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Research article

Does the transition to low-carbon energy alleviate urban-rural energy inequality? The case of China

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ABSTRACT

This paper aims to investigate whether China can reduce urban-rural energy inequality during its transition to low-carbon energy. Using data from 30 Chinese provinces between 2006 and 2019, we employ the system generalized method of moments (SYS-GMM) to investigate the correlation between low-carbon energy transition (LET) and urban-rural energy inequality. Furthermore, to investigate the mechanism, this study also considers energy service accessibility and industrial structure upgrading. The results of the study show that the degree of LET in China is increasing but with uneven spatial distribution. Moreover, LET is effective in reducing urban-rural energy inequality in China. Specifically, 1 % increase in LET corresponds to 0.045 % reduction in the urban-rural energy inequality index. Additionally, energy service accessibility and industrial structure upgrading are identified as effective channels for LET to mitigate urban-rural energy inequality. Furthermore, our study demonstrates that the alleviating impact of LET on energy inequality is more significant in regions where LET and urban-rural energy inequality levels are high. Drawing on our research results, we suggest policy recommendations to encourage the adoption of low-carbon energy sources and diminish urban-rural energy inequality.

1. Introduction

Energy plays a crucial role in propelling economic and social development, and a country's wealth status is significantly influenced by the type, accessibility, and availability of its energy resources [1]. As the world strives towards sustainable development, the acquisition and utilization of clean and low-carbon energy resources have become increasingly critical in promoting economic growth while safeguarding the environment [2]. Clean energy has a significantly smaller ecological footprint compared to fossil fuels. It emits considerably fewer carbon emissions and has a much lower adverse impact on both human health and the environment [3,4]. This makes the transition from traditional energy to low-carbon energy a fundamental priority for many countries seeking to address environmental and climate concerns. As a result, a growing number of countries are actively transitioning to low-carbon energy sources [5].

The adequate and equitable provision of clean energy remains a significant obstacle for many nations. While some countries are fortunate to possess plentiful energy resources, others confront substantial energy poverty and constrained access to contemporary energy amenities [6,7]. Even today, nearly 3 billion people worldwide continue to rely on traditional biomass fuels such as wood,

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agricultural residue, and animal waste for their daily energy requirements. Moreover, a significant proportion of the global population, approximately 1.4 billion individuals, continues to face a complete lack of access to electricity [8,9]. Energy inequality continues to be a pervasive problem, especially in developing nations [10,11].

Low-carbon energy distinguishes itself from conventional fossil fuels through its distinct methods of production, transportation, and consumption [12]. The subject of whether the shift to low-carbon energy exacerbates or ameliorates energy inequality is a matter of ongoing debate [13]. On one hand, low-carbon energy transition (LET) could reduce dependence on fossil fuels, providing more people with affordable and reliable energy services while promoting inclusive and sustainable energy development [14]. Additionally, the use of low-carbon energy can encourage economic growth and employment opportunities, thereby narrowing energy inequality [15]. On the other hand, LET could exacerbate energy inequality. Concentrating the production and distribution of low-carbon energy in wealthy areas could lead to inadequate energy availability in other regions [16]. Moreover, due to the relatively high cost of certain low-carbon energy sources, some low-income groups may not be able to afford the transition, further exacerbating energy inequality [17,18].

Although many studies have assessed the socioeconomic impacts of LET and have conducted preliminary explorations into how LET affect energy inequality, there has been a lack of attention to the issue of urban-rural energy inequality, especially in the Chinese context [19,20]. The study employs the Theil index to measure energy inequality. The Theil index is a commonly used metric for assessing economic and social inequality [21]. Additionally, there is a dearth of comprehensive and methodical investigation on the impact of LET on urban-rural energy inequality. Therefore, investigating the impact mechanism of LET on urban-rural energy inequality is crucial to help decision-makers develop targeted policies based on the specific pathways of impact. Furthermore, the heterogeneity of urban-rural energy inequality resulting from energy transition is often overlooked. With this context, we utilize a balanced panel dataset comprising 30 provinces in China from 2006 to 2019 to examine the quantitative association between urban-rural energy inequality and LET. To address potential cross-sectional dependence in the panel data, we employ the system generalized moment method (SYS-GMM) as our primary technique. Additionally, we examine the mechanism through which LET impacts urban-rural energy inequality. The moderating role of government governance in the impact of LET on urban-rural energy inequality is also examined Finally, given the significant variations in the degree of LET among different regions in China, we also conduct a heterogeneity analysis.

We provide four unique contributions to the current body of research on this topic. First, this study presents a holistic assessment of the influence of LET on urban-rural energy inequality by merging these concepts under a unified framework. Although prior research primarily concentrates on the economic and social consequences of LET, there is a lack of studies that assess its effect on urban-rural energy inequality. Our study emphasizes the significance of determining the influence of LET on urban-rural energy inequality, which can assist decision-makers in crafting efficient policies that facilitate the advancement of renewable energy industries and mitigate urban-rural energy inequality. Second, this study uncovers the mediating function of energy service accessibility and industrial structure upgrading in the association between LET and urban-rural energy inequality. Finally, we conduct heterogeneity analysis to explore the effectiveness of LET in alleviating urban-rural energy inequality in different regions. By identifying regional differences in the impact of LET on urban-rural energy inequality, this study provides valuable insights for policymakers and stakeholders to develop region-specific policies and strategies to encourage the establishment of a more sustainable and fair energy system.

The remainder of this study is structured as follows: Section 2 offers an overview of the pertinent literature. Section 3 is theoretical framework and hypotheses. In Section 4, we introduce the fundamental econometric models and data. Section 5 reports the preliminary results obtained from the analysis. Subsequently, we delve into the results in greater detail in Section 6. Finally, Section 7 summarizes this article and provides corresponding policy recommendations.

2. Literature review

2.1. Measurement of LET

In recent years, the academic community has increasingly focused on measuring the degree of LET in various contexts [22,23]. Currently, the energy transition trend is gradually substituting high-carbon energy with low-carbon alternatives, leading to a substantial surge in the proportion of non-fossil energy consumption [24]. Various indicators are used to measure the intensity of LET, and some scholars use renewable energy consumption indicators [25,26]. For example, Bouyghrissi et al. [27] employ data on renewable energy consumption to investigate the influence of Morocco's LET on carbon emissions. Inglesi-Lotz [28] employs the percentage of renewable energy consumption as a metric to assess the progress of LET. The findings suggest that LET is not only advantageous for environmental sustainability but also has positive impacts on the economic conditions of diverse nations. Other scholars argue that renewable energy production is a reliable indicator for evaluating LET [29,30]. Shahbaz et al. [31] utilize data on renewable energy generation to assess how the digital economy influences the transition towards low-carbon energy. Maennel and Kim [32] perform a comparative analysis of South Korea and Germany, exploring their potential to diminish greenhouse gas emissions by adopting renewable energy generation as a gauge of LET. This article posits that various factors, including infrastructure, economic development, and pricing, can all affect the consumption of renewable energy [33]. However, the production of renewable energy involves more energy-related aspects, which can more accurately describe the level of energy transition and development. Therefore, this study applies renewable energy production as a measure of LET.

2.2. *Socio-economic implications of LET*

To further assess the impact of this transition, many scholars analyze the socio-economic consequences of the LET process. He et al. [34] believe that China's gradual shift toward a low-carbon energy system has the potential to yield dual benefits for both the economy and the environment in the long term. Garcia-Casals et al. [35] demonstrate that, in addition to promoting GDP and employment growth, LET could also bring about greater welfare benefits. Sun et al. [36] investigate the influence of LET on technological innovation and discover that sustainable energy policies can facilitate the development of technological innovation within enterprises. Many scholars also explore the impact of LET on fairness and justice [37,38]. Chapman et al. [39] analyze some key factors that influence social equity and argue that LET typically results in improved social equity outcomes. Some scholars highlight the connection between energy poverty and the transition to low-carbon energy [40]. Dong et al. [41] conduct a study on the impact of LET on energy poverty in China. The study finds that LET can be an effective solution to alleviate energy poverty. Adom et al. [42] believe that the transition to green energy partially compensates for the adverse effects of energy poverty on the various development outcomes considered in this study. Lippert and Sareen [43] find energy poverty can be alleviated by transitioning to low-carbon energy infrastructure. Papadopoulou et al. [44] conclude that transition to a carbon-free environment is an effective way to solve energy poverty.

3. Theoretical framework and hypotheses

3.1. *The total effect of LET on urban-rural energy inequality*

The utilization of low-carbon energy sources has the potential to foster economic growth and create employment opportunities, consequently addressing urban-rural energy inequality [45,46]. The transition towards low-carbon energy offers a range of benefits, including reduced reliance on fossil fuels, enhanced accessibility to affordable and reliable energy services, and the promotion of inclusive and sustainable energy development. Conventional energy sources, like coal, tend to be concentrated in specific regions, whereas low-carbon energy can be harnessed and utilized across various regions [47]. This widespread adoption of low-carbon energy sources brings about diversified economic advantages and employment prospects, stimulating regional economic development, and enhancing consumer well-being.

Moreover, the extraction and utilization of traditional energy sources often lead to environmental pollution and health concerns, particularly affecting impoverished areas and their residents [48]. In contrast, the utilization of low-carbon energy technologies can mitigate pollution and health issues, resulting in an improved quality of life for individuals [49]. Additionally, low-carbon energy has the potential to lower energy costs, ensuring more equitable energy services for consumers [50]. As low-carbon energy technologies continue to advance and deployment costs decrease, the affordability of low-carbon energy gradually improves. This affordability enables a larger portion of the population to access and benefit from low-carbon energy sources. By facilitating access to affordable energy and fostering sustainable economic growth, low-carbon energy plays a crucial role in promoting urban-rural energy equality and supporting a more inclusive society.

Hypothesis 1. LET has the potential to mitigate urban-rural energy inequality.

3.2. *The mediating effect of energy service accessibility*

LET has the potential to improve energy inequality by increasing energy service accessibility. In traditional energy systems, energy sources are often concentrated in a few regions, leaving other areas without reliable and affordable energy services [51]. However, the widespread adoption of low-carbon energy can change this situation. Decentralized energy systems, such as installing solar panels or wind turbines in various regions, allow more areas to access reliable and affordable energy. This increase in energy supply helps address energy inequality by providing basic energy services like lighting, heating, and cooking to regions that previously faced energy shortages [52]. Moreover, the decreasing costs of low-carbon energy sources have made it more affordable for a larger population. This reduction in costs reduces the energy burden on individuals, making energy services more accessible [53]. By ensuring a reliable and affordable energy supply, LET can help narrow the energy gap between urban and rural areas and different regions, thereby improving the overall quality of life and promoting social equity.

Hypothesis 2. LET plays a crucial role in reducing urban-rural energy inequality by enhancing energy service accessibility.

3.3. *The mediating effect of industrial structure upgrading*

LET stimulates the growth and utilization of renewable energy, leading to the rapid development of associated industries [54]. As a result, the traditional fossil fuel industry may experience a decline, while clean energy sectors such as solar, wind, and hydropower are poised for significant growth. This process necessitates the upgrading and restructuring of industrial frameworks. When industrial structures are upgraded, new industries and technologies are introduced, thereby creating numerous employment opportunities [55]. The shift from traditional energy industries to low-carbon energy industries can foster the creation of green jobs, allowing more individuals to access sustainable sources of income. Furthermore, the restructuring of industrial sectors, particularly the advancement of low-carbon energy industries, can facilitate sustainable energy development [56]. By reducing reliance on finite resources, this transition helps mitigate the strain on limited resources and offers enhanced access to clean and dependable energy supplies. Consequently, it contributes to alleviating urban-rural energy inequality. Overall, LET not only drives economic and industrial restructuring but also has wide-ranging social and environmental benefits. It promotes the growth of green jobs, ensures sustainable energy development, reduces resource demands, and enhances access to clean and reliable energy sources.

Hypothesis 3. LET reduces urban-rural energy inequality by promoting industrial structure upgrading.

The specific impact mechanisms are depicted in Fig. 2.

3.4. *Literature gaps*

According to the analyses presented in Section 2.1 and Section 2.2, certain research gaps exist in the field of LET. First, although some scholars have studied some of the impacts of energy transition on energy inequality, however, no scholars have studied China as an example, especially exploring the impacts on energy inequality between urban and rural areas in China. Understanding the relationship between LET and urban-rural energy inequality is critical in formulating targeted policies to alleviate energy inequality. Second, there is insufficient research on the specific ways in which China's urban-rural energy inequality is affected by LET. This is particularly important for identifying effective strategies to mitigate urban-rural energy inequality through LET. Third, the heterogeneity of China's urban-rural energy inequality caused by LET is often overlooked. Examining regional differences can provide valuable insights for local governments in developing policies to mitigate urban-rural energy inequality.

4. Econometric model and data

4.1. *Variables and data sources*

The objective of our study is to explore and analyze the potential impact of LET on urban-rural energy inequality using a balanced dataset of 30 provinces in China (including 4 municipalities), spanning from 2006 to 2019. It is important to note that our study does not include Tibet, Taiwan, Hong Kong, and Macau, as we are unable to obtain relevant statistical data for these regions. The sample data utilized in this article is primarily obtained from the China Energy Statistical Yearbook and the China Statistical Yearbook [57, 58].

4.1.1. *Dependent variable*

The dependent variable under investigation is urban-rural energy inequality. Referring to Dou et al. [59], the calculation formula used for this study is expressed as follows:

$$EI_{i,t} = E_{UR,i,t} * ln\frac{E_{UR,i,t}}{P_{UR,i,t}} + E_{R,i,t} * ln\frac{E_{R,i,t}}{P_{R,i,t}} \tag{1}$$

Equation (1) is used to calculate urban-rural energy inequality for each province. E_{UR} and P_{UR} denote the share of residential energy

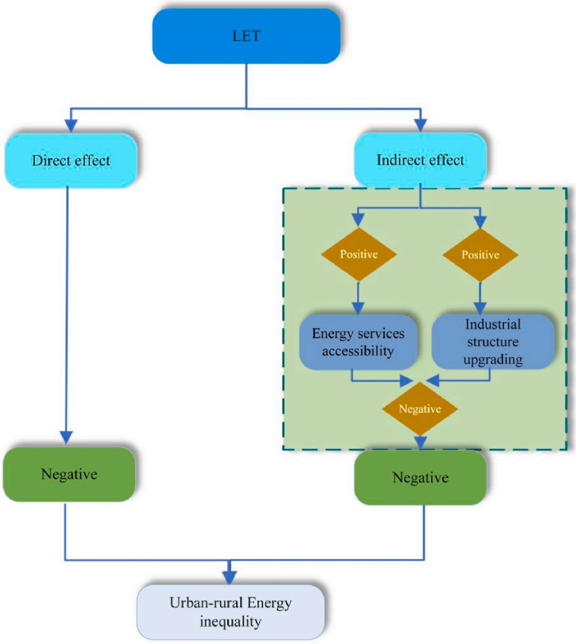

Fig. 1. Spatial-temporal distribution of LET in China for specific years.

consumption and population in urban areas of the province, respectively. Similarly, E_R and P_R denote the share of residential energy consumption and population in rural areas of the province, respectively. The urban-rural energy inequality index utilized in this study varies between 0 and 1. Higher values indicate higher levels of inequality in urban-rural energy consumption among the regions. A value of 0 indicates perfect equality, in which each region consumes an equal share of the total energy consumption, while a value of 1 indicates perfect inequality, in which one region consumes all the energy and the other regions consume none.

To improve the reliability of the empirical estimates, an alternative indicator of urban-rural energy inequality is introduced in this study based on the widely used Gini coefficient, which measures income distribution [60–62]. The calculation of this alternative urban-rural energy inequality indicator is as follows:

$$GINI_{i,t} = \frac{P_{R,i,t} * P_{UR,i,t} * \left|PE_{UR,i,t} - PE_{R,i,t}\right|}{PE_{UR,i,t} + PE_{R,i,t}} \tag{2}$$

In equation (2), the left-hand side term represents the Gini coefficient of energy distribution, denoted as GINI, with subscripts *i* and *t* representing each province and year, respectively. The right-hand side of the equation comprises four components: P_{UR} and P_{R} refer to the proportion of the urban and rural population in each province's total population, while $\mathrm{PE}_{\mathrm{UR}}$ and P_{ER} represent the per capita energy use in urban and rural areas, respectively.

4.1.2. Independent variables

The independent variable is LET. The selected proxy variable for LET is the proportion of renewable energy generation to total electricity generation [63]. This is because renewable energy is regarded as an important component of LET [64]. Compared with traditional fossil fuels, renewable energy has lower carbon emissions and thus is widely viewed as a form of low-carbon energy [65]. Therefore, the proxy variable we use for LET can reflect the extent to which a region or country uses renewable energy in energy production and reflects its efforts in LET.

To gain insights into the progress of LET in China, this study develops a spatial-temporal distribution map to depict the extent of LET across China. As depicted in Fig. 1, the dark-colored areas increase over time, indicating a steady improvement in China's energy transition. When viewed from a regional perspective, the western region of China exhibits a higher degree of LET compared to the central and eastern regions. The western region of China possesses unique advantages in terms of renewable energy resources [66]. These energy sources are relatively cleaner and more environmentally friendly, making the promotion of LET in this region comparatively easier. Moreover, the relatively low levels of industrialization and urbanization in the western region make it easier to develop new energy infrastructure [67]. Moreover, the central and eastern regions of China have more advanced economic development and higher energy demands [68]. Nevertheless, in recent years, the central and eastern regions gradually strengthen their utilization and promotion of renewable energy, including wind and solar energy.

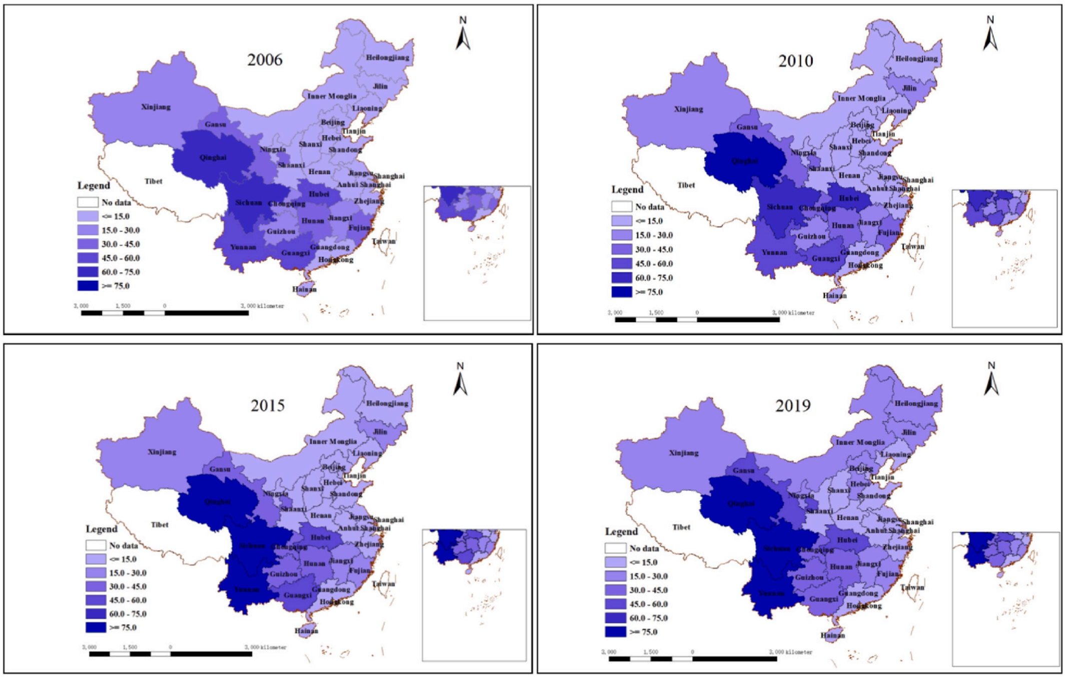

Fig. 2. Mechanism analysis of LET on urban-rural energy inequality.

4.1.3. Control variables

To accurately analyze the impact of LET on urban-rural energy inequality in China, this study selects five control variables to account for potential factors that affect the relationship between the dependent variable and the independent variables. These control variables are as follows.

Economic development level (PGDP), is measured by per capita Gross Domestic Product and is closely related to energy consumption [69]. As the level of economic development increases, people's living standards and energy consumption also increase, which may exacerbate urban-rural energy inequality between high-income and low-income groups.

Urbanization (URB) has a significant impact on energy consumption patterns and distribution [70]. Generally, urban populations have higher energy demands than rural populations and are more industrialized, which may worsen urban-rural energy inequality [71].

Foreign Direct Investment (FDI) is measured as the proportion of the GDP represented by the amount of FDI inflows. FDI has the potential to bring in new technology and management expertise, which can facilitate the enhancement of energy efficiency and the widespread adoption of clean energy technologies [72]. However, FDI tends to invest in regions with better economic development, leading to increased urban-rural energy inequality [73].

The technical level (RD) can be measured by the proportion of R&D investment to GDP. Advanced technological levels have the potential to improve energy efficiency and distribution, which could result in a decrease in urban-rural energy inequality [74]. However, uneven technological levels may exacerbate urban-rural energy inequality as some regions may find it difficult to obtain advanced energy technologies and facilities [75].

The degree of financial development (FIANCE) can be measured by the value added of the financial industry to the GDP. A well-established and sophisticated financial system has the potential to promote the flow and allocation of energy investments, ultimately contributing to the reduction of urban-rural energy inequality. Conversely, an unstable or inequitable financial system may worsen urban-rural energy inequality [76].

4.1.4. Mediating variables

Energy service accessibility refers to the availability of reliable energy services for people in a specific region [77]. Referring to Zhao et al. [78], this article aims to measure energy service accessibility in China from two perspectives: energy consumption and energy supply. The energy consumption aspect is represented by per capita annual electricity consumption and per capita natural gas consumption, while the energy supply aspect is indicated by urban natural gas penetration rate and per capita natural gas supply. These specific indicators are presented in Table 1. The detailed calculation process is provided in the appendix.

To construct a comprehensive index for measuring energy service accessibility, it is essential to use an effective method. In this study, we adopt the improved entropy method (IEM) to measure energy service accessibility. IEM enables us to assign different weights to each indicator while considering their distinct attributes, allowing for a more accurate and precise measurement [79].

Industrial structure upgrading refers to the adjustment and change of the proportion and structure of various industries in the economic system to adapt to the needs of economic development and achieve improvements in the quality of economic growth. In this article, the ratio between the tertiary industry and the secondary industry is used to represent industrial structure upgrading [80].

According to the available data, the following are the observed values, maximum values, minimum values, central trends (means), and discrete trends (standard deviations) for all variables listed in Table 2.

4.2. Econometric model

The objective of this article is to examine the potential influence of LET on urban-rural energy inequality, which is a crucial concern in the worldwide energy transition. However, the dynamic lag effect of the dependent variable could result in biased estimates when using traditional ordinary least squares regression [81]. To tackle this problem, some scholars suggest employing the generalized method of moments estimation (GMM). The GMM estimation comprises two methods, the differential GMM (DIF-GMM) and system GMM (SYS-GMM). When the size of the cross-sectional unit is much larger than the time unit, SYS-GMM may be more effective and accurate than DIF-GMM [82]. Therefore, we employ SYS-GMM as the benchmark regression method. To obtain reliable and robust estimation results, we also include additional variables in the study. The proposed framework is as follows:

$$\ln EI_{i,t} = \alpha_0 + \alpha_1 \ln EI_{i,t-1} + \alpha_2 \ln LET_{i,t} + \sum_{k=3}^{7} \alpha_k \ln M_{i,t} + \varepsilon_{i,t} \tag{3}$$

The symbol α_0 represents the intercept term, $\alpha_1 - \alpha_6$ denotes the estimated parameters, and $\varepsilon_{i,t}$ indicates the random disturbance term. The vector M includes the control variables.

Table 1
Indicator system for measuring energy service accessibility.

Category	Measurement	property
Energy consumption	Per capita electricity consumption	positive
	Per capita natural gas consumption	positive
Energy supply	Urban natural gas penetration rate	positive
	Per capita natural gas supply in cities	positive

Table 2
Descriptive statistics.

Variable	Mean	Std. Dev.	Min	Max
lnEI	0.063	0.227	−0.919	0.386
lnLET	2.324	1.538	−3.721	4.521
$lnLET_2$	2.978	1.161	−2.307	4.473
lnGINI	−0.032	0.012	−0.127	−0.016
lnPGDP	1.676	0.356	0.804	2.601
lnURB	3.980	0.244	3.313	4.495
lnFDI	0.687	1.931	−6.270	4.066
lnRD	0.208	0.626	−1.609	1.842
lnFIANCE	−2.685	0.516	−4.138	−1.284
lnACCESS	−2.167	0.974	−6.036	−0.159
lnIND	−10.717	0.408	−11.567	−9.49

5. Estimation results and analysis

5.1. Benchmark regression

The estimation results in Table 3 are validated by the Arellano-Bond (A-B) and Hansen tests, indicating the reliability of the SYS-GMM estimation method [83]. Based on empirical evidence, a 1 % increase in LET lead to a reduction of approximately 0.045 % in energy inequality. This suggests that LET is an effective measure to address energy inequality in China. Traditional energy sources, such as coal, are mostly concentrated in specific regions, while low-carbon energy sources can be developed and utilized in many more regions [84]. As a result, low-carbon energy can bring about more decentralized economic benefits and employment opportunities, promoting regional economic development and enhancing consumer welfare [85,86]. Furthermore, the extraction and use of traditional energy sources can result in environmental pollution and health issues, which can have a more severe impact on poor regions and residents. In contrast, LET can mitigate pollution and health problems, thus improving people's quality of life [87]. Additionally, LET can lead to lower energy prices, providing consumers with more equal access to energy services. As low-carbon energy technology continues to develop and deployment costs decrease, the price of low-carbon energy is gradually becoming more affordable, making it more accessible to a wider population [88]. This can help more people access affordable energy and promote sustainable economic growth.

From a controlled variable perspective, the aspects of economic development, foreign direct investment, and technological level have a negative impact on urban-rural energy inequality. Economic development can provide more energy services to energy-poor areas. Governments and enterprises invest more resources and funds into energy supply to meet people's needs, thus reducing urban-rural energy inequality [89]. Increasing FDI can bring more technology and capital, improve the competitiveness of China's energy industry, and promote the optimization and fairness of energy resource allocation [90]. Technological progress can make energy production and utilization more efficient and environmentally friendly, allowing more people to access clean and efficient energy and mitigating energy-inequality issues [91].

Financial development and urbanization can exacerbate urban-rural energy inequalities. The development of financial markets could bring about more capital and investment, which causes an imbalance in energy supply and prevents some regions or social groups from accessing sufficient energy services [92]. Urbanization might also exacerbate urban-rural energy inequality issues. As urbanization accelerates, energy demand and consumption face a corresponding increase in urban areas. However, the uneven distribution of energy between urban and rural areas could lead to some impoverished regions or populations being unable to access

Table 3
Benchmark regression and robustness results.

Variable	*lnEI*	*lnEI*	*lnEI*	*lnGINI*	*lnEI*
	SYS-GMM	DIF-GMM	lnLET_2	lnGINI	Selected samples
$lnEI_{i,t-1}$	0.468*** (5.66)	0.439*** (11.61)	0.201*** (9.56)		0.507*** (6.21)
$lnGINI_{i,t-1}$				0.529*** (20.14)	
lnLET	−0.045** (−2.01)	−0.018* (−1.72)		−0.001** (−1.99)	−0.058* (−1.91)
$lnLET_2$			−0.011** (−2.20)		
lnPGDP	−0.216* (−1.92)	−0.583*** (−3.72)	−0.107** (−2.06)	0.016*** (4.66)	−0.277* (−1.79)
lnURB	1.156*** (2.99)	0.598*** (4.14)	0.576*** (3.73)	0.007 (0.88)	0.872** (2.04)
lnFDI	−0.059 (−1.30)	−0.027 (−1.13)	−0.028*** (-3.73)	−0.004*** (2.76)	−0.081** (−2.54)
lnRD	−0.352** (−2.05)	0.266*** (3.21)	−0.144** (-2.23)	−0.030** (−7.39)	−0.144 (−1.11)
lnFIANCE	0.014 (−0.13)	0.147 (1.09)	0.023 (0.77)	0.005** (2.32)	0.016 (0.12)
_cons	−3.959** (−2.36)		−1.914*** (−2.96)	−0.047 (−1.56)	−2.715 (−1.49)
AR (1)	0.005	0.001	0.003	0.047	0.004
AR (2)	0.237	0.148	0.209	0.737	0.141
Hansen test	0.522	0.517	0.830	0.550	0.988

Notes: ***, **, *Indicates statistical significance at 1 %, 5 %, and 10 % levels, respectively; the value in parentheses represent z-statistics.

sufficient energy services [93].

5.2. Robustness checks

5.2.1. Replacing methods

To ensure the reliability of the benchmark results, the DIF-GMM method is employed as an alternative estimation technique in this study [94]. The results of the autocorrelation test indicate that the first-order autoregressive term (AR (1)) is significant at the 1 % significance level, while the second-order autoregressive term (AR (2)) is not significant. The results of the Hansen test are greater than 0.1, suggesting that the technique is appropriate for this study. Additionally, the consistency between the DIF-GMM results and the benchmark results demonstrates the robustness and reliability of the regression results.

5.2.2. Replacing independent variables

We replace the original independent variable with the percentage of renewable energy installed capacity (ET_2) [95]. The presented estimation results in Table 3 successfully pass both the Arellano-Bond (A-B) and Hansen tests, which suggests that the results are statistically significant and reliable. The correlation between the percentage of renewable energy installed capacity and energy inequality is consistent with the benchmark survey results. These findings provide evidence that LET effectively alleviates energy inequality in China.

5.2.3. Replacing dependent variables

The fourth column of Table 3 displays the outcomes obtained by replacing the urban-rural energy inequality substitute variable, and the findings are found to be in line with the fundamental regression results. This discovery underscores the robustness and dependability of the outcomes.

5.2.4. Removing the special samples

As there are significant differences in politics, economy, and culture between municipalities and ordinary provincial-level administrative regions in China, we remove the sample of municipalities and only retain the sample of ordinary provincial-level administrative regions for regression analysis [96,97]. As depicted in the fifth column of Table 3, the results continue to suggest that LET can efficiently alleviate China's urban-rural energy inequality problem.

In general, the results of this study provide support for the proposition that LET can be an effective solution for mitigating China's urban-rural energy inequality issue.

6. Further discussion

6.1. Mediating effect analysis

6.1.1. The role of energy service accessibility

We delve deeper into how the LET affects urban-rural energy inequality through energy service accessibility. The goal is to illuminate the underlying mechanism of the impact of LET on energy inequality by examining the mediating role of energy service accessibility (*ACCESS*). To achieve this, we use a mediation effect model in the empirical estimation. The model is constructed as follows:

Table 4
Results of mediating effects.

Variables	*lnEI*	*lnACCESS*	*lnEI*	*lnIND*	*lnEI*
	(1)	(2)	(3)	(4)	(5)
$lnEI_{i,t-1}$	0.468*** (5.66)		0.533*** (7.12)		0.445*** (13.73)
$lnACCESS_{i,t-1}$		1.010*** (40.30)			
$lnIND_{i,t-1}$				0.805*** (44.85)	
lnLET	−0.045** (−2.01)	0.028*** (3.35)	−0.043** (−2.19)	0.009* (1.76)	−0.038*** (−2.66)
lnPGDP	−0.216* (−1.92)	−0.215*** (−4.36)	−0.215** (−1.76)	−0.390*** (−6.54)	−0.356*** (−3.29)
lnURB	1.156*** (2.99)	0.102* (1.71)	1.323*** (3.17)	0.104 (1.14)	1.421*** (4.96)
lnFDI	−0.059 (−1.30)	0.014*** (3.07)	−0.067*** (−1.92)	−0.009 (1.41)	−0.074*** (−3.16)
lnRD	−0.352** (−2.05)	0.042** (2.09)	−0.360*** (−2.83)	0.179*** (5.84)	−0.357*** (−2.92)
lnFIANCE	0.014 (−0.13)	−0.066*** (−2.89)	0.027 (0.26)	0.258*** (11.01)	0.058 (0.59)
lnACCESS			−0.084** (−1.69)		
lnIND					−0.119* (−1.66)
_cons	−3.959** (−2.36)	−0.150 (−0.52)	−4.750*** (−2.62)	0.912** (2.52)	−4.670*** (−3.59)
AR (1)	0.005	0.017	0.003	0.015	0.002
AR (2)	0.237	0.561	0.245	0.692	0.220
Hansen test	0.522	0.180	0.793	0.240	0.530

Note: ***, **, *Indicates statistical significance at 1 %, 5 %, and 10 % levels, respectively; the value in parentheses represent z-statistics.

$$ln\,ACCESS_{i,t} = \theta_0 + \theta_1\, ln\,ACCESS_{i,t-1} + \theta_2\, ln\,LET_{i,t} + \sum_{k=3}^{7} \theta_k\, ln\,M_{i,t} + \varepsilon_{i,t} \tag{4}$$

$$ln\,EI_{i,t} = \delta_0 + \delta_1\, ln\,EI_{i,t-1} + \delta_2\, ln\,LET_{i,t} + \delta_3\, ln\,ACCESS_{i,t} + \sum_{k=4}^{8} \delta_k\, ln\,M_{i,t} + \varepsilon_{i,t} \tag{5}$$

where *ACCESS* is the mediating variable and θ_2 is the coefficients of LET on energy service accessibility. The coefficient δ_3 is the coefficients of the energy service accessibility on urban-rural energy inequality.

Table 4 presents the mediating role of energy service accessibility in the impact of LET on urban-rural energy inequality, as depicted in columns (1) through (3). Column (1) illustrates the effect of LET on urban-rural energy inequality. Column (2) indicates that a 1 % increase in LET corresponds to approximately a 0.028 % increase in energy service accessibility. This suggests a positive impact of LET on the accessibility of energy services in China. Column (3) shows that for every 1 % increase in energy service accessibility, urban-rural energy inequality decreases by 0.043 %. The research findings underscore both the direct and indirect effects of LET on urban-rural energy inequality, emphasizing the pivotal role of energy service accessibility as a conduit through which LET alleviates energy inequality between China's urban and rural areas.

One important aspect of China's LET is the promotion of distributed renewable energy use, and China makes significant progress in this regard [98,99]. Distributed renewable energy refers to the installation of solar photovoltaic panels, wind power generation equipment, and other energy facilities in communities, enterprises, households, etc., to meet local energy needs. Compared to traditional large-governance centralized power stations, distributed renewable energy is more flexible, efficient, and environmentally friendly [100]. The Chinese government formulates a series of policies to incentivize individuals and organizations, including households and enterprises, to invest in and install distributed renewable energy facilities like solar photovoltaic panels [101,102]. These policies include tax incentives, electricity price subsidies, and power purchase policies. Furthermore, the Chinese government provides substantial financial support to accelerate the promotion and development of distributed renewable energy. These policies and measures greatly increase the accessibility of energy services [103]. Through distributed renewable energy, people can obtain clean, sustainable energy more flexibly without relying entirely on traditional centralized power stations, which is particularly important in remote areas and for developing countries' energy services accessibility [104].

Significant advancements in improving access to energy services are crucial in reducing urban-rural energy inequality [105,106]. The Chinese government has devoted make significant efforts to promoting the electrification of rural areas by investing in the development of power grids and photovoltaic power generation. As a result, rural areas become more accessible and affordable in terms of electricity resources, which effectively reduce the energy gap between urban and rural areas [107,108]. Moreover, China continuously strengthens the reliability and stability of urban energy supply in the urbanization process, thereby addressing the energy needs of urban residents [109]. China also promotes clean energy, actively developing renewable energy, reducing dependence on traditional fossil fuels, and reducing competition for energy resources, which is conducive to improving energy inequality [110].

6.1.2. *The role of industrial structure upgrading*

In addition to the aforementioned factors, we also examine the mediating role of industrial structure upgrading (*IND*) in the impact of LET on urban-rural energy inequality. The mediating effect model is constructed as follows:

$$ln\,IND_{i,t} = \beta_0 + \beta_1\, ln\,IND_{i,t-1} + \beta_2\, ln\,LET_{i,t} + \sum_{k=3}^{7} \beta_k\, ln\,M_{i,t} + \varepsilon_{i,t} \tag{6}$$

$$ln\,EI_{i,t} = \gamma_0 + \gamma_1\, ln\,EI_{i,t-1} + \gamma_2\, ln\,LET_{i,t} + \gamma_3\, ln\,IND_{i,t} + \sum_{k=4}^{8} \delta_k\, ln\,M_{i,t} + \varepsilon_{i,t} \tag{7}$$

where *IND* is the industrial structure upgrading and β_2 is the coefficients of LET on energy service accessibility. The coefficient γ_3 is the coefficients of the industrial structure upgrading on urban-rural energy inequality.

The results from Table 4 (columns 1, 4, and 5) demonstrate the estimated mediating effect of LET through industrial structural upgrading on energy inequality. Similarly, column (1) represents the effect of LET on urban-rural energy inequality. The findings in column (4) indicate that for every 1 % increase in LET, there is an approximately 0.805 % increase in industrial structural upgrading. This suggests a positive correlation between LET and industrial structural upgrading in China. Furthermore, the results in column (5) demonstrate that for every 1 % increase in industrial structural upgrading, urban-rural energy inequality decreases by approximately 0.119 %. This implies that the upgrading of the industrial structure plays a significant role in reducing urban-rural energy inequality in China.

The mechanism behind this relationship can be explained by the fact that LET can promote the development of low energy intensity, high resource efficiency, and environmentally friendly industries. LET reduces the overall demand for energy by promoting energy-efficient technologies, optimizing production processes, and adopting renewable energy sources. By promoting the development of industries with lower energy intensity, LET helps to alleviate urban-rural energy inequality. These industries consume less energy per unit of output, reducing the disparities in energy access between different regions and socio-economic groups. As a result, communities that previously had limited access to energy resources can benefit from the more efficient utilization of energy in these upgraded industries.

Moreover, industrial structure upgrading brings about additional benefits that contribute to the reduction of urban-rural energy inequality. The development of industries with higher resource efficiency means that resources are utilized more effectively, reducing waste, and optimizing resource allocation. This efficiency leads to cost savings, which can then be reinvested in improving energy infrastructure and expanding energy access to underserved areas. Furthermore, the upgrading of the industrial structure creates new employment opportunities and stimulates economic growth. The transition to cleaner and more sustainable industries requires skilled labor and technological innovation, leading to job creation and economic development. This economic growth contributes to a more inclusive and balanced distribution of wealth and resources, which in turn reduces urban-rural energy inequality.

6.2. Heterogeneity analysis

6.2.1. Differences between high-EI and low-EI

To analyze the potential relationship of LET on urban-rural energy inequality across various regions, we compute the mean urban-rural energy inequality index and categorize regions with an index higher than the mean as high-urban-rural energy inequality regions (High-EI) and those with an index lower than the mean as low-urban-rural energy inequality regions (Low-EI). Our findings indicate that a 1 % increase in LET is associated with a reduction in urban-rural energy inequality by 0.027 % in low-EI. In contrast, in High-EI, this change is displayed as 0.219 %. These findings suggest that LET is particularly effective in regions with severe urban-rural energy inequality. This observation is significant as it highlights the potential of LET to improve urban-rural energy inequality in these regions.

The higher reduction in urban-rural energy inequality in High-EI compared to Low-EI could be attributed to several factors. First, regions with high urban-rural energy inequality tend to have a larger share of their population living in energy poverty [111]. This means that a LET could help provide access to affordable and clean energy to a larger proportion of the population in these regions. Second, High-EI often coincides with a greater reliance on fossil fuels, which can result in higher emissions and adverse environmental effects. LET can reduce dependence on fossil fuels and lead to a more environmentally friendly energy system [112].

6.2.2. Differences between high-LET and low-LET

To assess the effect of LET on urban-rural energy inequality and identify potential regional variations in the level of transition, we compute the average LET index. We classify regions with an index higher than the average as high low-carbon energy transition regions (High-LET) and those with an index lower than the average as low-carbon energy transition regions (Low-LET). Table 5 demonstrates that a 1 % increase in LET can reduce urban-rural energy inequality in the High-ET category, with a reduction of 0.836 %, compared to only 0.041 % in the Low-ET category. These findings suggest that the effectiveness of LET in reducing urban-rural energy inequality varies depending on the degree of transition, with more significant reductions in urban-rural energy inequality observed in regions with higher levels of LET.

Several factors could contribute to the regional variations. High-LET are likely to have greater access to clean energy sources and therefore experience a decrease in energy inequality due to a reduction in the cost of energy. Moreover, the Low-LET may place a greater emphasis on energy efficiency and conservation, which could be contributing to the observed reduction in urban-rural energy inequality [113]. On the other hand, Low-LET may have less access to clean energy sources and may be more reliant on fossil fuels, resulting in higher energy costs and greater urban-rural energy inequality [114].

7. Conclusions and policy implications

7.1. Conclusions

To investigate the dynamic relationship of LET on urban-rural energy inequality, an empirical study is carried out using a panel dataset comprising Chinese 30 provinces between 2006 and 2019. We use SYS-GMM as the benchmark method to determine the

Table 5
Heterogeneous results.

Dependent variable	*lnEI*	*lnEI*	*lnEI*	*lnEI*
	Low-EI	High-EI	Low-LET	High-LET
lnEI$_{i,t-1}$	0.365*** (12.78)	0.335* (1.75)	0.550*** (9.74)	1.800*** (4.62)
lnLET	−0.027*** (−2.87)	−0.219* (−1.74)	−0.041** (−2.52)	−0.836* (−1.90)
lnPGDP	−0.206* (−1.76)	−0.383 (−0.70)	−0.185 (−1.26)	1.370 (1.57)
lnURB	1.017*** (3.70)	0.552 (0.97)	0.825* (1.66)	−1.558 (−0.84)
lnFDI	−0.147*** (−4.79)	−0.115** (−2.00)	−0.048 (−1.25)	−0.298*** (−2.62)
lnRD	0.161 (1.22)	−0.002 (−0.01)	−0.271*** (−2.87)	−0.856 (−1.44)
lnFIANCE	−0.162* (−1.80)	−0.106 (−0.27)	0.110 (0.62)	−0.095 (−0.15)
_cons	−4.041*** (−3.10)	−0.964 (−0.28)	−2.484 (−1.00)	6.566 (0.71)
AR (1)	0.003	0.000	0.008	0.002
AR (2)	0.161	0.222	0.864	0.176
Hansen test	0.881	1.000	1.000	0.998

Note: ***, **, *Indicates statistical significance at 1 %, 5 %, and 10 % levels, respectively; the value in parentheses represent z-statistic.

relationship between LET and energy inequality. Furthermore, a robustness check is conducted on the benchmark results to ensure their reliability. Subsequently, the study delves into the specific mechanisms and heterogeneity of LET on urban-rural energy inequality, leading to several key findings.

First, from 2006 to 2019, China's LET shows a distinct upward trend, consistent with the predictions of many scholars. Furthermore, the spatial distribution of China's LET reveals a concentration of higher levels in the western regions, while the eastern and central regions are characterized by lower levels. Second, the primary results of this study indicate that LET can significantly ameliorate China's urban-rural energy inequality problem. More specifically, a 1 % increase in LET corresponds to a 0.045 % decrease in urban-rural energy inequality. Subsequently, the mechanism analysis demonstrates that enhancing the accessibility of energy services and industrial structural upgrading are effective approaches for LET to address urban-rural energy inequality. Finally, a heterogeneity analysis suggests that the influence of LET on urban-rural energy inequality is more pronounced in provinces with higher initial levels of energy inequality and greater levels of LET. This further verifies the effectiveness of LET.

7.2. Policy implications

Based on the findings presented in this article, we suggest the following policy implications:

First, the Chinese government should prioritize the development of renewable energy as an important task and take proactive measures to promote its growth. The government can attract more investors and businesses to participate in renewable energy projects by providing subsidies and tax incentives. These measures can alleviate the burden on businesses, reduce investment risks, and create a favorable environment for the development of the renewable energy industry. Additionally, the government should increase investment in research and development of renewable energy. By funding research institutions and companies to carry out innovative projects, breakthroughs, and improvements in renewable energy technologies can be achieved. This includes enhancing the efficiency of technologies such as solar cells and wind turbines, reducing production costs, and making renewable energy more competitive in the market.

Second, the government should improve the accessibility of energy services to reduce energy inequality. Investing in energy infrastructure in underdeveloped regions can promote equitable access to reliable energy services across all regions. Financial support to low-income households also ensures that they can afford energy services. Promoting energy efficiency and conservation measures further reduce energy consumption and improves energy affordability. In addition, The government can increase its efforts in education and training in the field of renewable energy, providing relevant knowledge and skills training to cultivate professionals and technical workers. This helps to enhance employment opportunities and provide more people with the chance to participate in the clean energy industry.

Finally, to ensure the effectiveness and sustainability of the LET, policies and plans should be tailored to the specific needs and characteristics of different regions. Targeted support should be provided to provinces with high levels of energy inequality and low levels of LET, including financial incentives, policy support, and technical assistance. This can facilitate greater participation and benefits from LET across a wider range of regions.

This study provides compelling evidence of the link between energy transition and energy inequality. Nevertheless, our paper still has the following limitations. One of the constraints is that we only consider the provincial level, and future research could delve further into the relationship between these two factors at the prefectural level. In addition, further exploration of mechanisms could investigate whether energy transition can affect energy inequality through other pathways.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Disclosure statement

No potential conflict of interest was reported by the authors.

CRediT authorship contribution statement

Chenzhou Sun: Writing – original draft, Software, Formal analysis, Data curation. **Shurui Sun:** Resources, Methodology, Conceptualization. **Xiaolu Yue:** Supervision, Methodology, Conceptualization.

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.

Appendix

Based on the differences among indicators and between dimensions, we used the improved entropy method to make a comprehensive measurement of energy service accessibility. The specific measurement steps are as follows:

(1) *Standardization of individual variables*

We define ij to denote the j indicator of the i province and obtain the matrix of the indicator system. Since the units are different among the indicators, we standardize each indicator.

For the positive indexes, the standardization process is as follows:

$$x'_{ij} = \frac{x_{ij} - \min(x_{1j}, \cdots, x_{nj})}{\max(x_{1j}, \cdots, x_{nj}) - \min(x_{1j}, \cdots, x_{nj})} \tag{8}$$

For negative indexes, the normalization process is as follows:

$$x'_{ij} = \frac{\max(x_{1j}, \cdots, x_{nj}) - x_{ij}}{\max(x_{1j}, \cdots, x_{nj}) - \min(x_{1j}, \cdots, x_{nj})} \tag{9}$$

where x'_{ij} denotes the j indicator of the i city after standardization.

(2) *Entropy calculation of each indicator*

In this process, we first calculate the ratio of the value of the j indicator of the i city to the so city, i.e., $p_{ij} = x'_{ij} / \sum_{i=1}^{n} x'_{ij}$ Based on the following equation, we find the entropy value of the j indicator:

$$e_j = -k \sum_{i=1}^{n} p_{ij} \ln(p_{ij}) \tag{10}$$

where $k = 1/ln(n) > 0$; $e_j \geq 0$.

(3) *Calculation of the weights of each index*

According to Eq. (3), we obtain the information entropy redundancy of the indicators by subtracting from the entropy in Eq. (1), $d_j = 1 - e_j$. The weight of each indicator can be calculated using Eq. (3), as follows:

$$w_j = \frac{d_j}{\sum_{j=1}^{m} d_j} \tag{11}$$

$$EP_i = \sum_{j=1}^{m} w_j \cdot p_{ij} \tag{12}$$

As a result, we obtain the energy service accessibility composite index. which is the explanatory variable of this study.

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