions?

Environmental protection and energy poverty are important issues in many countries, including China. However, relevant studies are in the primary stage, and the methodology and data require improvement. This study makes three key contributions to the existing literature: (1) it investigates the impact of environmental regulations on energy poverty from a regional perspective in China and goes beyond measuring the overall intensity of environmental regulations in various regions. Consequently, it provides a comprehensive understanding of the impacts of environmental regulations on energy poverty. (2) The study introduces an SDM incorporating spatial terms based on OLS regression. This innovative approach examines how environmental regulations affect regional energy poverty, considering China's governance context and inter-regional interactions, which have been overlooked in previous studies. (3) Unlike research with limited data, this study includes panel data from 29 provincial-level administrative regions spanning 19 years. This dataset represents the broadest and longest timeframe currently available for studying regional energy poverty in China, and provides robust evidence of the spatiotemporal dynamics of energy poverty and the role environmental regulations have played. Overall, this study extends the literature, offering a broader range of governance insights for academia and policymakers.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature and proposes the research hypotheses. Section 3 introduces the study's variables, data sources and methods. Section 4 presents the results. Section 5 presents the discussion of the main findings. Finally, the conclusions and implications are provided in Section 6 and 7.

2. Literature review and research hypotheses

2.1. Literature review

2.1.1. Micro and macro impact factors of energy poverty

Studies have identified the impact factors of energy poverty from both micro- and macro-socioeconomic perspectives. At the micro level, scholars have analyzed the relationships between energy poverty and various factors, including family income, gender, family size, and beliefs. First, as household income increases, families can access modern energy sources, thereby reducing their energy poverty level (Zou and Luo, 2019). Second, sex is a significant micro factor that influences energy poverty. Traditional gender norms burden women with increased household work (Listo, 2018), which limits their opportunities to earn more for modern energy services. According to Karpinska and Smiech (2021), large families are more likely to receive policy support, which enhances their ability to eliminate energy poverty. Ravindra et al. (2019) case study in India indicated that because food cooked on traditional stoves is considered crispier and more nutritious, some well-resourced families still use traditional stoves for cooking, thereby trapping them in energy poverty.

Macro factors also correlate with energy poverty. As economies expand, governments have more financial and material resources to invest in energy infrastructure and address energy poverty (Liang and Asuka, 2022). In recent decades, economic growth has led to a significant increase in the energy consumption of residents and a higher proportion of electricity and natural gas usage, thus leading to a substantial decrease in national energy poverty (Liang and Asuka, 2022). Second, advancements in energy technology can effectively alleviate energy poverty. Recent technological advances have led to a rapid decline in the cost of new energy power generation in Spain, Italy, and Japan—ultimately benefiting the residents (Wang and Hao, 2018). Technological advancements, including industry 4.0 (Khan et al., 2023a) and digital transformation (Khan et al., 2022), have been validated for their favorable impact on economic and societal sustainability. Moreover, as an integral aspect of sustainability, energy poverty is inherently likely to benefit from technological progress (Batool et al., 2022).

Studies on energy poverty have primarily emphasized the associated demographic and socioeconomic factors, and neglected the impacts imposed by government governance, particularly regulations. Energy poverty refers to the insufficiency of modern energy services. These services are a typical kind of quasi-public good and the effective provision is intimately intertwined with government action. Therefore, it is necessary to incorporate regulatory factors in energy poverty studies.

2.1.2. Negative impacts of environmental regulations on societal welfare

Environmental protection has become a focus for governments and academics since the dawn of the 21st century (Khan et al., 2023b). While environmental regulations have effectively reduced pollution and carbon emissions, scholars have highlighted the potential drawbacks, particularly on societal welfare.

Environmental regulations may encroach on the living spaces of residents. As environmental regulations are often enacted by governments and enforced by large-scale corporations, they may marginalize disadvantaged groups such as farmers and family workshops, and ignore their welfare in decision-making and resource allocation processes (Robbins, 2019). This trend has been especially noticeable during the development of biofuel production, where the excessive exploitation of natural resources has aggravated deforestation in tropical forests that residents depend on for survival (Sovacool, 2021). Similarly, the expansion of wind power can infringe on farmlands and lead to significant livelihood challenges for farmers (Robbins, 2019).

However, environmental regulations can indirectly influence the lives of residents. Encouraging enterprises to bear the costs of their environmental impact and resource waste may increase the production and supply costs of goods, particularly energy. This situation may burden residents, and result in deteriorating work conditions and fewer job opportunities. Sovacool (2021) observed that occupational hazards and toxic pollution during solar panel manufacturing threatened workers' health. Regression analysis suggests stringent environmental regulations may increase unemployment rates (Liu et al., 2017). Furthermore, the energy burden on residents' daily lives may increase during the implementation of environmental regulations. In Germany, electricity prices for households have doubled since the low-carbon transition in the energy sector (Frondel et al., 2015). In China, households that rely on nonclean energy have suffered a higher energy burden and more severe energy poverty after the enactment of the new Environmental Protection Law (Ma et al., 2022).

Although scholars have investigated the impact of environmental regulations on societal welfare, no study has comprehensively examined the overall impact of entire environmental regulation system on energy poverty from a regional perspective. Existing studies have been limited to specific regulations (Ma et al., 2022). This limitation hampers the reliability and generalizability of the findings.

As a prime example of a developing nation, China encompasses numerous regions with diverse environmental regulation practices. In Hubei province, the government is working towards its ambitious target of becoming an "Ecological Province" by 2025. This vision comprises ecological development strategies at multiple levels, encompassing urban centers, rural regions, and villages, and primarily focuses on effectively managing the release of waste gases, wastewater, and solid waste. Likewise, in Zhejiang province, the government has launched a "Zero Direct Sewage Discharge" action to advance the construction of sewage networks in pivotal zones, concurrently improving wastewater treatment and discharge process adopted by enterprises. To accurately evaluate the impacts of environmental regulations, further studies should expand the scope from localized areas to a nationwide scale, and from specific regulations to the overall intensity of environmental regulations. This study bridges this gap by considering China as the research object and employing provincial panel data and a spatial Durbin model to analyze the impacts of environmental regulations on energy poverty.

2.2. Research hypotheses

Energy poverty, characterized by the limited accessibility or affordability of modern energy services, is a pressing issue that warrants attention. As a quasi-public commodity with both public and private attributes, energy services are partially non-excludable and prone to rivalry, and necessitate government intervention for equitable distribution (Savas, 1999). Environmental regulations—primarily aimed at reducing pollution from energy enterprises—can influence the supply of energy services and, consequently, energy poverty. This study analyzes these effects. Additionally, China's recent implementation of pro-poor regulations—as part of "the Fight against Poverty" —has significantly alleviated energy poverty by providing necessary energy assistance to low-income families (Bonatz et al., 2019). This aspect is thus incorporated into the analytical framework. A framework grounded in quasi-public goods theory is proposed to investigate the impact of environmental regulations on regional energy poverty. Accordingly, this study posits the following hypothesis.

2.2.1. Influence of environmental regulations on energy poverty

Environmental regulations comprise a range of laws, policies, and restrictions that aim to protect the environment and avoid environmental damage caused by human activities (McManus, 2009). In response to the serious consequences of environmental pollution, governments are endeavoring to regulate stakeholder conduct through environmental regulations, and public awareness of environmental pollution drives governments to strengthen existing regulations. Environmental regulations aim to safeguard the public's overall environmental rights while sometimes disregarding the energy welfare of vulnerable individuals. Environmental protection and energy welfare goals are often contradictory (World Energy Council, 2022). Excessive environmental regulations may harm the energy welfare of residents, thus leading to energy poverty. During the 2010s, the implementation of the "Action Plan for Air Pollution Prevention and Control" and the "Coal-to-Gas Plan" in China significantly mitigated the haze problem nationwide. However, these regulations have also caused energy service shortages for many residents (Wang and Ren, 2020). For example, the "Coal-to-Gas Plan" is a significant environmental regulation implemented in northern China—in the Beijing-Tianjin-Hebei region. The government aimed to enhance residential heating systems by switching from coal—a primary pollution source—to natural gas, a cleaner alternative. This shift promised to mitigate dire haze issues. However, the "Coal-to-Gas Plan" exceeded expectations by converting four million coal-based households, thereby resulting in an overwhelming surge in natural gas demand that outstripped the region's supply. This situation led to a severe natural gas shortage and posed challenges to residents accessing adequate heating during winter. Many scholars have confirmed that environmental regulations can negatively affect trade, employment, plant location, and productivity, thereby increasing enterprises' economic costs (Dechezleprêtre and Sato, 2017). Specifically, for energy enterprises, excessive regulations can raise energy infrastructure construction costs, dampen investment motivation, and result in energy shortages. Consequently, environmental regulations may exacerbate energy poverty in certain regions. Therefore, Hypothesis 1 is proposed:

H1. Environmental regulations will worsen a region's energy poverty condition.

2.2.2. Influence of pro-poor regulations on energy poverty

Pro-poor regulations are laws or policies that improve the well-being of low-income individuals by addressing their specific needs and concerns (dos Santos and Gupta, 2017). In the energy field, pro-poor regulations comprise service, price, and quality regulations aimed at helping residents obtain sufficient modern energy (Qiu, 2012). By implementing these regulations, the government encourages energy enterprises to provide affordable energy services to vulnerable groups, thus enabling them to access modern, affordable energy sources. Electric lifeline programs implemented in developed countries are typically pro-poor regulations. In China, the principles of basic energy rights for residents are affirmed by the Energy Law and various regulations by local governments prioritizing vulnerable groups in energy construction and pricing. They are categorized as pro-poor regulations. Chinese residents in various regions enjoy the benefits of pro-poor regulations—natural gas subsidies, civilian electricity price discounts, electricity fee reductions for impoverished households, and subsidies for household appliances in rural areas. Pro-poor regulations ensure that energy enterprises provide equal services to all residents and that residents can access the power necessary for their lives at an affordable price. Consequently, pro-poor regulations can effectively reduce regional energy poverty levels. Accordingly, this study proposes Hypothesis 2.

H2. Pro-poor regulations will alleviate a region's energy poverty condition.

2.2.3. Interaction between environmental regulations and pro-poor regulations

There is a competitive relationship among different types of regulations in the actual implementation process. While pro-poor regulations encourage energy enterprises to invest in the resources necessary to help vulnerable groups that struggle with energy poverty, environmental regulations can drive enterprises' running costs (Wang and Feng, 2014). For instance, the Chinese government implemented a new environmental protection law in 2015, considered the "strictest" in history, which incorporated environmental protection objectives into the assessments of local government officials. It encouraged local governments to attend to environmental governance and prompted numerous energy enterprises to invest resources in clean energy transformation projects (Bai et al., 2021). Consequently, when other investments and running costs increase, enterprises may lose the impetus to continue investing and prioritize support for vulnerable groups (Latapí Agudelo et al., 2020). Therefore, it can reasonably be inferred that environmental regulations weaken the effectiveness of pro-poor regulations. Thus, this study proposes Hypothesis 3.

H3. Environmental regulations weaken the effectiveness of pro-poor regulations.

2.2.4. Spatial spillover effect of regulations

The spatial spillover effect refers to the impact of one region's organizational actions on other regions. The two theories, "Administrative Subcontract" and "Promotion Tournament," demonstrate how government regulations in different regions can affect each other and result in spatial spillover effects (Zhou, 2007, 2014). Administrative subcontract theory refers to the central government entrusting specific affairs to local governments through contracts, granting local governments significant discretion despite the central government's formal authority. The promotion tournament theory concerns a competition among multiple local governments, instituted by the central government, to evaluate their performance based on specific criteria and select winners for promotion. These two aspects—sufficient discretion (i.e., "vertical subcontract") and robust incentive competition mechanisms (i. e., "horizontal competition")—jointly shape China's governance reality. Inter-regional influence is apparent when governments undertake actions related to environmental protection and energy construction. For example, in response to one regional government's plan to implement strong environmental regulations, others will strengthen their environmental regulations to avoid falling behind. Thus, hypothesis 4 explores whether environmental and pro-poor regulations have spatial spillover effects to a certain degree.

H4. Regulations have a spatial spillover effect.

This study draws on the theoretical analysis to outline the impact of environmental regulations on regional energy poverty (Fig. 1). Environmental regulations directly exacerbate regional energy poverty, as well as exert impacts by weakening the poverty reduction effects of pro-poor regulations. Moreover, through spatial spillover effects, regulations affect local and other areas' energy poverty conditions.

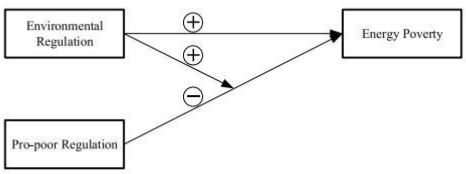


Fig. 1. Research framework.

3. Variables and methodology

3.1. Variable selection and data source

3.1.1. Dependent variable

The dependent variable is regional energy poverty in China. In China and other developing nations, energy poverty comprises the accessibility and affordability of modern energy services (González-Eguino, 2015). Accessibility pertains to the supply of energy services to residents, whereas affordability relates to consumption capacity.

This study constructs an energy poverty index system based on established measurement standards, and considering both the accessibility and affordability of modern energy (Liang and Asuka, 2022), to measure regional energy poverty precisely. It comprises six indicators, including the proportion of nonsolid energy, diversity of household energy sources, and density of transmission lines, which reflect energy accessibility. Moreover, energy price burden, penetration of modern energy equipment, and household energy consumption reflect energy affordability. Table 1 lists the meanings of the indicators. Based on previous research, the various indicators are normalized by sum normalization method, and entropy-TOPSIS method is used to measure the energy poverty level of a specific region. Entropy-TOPSIS method avoids the subjectivity of weight allocation (Chen, 2019). For more information on the specific procedures of the entropy-TOPSIS method, please refer to Appendix.

3.1.2. Independent variables

The independent variables of this study are environmental and pro-poor regulations.

To measure the intensity of environmental regulations, this study used the investment ratio in industrial pollution control to industrial value added as an indicator, by referring to Guan et al. (2022). This indicator contains investment for environmental infrastructure facilities, pollution sources treatment, and environmental components for new projects, thus reflecting the government's emphasis on environmental issues (Wang et al., 2021).

For pro-poor regulations, this study collects regional legal documents to measure the intensity. The number of documents is used because there is no mature indicator (Zeng et al., 2019). Specifically, the Beida Fabao Database (pkulaw.cn) is utilized to obtain the legal documents related to pro-poor. The Beida Fabao Database is a comprehensive legal database commonly used by public management scholars in areas such

Table 1
Energy poverty index system.

First level indicator	Second level Indicator	Attribute	Meaning
Accessibility	Proportion of non-solid energy	Negative	High proportion of non-solid energy indicates low regional energy poverty level.
	Diversity of household energy sources	Negative	High energy diversification indicates low regional energy poverty level.
	Density of transmission lines	Negative	High density of transmission lines in one region indicates low regional energy poverty level.
Affordability	Energy price burden	Positive	High energy price in one region indicates high energy poverty level.
	Penetration rate of modern energy equipment	Negative	High rate of energy equipment penetration can indicate low regional energy poverty level.
	Household energy consumption	Negative	High level of energy consumption indicate low regional energy poverty levels.

as industrial policy (Tian et al., 2022). First, the study uses Python to retrieve related legal documents from the Beida Fabao Database. Subsequently, the statistics on the legal documents are analyzed. According to China's Legislation Law, there are four types of legal documents, including "Regulation," "Government rule," "Normative document," and "Work document." In practice, "Regulation" has greater potency than "Government rule," "Normative document" exerts a lower potency than "Government rule," and "Work document" has the lowest potency. Therefore, the study assigns "Regulation," "Government rule," "Normative document," and "Work document" with the values of 4, 3, 2, and 1, respectively. Then, annual accumulations are performed based on the summation of these values. Finally, this sum is used to measure the intensity of pro-poor regulations in specific regions and years.

3.1.3. Control variables

The study has a comprehensive set of control variables to prevent bias from omitted variables. Specifically, the socioeconomic factors are incorporated, including economic development, technological development, urbanization rate, industrial structure, and resource endowment(Cai et al., 2021). In addition, to reflect the characteristics of China's governance system, institutional factors such as government efficiency, legalization level, and nationalization are also incorporated (Yan et al., 2019).

For socioeconomic factors, per capita GDP is used to measure economic development, patents per ten thousand people to measure technology development, urban population proportion to measure the urbanization rate, and the ratio of tertiary industry output to secondary industry output to measure industry structure. Additionally, the ratio of primary energy industry output to total industrial output is used to measure energy resource endowment.

The authoritative report "Marketization Index of China's Provinces" by Wang (2019) is used as a data source for institutional factors. First, the report includes the "government-market relationship" dimension, which contains specific indicators such as administrative-approval convenience and government scale, thus reflecting government efficiency. Second, the "development of market intermediary organizations and legalization environment" dimensions of the report contain specific indicators such as enforcement agencies' efficiency, organizations' service conditions, and intellectual property protection, thus reflecting the legalization level. In addition, the ratio of state-owned energy industry investment to total asset investment is used to measure nationalization.

3.1.4. Data source

This study selects China as the research subject, and analyzes panel data from 29 provincial-level administrative regions in mainland China from 2000 to 2018. Hainan, Tibet, Hong Kong, and Macau are excluded from the analysis due to missing data.

The data sources for the dependent variable and socioeconomic control variables are statistical yearbooks—China Statistical Yearbook, China Energy Statistical Yearbook, China Rural Statistical Yearbook, China Environmental Yearbook, and China Electric Power Yearbook. The data source for environmental regulation intensity (independent variable) is the China Statistical Yearbook, and the data source for pro-poor regulation intensity is the Beida Fabao Database. The data source for the institutional control variables—including government efficiency and legalization level—is the report of Marketization Index of China's provinces (Wang, 2019). The data source for nationalization is the China Statistical Yearbook.

The study employs linear interpolation to supplement the missing data for certain regions or years (Tian and Lin, 2018). Further, it uses a logarithmic transformation for all data (Wen et al., 2020) to mitigate the impact of outlier data on the regression results. Tables 2 and 3 present the variable settings and descriptive statistics, respectively. In addition, following Zhou et al. (2022) research, a stationery (LLC/IPS) test is conducted for all variables. As Table 4 reveals, the LLC and IPS tests indicate that the null hypothesis is rejected for all variables in the LLC test and for all variables except the energy poverty level in the IPS test. Therefore, the researchers conclude that the panel data used in this study is stationary and can be further processed in regression models. Additionally, because the Hausman test result is 78.36, with a p-value of 0.0000, fixed effects are selected for further regression analyses.

Table 2
Variable settings.

Variable type	Variable	Measurement
Dependent variable	Energy poverty	Energy poverty index
Independent variable	Environmental regulation	Ratio of investment in industrial pollution control to industrial value-added
	Pro-poor regulation	Number of relevant legal documents
Control variable	Resource endowment	Ratio of primary energy industries output to total industrial output
	Technology development	Patents per ten thousand people
	Industrial structure	Ratio of tertiary industry output to secondary industry output
	Urbanization rate	Urban population proportion
	Economic development	Per capita GDP
	Government efficiency	Index of government-market relationship
	Legalization level	Index of development of market intermediary organizations and legalization environment
	Nationalization	Ratio of state-owned energy industries investment to that of total asset investment

Table 3
Descriptive statistics of variables.

Variable	Observations	Mean	Std. Dev	Min	Max
Energy poverty	551	0.6436	0.0777	0.3389	0.7683
Environmental regulation	551	0.0400	0.0595	0.0000	0.7113
Pro-poor regulation	551	0.0049	0.0030	0.0000	0.0259
Resource endowment	551	0.0773	0.0944	0.0000	0.4118
Technology development	551	5.3452	8.7176	0.1300	57.3333
Industrial structure	551	0.9539	0.4840	0.4944	4.3468
Urbanization rate	551	0.5027	0.1510	0.2322	0.8961
Economic development	551	33179	26137	2662	140211
Government efficiency	551	6.9509	1.7255	1.6009	10.5300
Legalization level	551	8.1722	6.7307	−0.7607	41.2157
Nationalization	551	0.5196	0.1863	0.1547	0.9922

3.2. Methodology

3.2.1. Spatial autocorrelation analysis

Spatial autocorrelation analysis is an essential method for spatial data analysis that combines location and attribute data to effectively investigate the impact of a specific geographic unit on neighboring units. This study verifies the spatial autocorrelation features of regional energy poverty using Moran's index, as represented by equations (1) and (2). Here, *Moran'I* represents Moran's index, $\overline{x}$ and s^2 respectively denote the mean and standard deviation of all samples for a specific year, and $weight_{ij}$ represents the spatial relationships between different regions.

Table 4
Data stability test for variables.

Variable	LLC test			IPS test	
	Intercept and trend	Intercept	none	Intercept and trend	Intercept
Energy poverty	−4.1035***	0.8679	6.2256	−0.1478	3.7772
Environmental regulation	−34.1451***	−14.6195***	−15.6806***	−16.5728***	−17.9903***
Pro-poor regulation	−12.0900***	−22.3548***	−15.7233***	−11.3638***	−15.7130***
Resource endowment	−6.1782***	0.1130	6.0456	−0.3806	2.9842
Technology development	−2.2792**	−1.6818**	−1.5213*	1.3838	0.2440
Industrial structure	−1.4633*	−3.2770***	−1.5472*	2.3780	−0.2149
Urbanization rate	−6.7401***	−5.3789***	−21.8966***	−2.0892**	−2.0425**
Economic development	−3.1345***	0.7619	−4.7435***	1.1848	3.7301
Government efficiency	−4.8406***	−3.1808***	−2.1551**	−1.9827**	−2.1010**
Legalization level	−8.7180***	−4.6729***	0.4174	−5.0620***	−3.1261***
Nationalization	−5.8325***	−2.9189***	−4.9179***	−2.0703**	−1.4189*

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

$$Moran'I = \left[\Sigma_{i=1}^{m}\Sigma_{j\neq i}^{m} weight_{ij}(x_i - \overline{x})(x_j - \overline{x})\right] \Big/ \left[s^2 \Sigma_{i=1}^{m}\Sigma_{j\neq i}^{m} weight_{ij}\right] \quad (1)$$

$$\overline{x} = \left(\Sigma_{i=1}^{m} x_i\right) / n, s^2 = \left[\Sigma_{i=1}^{m}(x_i - \overline{x})^2\right] / n \quad (2)$$

Moreover, gravity center analysis is often regarded as a complementary approach to spatial autocorrelation analysis. Gravity center refers to the overall point of the gravitational force. Scholars have introduced gravity centers into economic geography, revealing the evolutionary trajectory of a specific element of a region. This study conducts a gravity center analysis to explore the trajectory of energy poverty levels among different regions in China, as shown in Equations (3) and (4). Here, X and Y represent the longitude and latitude coordinates of regional energy poverty's gravity center, EPI_i represents the energy poverty level of each region, and X_i and Y_i represent the longitude and latitude coordinates of each region.

$$X = (\Sigma EPI_i X_i) / \Sigma X_i \quad (3)$$

$$Y = (\Sigma EPI_i Y_i) / \Sigma Y_i \quad (4)$$

3.2.2. Spatial weight matrix

It is crucial to incorporate an appropriate spatial weight matrix before constructing the spatial model. General spatial weight matrices are geographic adjacency, distance, and economic geographic weight matrix (Haibo et al., 2020). The geographic adjacency weight matrix is the most commonly used (Shen et al., 2023), so it was selected as the spatial weight matrix—which assigns a value of 1 to the corresponding position when two regions are adjacent; otherwise, the value is set to 0. It is assumed that the degree of inter-regional correlation is determined by adjacency.

3.2.3. Spatial model construction

Spatial models have been used to investigate the impact of environmental regulations on regional energy poverty. Based on the previous analysis, environmental regulations may have spatial spillover effects. Spatial econometric models are essential in exploring phenomena such as spillover effects among neighboring regions (Zhao and Wang, 2022). The three commonly used models in this field are the Spatial Autoregressive Model (SAR), the Spatial Error Model (SEM), and the Spatial Durbin Model (SDM) (LeSage and Pace, 2009). Therefore, spatial econometric models are established by following the progression from SAR and SEM to SDM.

Initially, a SAR model is constructed by incorporating the spatial effects of the independent variables into the traditional OLS model. The SAR model is represented by equation (5), where "*povene*" is the dependent variable denoting the energy poverty level, and "*reguenvi*," "*reguene*," "*cros*" are independent variables representing environmental regulation, pro-poor regulation, and the regulation interaction terms, respectively. Additionally, the variable "*controls*" represents control variables. The correlation coefficients of these variables are denoted by $\beta 1$, $\beta 2$, $\beta 3$, etc., while u represents fixed effects, and "ε" represents the error term. Additionally, $\delta W \ln povene$ denotes the spatial effect of energy poverty, where W is the spatial weight matrix, and δ is the coefficient of the spatial lag term.

$$povene = \beta_0 + \delta Wpovene + \beta_1 reguene + \beta_2 reguenvi + \beta_3 cros + \beta_4 controls + u + \varepsilon \quad (5)$$

Moreover, SEM and SDM models are constructed. The SEM model is shown in Equation (6), where φ represents the error term containing the spatial effects. The SDM is shown in Equation (7), including the spatial lag of the dependent variable and that of the independent variable.

$$povene = \beta_0 + \beta_1 reguene + \beta_2 reguenvi + \beta_3 cros + \beta_4 controls + u + \varphi$$

$$\varphi = \rho W\mu + \varepsilon \quad (6)$$

$$povene = \beta_0 + \delta Wpovene + \beta_1 reguene + \beta_2 reguenvi + \beta_3 cros + \beta_4 controls + \theta_1 Wreguene + \theta_2 Wreguenvi + \theta_3 Wcross + u + \varepsilon \quad (7)$$

4. Results

4.1. Spatial agglomeration characteristics

Fig. 2 illustrates the evolution of regional energy poverty. Over the past 19 years, China has significantly reduced its overall energy poverty. It indicates that the country's economic and infrastructure construction efforts have been effective. However, the degree of alleviation varies considerably among different areas. Direct-administered municipalities such as Beijing and Shanghai, and provinces along the southeastern coast, have shown the lowest energy poverty levels in recent years. Conversely, the western and northern regions experienced limited alleviation of energy poverty.

This study performs Moran's I analysis and gravity center analysis to explore the spatial autocorrelation of regional energy poverty. First, as Fig. 3 illustrates, Moran's I index indicates significant spatial agglomeration among regions. From 2000 to 2018, the global Moran's I continued to increase while the p-value gradually decreased, thereby reflecting increasing spatial agglomeration over time. Second, Fig. 4 illustrates that the latitude of the energy poverty center is approximately between 33.38° N and 33.50° N, located south of the latitude reference line, while the longitude is approximately between 112.46° E and 112.76° E, located west of the longitude reference line. This suggests that Western China's overall energy poverty level is higher than Eastern China's and that the southern region exhibits a greater energy poverty level than its northern counterpart. In summary, significant regional differences exist in China's energy poverty, which also has an increasing

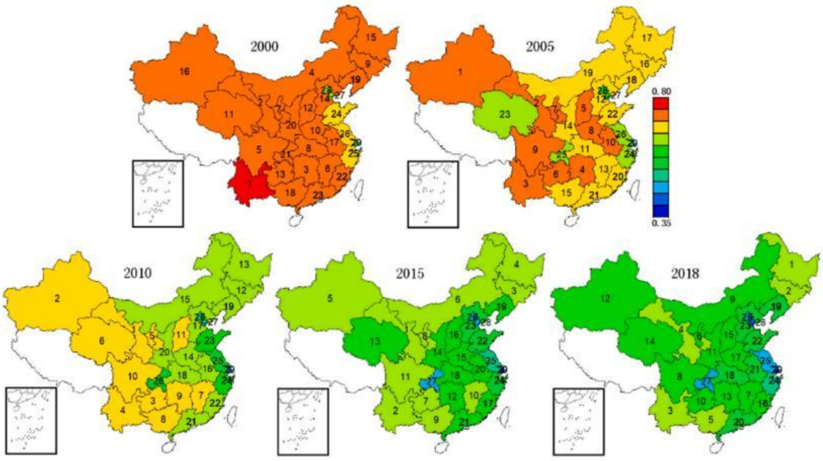
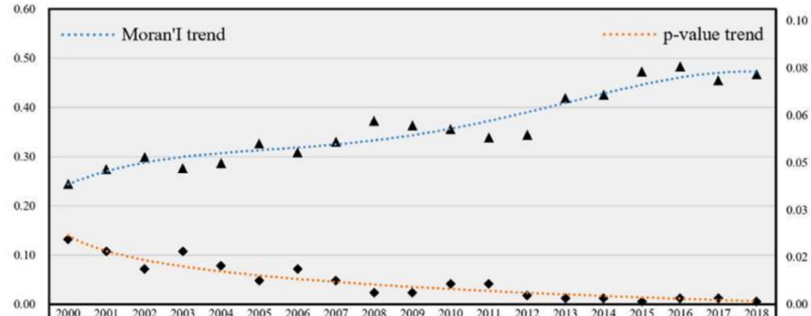


Fig. 2. Regional energy poverty level since 2000.



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
▲Moran'I	0.245	0.275	0.300	0.277	0.287	0.327	0.309	0.331	0.373	0.364	0.356	0.339	0.345	0.419	0.426	0.473	0.483	0.455	0.467
◆p-value	0.022	0.018	0.012	0.018	0.013	0.008	0.012	0.008	0.004	0.004	0.007	0.007	0.003	0.002	0.002	0.001	0.002	0.002	0.001

Fig. 3. Global Moran's I analysis.

spatial agglomeration. The above analysis supports this exploration of the impact of environmental regulations on regional energy poverty using spatial econometric models in the following sections.

4.2. Spatial econometric model selection and regression results

An effective spatial econometric analysis requires selecting the most appropriate model based on testing and regression results. This study compares the SAR, SEM, and SDM using an adjacency matrix as the spatial matrix and selected fixed effects for each model. Table 5 suggests that when the regression results of the SAR, SEM, and SDM models are compared, SDM has a stronger significance in regulation variables, thereby indicating that it is the most suitable spatial econometric model for this study.

Furthermore, Wald and LR tests are performed according to Yang et al. (2021) to ensure the reliability of the SDM model. The p-values of both the LR and Wald tests in Table 6 are significant at the 1% level, thus revealing that the SDM model cannot be reduced to SAR or SEM models, and further confirming the suitability of the SDM model.

The regression analysis of the SDM reveals that environmental regulations have a significant positive impact on energy poverty. In contrast, pro-poor regulations have a significant negative impact, thereby supporting Hypotheses 1 and 2. Additionally, the interaction between environmental and pro-poor regulations display a significant positive effect, thus supporting Hypothesis 3. As Fig. 5 illustrates, over the past 19 years, the dominance of environmental and pro-poor regulations has appeared alternately, and reflects a conflict between energy welfare and environmental protection. The spatial lag terms of environmental regulations, pro-poor regulations, and their interactions are statistically significant, thus supporting Hypothesis 4. These results underscore the unexpected consequences of stringent environmental regulations in addressing regional energy poverty. Government-enforced environmental regulations designed to protect the environment can directly exacerbate regional energy poverty and undermine

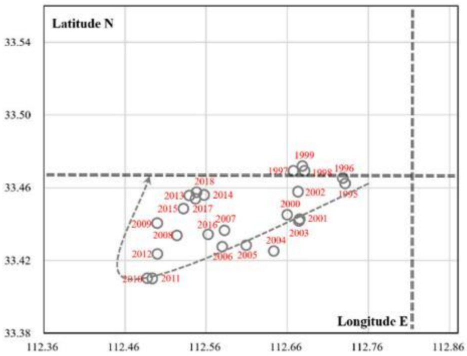


Fig. 4. Gravity center analysis.

Table 5
Spatial regression results based on SAR, SEM and SDM model.

	SAR model	SEM model	SDM model
δ	0.583313***	0.395198***	0.502106***
	(0.043648)	(0.074088)	(0.047577)
Environmental regulation	0.005299**	0.005646*	0.005523**
	(0.002469)	(0.003025)	(0.002609)
Pro-poor regulation	−1.011761*	−0.886406	−1.161008**
	(0.586434)	(0.684145)	(0.562988)
Interactions between regulations	1.456837*	1.555080*	1.796772**
	(0.758829)	(0.841010)	(0.724804)
W*Environmental regulation			0.005625
			(0.004110)
W*Pro-poor regulation			−2.930832***
			(0.947391)
W*Interactions between regulations			1.271988
			(1.660981)
Resource endowment	0.006206**	0.010451***	0.000386
	(0.002448)	(0.003130)	(0.002458)
Technology development	−0.004033	−0.008478	0.002720
	(0.005067)	(0.006413)	(0.005041)
Industrial structure	−0.034834***	−0.063018***	−0.013693*
	(0.007425)	(0.008449)	(0.007585)
Urbanization rate	−0.051159***	−0.059569***	−0.018474
	(0.019428)	(0.022405)	(0.019158)
Economic development	−0.017176**	−0.065431***	−0.008442
	(0.006715)	(0.009449)	(0.006949)
Government efficiency	−0.019909**	−0.024240**	−0.041182***
	(0.008286)	(0.011340)	(0.012017)
Legalization level	−0.020050***	−0.020664***	−0.015104***
	(0.005108)	(0.005852)	(0.004950)
Nationalization	−0.020140***	−0.022168***	−0.018598***
	(0.005173)	(0.006173)	(0.005303)
W*Government efficiency			0.064350***
			(0.015624)
W*Legalization level			−0.071492***
			(0.009457)
W*Nationalization			0.018074*
			(0.009395)

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

the beneficial effects of pro-poor regulations. Moreover, the significant spillover effects suggest that overly restrictive environmental regulations may adversely affect the energy welfare of residents and that of neighboring regions.

The regression results of the socioeconomic control variables show that the regression coefficient of resource endowment is negative, thus confirming the existence of the "resource curse" phenomenon to some

Table 6
LR and Wald test for the spatial panel model.

Test	Test type	Statistics
LR test	spatial lag	72.500***
	spatial error	169.620***
Wald test	spatial lag	74.660***
	spatial error	84.490***

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

extent (Papyrakis and Gerlagh, 2007). In other words, areas with abundant energy resources are more likely to experience energy poverty. However, the regression results also reveal that economic development, urbanization, and industrial structure optimization can help alleviate regional energy poverty. Among these factors, poverty alleviation brought about by industrial structure optimization is significant, thereby confirming the conflict between the secondary industry and energy welfare of residents, and the mutual benefit between the tertiary industry and residents' energy welfare (Wang and Wang, 2016).

The regression results of the institutional control variables show that the coefficients of government efficiency and legalization levels are negative and significant at the 5% and 1% levels, respectively, thus confirming that improvements in government efficiency and legalization levels can effectively promote the construction of energy infrastructure and alleviate energy poverty. Furthermore, the coefficient of nationalization is negative and significant at the 1% level, which indicates that a certain degree of nationalization in the energy field can ensure universal access to modern energy services.

4.3. Decomposition effects and heterogeneity analysis

According to LeSage and Pace (2009)'s method, the total effect of regulations on regional energy poverty can be divided into direct and indirect effects. As Table 7 suggests, environmental regulations have a significant positive impact on both the direct and indirect aspects of regional energy poverty. Specifically, the direct effect accounts for approximately 30% of the total effect, with a value of 0.006687, whereas the indirect effect accounts for approximately 70% of the total effect, with a value of 0.015137. Notably, the effect values in Table 7 do not align with the regression coefficients in Table 5. This discrepancy results from the interaction and cyclic feedback mechanisms between regions, emphasizing that spatial spillover is a crucial factor in the influence of environmental regulations on regional energy poverty (Meng et al., 2022). Therefore, overly stringent environmental regulations worsen local energy poverty and intensify environmental regulations in neighboring areas through inter-regional competition, ultimately exacerbating neighboring regions' energy poverty. These results confirm hypotheses 1, 2, 3, and 4.

As mentioned, regional energy poverty can be categorized into accessibility and affordability. Accessibility poverty concerns the supply of modern energy service to residents, whereas affordability poverty reflects residents' ability to consume it. To fully comprehend the impact of regulations on energy poverty, this study employs an SDM regression with accessibility poverty and affordability poverty as dependent variables, as Table 8 indicates. Environmental regulations have a greater total effect on accessibility poverty than on affordability poverty. It is because government regulations directly influence the behavior of enterprises, thereby impacting energy infrastructure development and supply. However, the ability of residents to afford energy costs may be influenced more by socioeconomic factors, and results in a weaker effect of environmental regulations on poverty affordability. Pro-poor regulations have a similar effect, which is not discussed further.

The study examines the disparate effects of regulations across distinct periods by analyzing two phases: 2000–2010 and 2011–2018, using 2010 as the dividing point. The initial phase encapsulates the "10th Five-Year Plan" and the "11th Five-Year Plan," while the latter

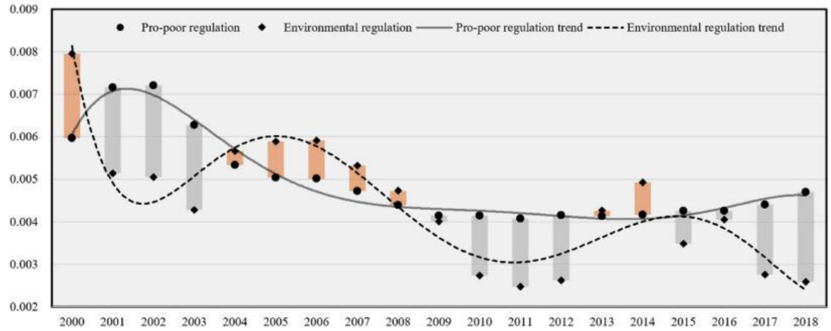


Fig. 5. Intensity of environmental and pro-poor regulations over the past 19 years.

Table 7
Estimation results of decomposition effects.

	Direct effect	Indirect effect	Total effect
Environmental regulation	0.006687*** (0.002535)	0.015137** (0.006828)	0.021823*** (0.007656)
Pro-poor regulation	−1.683974*** (0.623568)	−6.460621*** (1.868748)	−8.144595*** (2.206514)
Interactions between regulations	2.200603*** (0.799368)	4.129753 (3.177893)	6.330356* (3.645351)

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

Table 8
Estimation results of decomposition effects for different dimensions.

Accessibility dimension	Direct effect	Indirect effect	Total effect
Environmental regulation	−0.007418 (0.010615)	0.041839** (0.018420)	0.034420* (0.018767)
Pro-poor regulation	−4.172743* (2.460135)	6.731186 (4.576232)	2.558443 (5.276815)
Interactions between regulations	9.356918*** (3.024135)	−2.733886 (8.042749)	6.623033 (8.911942)
Affordability dimension	**Direct effect**	**Indirect effect**	**Total effect**
Environmental regulation	0.004602* (0.002633)	0.006808 (0.004593)	0.011409** (0.004730)
Pro-poor regulation	−0.269610 (0.610872)	−2.965296** (1.158563)	−3.234906** (1.340423)
Interactions between regulations	−1.073379 (0.754801)	0.399798 (2.038221)	−0.673581 (2.267586)

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

covers the majority of the "12th Five-Year Plan" and the "13th Five-Year Plan." The regression results in Table 9 highlight the more pronounced influence of regulations from 2000 to 2010 compared to 2011–2018, and illustrate China's development model transformation over the past two decades.

During 2000–2010, the regions displayed considerable variations in energy-related governance practices, with energy sector development adhering to the input-driven trajectory established in the 20th century (Wu and Li, 2015). Bolstered by government support, the energy infrastructure witnessed rapid growth as large-scale high-volume transmission projects and rural power grid transformations have been completed across regions (Zhou, 2011). Consequently, residents experienced significant improvements in energy welfare, with both regulatory factors exerting a more prominent influence on energy poverty.

Table 9
Estimation results of decomposition effects for different periods.

Period: 2000–2010	Direct effect	Indirect effect	Total effect
Environmental regulation	0.005928** (0.002450)	0.015209** (0.006784)	0.021137*** (0.007564)
Pro-poor regulation	−0.695008 (0.428676)	−5.027241*** (1.477994)	−5.722249*** (1.710432)
Interactions between regulations	0.512599 (0.583959)	−0.229222 (2.346260)	0.283377 (2.725694)
Period: 2011–2018	**Direct effect**	**Indirect effect**	**Total effect**
Environmental regulation	0.000479 (0.002972)	−0.002003 (0.006341)	−0.001524 (0.007248)
Pro-poor regulation	1.548338 (3.009169)	−18.45082* (9.821636)	−16.90248 (11.373090)
Interactions between regulations	2.515986 (1.663337)	8.913332 (6.019069)	11.429320* (6.815020)

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

From 2011 to 2018, China transitioned into a new economic development phase characterized by energy infrastructure and livelihood projects approaching saturation. Governments have ceased to regard large-scale construction investments as an exclusive path for development. As governance modernization progressed, regional disparities in regulations gradually diminished. Consequently, the regulations had a relatively limited impact on energy poverty during this period.

4.4. Robustness test

Robustness tests are conducted after regression analysis to ensure the reliability of the findings. The independent variable is replaced according to previous studies (Li and Liao, 2022). For environmental regulations' intensity, the proportion of environmental pollution control investment in the GDP is used as an alternative independent variable. SDM regressions are conducted, and the coefficients, signs, and significance levels of the variables remain fundamentally unchanged, thereby confirming the robustness of the conclusions, as Table 10 reveals.

Endogeneity is another concern in regression analyses. As lagged variables are often used as instrumental variables to alleviate endogeneity (Zhao and Wang, 2022), the regulation variables lagged by one period are used as instrumental variables, and regressions are then conducted. As Table 10 suggests, the regression results demonstrate high consistency with previous findings, thus indicating that the study does not suffer from significant endogeneity issues.

Table 10
Robustness test.

	SDM for substitution variable	SDM for lagged regulation
δ	0.583611*** (0.047783)	0.533937*** (0.047392)
Environmental regulation	0.010276** (0.004105)	0.005274** (0.002648)
Pro-poor regulation	−1.286636** (0.554315)	−1.286636** (0.554315)
Interactions between regulations	7.107011*** (1.605943)	1.293720* (0.715294)
W*Environmental regulation	−1.979386 (1.778115)	−2.380776** (0.957714)
W*Pro-poor regulation	0.009967*** (0.003612)	0.001829 (0.004209)
W*Interactions between regulations	−5.349275 (4.065699)	0.115169 (1.628429)
Resource endowment	0.000541 (0.002709)	0.001133 (0.002579)
Technology development	0.005692 (0.005204)	0.002496 (0.005163)
Industrial structure	−0.016451** (0.007995)	−0.016997** (0.007777)
Urbanization rate	−0.026992 (0.021918)	−0.023739 (0.020721)
Economic development	−0.013866* (0.008181)	−0.010849 (0.007310)
Government efficiency	−0.047352*** (0.012916)	−0.047352*** (0.012916)
Legalization level	−0.011116** (0.005069)	−0.011116** (0.005069)
Nationalization	−0.021975*** (0.005473)	−0.021975*** (0.005473)
W*Government efficiency	0.076659*** (0.018415)	0.069718*** (0.016799)
W*Legalization level	−0.051847*** (0.009688)	−0.063404*** (0.009828)
W*Nationalization	0.029116*** (0.010067)	0.018628* (0.009785)

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

5. Discussion of findings

Governments must understand the potential impact of environmental regulations on energy poverty to achieve a balance between environmental protection and the alleviation of energy poverty. This study presents a comprehensive framework to address the issue and provides valuable guidance to China and other developing countries committed to environmental sustainability and inclusive growth.

From 2000 to 2018, China witnessed a decline in its overall energy poverty level, with municipalities such as Beijing, Tianjin, Shanghai, and Chongqing maintaining lower poverty levels. These municipalities are directly under the central government, with concentrated populations and smaller areas. They find implementing the central government's energy development roadmaps easier, yielding quicker progress. Conversely, the Western and Northern regions—which relied heavily on biomass and coal as cooking fuels—have faced challenges, as observed by Tang and Liao (2014). This study expands on Tang's findings by confirming the existence of greater energy poverty challenges in these regions. Additionally, the significant spatial agglomeration of energy poverty revealed by Moran's index further reinforces this disparity.

Environmental regulations exacerbate regional energy poverty. Specifically, when environmental regulations are stringent, the construction costs of energy infrastructure significantly increase. The operational costs of energy production and transmission correspondingly increase, ultimately burdening residents with higher energy expenses. Zhang (2018) pointed out that environmental regulations significantly influence market functioning. Consumers must bear almost all the additional burdens when environmental regulations are imposed on products with low demand elasticity, such as energy services. During the 2017 heating season, extensive environmental regulations in China's energy industry led to a significant gas shortage, trapping residents who typically have access to energy in energy-poor conditions. According to the World Energy Council (2011), an inherent contradiction and trade-off exists between environmental protection and energy welfare goals, consistent with the empirical results of this study. Therefore, future governance efforts should consider social compensation costs arising from environmental regulations.

Pro-poor regulations can effectively alleviate regional energy poverty; however, this effect is susceptible to the adverse impacts of environmental regulations. As a collection of measures aimed at improving the living conditions of residents, pro-poor regulations encompass various approaches, including direct and cross-subsidies. China's central and local governments have made extensive efforts to ensure energy services for residents. Preferential policies such as tiered electricity pricing and allowances for larger households further promote the inclusivity of modern energy services. Notably, according to the photovoltaic poverty alleviation program, the government collaborates with enterprises to support residents in installing photovoltaic power generation equipment near their homes. The generated electricity serves the daily needs of residents and can be fed back into the grid (World Energy Council, 2011). Governments should strengthen these effective pro-poor regulations, which are crucial in safeguarding energy welfare.

Furthermore, environmental regulations and pro-poor regulations have significant spillover effects. According to Zhou's (2007) promotion tournament theory, when the central government designates an issue as a central task, local officials and the entire bureaucratic system in specific regions tend to adopt strict regulations to ensure promotion. Adjacent regions may also implement equally or more aggressive regulations to avoid falling behind. Conversely, issues not included in this "tournament" receive less attention and reduce regulations in specific regions, with neighboring regions following similar strategies. Consequently, regional regulations influence energy poverty within and beyond their jurisdictions through competition among bureaucratic systems. To some extent, the regulations' spillover effects provide a feasible path for the central government to implement top-down environmental protection and energy poverty governance.

The empirical results of this study validate previous theoretical analyses by quantitatively revealing the specific impacts of environmental regulations on regional energy poverty. This study can assist academia and policymakers in understanding the trade-off between environmental protection and energy poverty governance.

6. Conclusion

This study employs China's provincial panel data and the spatial Durbin model to examine the impact of environmental regulations on regional energy poverty. The main conclusions are: (1) Since 2000, China has significantly reduced energy poverty. However, energy poverty conditions vary across different regions. Directly administered municipalities have shown the lowest energy poverty levels in recent years, whereas other regions have not. (2) Environmental regulations positively correlate with regional energy poverty, whereas pro-poor regulations negatively correlate. Moreover, the interaction between these two types of regulations demonstrates a notable positive association with energy poverty. Environmental regulations intended to safeguard the environment may exacerbate regional energy poverty and counteract the benefits of pro-poor regulations, highlighting the challenge of striking a balance between residential energy welfare and environmental protection. (3) The significant spillover effect illustrates that stringent environmental regulations in one region intensify its energy poverty and aggravate its neighboring regions. (4) The heterogeneity analysis shows that regulations primarily influence the accessibility dimension of energy poverty, with more pronounced effects in the first decade of the 21st century.

In summary, this study constructs a comprehensive analysis framework, revealing the impact of environmental regulations on regional energy poverty, and the regulations' spatial spillover effects in the context of China. This research provides a fresh perspective for the academics and policymakers to understand the unintended consequences of environmental regulations. Moreover, it offers crucial insights for developing countries like China to modify environmental regulations and implement effective energy poverty governance in the future.

7. Implications of the study

7.1. Theoretical implications

This study addresses emerging demands concerning environmental and energy-related sustainable development issues in developing countries, including China. Energy poverty refers to the insufficient provision of modern energy services—considered as quasi-public goods. Consequently, their efficient and equitable distribution relies heavily on governmental regulations. In China, environmental regulations have emerged as important factors influencing regional energy poverty. This study draws on the theory of quasi-public goods and employs a regional perspective to establish an insightful analytical framework, thereby revealing the impact of environmental regulations on regional energy poverty and shedding light on the mechanisms involved—direct effects, spatial spillover effects, and interactions with pro-poor regulations. By incorporating spatial autocorrelation analysis, gravity center analysis, and spatial Durbin model regression, it provides a comprehensive understanding of the evolution of China's regional energy poverty and how it is affected by regulations, ensuring the reliability of the research. This study expands the theoretical foundation of environmental regulations and energy poverty research and offers valuable insights into the intrinsic logic of environmental protection and energy poverty governance.

7.2. Practical implications

This research offers important practical implications for future environmental and energy poverty governance under the multiple sustainable goals in developing countries.

First, governments should balance environmental and energy welfare goals. Strict environmental regulations lead to increased energy supply costs, imposing economic burdens on residents. Therefore, before implementing environmental regulations, the energy needs of vulnerable groups should be thoroughly investigated to minimize unexpected consequences. During the implementation of environmental regulations, the government should always observe fluctuations in energy prices and proactively take actions to mitigate the impacts, such as providing the necessary financial support to residents prohibited from using solid fuels.

Second, the fundamental solution to energy poverty requires continuous effort to strengthen pro-poor regulations. The government should serve as a "gatekeeper" during the energy service supply process and prioritize energy inclusiveness and equitable distribution. Developed countries have implemented relief policies to address energy poverty. In the United States, for instance, the government has allocated funds and initiated programs, such as the Weatherization Assistance Program and the Low-Income Home Energy Assistance Program, benefiting millions of eligible low-income families by providing energy efficiency improvements and bill subsidies. Japan has set "lifeline" electricity prices to ensure vulnerable groups can access essential energy services. France has established a universal service fund that requires industry stakeholders to contribute to compensating certain energy companies for the cost losses incurred owing to their universal service obligations. Considering that developing countries such as China have not established institutionalized operations in energy poverty governance, their governments should draw upon the experiences of developed countries and implement diverse and flexible measures to provide the necessary support to residents.

Furthermore, considering spillover effects, a country's central government should establish appropriate promotion incentives during the governance of energy poverty. It should fully utilize institutional advantages, and continuously enrich and optimize the assessment criteria for regional government officials. The "Promotion tournaments" have been effective in economic development, industrial transformation, and other fields. Therefore, the central government can conduct similar "tournament" activities to motivate regional governments to focus on energy governance and strengthen pro-poor regulations.

Finally, considering the uneven distribution of energy poverty, governments should target vulnerable regions and groups when addressing energy poverty. Specifically, the central government should prioritize relatively underdeveloped regions in resource allocation and effectively improve the energy infrastructure in these areas, thereby preventing further diffusion of energy poverty. When implementing pro-poor regulations, local governments should concentrate on vulnerable groups such as rural residents and women. Additionally, strategies for each region should be tailored to their specific circumstances owing to significant differences in resource endowment and economic development. For instance, regions with abundant biomass resources and developed agriculture should prioritize biomass power generation and large-scale biogas production, and areas with ample wind resources should focus on promoting wind power station construction and implementing the on-site use of wind energy to meet the energy needs of the local population.

This study offers novel insights into environmental regulations and energy poverty but has some limitations. Owing to data constraints, it does not explore the in-depth mechanisms through which environmental regulations impact regional energy poverty, such as the potential mediating effects of energy prices and structures. Furthermore, this research primarily focuses on the region's overall energy poverty and leaves the conditions of individual residents unexplored. Future research should address these aspects to provide a more comprehensive understanding of the topic.

CRediT authorship contribution statement

Yiming Xiao: Conceptualization, Methodology, Investigation, Writing – original draft. **Zhijun Feng:** Investigation, Writing – review & editing, Supervision. **Han Wu:** Writing – review & editing. **Shangrui Wang:** Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.138285.

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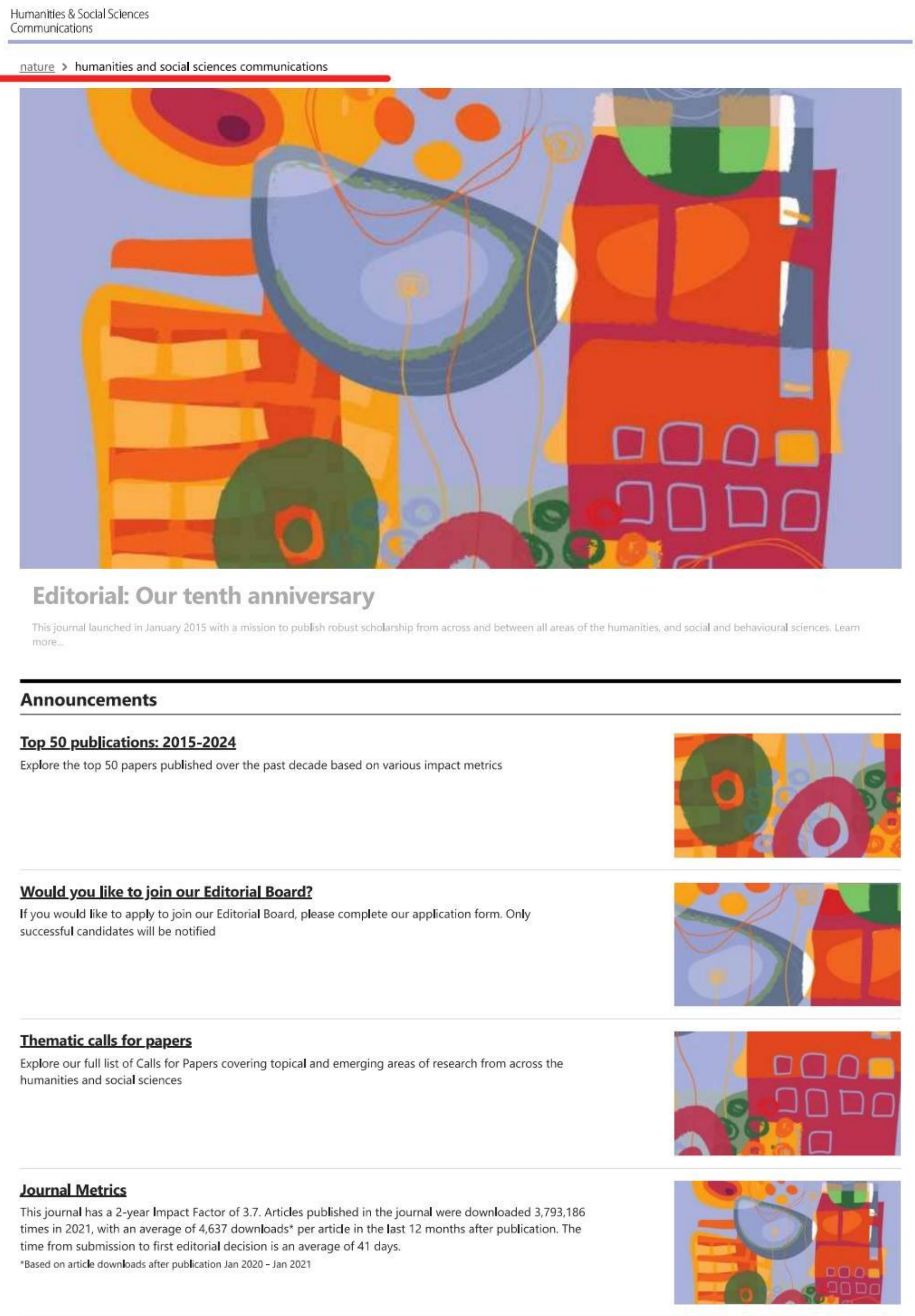

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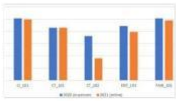

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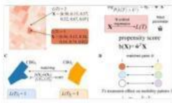

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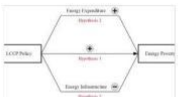

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Low-carbon transition and energy poverty: quasi-natural experiment evidence from China's low-carbon city pilot policy

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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.

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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,

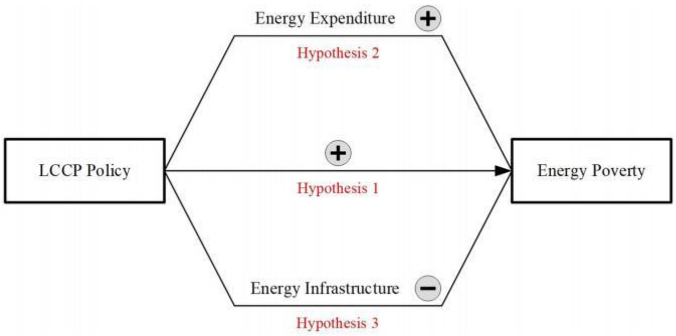

Fig. 1 Impact path of the LCCP policy on energy poverty.

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 $(G_i \times D_t)$ 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.

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

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).

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

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.

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

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

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.

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

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.

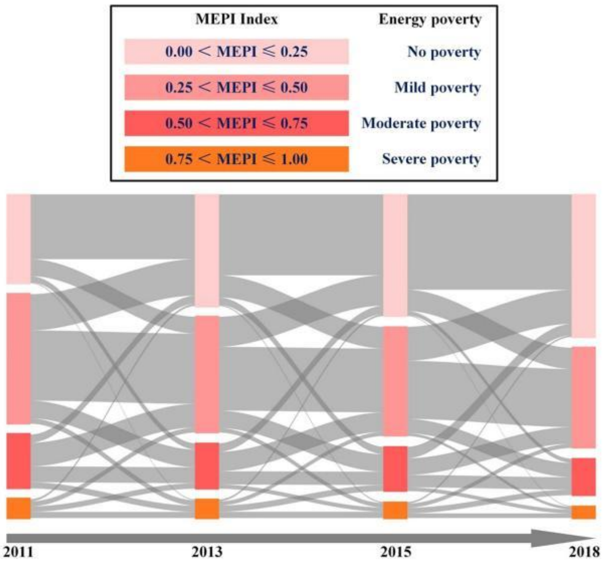

Fig. 2 The evolution of residents' energy poverty condition.

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

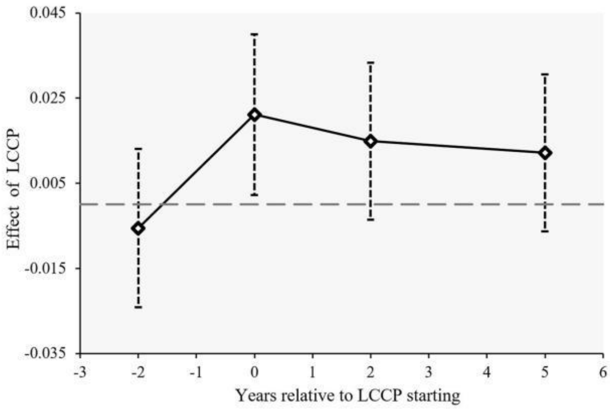

Fig. 3 Parallel trend test.

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

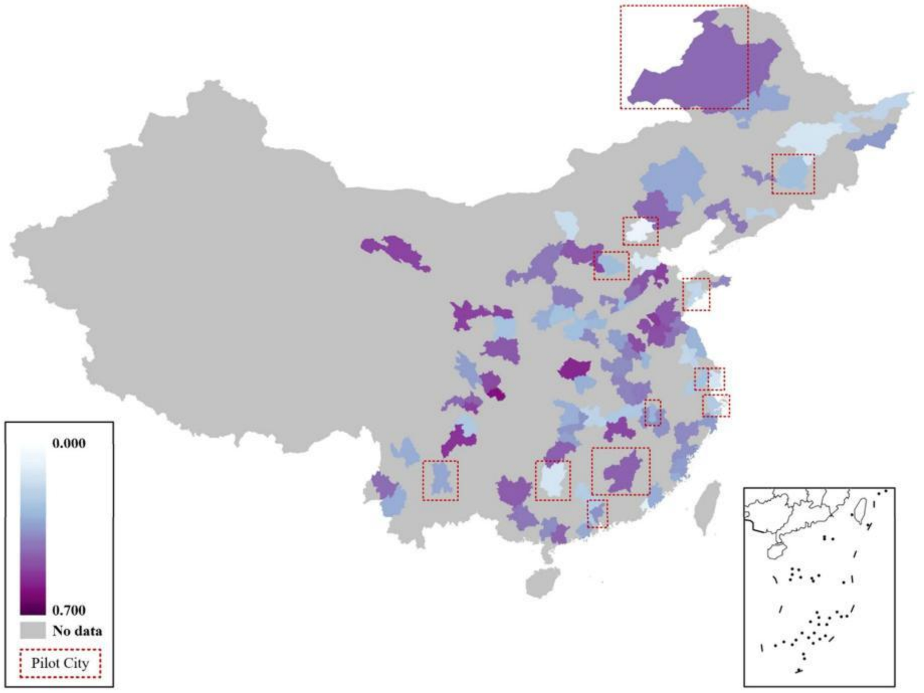

Fig. 4 Average energy poverty conditions of cities before policy implementation.

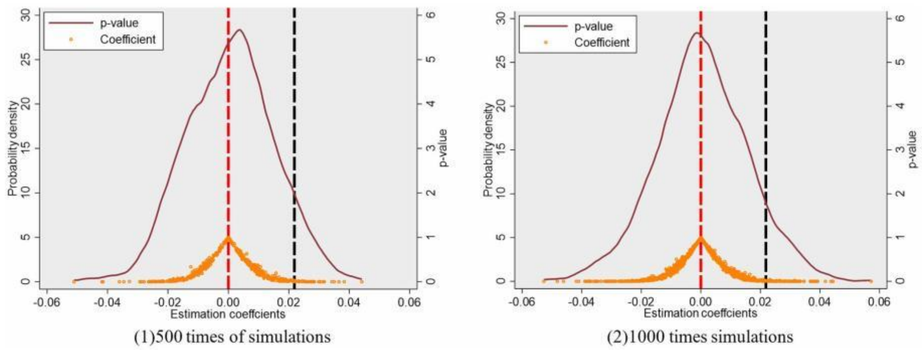

Fig. 5 Placebo test.

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/.

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

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The authors declare no competing interests.

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

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Additional information

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