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Exploring the role of renewable energy expansion in mitigating energy poverty in China

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Abstract
China has formulated ambitious but costly renewable energy targets for carbon reduction, energy security, and rural revitalization. However, nearly 13.2%-35.3% of Chinese are still suffering from energy-poor. As the transformation of energy structure accelerates, whether the expansion of renewable energy can alleviate energy poverty is rarely discussed. Therefore, this paper collects panel data from 30 provinces and regions in China from 2004 to 2020, and uses the difference-generalized moment method (GMM) to verify the role of renewable energy expansion in alleviating energy poverty. With the objective of rigorously measuring energy poverty, this paper establishes a four-dimensional comprehensive assessment system. Finally, robustness tests and heterogeneity analysis were performed to ensure the reliability of the results. According to the findings, (i) From the full sample data analysis results, the expansion of renewable energy has not significantly promoted the alleviation of energy poverty. (ii) The role of renewable energy expansion in alleviating energy poverty shows considerable variation across regions. In regions with serious energy poverty and large-scale expansion of renewable energy, the development of renewable energy is an effective means to mitigates energy poverty. However, in regions with lower levels of energy poverty and renewable energy expansion, the role of renewable energy expansion is not matter.

Keywords Renewable energy expansion · Energy poverty · China

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1 Introduction

Tackling energy poverty is essential to achieving more inclusive and shared prosperity (Chai et al., 2021). Compared to other forms of poverty, energy poverty is often less intuitive to perceive. For example, many people may not realize that some communities or households lack basic energy supply. Due to energy poverty's critical danger to human health and social well-being increasingly apparent, it becomes a hot topic for researchers (Wu et al., 2022). Ensuring energy poverty is eradicated by 2030 is one of the Sustainable Development Goals (Yang et al., 2024). Although China has accelerated the popularization of electricity, the instability of electricity and the lack of clean energy in remote areas or poor communities have resulted in little significant reduction in energy poverty (Zhao et al., 2023). Approximately 2.73 million individuals lack access to electricity, about 10% of rural households use firewood as the cardinal household fuel, and about 40% of families live in energy poverty (Liu et al., 2023). And energy poverty is growing due to the COVID-19 crisis in China. Moreover, because of the disparities in energy development between regions, as well as differences in geographical location, meteorological circumstances, and resource endowments, China's energy poverty exhibits typical traits compared to other countries (Hu et al., 2024).

Simultaneously, countries worldwide are shifting their energy composition from fossil fuels to renewables to curb carbon and pollutant emissions (Lee & Yuan, 2024). In this process, China made a great effort. As stated by China Renewable energy expansion Report 2022, renewable energy accounts for more than 47.3% of the full installed capacity of power generation, ranking top in the global countries. The northwest region of China is rich in solar, wind, and hydropower resources, the main installed area of renewable resources (Hille & Oelker, 2023). Studies have already pointed out that renewable energy expansion contributes to poverty alleviation by promoting employment and increasing income in poor regions, reducing income inequality (Li et al., 2022). It is crucial to shift towards renewable energy and figure out its influence on energy poverty.

Most researchers link energy consumption and renewable energy from the perspective of unfairness in the existing literature. For example, Dong et al. (2021) explored the role of natural gas popularization in the process of eliminating energy poverty. Oosthuizen et al. (2022) analyzed the impact of renewable energy expansion on electricity affordability. McGee and Greiner (2019) find that inequality impedes the environmental friendliness of renewable energy expansion. Henry et al. (2021) analyzed the role of renewable energy use in alleviating energy poverty in Guatemala, a highly underdeveloped country. So far, the studied region includes Bangladesh (Barnes et al., 2011), India (Sadath & Acharya, 2017), America (Wang et al., 2023), Spain (Aristondo & Onaindia, 2018), Japan (Castaño-Rosa & Okushima, 2021), Philippines (Mendoza et al., 2019), European (Muhammad et al., 2023) ADDIN, Australian (Zhao et al., 2022a, 2022b) and the global (Zhao et al., 2022a, 2022b). Based on the existing literature, whether the expansion of renewable energy has promoted the elimination of energy poverty in China has not yet been explored.

To address this issue, this paper conducts an empirical test, focusing on whether the expansion of renewable energy in China has alleviated energy poverty. Furthermore, the differential generalized method of moments is used in this paper, which has more advantages in dealing with sample data that may have cross-sectional dependencies There are significant differences in the level of economic development among various regions in China. The eastern coastal areas are generally more economically developed, while the central and western regions are relatively lagging. Moreover, natural resources, infrastructure and public services are unevenly distributed across regions, which may lead to different responses to policies in different regions. Therefore, this paper further conducts regional heterogeneity analysis.

The primary academic contributions of this paper are as follows: (1) While China is a global leader in renewable energy expansion, few studies have explored whether this growth alleviates or exacerbates energy poverty. This paper aims to provide empirical evidence on this issue. (2) By employing an enhanced entropy method and a set of indicators, we introduce an innovative, comprehensive metric for evaluating energy poverty. This approach enables a more accurate analysis of energy poverty in China and offers valuable recommendations for local policymakers in addressing the issue. (3) This paper investigates the relationship between renewable energy expansion and energy poverty in four distinct regional contexts: low-energy poverty, high-energy poverty, low-renewable, and high-renewable energy expansion areas, thereby providing a more nuanced understanding of the impact of renewable energy in different regions.

The remaining portions of the paper are structured in the following way: A review of the literature is the focus of Sect. 2. Section 3 outlines the data utilized and the research methodology employed. Section 4 is dedicated to the presentation and elaboration of the empirical outcomes. Finally, Sect. 5 draws the conclusions and assesses the potential policy impacts.

2 Literature review

2.1 Renewable energy expansion

Renewable energy can be continuously replenished and recycled by humans in nature, including water energy, geothermal energy, and photovoltaics. Renewable energy has gradually become essential towards the global energy mix, especially in the power sector. In 2021, the distribution of clean energy in power generation has reached 38%. Renewable energy is gaining increasing attention in China and is growing exponentially, nearly doubling by 2021. In recent years, renewable energy has received importance in China and will nearly be doubled in 2021. By reviewing the literature related to renewable energy expansion, the research topics can be summarized into the following aspects: energy pricing, renewable energy development level assessment, environmental impact assessment, policy analysis, etc. Zhao et al., (2022a, 2022b) combining the two dimensions of theory and demonstration, taking wind power as an example, analyze the optimal electricity price mechanism. Wang et al. (2020) developed a five-dimensional index to quantify renewable energy expansion level in China. Zheng et al. (2021) found that the expansion of the proportion of renewable energy will promote the reduction of greenhouse gas emissions. Against the backdrop of a substantial increase in solar power installed capacity, Yu et al. (2022) empirically tested whether solar power installed capacity can help reduce carbon emissions. The results indicate that carbon emissions exhibit a significant downward trend as solar installed capacity increase. Zhang et al. (2022) analyzed the impact of carbon emission policies on renewable energy expansion strategies. The study showed that carbon trading reduced fossil fuel dependence, improved energy efficiency, and promoted green progress, all of which led to a slowdown in the deployment of renewable energy.

2.2 Energy poverty

Energy poverty is mainly caused by low-income levels, inadequate regional infrastructure, difficulty in obtaining technology, insufficient policy support, social inequality, and the impact of climate change. These factors together make it difficult for certain groups or regions to obtain reliable, affordable, and clean energy services. Although most households have access to electricity, some still find it difficult to afford the costs. Energy poverty therefore remains a pressing issue in the context of improving and growing electrification. For those who can afford it, there is a need for reliable electricity supplies. In addition, many people still lack all kinds of necessary electrical appliances, such as refrigerators, TVs, natural gas stoves (Nussbaumer et al., 2012).

Until now, the measurement and definition of energy poverty have not been agreed upon. In the past, the essence of energy poverty was captured by the lack of availability to advanced energy solutions. It was not until 1991 that Boardman (1991) first defined energy poverty as a household spending over 10% of its earnings on energy-related expenses. However, the drawback of this single indicator definition approach is that it only considers income and is not suitable for countries in the southern hemisphere. Therefore, scholars have tried to consider factors such as energy convenience, economical, and energy quality (Adesanya & Pearce, 2019; Awaworyi Churchill et al., 2021) and redefined as a household that lacks adequate options for access to sufficient, inexpensive, reliable, quality, and eco-friendly novel energy systems, or whose health is unfavorably disturbed by excessive use of dirty fuels and inefficient appliances, is considered poverty. This definition includes people who do not have access to clean energy sources, reliable electricity, cooking fuel, and heating/cooling infrastructure. The International Energy Agency considers energy poverty to be a function of either the use of traditional biomass as a cooking fuel or the unavailability and non-usage of electricity.

Concerning the measurement, Pachauri et al. (2004) first established a two-dimensional evaluation system to assess energy poverty, which includes various energy categories and consumption levels. Buzar (2007) proposed an energy poverty index that centered on the percentage of the population lacking the capacity to maintain appropriate indoor warmth in their homes. To quantify energy poverty in European Union countries, Thomson and Snel (2013) used three proxy variables to quantify energy poverty, including the inability of the household to maintain adequate warmth, the difficulty in affording utility bills, and the ageing of the household. However, due to data unavailability and regional restrictions, the above measurement aspects are not applicable to China's energy poverty measurement. Considering China's actual limitations, Wang et al. (2015) proposed a comprehensive energy poverty measurement indicator system suitable for China's national conditions, which was subsequently widely used in research.

2.3 Renewable energy expansion and energy poverty

Previous studies have examined the potential impact of renewable energy penetration on energy poverty. Empirical research by some scholars shows that the development of renewable energy will aggravate poverty. They believe that the expansion of renewable energy may lead to high initial investment, insufficient infrastructure and technology, uneven policy support, market price fluctuations, short-term supply shortages, and insufficient awareness of renewable energy. These factors may prevent low-income households or regions from effectively using renewable energy, thereby exacerbating their energy poverty. The government's main goal in vigorously developing renewable energy is to achieve net zero emissions. While the government has provided subsidies and incentives to fuel renewable energy expansion, it still disproportionately increases the percentage of households spending on energy consumption (Carley & Konisky, 2020). It is because these subsidies and incentives may eventually be transited onto consumers in the pattern of surcharges or taxes (Filippidis et al., 2021).

Another view is that the expansion of renewable energy can help alleviate energy poverty (Kocak et al., 2023). They argue that renewable energy projects are typically installed in remote and impoverished areas, which lack alternative sources of electricity. This helps improve the energy production and usage conditions in regions with weak energy infrastructure and conventional energy shortages, assisting residents in utilizing clean energy (Wang et al., 2021). The widespread availability of solar resources across countries makes off-grid solar installations a promising solution to enhance rural electrification (Bhide & Monroy, 2011). Solar photovoltaic technology is more competitive than diesel power generation, mainly because of its significant cost reduction, low operating cost, environmental friendliness, renewable resources, improved energy independence, continuous technological progress, and policy support. These factors make photovoltaic technology superior to diesel power generation in terms of economy and sustainability, and it is increasingly becoming the preferred energy source in the market[39]. Solar energy is widely used and has abundant resources, reduces greenhouse gas emissions, and can be applied on different scales; wind energy is clean and efficient, has extremely high-power generation potential in suitable areas, and can be deployed quickly; hydropower has stable power generation capacity and energy storage advantages, and can provide reliable base load power for the power grid. These advantages jointly promote sustainable development and reduce dependence on traditional fossil fuels (Gamel et al., 2017). The application of solar photovoltaic systems to generate electricity can provide reliable electricity in remote and rural areas, reduce energy costs, and improve residents' living conditions.

Based on existing literature, we propose the following research hypotheses:

Hypothesis 1: The development of renewable energy helps alleviate energy poverty.

3 Methodology and data

This study aims to explore the role of renewable energy expansion in alleviating energy poverty. Energy poverty is the focus of this paper, that is, the explained variable. The expansion of renewable energy is the pivotal explanatory factor, while energy poverty is the variable being explained. Since changes in energy poverty usually have a time lag effect, this paper adopts a dynamic panel model building method. As Aisen and Veiga (2013) mentioned, estimates of dynamic panel models using ordinary least squares (OLS) can easily bias empirical results. Arellano and Bond (1991) differential GMM model, which performs first-order differencing on the base model to remove the effects of fixed effects. The explained variables and error terms in the model may be correlated, fitting instrumental variables need to be employed. Considering that the instrumental variable method (IV) is difficult to find suitable instrumental variables, differential GMM often uses suitable explanatory variables and lags of the explanatory variables as instrumental variables. System GMM is another commonly used GMM. Systematic GMM results are more effective only when the sample size is large enough. Therefore, to further deal with the potential endogeneity obstacle and fixed effects, this paper uses differential GMM as the standard model for regression.

3.1 Variables and data

This article collects data from 30 provinces in China from 2004 to 2020. Since there is a lot of missing data after 2020, our data is up to 2020. Energy poverty is calculated using several indicators, and these variables are described extensively in Sect. 3.4. Without loss of generality, this paper uses the proportion of renewable energy consumption in total energy consumption to measure the level of renewable energy expansion. In order to exclude the potential impact of factors other than renewable energy expansion on energy poverty, this paper incorporates four commonly used control variables into the research framework: industrial structure upgrading, economic growth, technological progress, and level of openness. These indicators have been widely used in the existing literature (Chai et al., 2021; Muhammad et al., 2023; Zhao et al., 2022a, 2022b).

(1). Economic growth (GDP). Economic development provides a guarantee for the promotion of clean energy, so it is included as a control variable to reduce its impact on the main conclusions. In addition, to eliminate the impact of inflation, this study calculates real GDP based on constant prices in 2000.
(2). Industrial structure upgrade (IS). Without loss of generality, industrial structure upgrading is expressed by the ratio of the added value of the tertiary industry to the added value of the secondary industry.
(3). Technological progress (TE). Technological innovations significantly contribute to reducing energy poverty by improving energy efficiency, reducing the cost of renewable energy, enhancing its accessibility, introducing smart grid management, promoting distributed generation, and creating jobs. These innovations make it easier for low-income households to access reliable energy supplies and improve living conditions, thereby promoting sustainable development. The number of patents reflects the level of technological innovation activity, and this study uses the number of patent applications approved per 10,000 people to represent it.
(4). Opening up level (Open). Frequent domestic and foreign trade exchanges will meet the needs of overseas consumers by providing more production opportunities. Replacing fossil fuels with renewable energies has a positive impact on the production process, reduces production costs and lessens the impact on the environment. Therefore, foreign trade can affect the development of renewable energy. We consider trade openness in the estimation model and represent it by the proportion of total import and export trade to total output value.

To eliminate data fluctuation and likely heteroscedasticity, all data are treated logarithmically in this paper. The descriptive analytics for the data sets under consideration are shown in Table 1. The renewable energy expansion series exhibits the greatest degree of volatility,

Table 1 Summary statistics of the independent variables

Variable	Obs	Mean	St. dev	Minimum	Maximum
LnEP	510	-0.998	0.251	-3.586	-0.357
LnRE	510	-4.279	1.671	-11.569	-1.352
LnGDP	510	9.074	1.005	6.028	11.184
LnIS	510	0.084	0.387	-0.640	1.657
LnTE	510	1.190	1.375	-2.041	4.309
LnOpen	510	-1.676	0.975	-4.880	0.457
LnELP	510	0.221	0.554	-0.828	1.749

as evidenced by the standard deviation, minimum, and maximum values. This volatility can be attributed to notable regional disparities among provinces.

Table 2 displays the pairwise correlation based on a linear connection among the variables under inquiry. The results of the correlation analysis indicate that there is a positive relationship between energy poverty and renewable energy expansion. It is worth noting that our goal is to analyze these associations in depth using nonlinear econometric methods. Therefore, we anticipate that conducting further analysis will provide a clearer insight into these actual relationships.

3.2 Measuring energy poverty

Quantifying energy poverty is challenging due to the lack of a universally accepted measurement system. Preceding research has explored energy poverty by leveraging statistical information and constructing either a one-variable or multi-variable system customized to relevant regional contexts. In addition to a single indicator, other measures are more suitable for specific countries. Owing to the multidimensional aspects of energy poverty, it is essential to formulate multi-dimensional indicators to address its complexity. However, the existing index construction methods are not necessarily applicable to China.

Therefore, based on the existing classical methods for measuring energy poverty, this paper refers to several indicators suitable for China's national conditions, such as investment in energy availability and household energy consumption, modern household fuel expenditure, and numerous household appliances. Drawing upon the research conducted by Wang et al. (2015), and Dong et al. (2021), this paper develops an energy poverty assessment framework based on China's actual national conditions. This study established an evaluation framework from four aspects, namely accessibility, cleanliness, management, affordability, and efficiency. The information for each metric in the system is drawn from diverse statistical yearbooks (Table 3).

Table 2 Correlation matrix

	LnEP	LnRE	LnGDP	LnIS	LnTE	LnOpen
LnEP	1					
LnRE	0.146***	1				
LnGDP	0.320***	-0.116***	1			
LnIS	0.331***	0.0470	0.00100	1		
LnTE	-0.00300	-0.00600	-0.0150	-0.138***	1	
LnOpen	0.247***	-0.461***	0.442***	0.212***	-0.0260	1

***, **, and * indicates significance at 1%, 5%, and 10% level

Table 3 Energy poverty assessment framework for China

Division	Indicator	Meaning	Attribute
Energy service availability (ESA)	Residential energy consumption	Electricity usage per people	Positive
		Natural gas usage per people	Positive
	Energy provision	Urban natural gas popularizing percentage	Positive
		Natural gas provision per capita in cities	Positive
Energy consumption cleanliness (ECC)	Low-carbon energy consumption structure	Non-thermal power generation ratio	Positive
	Modernization of energy consumption structure	Rural biogas production per people	Positive
Energy management completeness (EMC)	Energy investment	Per people energy investment of rural residents	Positive
Household energy affordability & energy efficiency (EAE)	Energy facilities	Number of households with air conditioners per 100 households in cities	Positive
		Number of households with refrigerators per 100 households in cities	Positive
		Number of households with kitchen hood per 100 households in cities	Positive
		Number of households with solar water heater per 100 households in rural	Positive
	Air pollution caused by residential energy use	Per capita sulfur dioxide domestic waste gas emissions	Negative
		Per capita smoke and dust domestic waste gas emissions	Negative

The energy poverty assessment system established in this paper includes 13 basic indicators. Define a_{ij} as the j indicators od i province and obtain the Index system matrix. Indicators were standardized due to inconsistencies in the units of the indicators. The normalization method for positive indicators and negative indicators is

$$a_{ij}\prime = \frac{a_{ij} - \min(a_{1j,} \cdots, a_{nj})}{\max(a_j, \cdots, a_{nj}) - \min(a_{1j,} \cdots, a_{nj})} \tag{1}$$

$$a_{ij}\prime = \frac{\max(a_{1j}, \cdots, a_{nj}) - x_{ij}}{\max(a_{1j}, \cdots, a_{nj}) - \min(a_{1j}, \cdots, a_{nj})} \tag{2}$$

where $a_{ij}\prime$ refers to the j-th standard index of i province.

Then, the weight of each basic indicator is calculated. The specific calculation process can be expressed as First, the proportion of the jth indicator of the ith province in the entire sample is evaluated. Finally, the entropy value of the jth indicator can be calculated.

$$\rho_{ij} = \frac{a_{ij}\prime}{\sum_{i=1}^{n} a_{ij}\prime} \tag{3}$$

$$e_j = -\frac{\sum_{i=1}^{n} a_{ij}\prime}{Ln(n)} \tag{4}$$

where n indicates the number of provinces.

The information entropy redundancy calculation method of each indicator is shown in formula (5):

$$d_j = 1 - e_j \tag{5}$$

Finally, the calculation method of each index weight is

$$w_j = \frac{d_j}{\sum_{j=1}^{m} d_j} \tag{6}$$

After following the steps, the comprehensive energy poverty index is ultimately derived as

$$EP_i = \sum_{j=1}^{m} w_j \rho_{ij} \tag{7}$$

According to the measurement method in this paper, the lower the energy poverty calculation score, the more serious the energy poverty in the region.

3.3 Econometric model

This paper focuses on the explained variable energy poverty, of which renewable energy expansion is the key explanatory variable. This paper introduces economic growth, Industrial structure upgrade, Technological progress, and opening level as control variables and establishes the model as follows.

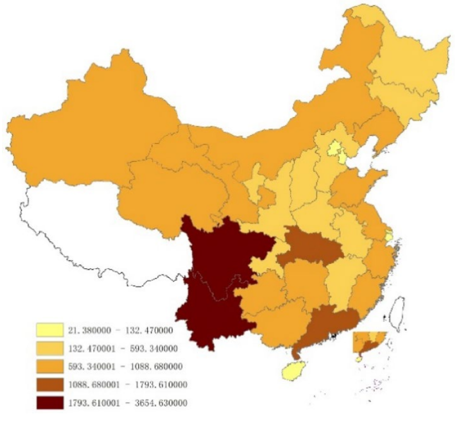
$$EP_{it} = f\left(EP_{i,t-1}, RE_{it}, GDP_{it}, IS_{it}, TE_{it}, Open_{it}\right) \tag{8}$$

where subscript i is the provinces, *t* indicates the year, RE denotes the renewable energy expansion, GDP is usually used to measure the economic development of a country, IS marks the degree of upgrading of industrial structure from secondary industry to tertiary industry, TE stands for the advanced level of technology, and Open stands for the degree of openness to foreign trade. To effectively mitigate the impact of variable heteroscedasticity on the results, all variables in the equation are converted to their natural logarithmic forms. In summary, the econometric model established in this paper is as follows:

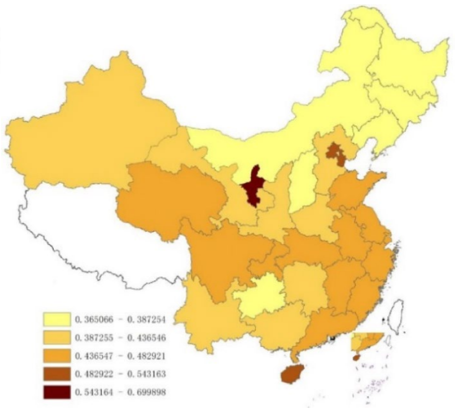
$$\ln EP_{it} = \alpha_{it} + \beta_1 \ln EP_{i,t-1} + \beta_2 \ln RE_{it} + \beta_3 \ln GDP_{it} + \beta_4 \ln IS_{it} + \beta_5 \ln TE_{it} + \beta_6 \ln Open_{it} + v_i + \mu_t + \varepsilon_{it} \tag{9}$$

where subscript i represents the provinces, *t* indicates the year, α and β are coefficients that remain to be estimated, v_i represents provincial fixed effects, μ_t denotes time fixed effects, ε_{it} signifies the error term.

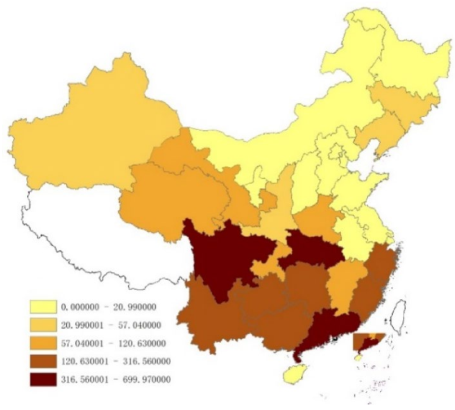
The spatial configuration of renewable energy and energy poverty are portrayed in the graphical representation identified as Fig. 1. It can be found that all the two variables have significant regional difference. Compared with other provinces, renewable energy expansion in Yunnan, Sichuan, Guangdong, and Hubei performs better. In terms of energy poverty, Heilongjiang, Jilin, and Liaoning in northeast region suffer in more severe energy



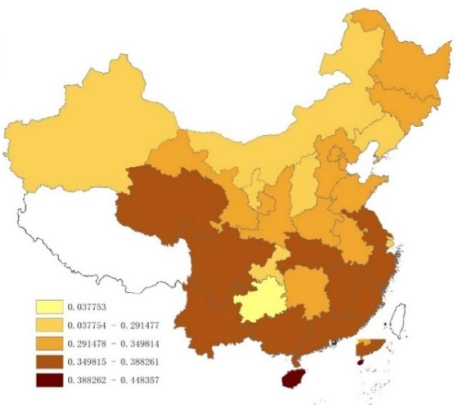
(a) Renewable energy expansion in 2020



(b) Energy poverty in 2020



(c) Renewable energy expansion in 2004



(d) Energy poverty in 2004

Fig. 1 Distribution of renewable energy expansion and energy poverty

poverty. Energy poverty performs better in eastern coastal provinces, such as Zhejiang and Jiangsu. Scrutinizing the shifts in renewable energy and energy poverty from 2004 to 2020, it is evident that the growth of renewable energy has been substantial, while energy poverty has also demonstrated gradual amelioration during this 15-year timeframe.

4 Results

The precise regression methodology involves a four-stage process: As the initial step, perform the Breusch-Pagan Lagrange multiplier (LM) test and the Pesaran cross-sectional dependence (CD) test t to examine the presence of cross-sectional correlation in the panel data. As the next step, this paper conducts the Pesaran cross-sectionally augmented Dickey-

Fuller (CADF) test and the cross-sectionally augmented Im, Pesaran, and Shin (CIPS) test to examine the stationarity of each variable; Thirdly, adopt differential GMM to perform benchmarking, mechanism analysis, and heterogeneity analysis; Lastly, conduct a robustness test to ensure the reliability of the findings.

4.1 Cross-sectional dependence examination

Considering the interdependence among provinces, each province cannot be treated as an independent entity. As a result, the sample data exhibits cross-sectional interdependencies. Neglecting these dependencies in panel data analysis may result in inconsistent and unreliable estimation outcomes (Al Kez et al., 2024). Hence, the analysis proceeds to execute the Breusch-Pagan Lagrange multiplier (LM) test and the Pesaran cross-sectional dependence (CD) test. As illustrated in Table 4, the p-values for the Breusch-Pagan LM and Pesaran CD tests are 0. This means that the null hypothesis, which claims no cross-sectional correlation between the provinces, is forcefully rejected with high statistical confidence. Consequently, it is necessary to consider the presence of cross-sectional dependencies in the panel data when conducting the upcoming estimations.

4.2 Panel unit root tests

Mitigating the concern of spurious regression calls for a vital evaluation of the stationarity conditions of the variables. Two kinds of unit root test methods Pesaran CADF test and Pesaran CIPS test, are employed in this paper. The data presented in Table 4 confirms the null hypothesis that the data are not stationary and have a unit root. However, all variables exhibit a stationary series with no unit root. Following the implementation of a first-order differencing, the null hypothesis is decisively denied at the 1% significance level (Table 5).

4.3 Cointegration test

This research utilizes the Kao panel cointegration examination to validate the long-term associations involving the variables. The study makes use of the Kao panel cointegration test, which is a residual-based Engle-Granger test carried out within an ADF (Augmented Dickey-Fuller) setting. The findings shown in Table 6 reveal that the Kao test upholds the null hypothesis, implying the lack of a long-run association among the variables.

4.4 Panel econometric analysis

The Hausman test produces a P-value below 0.01, which implies that the null hypothesis can be decisively rejected. As a result, the fixed-effects model is considered the more suitable choice for this analysis. Prior to undertaking the dynamic panel data analysis, the

Table 4 Cross-sectional dependence examination

Test	Statistics	Prob
Breusch-Pagan LM test	618.89 ***	0.0000
Pesaran CD test	14.245 ***	0.0000

***, **, and * indicates significance at 1%, 5%, and 10% level

Table 5 Panel unit-root tests for stationarity

Variables	Level		1st difference	
	Intercept	Intercept & trend	Intercept	Intercept & trend
Pesaran CADF test				
LnEP	-1.806	-2.066	-2.682***	-2.803***
LnRE	-2.672***	-2.994***	-2.756***	-2.625**
LnGDP	-1.976	-2.403	-2.008*	-2.166**
LnIS	-1.854	-2.911***	-2.943***	-2.938***
LnTE	-2.455***	-2.351	-4.263***	-4.140***
LnOpen	-0.967	-1.933	-2.327***	-2.338**
Pesaran CIPS test				
LnEP	-1.708	-1.817	-3.561***	-3.979***
LnRE	-2.246*	-2.367	-3.783***	-3.821***
LnGDP	-2.075*	-2.737**	-2.454***	-2.828**
LnIS	-1.767	-2.617*	-3.239***	-3.235***
LnTE	-4.023***	-3.866***	-5.803***	-5.722***
LnOpen	-0.960	-2.210	-3.243***	-3.449***

***, **, and * indicates significance at 1%, 5%, and 10% level

Table 6 Kao panel cointegration test

Kao cointegration test	Coefficient	P-value
Modified Dickey-Fuller t	1.4009*	0.0755
Dickey-Fuller t	-5.7839***	0.0000
Augmented Dickey-Fuller t	4.6655 ***	0.0000
Unadjusted modified Dickey-Fuller t	-9.2516***	0.0000
Unadjusted Dickey-Fuller t	-13.9928***	0.0000

***, **, and * indicates significance at 1%, 5%, and 10% level

researchers conducted the Arellano-Bond (AR) test and Sargan test to verify the suitability of the D-GMM approach. The AR test checks for first-order autocorrelation in the estimated random disturbance term adopting the Generalized Method of Moments (GMM) while ensuring the absence of second-order correlation. Meanwhile, the Sargan test is applied to scrutinize the validity of the instrumental variables implemented in the analysis. The findings reveal that the Arellano-Bond (AR) and Sargan tests were successfully cleared, and the paper further employs OLS, fixed-effect, and system GMM models to verify the robustness and precision of the results. The findings reveal that the differential GMM estimation lies between the OLS regression and the fixed effects model, which corroborates the credibility of the results.

Table 7 reveals that the coefficient for renewable energy expansion is positive yet not significant, a pattern that is consistent with the outcomes presented by Muhammad et al., (2023). The findings indicate that renewable energy projects have higher upfront or capital costs owing to the expensive nature of the underlying technologies. In China, renewable energy projects, such as wind power, mostly installed in remote areas, have a high cost of connecting to the central grid. Therefore, renewable energy expansion does not alleviate energy poverty in the research period. The outcomes of this study suggest that the electricity supplied from renewable sources has not succeeded in lowering electricity prices.

Table 7 Baseline regression results

Variable	OLS	FE estimation	D-GMM	S-GMM
$LnEP_{i,t-1}$	0.770***	0.662***	0.721***	0.679***
	(0.0204)	(0.0294)	(0.154)	(0.0948)
$LnRE$	0.00275	0.00274	0.00764	0.0172
	(0.00304)	(0.00840)	(0.0183)	(0.135)
$LnGDP$	-0.00788	-0.0982	-0.354	-1.242
	(0.00659)	(0.0936)	(1.817)	(1.326)
$LnIS$	0.0102	-0.0100	0.0537	0.0551
	(0.0153)	(0.0452)	(0.595)	(0.777)
$LnTE$	0.00166	0.00399	0.00367	0.0784
	(0.00312)	(0.00443)	(0.00444)	(0.0901)
$LnOpen$	0.0173*	0.0197	0.00145	0.0496
	(0.00698)	(0.0175)	(0.0500)	(0.156)
AR (1)			0.073	0.043
AR (2)			0.589	0.470
Sargan test			0.589	0.627
R-squared	0.847	0.859		
Obs	480	480	450	480

***, **, and * indicates significance at 1%, 5%, and 10% level

4.5 Robust analysis

To demonstrate the robustness of the conclusion, a robust analysis is provided. Firstly, this paper showed the results of four methods. The results of the four methods are consistent, which proves the robustness of the conclusions. Secondly, this paper further added control variables into the regression. This paper introduced energy efficiency into the regression as a control variable. Prior studies have investigated the relationship between energy efficiency and energy poverty. They emphasized the vital importance of energy efficiency in mitigating energy poverty. The indicator used to assess energy efficiency is the level of energy consumption relative to the gross domestic product (GDP). Table 8 demonstrates that the signs and significance levels of the coefficients for the relevant variables are analogous. More importantly, the value range of each variable coefficient is similar to the conclusion in Table 7. In summary, the conclusions of this paper are robust.

4.6 Regional heterogeneous influence of renewable energy expansion on energy poverty

For the purpose of empirically exploring the regional disparities in the relationship between renewable energy growth and energy poverty, the 30 provinces are partitioned into four categories, adopting the same approach as Dong et al. (2021). The method for classifying provinces consists of three steps: (1) Assess the average magnitudes of energy poverty and renewable energy expansion observed in each province over the previous five-year period; (2) Compute the average values of energy poverty and renewable energy expansion across all the studied provinces for the preceding five-year period; (3) The 30 provinces are partitioned into four categories, as determined by the calculation outcomes: (1) High EP categories, provinces with higher than average levels of energy poverty; (2) Low-EP categories, provinces with lower than average levels of energy poverty; (3) High-RE categories,

Table 8 Robust test

Variable	OLS	FE estimation	D-GMM	S-GMM
$LnEP_{i,t-1}$	0.756***	0.662***	0.701***	0.735***
	(0.0216)	(0.0295)	(0.105)	(0.108)
$LnRE$	0.00186	0.00284	-0.0505	-0.0320
	(0.00308)	(0.00842)	(0.0454)	(0.0893)
$LnGDP$	-0.0163*	0.101	-0.172	-0.422
	(0.00808)	(0.0946)	(0.572)	(1.220)
$LnIS$	0.00381	-0.00971	0.0181	0.380
	(0.0156)	(0.0453)	(0.268)	(1.064)
$LnTE$	0.00266	0.00404	-0.0236	-0.0343
	(0.00316)	(0.00444)	(0.0269)	(0.0841)
$LnOpen$	0.0134	-0.0190	-0.0286	-0.0325
	(0.00730)	(0.0178)	(0.0935)	(0.0920)
$LnELP$	-0.0268	0.0100	0.0586	-0.545
	(0.0149)	(0.0499)	(0.877)	(1.029)
AR (1)			0.071	0.079
AR (2)			0.268	0.236
Sargan test			0.585	0.391
R-squared	0.848	0.859		
Obs	480	480	450	480

***, **, and * indicates the significance level at 1%, 5%, and 10%, respectively

provinces with higher than average levels of renewable energy expansion; (4) Low- RE categories, provinces with lower than average levels of renewable energy expansion.

Utilizing the methodologies mentioned beforehand, the categorization results are distinctly displayed in Fig. 2. This study conducted a more in-depth examination of the vary-

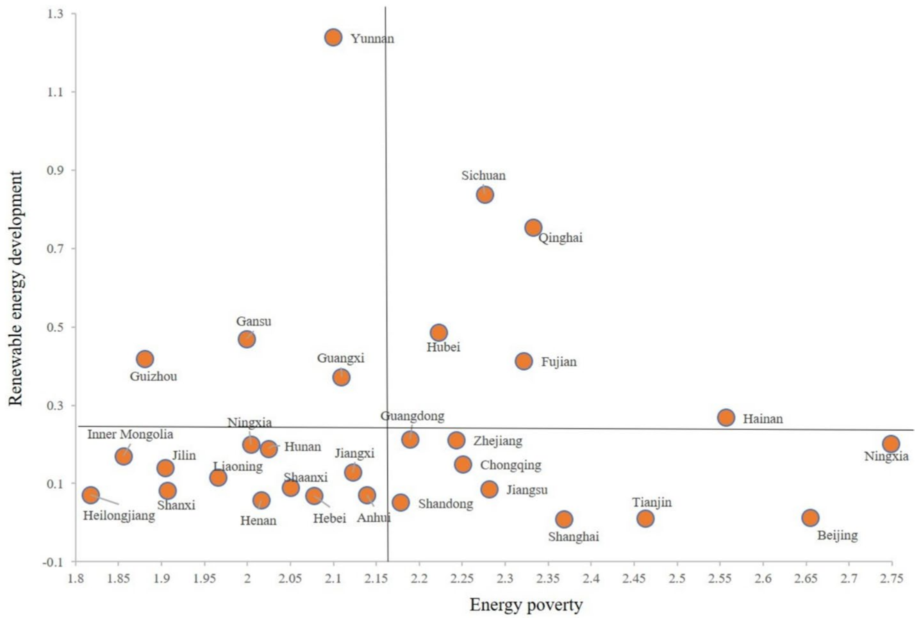


Fig. 2 Regional heterogeneity division

ing impact that renewable energy expansion has on energy poverty, utilizing the D-GMM approach. The findings from the regional heterogeneity analysis, as detailed in Table 8, underline the notable differences across regions in the way renewable energy expansion and energy poverty are interlinked. I It is important to note that in the category with low energy poverty values, the expansion of renewable energy significantly ameliorates energy poverty. Specifically, in the frigid winter climate of Heilongjiang, a sizeable amount of energy must be consumed to ensure proper heating and warmth in residential buildings. Utilizing renewable energy sources helps to decrease household reliance on dirty and inefficient forms of energy consumption. For the province, in the areas with high energy poverty levels, the growth of renewable energy shows a positive association, but does not lead to a substantial reduction in energy poverty. Concerning the driving forces, the region chiefly consists of provinces that have experienced faster economic progress and lower energy poverty rates. Within the category exhibiting a high level of renewable energy deployment, the predominant provinces are economically disadvantaged and particularly reliant on conventional energy. The expansion of renewable energy has the potential to displace the consumption of polluting fuels and ultimately lead to a significant alleviation of energy poverty within the region. Corresponding to the high energy poverty setting, the low renewable energy region is marked by a relatively flourishing economy and decreased energy poverty. Therefore, the coefficient of renewable energy expansion is not significant. In summary, the transformative influence of renewable energy growth on energy poverty exhibits observable disparities across regions. The promotion of renewable energy will solely contribute to improving energy poverty in regions plagued by severe energy poverty and high levels of renewable energy expansion (Table 9).

Table 9 Results of the regionally diversified examination

Variable	High-EP region	Low-EP region	High-RE region	Low-RE region
$LnEP_{i,t-1}$	0.889***	0.630***	0.579***	0.526*
	(0.0464)	(0.0411)	(0.0636)	(2.562)
$LnRE$	0.00636	0.00297**	0.0680**	-0.00345
	(0.00620)	(0.0201)	(0.0578)	(0.0114)
$LnGDP$	0.00927**	0.166	1.246*	-49.10*
	(0.0745)	(0.182)	(0.611)	(22.69)
$LnIS$	-0.0561	-0.00126	0.343	-5.541*
	(0.0440)	(0.0748)	(0.191)	(2.217)
$LnTE$	0.000460*	0.00608*	0.00248	0.0315*
	(0.00355)	(0.00744)	(0.0145)	(0.0142)
$LnOpen$	0.00250	-0.0440	-0.0808	0.228
	(0.0136)	(0.0336)	(0.0530)	(0.135)
AR (1)	0.079	0.023	0.070	0.032
AR (2)	0.252	0.321	0.515	0.366
Sargan test	0.118	0.625	0.833	0.16
R-squared	0.922	0.819	0.833	0.934
Obs	210	240	135	315

***, **, and * indicates the significance level at 1%, 5%, and 10%, respectively

5 Conclusions and policy implication

5.1 Conclusions

The objective of this research is to investigate the connection between the growth of renewable energy and the mitigation of energy poverty in China, the world's foremost developing nation experiencing expeditious renewable energy expansion. To achieve this purpose, we utilized panel data covering 30 provinces in China over the period from 2005 to 2020. This study first developed a composite index to assess energy poverty, encompassing factors such as energy service availability, energy consumption cleanliness, energy management comprehensiveness, and household energy affordability & energy efficiency. The paper then explored the potential ramifications of renewable energy on the amelioration of energy poverty using the differential Generalized Method of Moments (GMM) approach. Moreover, the analysis delved into the potential regional differences observed in low-energy poverty zones, high-energy poverty zones, low-renewable energy expansion zones, and high-renewable energy expansion zones, respectively. The results point to the conclusion that the expansion of renewable energy did not bring about a decrease in energy poverty over the course of the research period. The findings also indicate that the dynamic relationship between renewable energy expansion and energy poverty demonstrates clear regional heterogeneity. The promotion of renewable energy will only result in the mitigation of energy poverty in regions with acute energy poverty challenges and robust renewable energy growth.

This study also conducted a robustness analysis to verify the reliability of the results. In the research design, energy efficiency is used as a control variable to deeply explore the relationship between renewable energy development and energy poverty. The study found that the expansion of renewable energy has no significant impact on energy poverty. This result is consistent with previous research and further supports the robustness and credibility of the research conclusion.

5.2 Policy implication

Drawing from the empirical findings, the researchers offer the following policy suggestions.

1) Formulate differentiated policy measures based on the energy poverty status and renewable energy development level of each region. Provide more precise support for low energy poverty areas and high renewable energy expansion areas to ensure that the promotion of renewable energy can effectively improve the energy access capabilities of residents.
2) Increase investment in renewable energy infrastructure, especially in areas with severe energy poverty. Build and improve renewable energy facilities such as solar and wind power to ensure that residents in remote and poor areas have access to reliable energy services.
3) Encourage enterprises and scientific research institutions to increase investment in the research and development of renewable energy technologies, especially in improving energy efficiency and reducing costs. The government can stimulate innovation activities and promote the popularization of renewable energy technologies through tax incentives and financial support.

This study has several limitations. The panel data covers only 30 provinces, which may not fully represent the complexity of renewable energy and energy poverty across all regions, especially in remote or minority areas. While a composite index was developed to assess energy poverty, other critical factors such as policy changes and socio-economic conditions were not included.

For future research, expanding the data set to include more provinces or county-level data could provide a more comprehensive assessment. Longitudinal studies that analyze the long-term impacts of renewable energy on energy poverty are also needed. Future work should consider developing more nuanced energy poverty indicators that incorporate factors like education and employment. In-depth case studies of specific regions, particularly minority or rural areas.

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Data availability Data will be made available on request.

Declarations

Competing interest The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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