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Renewable energy development efficiency: Spatial dynamic evolution and influencing factors

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Abstract

This paper aims to estimate the spatial dynamic evolution of renewable energy development efficiency and justify the dimensions that impact renewable energy development efficiency. The study applies the following methods: the ultra-efficient slack-based model (SBM) (to measure the efficiency of renewable energy development); the Dagum-Gini coefficient decomposition process (to measure the interregional differences in the development of renewable energy efficiency); nuclear density estimation (to measure the dynamic distribution); the Markov model (to forecast renewable energy development efficiency); and the Tobit model (to justify the influencing factors of renewable energy development efficiency). The empirical findings confirm that the overall regional gaps in renewable energy development efficiency in China are widening year by year. The average value of renewable energy development efficiency increased from 0.932 in 2006 to 1.078 in 2020. The mean Gini coefficient increased gradually from 0.028 in 2006 to 0.174, with mean differences exceeding the average growth trend after 2011 and slowly decreasing post-2016. There is polarization in the eastern region, while there is no polarization in the northeast. The overall level of renewable energy development efficiency in the middle and western areas is improving and showing a trend of absolute difference narrowing. In

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addition, economic development, green finance, technological progress, urbanization rate, and economic openness are conducive to renewable energy development efficiency, and renewable energy development efficiency is in a rapid development trend. Considering the findings, China should implement targeted regional development strategies, enhance green finance mechanisms, promote technological innovation, and align urbanization policies with renewable energy goals to reduce regional disparities and accelerate sustainable renewable energy development.

KEYWORDS
dynamic distribution, interval difference, Markov and Tobit model, renewable energy efficiency

1 | INTRODUCTION

The rapid growth of the world economy, globalization and intensification of production have provoked a snowballing increase in energy consumption and environmental degradation (Hussain et al., 2021; Li, Xin, et al., 2022; Prokopenko et al., 2023; Saługa et al., 2021; Sotnyk et al., 2021; Szczepańska-Woszczyna & Gatnar, 2022). In particular, the burning of fossil fuels has caused environmental emissions and climate change (Elahi, Khalid, & Zhang, 2022; Elahi, Khalid, Zhang, & Lirong, 2022). As a country with rapid economic growth, China faces multiple challenges in energy production and consumption, especially the pressure of rapid population growth on energy demand, which leads to insufficient energy supply. Despite rapid growth in energy consumption and a heavy dependence on coal, countries around the world face energy shortages and other problems. In addition, China has been a source of various environmental issues, such as air and water contamination. Green, clean, and renewable energy is tackling the deteriorating environment while maintaining economic growth and attracting the attention of more countries (Prokopenko et al., 2023; Sotnyk et al., 2021). Clean and renewable energy is considered one of the main ways governments can lessen their ecological footprint, especially in developing and using renewable energy (Dźwigoł, 2021; Dzwigol et al., 2021; Statistical Review of World Energy–BP, 2021; Zhang et al., 2017).

Renewable energy sources refer to recyclable and renewable energy sources, mainly including solar, biological, wind, water, ocean, hydrogen, and nuclear energy. China's renewable energy share in the entire energy combination is still reasonably low (less than a quarter), as crude oil and coal remain the energy source of the dominant Chinese people and one of the infamous culprits of air pollution (Statistical Review of World Energy–BP, 2021). From a public health perspective and from a justifiable expansion perspective, China has become an active promoter of global renewable energy development and a producer and investor in renewable energy, especially solar energy. China consumes the largest amount of coal globally, while its consumption of renewable energy is relatively low (Statistical Review of World Energy–BP, 2021). With the goal of “carbon peak, carbon neutral”, various countries advocate for a green and low-carbon transition to renewable energy as the primary energy source of power formation. The employment of renewable energy in China has achieved long-term development. The installed capacity for renewable energy is 1 billion KWH (Statistical Review of World Energy–BP, 2021). Renewable energy has further promoted the sustainable development of China and has become China's primary energy source for power creation. With the consumption of renewable energy, China's solar power generation has doubled to more than 100 kilowatt hours, making wind energy China's second most important renewable energy source. Between 2014 and 2018, the cumulative volume of allied wind power increased to nearly 200 million kilowatts (Statistical Review of World Energy–BP, 2021). China has many water resources, and hydropower also plays an important role, from traditional (i.e., fossil) fuels to the transition of renewable fuels. Domestic hydropower consumption tripled to more than 250 million tons of equivalent oil during 2004–2017 (Statistical Review of World Energy–BP, 2021). Studying the efficiency, range modifications, dynamic distribution, and inducing features of China's energy development can better analyse existing problems and further realize the sustainable development of China's renewable energy. In this case, this study aims to analyse the factors influencing renewable energy in China from the aspects of economy, green finance, science and technology, urbanization, industrial structure, and economic openness. The object of investigation is China for 2006–2020. China is the major global player in renewable energy, its diverse geography, significant policy relevance, and the substantial environmental and economic impact of its renewable energy sector. The availability of comprehensive data further enhances the suitability of China as a case study for understanding regional variations and factors influencing renewable energy development efficiency.

Thus, the following research question will be investigated in this study: (1) How can renewable energy development efficiency in China be accurately estimated, considering undesirable output and model heterogeneity? (2) What are the interregional differences in the development of renewable energy efficiency in China, and how can they be measured effectively? (3) What are the dynamic distribution patterns of renewable energy development in China, and how can they be explored using nuclear density estimation? (4) What factors influence renewable energy development in China, and how can they be analysed using space econometric models? (5) How do the developed approaches contribute to a better understanding of China's expansion of renewable energy efficiency sources and inform sustainable energy policies?

The paper makes a significant contribution to the literature by examining the determinants that impact renewable energy development efficiency and assessing its spatial dynamic evolution. It utilizes the ultraefficient slack-based model (SBM) to estimate the efficiency of renewable energy development, providing a methodology to account for undesirable output and model heterogeneity. Furthermore, the paper employs the Dagum-Gini coefficient decomposition process to analyse variations in renewable energy efficiency across regions, shedding light on regional disparities. The study also utilizes nuclear density estimation to explore the dynamic distribution of renewable energy, offering insights into evolving geographical patterns. Additionally, the research conducts a comprehensive examination of the factors influencing renewable energy through the use of space econometric models, providing a thorough understanding of efficiency determinants.

The paper has the following structure: literature review–exploring the theoretical background on approaches to estimate renewable energy development efficiency and impactful dimensions; materials and methods–describing methods and data sources to achieve the paper's aim; results–explaining findings of investigation; discussion–comparison analysis of the obtained findings with the previous studies; conclusions–describing the core results, policy implications, limitations and directions for further investigations.

2 | LITERATURE REVIEW

As the world's leading energy producer and renewable energy user (Jiao, 2021), China has also become the world's largest renewable energy market. Currently, the mechanism for cost recovery and share of renewable energy development efficiency in China is not reasonable (Zhou et al., 2022), and the development of energy technology is difficult to accurately predict (Liao & Xiang, 2021). With the aim of “carbon topmost and neutral”, China must achieve large-scale, high-proportion, market-oriented, and high-quality development goals for renewable energy. China must improve the existing renewable energy policy scheme (Yu et al., 2022) to cope with its uncertainty of development (Peidong et al., 2009).

Related studies on energy efficiency measurement were initially used for energy efficiency measures in the radial DEA model (Cai & Cheng, 2022; Makridou et al., 2016). Radial DEA models have disadvantages. Inefficient parts of input and output that can only be measured proportionally. The later-developed SBM model fully considers the input, output, and undesirable output to achieve a more efficient energy efficiency measurement (Li &

Hu, 2012). As research questions have progressed, the SBM-DEA model has been widely used (Zhou et al., 2006) and improved (Zha et al., 2016); heterogeneity, randomness, and dynamics were included in the consideration framework, making the measurement results more consistent with reality Zhang et al., 2015; Amowine et al., 2020). The drivers of renewable energy are multidimensional and dynamic, mainly driven by government policies in the early stage (Lan, 2021; Tang et al., 2022) and in the later stage, significantly affected by financial development (Ma & Huang, 2022). Xia and Wang (2018) used the BP method and the LMDI decomposition model to decompose the energy intensity to study the influence of different factors on energy development. There exists a nonlinear "U-shaped" connection between renewable energy investment and the green institutional environment index (Yang et al., 2019) and a nonlinear relationship between green credit and green development at different levels of renewable energy investment (Chen & Deng, 2020). There are also studies on renewable energy from various industries. They study the electricity market, balance electricity price subsidies, and improve the market electricity price mechanism (Meng et al., 2021). Renewable energy hydrogen production is the inevitable choice to adhere to the green and low-carbon development path (Ouyang, 2022).

Several studies (Gavkalova et al., 2022; Kharazishvili et al., 2020, 2021; Kotowicz et al., 2022) have examined the interconnections and interdependencies among core dimensions and renewable energy efficiency in the context of sustainable development and the transition to a low-carbon economy. Renewable energy and green finance are closely linked, as the development and deployment of renewable energy technologies require substantial investments. Green finance mechanisms, such as sustainable investment funds, carbon markets, and green bonds, provide financial resources for renewable energy projects and help drive their growth (Dźwigol et al., 2019; Miskiewic, 2020; Miśkiewicz et al., 2022; Prokopenko & Miśkiewicz, 2020; Saługa et al., 2020). Past studies (Drożdż et al., 2021; Miśkiewicz, 2021; Miśkiewicz et al., 2021) outline that science and technology play a crucial role in advancing renewable energy solutions. Research and development efforts contribute to improving the efficiency and cost-effectiveness of renewable energy technologies, making them more accessible and competitive (Drożdż et al., 2021; Miśkiewicz, 2021; Szczepańska-Woszczyna et al., 2022). Technological innovations also enable the integration of renewable energy into existing urban infrastructure and industrial processes. Cui et al. (2022), Yang et al. (2016) and Han et al. (2022) justify that urbanization and industrial structure have significant implications for renewable energy adoption. Rapid urbanization increases energy demand, making cities important focal points for renewable energy implementation (Cui et al., 2022; Han et al., 2022; Yang et al., 2016). Urban areas provide opportunities for scaling up renewable energy projects, such as solar panels on rooftops and wind turbines in urban landscapes. Additionally, the industrial structure of a region influences its energy consumption patterns and the feasibility of transitioning to renewable energy sources (Han et al., 2022; Yang et al., 2016). Considering the studies (Cui et al., 2022; Han et al., 2022; Yang et al., 2016), economic openness, including international trade and collaboration, plays a vital role in the exchange of knowledge, technology, and financial resources related to renewable energy. International cooperation can facilitate the transfer of best practices, support capacity building in developing countries, and foster innovation in renewable energy technologies. Woo et al. (2015) employed the Malmquist productivity index to assess the evolving environmental efficiency of renewable energy within OECD countries from 2004 to 2011. Their findings highlight notable variations in the environmental efficiency of renewable energy across the OECD, with OECD America exhibiting the highest average efficiency levels and OECD Europe displaying the greatest standard deviation. Furthermore, the study reveals that the dynamics of efficiency were significantly impacted by the global financial crisis, which originated in the United States. The panel data from 36 countries spanning 2009 to 2018 were analysed by Li, Ji, et al. (2022) to estimate the efficiency of renewable energy power generation (PGE) using the super-efficiency data envelopment analysis (DEA) model and the Malmquist index. They also employed the random forest regression model to explore the determinants of renewable energy PGE in each country, revealing that only 41.67% of countries demonstrated PGE improvement, emphasizing the critical need for advancements in renewable energy technology. Among the eleven factors examined, carbon emissions levels and industrial structure emerged as the most influential, followed by electricity structure, technology level, and economic conditions. Menegaki (2013) employed a combination of DEA and the Malmquist method to assess the renewable energy performance in various European countries. The analysis yielded an average renewable energy efficiency score of 0.892. The findings were emphasized as valuable for monitoring and benchmarking, particularly in relation to the fulfilment of their 2020 renewable energy commitments based on the 2009/28/ED Directive. Similar to Menegaki's investigation (Menegaki, 2013), Gökgöz and Güvercin (2018) utilized DEA and the Malmquist-Luenberger Index to evaluate the effectiveness of renewable energy in specific EU nations during the period from 2004 to 2014. The study's results highlight a growing convergence in renewable energy efficiency within the EU. The authors stress the critical importance of employing total factor productivity techniques and efficiency analyses for evaluating the varying levels of renewable energy efficiency across countries. Pan and Dong (2022) based on the empirical results of the China's new energy development reveals regional disparities, with stronger development in the north and east and weaker in the south and west. It suggests that technology drives early-stage development, while economic factors become more influential in the later stages, with lagging regions learning from more advanced areas. Li, Xin, et al. (2022) and Li, Ji, and Dong (2022) applied super-efficiency DEA model, Malmquist index and random forest regression model to analyse global renewable energy development, assessing power generation efficiency (PGE) in 36 countries from 2009 to 2018. It identifies a pattern of global renewable energy development, highlights significant variations in PGE between countries, and suggests that technological progress can hinder PGE growth. Furthermore, the study identifies key influencing factors, including carbon emissions, industrial structure, electricity structure, technology level, and economic level, emphasizing the need for improvements in renewable energy power generation technology. Cao et al. (2021) examines the temporal and spatial evolution of China's provincial Population, Resources, Economy, and Environment (PREE) systems and finds that the overall coordination level improved over time, with shifting regional patterns. Factors such as per capita GDP and environmental investment played a role in promoting the coordinated development of China's PREE system, suggesting the need for region-specific adjustments for sustainable development. Zhong et al. (2020) employs the SBM to estimate the energy economic efficiency of cities within the Yangtze River Urban Agglomeration using data from 2008 to 2017. It finds that energy economic efficiency in the YRUA initially declined and then improved, with some cities, like Suzhou and Wuxi, displaying effective efficiency, while others, including Yangzhou, Taizhou, and Zhenjiang, exhibited lower efficiency. Scale efficiency is identified as the primary constraint, and the study emphasizes the role of factors such as industrial structure, economic development, and urbanization in enhancing energy economic efficiency in the region. Wu (2023) assesses China's investment in energy technology and its impact on economic growth and environmental improvement. It employs the super-efficiency slack base model to measure green energy efficiency in 30 Chinese provinces from 2010 to 2019 and uses a spatial Durbin model to analyse the influence of economic variables. The findings indicate that China's green energy efficiency improved during the study period, but there is room for further enhancement, with economic development playing a significant role. The study suggests the importance of energy-saving technologies, environmental regulation policies, and regional development planning for China's sustainable energy use and economic growth.

While the literature provides valuable insights into renewable energy development efficiency, it is important to justify the impactful dimensions that affect renewable energy development efficiency in China. The main innovations of this paper are as follows: (1) using the more cutting-edge ultraefficiency SBM model to compensate for the defects of the traditional model; (2) using the Dagum method and nuclear density estimation method to analyse the interval difference and evolution dynamics of renewable energy development efficiency in China; and (3) using the Markov chain model to analyse the future development trend of renewable energy development efficiency in China.

3 | RESEARCH METHODOLOGY

3.1 | Ultraefficiency SBM model and Malmquist efficiency index

The SBM model based on undesirable output is the model first proposed by Tone (2001) to measure ecological efficiency. Compared with the traditional data envelope model (DEA), the SBM model can effectively solve the "crowding" or "relaxation" phenomenon of input elements caused by the radial and angular traditional DEA model.

However, for SBM models, such as the traditional DEA model, it is difficult to further distinguish the efficiency difference between efficient decision-making units (DMUs). In 2002, on the basis of the SBM model, Tone (2001) further defined the ultraefficiency SBM model, combined with the advantages of the ultraefficiency DEA model and SBM model, which can effectively further compare and evaluate DMU in the forefront.

The DEA-Malmquist index model is obtained based on the evolution of the DEA method. The Malmquist index (total factor productivity (TFP)) allows for the dynamic analysis of annual technology, scale, and pure technical efficiency and can dynamically analyse the internal factors affecting changes in efficiency. The Malmquist index is used to measure renewable energy development efficiency in China from 2006 to 2020. The specific formula is as follows:

$$M_{(y_{i+1},x_{i+1},y_i,x_i)} = \sqrt{\frac{Di(x_{i+1},y_{i+1}) * Di+1(x_{i+1},y_{i+1})}{Dt(x_i,y_i) * Dt(x_i,y_i)}} \tag{1}$$

where M–the Malmquist index, which could be decomposed into technical changes (TECH) and changes in technical efficiency (EFFCH), and changes in technical efficiency could be decomposed into changes in scale efficiency (SECH) and changes in pure technical efficiency (PECH).

TECH refers to improvements in technology or changes in the production process that result in increased productivity. In the context of the Malmquist Index, the TECH component measures how much productivity has changed due to advancements in technology or changes in the production process over a specific period. Positive values of TECH indicate technological progress or improvements in the production process, leading to higher productivity. Changes in technical efficiency (EFFCH) are related to the effectiveness with which inputs are used to produce outputs. In the context of the Malmquist Index, the EFFCH component measures how changes in technical efficiency have affected productivity. Positive values of EFFCH suggest that firms or entities have become more efficient in their use of resources, leading to increased productivity without changes in technology.

The returns to scale assumption is based on Variable Returns to Scale (VRS). In a VRS production process, the output does not scale proportionally with changes in inputs. This means that increasing inputs by a certain factor may lead to output scaling at a different rate, which can result in either increasing returns to scale (IRS) or decreasing returns to scale (DRS).

3.2 | Dagum Gini coefficient and decomposition method

Dagum (1997a, 1997b) decomposed the overall Gini coefficient into tierce segments: the involvement of differences within regions, the assistance of the net worth difference between regions, and the participation of super variable density. The last two constitute the total contribution of alterations between regions. It denotes the overall Gini coefficient; the higher the value of G is, the more significant the inclusive gap in renewable energy development efficiency. The general Gini coefficient is divided into the contribution to interregional difference contribution G_w, the interregional difference contribution G_{nb}, and the hypervariable density contribution G_t (Formula 2):

$$\mathrm{G} = \frac{\sum_{j=1}^{k}\sum_{h=1}^{k}\sum_{i=1}^{n_j}\sum_{r=1}^{n_h}\left|y_{ji} - y_{hr}\right|}{2n^2\overline{y}} = \mathrm{G_w} + \mathrm{G_{nb}} + \mathrm{G_t} \tag{2}$$

where y_{ji} and y_{hr} are the renewable energy expansion index of province i in region j and area i in region h, respectively; $\overline{y}$ is the average value of the renewable energy development level; and n is the number of divided regions i and r provinces.

First, each region is ranked consistently with the average value of the renewable energy development efficiency $(\overline{Y})$ within each area.

$$\overline{Y}_h \le \cdots \le \overline{Y}_h \cdots \le \overline{Y}_{k.} \tag{3}$$

Furthermore, the Gini coefficient is decomposed into intraregional differences and interregional modifications:

$$G_{jj} = \frac{\frac{1}{2\overline{Y}_j}\sum_{i=1}^{n_j}\sum_{r=1}^{n_j}\left|y_{ji}-y_{hr}\right|}{n_j^{2}} \tag{4}$$

$$G_w = \sum_{j=1}^{k} G_{jj} p_j s_j \tag{5}$$

$$G_{jh} = \frac{\sum_{i=1}^{n_j}\sum_{r=1}^{n_h}\left|y_{ji}-y_{hr}\right|}{n_j n_h\left(\overline{Y}_j+\overline{Y}_h\right)} \tag{6}$$

$$G_{nb} = \sum_{j=2}^{k}\sum_{h=1}^{j-1} G_{jh}\left(p_j s_h + p_h s_j\right) D_{jh} \tag{7}$$

$$G_t = \sum_{j=2}^{k}\sum_{h=1}^{j-1} G_{jh}\left(p_j s_h + p_h s_j\right)\left(1-D_{jh}\right) \tag{8}$$

where G_{jj} is the Gini coefficient of the region; G_w is the contribution of the intraregional difference; G_{jh} is the interregional Gini coefficient of the region; G_{nb} is the contribution of the interregional difference; D_{jh} is the relative impact of the renewable energy development efficiency of region j and region h; and G_t is the contribution of the hypervariable density.

Finally, calculate the relative impact of the efficiency of renewable energy development:

$$G_{jh} = \frac{d_{jh}-p_{jh}}{d_{jh}+p_{jh}} \tag{9}$$

$$d_{jh} = \int_0^{\infty} dF_j(y)\int_0^{y}(y-x)dF_h(x) \tag{10}$$

$$p_{jh} = \int_0^{\infty} dF_h(y)\int_0^{y}(y-x)dF_j(x) \tag{11}$$

where $p_j = p_j/n$, $s_j = n_j\overline{Y}_j/n\overline{Y}$, and $j = 1,2,\ldots,k$. It represents the difference in the renewable energy development efficiency index between regions, where p_{jh} is the supervariable first-order moment.

3.3 | Kernel density estimation

The kernel density estimation method was used to examine the distribution of the comprehensive index of the efficiency of renewable energy development in the country and the four central regions. The assumption is the density function of the comprehensive index of China's renewable energy development efficiency:

$$f(x) = \frac{1}{Nh}\sum_{i=1}^{N} K\left(\frac{X_i - x}{h}\right) \tag{12}$$

where N is the numeral of observations; X_i is the independently and identically distributed annotations; x is the mean of the observations; $K(\cdot)$ is the kernel density function; and h is the bandwidth. The lower the bandwidth is, the more accurate the estimation is.

$$K(x) = \frac{1}{\sqrt{2\pi}}\exp\left(-\frac{x^2}{2}\right) \tag{13}$$

3.4 | Markov model

As a discrete random process of both time and state, the research objects are divided into K types according to the law of thing evolution. The transfer between different types at different times can be expressed by the KK transition probability matrix. The transition probability K×K is the probability of time *t* type *i* from transfer to *j*. The formula is as follows:

$$m_{ij} = \frac{n_{ij}}{n_i} \tag{14}$$

where n_{ij}–the number of samples with time t type i transferred to j; n_{ij}–the number of all samples at time *t*.

According to the characteristics of the Markov transition probability being stable in time, there is the following formula:

$$F_{t+1} = M^s F_t \tag{15}$$

where F_{t+1} and F_t are probability distributions at different times and M^s is the S power of the transition probability matrix M.

3.5 | Tobit model

The DEA model, a nonparametric method for measuring efficiency, often yields efficiency scores that are bounded between 0 and 1. These scores are censored or truncated, as they cannot fall below 0 (inefficiency) or exceed 1 (perfect efficiency). This feature poses a challenge for conventional linear regression models, which assume normally distributed errors and are not equipped to handle bounded dependent variables. The Tobit model accounts for the presence of upper and lower bounds on the dependent variable, making it a suitable choice for analysing efficiency scores derived from DEA. The Tobit model allows for the inclusion of both censored and uncensored data points, offering a more robust method of analysis for such scenarios. The Tobit measurement model is selected for regression as follows:

$$y_{ij}^* = \beta x_{ij} + a_{ij} + \varepsilon_{ij}, \varepsilon_{ij} \sim N\left(0, \sigma^2\right)$$

$$y_{ij} = \begin{cases} y_{ij}^*, 0 \le y_{ij}^* \le 1 \\ 0, y_{ij}^* < 0 \\ 1, y_{ij}^* > 1 \end{cases} \tag{16}$$

where y_{ij}^* is the latent variable affecting renewable energy development efficiency, x_{ij} is the independent variable affecting each year, a is the constant term, and ε_{ij} is the error term, whose values fit the normal distribution.

3.6 | Selection of indicators and data sources

To better estimate the efficiency of renewable energy development in 30 Chinese provinces from 2006–2020, the input, desirable, and undesired output indicators are constructed below (see Table 1).

The capital stock index measures the capital input, estimated using the perpetual inventory method (Zhang et al., 2004). The specific formula is as follows:

$$K_{it} = I_{it} + (1 - \delta_{it}) \times K_{it-1} \tag{17}$$

where K_{it}–the current capital stock; K_{it-1}–the previous capital stock; I_{it}–the investment amount, selecting the total formation of fixed assets of every province, δ–the rate of depreciation (9.6%) and reducing the assets or capital stock in 2004 as a base period. Based on the concept of energy demand elasticity (Gorus & Karagol, 2022; Taghvaee et al., 2022; Wang et al., 2022), particularly the relationship between GDP and electricity consumption elasticity, the energy input is expressed by annual electricity consumption. Energy input is a fundamental factor in assessing economic development and sustainability, and to capture this input effectively, researchers often rely on various metrics,

TABLE 1 Renewable energy development efficiency input–output index system.

Variable	Measurement method	Unit	Mean	Std	Min	Max
Input						
Fixed assets	The capital stock of the provinces	100 million	9652.86	8634.43	289.18	43096.19
Labour	Number of employees by province	Ten thousand people	499.39	347.34	42.50	2135.06
Energy resources	Energy consumption	Ten thousand tons	13212.07	8494.33	742.48	42199.00
Renewable energy	Renewable energy generation capacity	Billion kWh	1625.78	1202.85	68.74	5781.00
Expect output						
GDP	GDP in the provinces	100 million	6994.10	5513.36	466.10	28083.28
Undesired output						
Carbon emission	Carbon emissions from 9 types of energy consumption	Million tons	3303.56	15194.45	16.50	155811.90
Industrial sulphur dioxide	Industrial sulphur dioxide emissions	Ten thousand tons	50.30	39.75	0.09	171.50
Industrial wastewater	Industrial wastewater discharge	Ten thousand tons	67397.47	61126.04	698.27	322158.00
Industrial soot emissions	Industrial soot emissions	Ten thousand tons	38.15	31.24	0.43	160.50

such as electricity consumption, as a proxy for overall energy usage. This choice is justified by the close empirical relationship between electricity consumption and the broader energy demand within an economy. The elasticity of GDP (gross domestic product) with respect to energy consumption represents the sensitivity of a country's economic output to changes in energy usage, quantifying how a change in energy consumption affects economic growth (Gorus & Karagol, 2022; Taghvaee et al., 2022; Wang et al., 2020). Understanding this elasticity is crucial because it reveals insights into the energy efficiency of an economy and its ability to decouple economic growth from increased energy consumption. In many cases, higher elasticity indicates that a country's economic development is closely tied to energy-intensive industries or practices, while lower elasticity suggests a more energy-efficient economy where GDP can grow without a significant increase in energy consumption (Gorus & Karagol, 2022; Taghvaee et al., 2022; Wang et al., 2022).

Data are taken from China's Energy Statistics Yearbook; Renewable energy input using renewable energy generation capacity, total electricity generation from environmentally friendly energy sources, for example, geothermal, solar, wind, biomass, and biofuels are used as variables to show the indicators of renewable energy (Ray, 2019), data are from the China's Electric Power Statistical Yearbook; Desirable output, selecting GDP and converting nominal to actual GDP as desirable output, data are from the Statistical Yearbook; undesired output, selecting illustrative industrial dust and SO_2, wastewater and carbon dioxide emissions from exhaust gas, data are from the China's Environmental Statistical Yearbook; Environmental pollution and carbon emissions will stimulate the development. The following formula:

$$CE = \sum_{i=1}^{8} (CO2)_i = \sum_{i=1}^{8} Q_i \times NCV_i \times CEF_i \times COF_i \times \frac{44}{12} \tag{18}$$

where *i*–ranges from 1,2 … 8 and corresponds to eight energy sources; *Q*–the consumption of eight energy sources in kg; *NCV*–the net heat of energy in kJ/kg; *CEF*–the carbon emission factor of power in kg CO_2/kg; *COF*–the dimensionless unit conversion coefficient of energy.

3.7 | Identification of influencing factors

Measuring the efficiency characteristics, amplitude change characteristics and dynamic distribution of China's energy development is of great practical significance for the scientific and rational allocation of resources, promoting economic and social development, and meeting the needs of the people for a better life. Energy development efficiency serves economic development and production and supply, and the per capita GDP value (X1) of each province in the country after price deflation is selected to reflect the level of economic development. Price deflation is necessary to adjust the nominal GDP (measured in current market prices) for inflation. Inflation can cause the nominal GDP to overstate the true economic output because it includes price increases. Deflating allows removing the inflationary effect, providing a more accurate representation of real economic growth. Furthermore, price deflation allows for meaningful comparisons of economic output across different years. Without adjusting for price changes, it would be challenging to determine whether the increase in GDP is due to actual growth in production or simply the result of rising prices. At the same time, the development of green finance has an important impact on energy development efficiency, a high level of green finance development can promote the improvement of energy efficiency, and green credit, green bonds and other indicators are used to measure the development of green finance (X2). It was calculated by the entropy evaluation method. The core variable of the Green Finance Development Index is shown in Table 2.

Green finance development promotes the expansion of green credit. Therefore, idle social resources can be lent to companies that need financial support to break constraints, improve energy efficiency, and solve corporate financing problems. The development of green finance enables enterprises to continuously expand

TABLE 2 Green finance development index system.

Index	Measurement method
Green credit	The ratio of the interest expense of the high-energy consumption industry to the total interest expense of the industrial industry
Green Insurance	The ratio of agricultural insurance premium income to the total premium income of property insurance business
Government green spending	The ratio of government environmental expenditures to general fiscal expenditures
Green investment	The ratio of environmental pollution control investment to GDP

Source: Authors.

production scale, improve capital use efficiency, and reduce transaction costs, which can further improve energy efficiency.

Technological progress can promote energy development to a certain extent, and technological progress is measured by the ratio of technology market turnover to regional GDP (X3). The higher the level of urbanization is, the higher the requirements for energy efficiency, and the ratio of urban population to total population is chosen to measure the level of urbanization (X4). Industrial structure adjustment will affect the energy consumption structure and energy consumption intensity and then affect energy efficiency. Then, the proportion of tertiary industry output value and secondary industry output value will be selected to measure industrial structure (X5). The expansion of opening up is conducive to the introduction of advanced technology, equipment and advanced experience, and the host region will achieve energy efficiency improvement under the effects of the technology spillover effect, demonstration-imitation effect, competition effect, etc. This paper uses the ratio of total import and export of goods * USD/RMB exchange rate to regional GDP to measure the degree of openness (X6). In addition, government intervention will also affect energy efficiency. On the one hand, the more government intervention there is, the more reasonable the energy market will be because of the strict control of the government, and there will be no waste of energy to improve the quality of energy utilization. On the other hand, the more government-led intervention there is, the more the price of energy will be affected, and the resulting energy use will be biased towards cheap, highly polluting fossil energy, making it less energy efficient. Fiscal expenditure and GDP are selected to measure the degree of government intervention (X7). The improvement of technological innovation can promote energy conservation, and the natural logarithm of the number of invention patent applications received is selected to measure the level of innovation (X8). Finally, improvements in the transport base can have an impact on energy efficiency, and the logarithm of road mileage and freight volume is chosen to measure the transport base (X9). The data in this article are all from the China Statistical Yearbook, China Urban Statistical Yearbook, and the data and statistical bulletins released by the provincial statistical bureaus. Table 3 summarizes the variables of the index system of the influencing factors.

Descriptive statistics and results of unit root tests for the dimensions of renewable energy development efficiency are shown in Table 4.

The Table 4 presents the results from three different unit root tests (Levin–Lin–Chu, Im-Pesaran-Shin, and Augmented Dickey-Fuller) for nine variables (X1 to X9), assessing their stationarity. In the "level" tests, all variables show very low p-values, indicating non-stationarity in their levels. However, in the "first difference" tests, all variables exhibit p-values below 0.05, suggesting that differencing the series renders them stationary. This implies that the variables are non-stationary in their original form but become stationary after taking the first differences.

4 | RESULTS

Equations (1)–(5) are used to calculate the renewable energy development efficiency values of different provinces in China, as shown in Table 5.

TABLE 3 Index system of influencing factors.

Variable	Name of index	Symbol	Method of calculation
Explained variable	Renewable energy development efficiency	Ren	Malmquist Index
Explanatory variable	Economic development level	X1	Per capita GDP index to do the price reduction
	Green finance development	X2	Entropy evaluation method
	Technical progress	X3	Technology market turnover/GDP
	Urbanization level	X4	Urban population/total population
	Industrial structure	X5	Output value of tertiary industry/output value of secondary industry
	Open	X6	Total imports and exports of goods * USD/RMB exchange rate/GDP
	Government intervention	X7	Fiscal expenditure/GDP
	Innovation level	X8	The amount of invention patent application accepted (piece) takes the natural log
	Traffic foundation	X9	The highway mileage takes the logarithm of the log and the total freight volume

Renewable energy development efficiency has significant heterogeneity in time and space. On the whole, China's renewable energy development efficiency has been significantly improved. In 2006, Beijing, Guangdong, and Shanghai took the lead in renewable energy development efficiency; in 2020, renewable energy development efficiency increased in all provinces, and the average value increased from 0.932 in 2006 to 1.078 in 2020.

Thinking about China's renewable energy development is severely regionally unbalanced. Based on the green economy development index calculated above, regional differences and sources of renewable energy development are accurately calculated by applying the Dagum Gini factor and its subgroup disintegration technique to further clarify this problem. The measurement inferences are shown in Table 6.

According to Figure 1, with regional economic expansion in 2010–2019, China's regional gap in the development of renewable energy increased annually. The eastern part has an enormous difference, the northeast region has the most negligible difference, and the slowest difference is in the western part. Explicitly, the mean Gini coefficient is 0.11, which grew slowly from 0.028 in 2006 to 0.174. After 2011, the mean differences were 1.04 and 0.938, respectively, exceeding the average growth trend from 2010–2016 and slowly decreasing after 2016. The mean intra-Northeast regional difference was 0.018, rising from 2006–2009 and declining after 2009. From 2010 to 2020, regional changes are relatively noticeable, indicating that all provinces consider ecological matters and promote the development of renewable energy.

In Figure 2, the average (i.e., mean) Gini coefficient between the central-west–east–northeast areas is extensive, with 1.171 and 1.442, respectively, while that between the east–west regions is trivial, with 1.255. The trend of alteration in regional differences is similar. Shows the direction of rising, then falling, and finally rising and slowly falling and rising after 2020, mainly due to apparent discrepancies between regions. The energy shortage in 2020 led to the growth of the demand for renewable energy, and the government advocated its development.

An immense contribution to the disparity is the source of the difference in renewable energy progress. The interregional disproportions with an average immersion amount of 0.495 have become the primary and most significant reason for the overall contrast in renewable energy development. The intraregional disproportion amount change ranges from 0.02–0.06, and the average is 0.411. Interregional disparities, compared to intraregional disparities, contribute more to the regional gap in renewable energy development efficiency. Within regions, the contribution rate to disparities is between 0.01 and 0.04, with an average of 0.318. This implies that the overlying samples between areas have little influence on regional gaps in renewable energy growth. Consequently, the

TABLE 4 Descriptive statistics and unit root tests for the dimensions of renewable energy development efficiency.

Variable	Obs	Mean	Std	Min	Max
X1	450	42641.46	26963.18	5394	164,220
X2	450	0.165	0.104	0.05	0.839
X3	450	75749.81	124551.7	325	967,204
X4	450	0.552	0.136	0.274	0.896
X5	450	0.891	0.065	0.605	1.104
X6	450	0.339	0.390	0.008	1.918
X7	450	0.230	0.100	0.083	0.643
X8	450	9.007	1.615	4.369	12.285
X9	450	11.429	0.855	8.892	12.981

Unit root tests

	Levin–Lin–Chu				Im-Pesaran-Shin				Augmented Dickey-Fuller (ADF) Test			
	Level		First difference		Level		First difference		Level		First difference	
Variable	Stat	Prob	Stat	Prob	Stat	Prob	Stat	Prob	Stat	Prob	Stat	Prob
X1	4.66	1.00	−6.53	0.00	14.70	1.00	−7.50	0.00	−3.72	0.99	2.26	0.01
X2	4.31	1.00	−6.53	0.00	13.99	1.00	−7.33	0.00	−5.16	1.00	24.74	0.00
X3	12.72	1.00	−6.77	0.00	19.11	1.00	−4.07	0.00	−5.29	1.00	19.87	0.00
X4	2.29	0.98	−13.84	0.00	11.82	1.00	−4.49	0.00	−4.37	1.00	11.19	0.00
X5	−15.28	0.00	−19.02	0.00	−8.46	0.00	−11.72	0.00	22.44	0.00	65.21	0.00
X6	−6.04	0.00	−12.17	0.00	−0.61	0.26	−8.69	0.00	0.02	0.49	27.85	0.00
X7	11.01	1.00	−2.80	0.00	−2.48	0.01	−13.06	0.00	2.53	0.00	122.52	0.00
X8	−8.76	0.00	−3.19	0.00	−1.57	0.05	−6.65	0.00	2.42	0.00	18.03	0.00
X9	−14.91	0.00	−11.96	0.00	−3.59	0.00	−7.03	0.00	7.82	0.00	20.87	0.00

focus should be on narrowing regional discrepancies and further reducing interregional renewable energy progress (see Figure 3).

The results of calculating the dynamic evolution trend of renewable energy advancement in China and drawing dynamic maps using MATLAB are shown in Figure 4.

In Figure 5, the general inclination is changed to the right, and the elevation of the projecting top continues to increase. The distribution curve always has a right trail, and the ductileness is broadened. There is only a single central topmost division and no regional division. In line with the previous analysis of the Gini coefficient, the overall development of renewable energy in the western and central regions is enlightening, and the complete change is shrinking. Consistent with Figure 6a, the leading place for renewable energy development in the eastern section has shifted mainly to the right side. The slow fluctuation trend of first decreasing and then rising between 2006 and 2020 indicates a polarization phenomenon in the progress of renewable energy in the eastern region. According to Figure 6b,c, the location of the highest peak of the dispersal arc of renewable energy expansion in the western and central sections has generally shifted to the right. The general trend of the altitude of the highest peak increased, reaching the highest point in 2018–2020. The width of the highest mountain and the right trail did not change significantly. One prominent peak, without regional polarization, indicates that renewable energy development in the

TABLE 5 Index of renewable energy development efficiency.

Region	2006	2008	2010	2012	2014	2016	2018	2019	2020
Beijing	0.953	1.653	1.232	1.241	0.961	1.577	0.568	0.980	0.872
Tianjing	1.046	1.032	0.933	1.370	1.019	0.989	1.042	0.877	0.987
Hebei	0.995	0.975	0.961	1.132	1.002	1.020	1.005	0.932	0.992
Shanxi	1.214	0.974	0.552	1.116	0.987	0.952	1.078	0.843	1.087
NeiMonggu	0.819	0.922	0.599	0.995	0.990	1.027	1.101	0.828	1.015
Liaoning	0.903	0.854	0.888	1.155	0.962	0.945	1.081	0.858	1.051
Jilin	0.861	0.889	0.625	1.096	1.846	0.973	1.205	0.797	1.013
Heilongjiang	0.830	0.976	0.612	1.036	1.484	1.103	1.112	0.944	1.070
Shanghai	0.961	0.909	0.898	1.145	1.648	1.054	1.305	0.766	1.008
Jiangsu	0.919	1.034	0.824	1.794	1.209	1.018	1.070	0.963	1.090
Zhejiang	0.957	0.907	0.745	1.070	1.323	1.001	1.075	0.995	0.978
Anhui	0.818	0.997	0.824	1.099	1.228	0.996	0.947	0.953	1.015
Fujian	0.966	0.933	0.927	1.107	1.135	1.048	1.036	0.925	0.964
Jiangxi	0.930	1.009	0.817	1.080	1.386	1.049	1.088	0.915	1.171
Shandong	0.945	0.834	0.972	1.010	1.104	1.161	1.031	0.936	1.105
Henan	0.966	0.910	0.917	1.067	1.063	1.081	1.212	0.801	1.097
Hubei	1.081	1.777	1.212	1.097	1.111	2.039	0.895	0.979	1.171
Hunan	0.856	1.902	0.895	1.026	1.093	1.118	1.131	0.845	1.145
Guangdong	0.968	1.870	0.963	1.034	1.073	1.140	0.934	0.892	1.045
Guangxi	0.989	1.111	0.877	1.040	1.117	1.099	1.008	0.913	0.995
Hainan	0.830	1.634	0.658	1.188	1.077	1.286	1.459	0.733	2.031
Chongqing	0.894	1.234	0.838	1.085	1.124	1.191	1.118	0.808	1.051
Sichuan	0.966	1.042	0.944	1.075	1.118	1.121	0.990	0.870	1.027
Guizhou	0.950	1.125	0.629	1.073	1.026	1.107	1.029	0.864	1.066
Yunnan	0.942	1.101	1.026	1.029	1.047	1.133	1.094	0.859	1.030
Shaanxi	1.055	1.101	1.055	1.105	0.965	1.260	1.016	0.847	1.157
Gansu	1.132	1.047	0.920	1.091	0.976	1.190	0.997	0.984	1.041
Qinghai	0.050	1.887	0.867	1.270	0.974	1.152	0.897	0.987	1.044
Ningxia	1.092	1.298	0.918	0.643	0.951	1.024	0.934	1.012	1.001
Xinjiang	1.081	0.642	0.939	0.934	0.947	1.168	0.853	0.976	1.032
Average	0.932	1.153	0.869	1.107	1.132	1.134	1.044	0.986	1.078

Source: the author calculations.

central and western regions is growing and shows a trend of absolute difference reduction. Along with Figure 6d, the overall right shift of the distribution curve of the advance of renewable energy in the northeast region is noticeable. The height of the principal peak is also increasing, the flexibility of the right-side trail is broadened, around is constantly the central peak, and there is no phenomenon of divergence.

The provinces with more renewable energy development in 2006 include Beijing, Guangdong, Shanghai, and Zhejiang (Figure 6). The green economic advance efficiency of other easterly regions is wholly at a low level, demonstrating that the efficiency of renewable energy development for areas with fast economic growth is rapid. Most western China is slow, and the efficiency of renewable energy is relatively slow. In 2020, China's renewable energy development efficacy was meaningly upgraded. The number of provinces experiencing elevated progress will

TABLE 6 Gini coefficient and disintegration results of renewable energy development efficiency in China.

		Gini coefficient within the region				Interregional Gini coefficient						Contribution rate (%)		
Year	Total Gini	E	M	W	NE	EM	EW	EN	MW	MN	WN	WR	IR	SV
2006	0.053	0.028	0.068	0.051	0.019	0.055	0.047	0.053	0.069	0.060	0.076	24.528	35.849	39.623
2007	0.059	0.027	0.019	0.095	0.017	0.030	0.074	0.032	0.065	0.048	0.088	28.814	25.424	45.763
2008	0.152	0.157	0.163	0.122	0.030	0.166	0.156	0.143	0.164	0.167	0.139	26.974	25.000	48.026
2009	0.161	0.107	0.199	0.128	0.084	0.175	0.126	0.218	0.190	0.214	0.214	22.981	32.298	44.720
2010	0.094	0.084	0.072	0.083	0.087	0.094	0.087	0.143	0.088	0.114	0.130	26.596	38.298	35.106
2011	0.070	0.060	0.013	0.102	0.010	0.043	0.089	0.048	0.073	0.038	0.073	30.000	28.571	40.000
2012	0.069	0.087	0.015	0.068	0.024	0.068	0.096	0.068	0.047	0.022	0.053	28.986	53.623	17.391
2013	0.062	0.115	0.029	0.029	0.001	0.080	0.082	0.076	0.032	0.034	0.039	29.032	20.968	51.613
2014	0.089	0.083	0.061	0.036	0.137	0.074	0.076	0.161	0.068	0.158	0.184	20.225	55.056	24.719
2015	0.088	0.102	0.053	0.051	0.146	0.083	0.089	0.145	0.061	0.138	0.146	25.000	40.909	35.227
2016	0.078	0.074	0.134	0.033	0.035	0.113	0.062	0.072	0.103	0.108	0.064	24.359	26.923	48.718
2017	0.068	0.081	0.091	0.034	0.036	0.101	0.068	0.068	0.070	0.073	0.037	26.471	44.118	30.882
2018	0.073	0.105	0.056	0.045	0.024	0.091	0.081	0.092	0.058	0.050	0.063	27.397	32.877	39.726
2019	0.046	0.048	0.040	0.042	0.038	0.048	0.048	0.050	0.042	0.042	0.044	28.261	10.870	58.696
2020	0.060	0.110	0.027	0.019	0.012	0.089	0.075	0.073	0.040	0.037	0.017	26.667	26.667	46.667
Mean	1.222	1.268	1.040	0.938	0.700	1.310	1.255	1.442	1.171	1.303	1.367	26.023	33.633	40.507

Abbreviations: E, east; East-Middle, EM; EN, East–Northeast; EW, East, West; IR, Interregional; M, middle; MN, Middle-Northeast; MW, Middle-West; NE, Northeast; SV, Super variable density; W, west; WN, West–Northeast; WR, within the region.

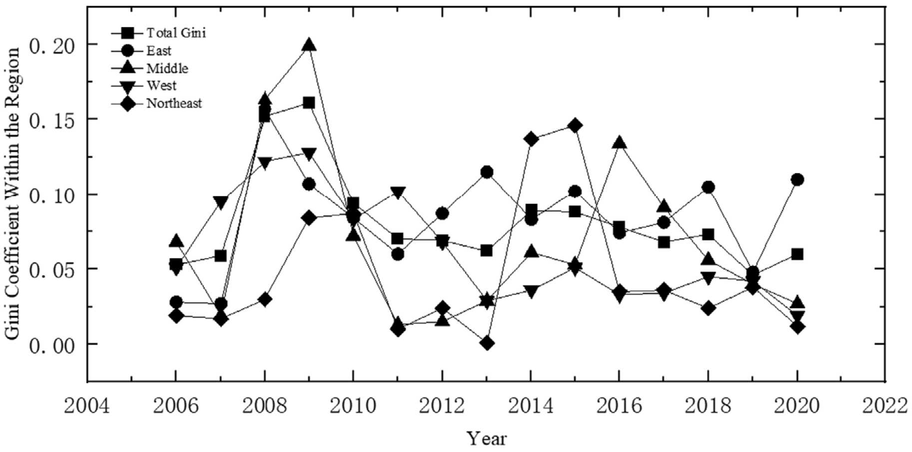


FIGURE 1 General and regional differences in renewable energy growth.

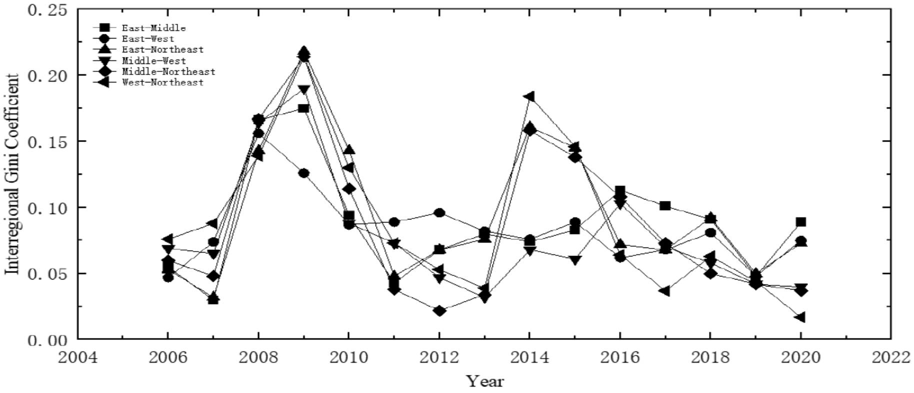


FIGURE 2 Regional differences in the development of renewable energy.

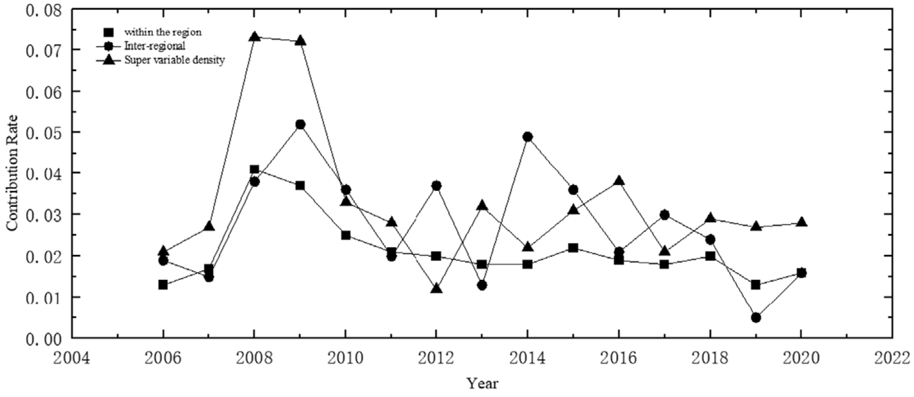


FIGURE 3 Renewable energy development efficiency of contribution rate.

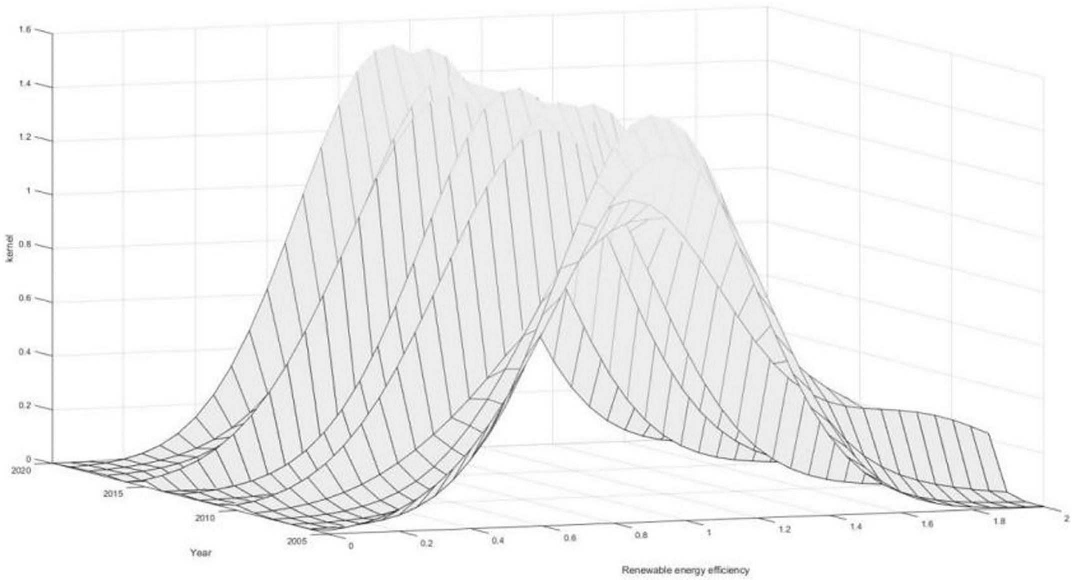


FIGURE 4 Dynamics of the distribution of renewable energy development efficiency in China.

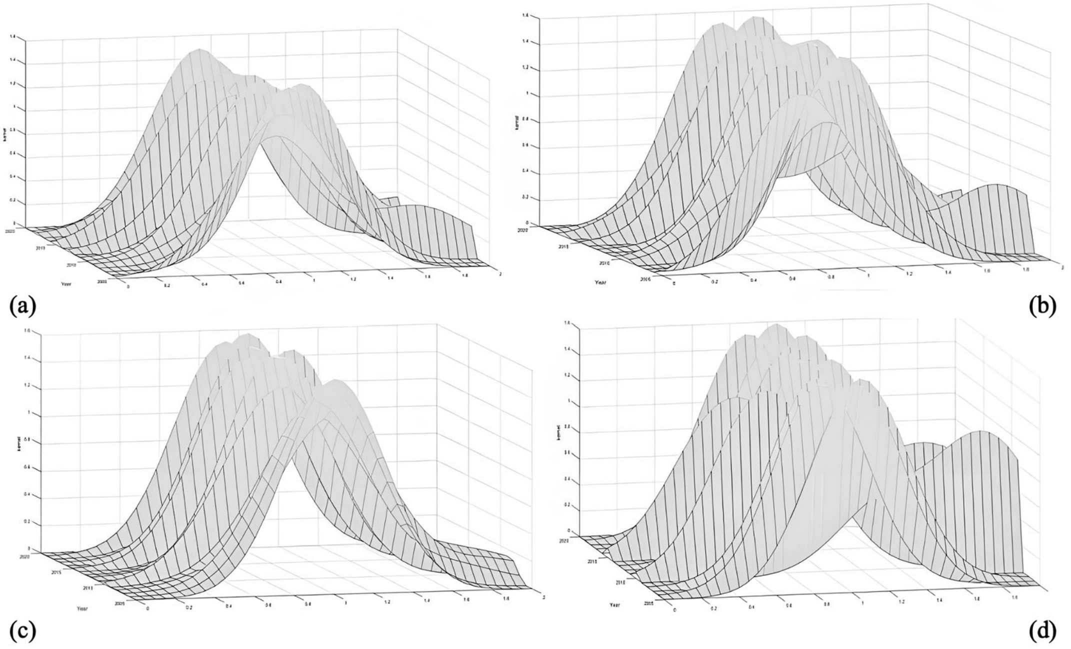
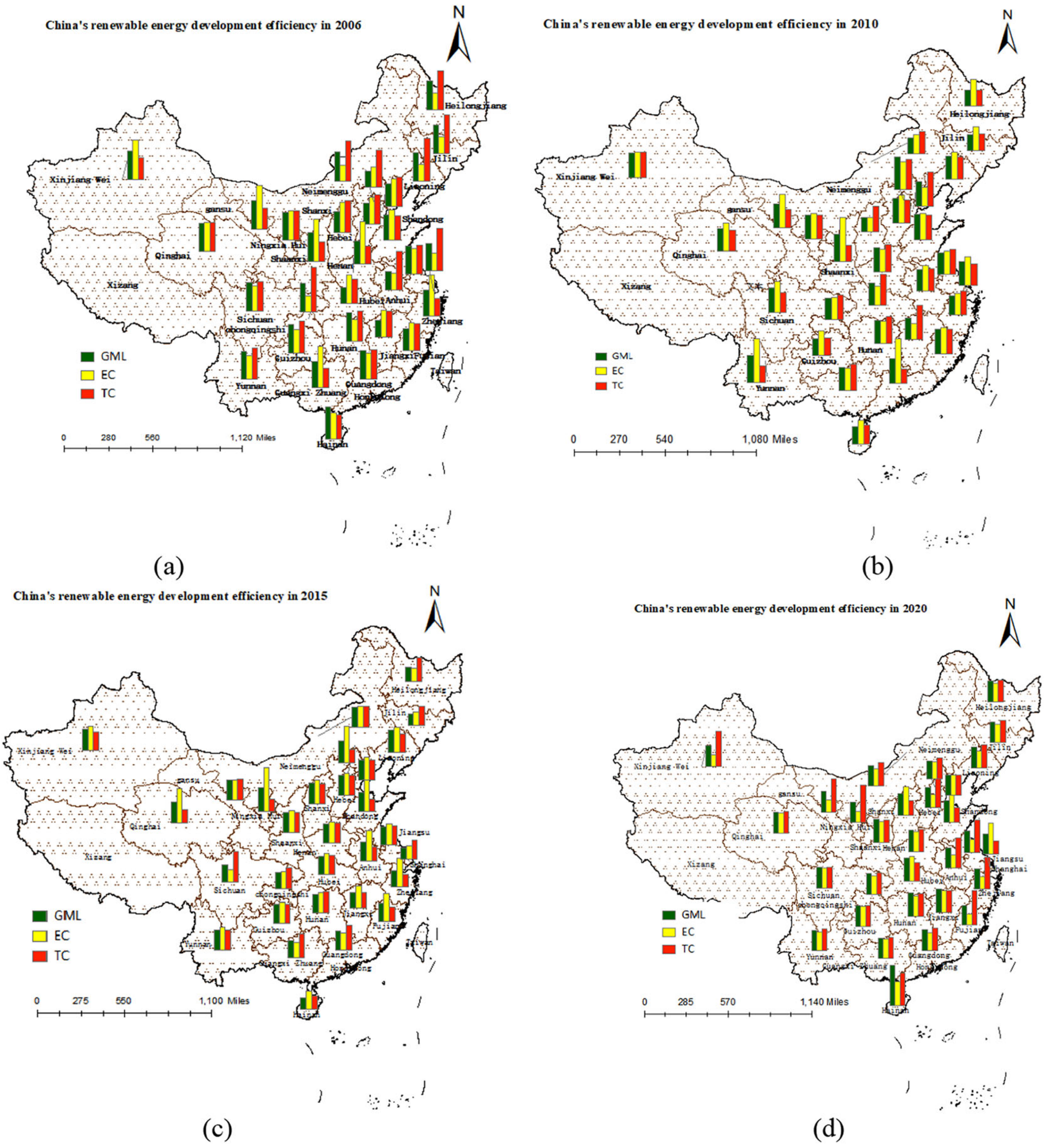


FIGURE 5 Regional distributing subtleties of renewable energy development efficiency. a–east; b–middle; c–west; d–northeast.

increase, and the number of areas experiencing low-level evolution will likewise decline, indicating that renewable energy development will develop while accomplishing first-class economic advances.

China's renewable energy efficiency is divided into four groups according to the quartile in 2006, showing four states in turn: low, medium low, medium high and high, and the Markov transfer matrix probability is shown in



(a) (b) (c) (d)

FIGURE 6 China's renewable energy development efficiency.

Table 7. The diagonal elements of the Markov state transition matrix indicate the probability of renewable energy efficiency maintaining the current state at each time during the study period, the probability of being in the L state is 76.7%, and the probability of the main diagonal element is higher than that of other elements, indicating that China's renewable energy efficiency tends to a higher level of development mode. At the same time, the probability of H-H is 93.2%, indicating that China's renewable energy development efficiency is developing to a high level.

Using the Malmquist index as a basis, a Tobit model was employed to perform a regression analysis aimed at investigating the critical factors influencing the efficiency of renewable energy development. This paper conducted a

TABLE 7 Markov transition probability matrix.

t	$t+1$			
	L	**L-M**	**M-H**	**H**
L	76.7%	23.3%	0	0
L-M	4.2%	87.5%	8.3%	0
M-H	0	5.3%	73.7%	21.1%
H	0	0	6.8%	93.2%

TABLE 8 Results of VIF.

Variable	y	X1	X2	X3	X4	X5	X6	X7	X8	X9
VIF	-	7.88	5.64	2.32	7.31	1.05	2.32	1.17	6.68	3.66

TABLE 9 Results of the Tobit regression analysis for renewable energy development efficiency.

Variable	Coefficient	Std.	*Z* value	*p* value
X1	−1.66e−0.6	9.74e−07	−1.70	.088
X2	0.737	0.221	3.74	.001
X3	1.93e−07	1.13e−07	1.70	.089
X4	0.240	0.1884	1.27	.203
X5	0.252	0.139	1.82	.069
X6	−0.032	0.038	−0.85	.397
X7	0.222	0.097	2.28	.022
X8	−0.034	0.016	−2.17	.030
X9	−0.068	0.022	−3.12	.002
_cons	1.416	0.232	6.11	.000
N	450	450	450	450

VIF test, and the results indicate that the VIF values are all below 10, indicating the absence of collinearity issues (Table 8).

Tobit model analysis. To further increase energy efficiency, the comprehensive technical efficiency value of energy utilization was taken as the explanatory variable, and nine indicators, such as the economic development level, were selected as explanatory variables for analysis and research. Considering that the range of efficiency values is between 0–1, the Tobit model is selected, and Stata15 software is used to perform regression analysis of the influencing factors of energy efficiency (Table 9). From the regression results, the development of green finance and transportation foundation passed the 1% significance level test, and the development of green finance and energy efficiency showed a significant positive correlation, which showed that green finance has the function of resource allocation, and more funds have flowed to the environmental protection industry through green credit, green bonds and green funds, driving the development of the environmental protection industry, giving birth to more environmentally friendly and efficient enterprises, and then improving energy efficiency. The construction and use of transportation infrastructure will consume considerable energy, and if the frequency of infrastructure use does not reach the corresponding degree within a certain period of time, its energy efficiency will decline.

The degree of government intervention and innovation level passes the test of the 5% significance level, in which the degree of government intervention has a positive impact on energy efficiency, and the government's strict control of the energy market can effectively curb energy waste, make energy distribution more reasonable, and improve energy efficiency. There is a significant negative correlation between the level of innovation and energy efficiency, which can obtain more energy sources, improve energy efficiency, reduce energy waste, and promote sustainable development in the energy field. Innovative technologies face high costs in their implementation, and energy efficiency cannot be improved until innovative technologies are matured and widely rolled out to achieve large-scale production. The levels of economic development, technological progress and industrial structure are significant at the 10% level. From the level of economic development, its impact on energy efficiency is negative. The effect of technological progress on energy efficiency is not large but significant. In addition, industrial structure promotes energy efficiency. The more optimized the industrial structure is, the more the proportion of secondary industry products decreases, the proportion of tertiary industry increases, and the energy consumption intensity decreases, supporting energy conservation and improving energy efficiency. Finally, there is a positive correlation between urbanization level and energy efficiency, but it fails the significance test. In the process of urbanization, infrastructure construction and use will consume a large amount of energy, while urban infrastructure has the characteristics of a natural monopoly. In the early stage of urban density increase, the increase in urban population makes the frequency of infrastructure use increase, the average cost of infrastructure continues to decline, and the energy efficiency embedded in infrastructure can be improved. There is a negative correlation between openness and energy efficiency, but it also fails the significance test. To some extent, this shows that China's goods import industry may save less energy than export products, and the structure of China's foreign trade products needs to be adjusted accordingly.

To investigate the issue of heteroskedasticity, a Breusch-Pagan test was conducted, resulting in a λ^2 value of 6.01 with a *p*-value of .11. This test suggested the presence of homoscedasticity in the error term, indicating that the variances of the error terms across observations are relatively constant. Furthermore, a Ramsey's regression specification error test (RESET) was utilized, which produced a Ramsey test value of 0.77 with a *p*-value of .47. This result signified the absence of omitted relevant variables in the model.

5 | DISCUSSION

Therefore, the investigation and examination of renewable energy development efficiency in China hold significance on multiple fronts. First, it is crucial for ensuring national energy security by diversifying the energy mix and reducing dependence on fossil fuels, as highlighted by Özbuğday and Erbas (2015). Additionally, the study illuminates the path towards achieving a more sustainable energy structure, which is essential in mitigating the environmental degradation associated with conventional energy sources, as emphasized by Akram et al. (2020).

Furthermore, the research plays a pivotal role in safeguarding the ecological environment. As climate change becomes an increasingly pressing global concern, the transition to renewable energy sources, as indicated by Akram et al. (2020), becomes a critical strategy in reducing greenhouse gas emissions and combating climate change effects. The findings of this study provide valuable insights into how renewable energy development can contribute to these objectives.

The pursuit of renewable energy development efficiency, as explored in this article, is integral to advancing China's sustainable economic growth, in line with the findings of Akram et al. (2021). Renewable energy development efficiency not only creates jobs and stimulates economic activity but also fosters technological innovation and enhances energy resilience.

This research extends our understanding of renewable energy development by addressing critical gaps in knowledge. By doing so, it contributes to enhancing energy security, promoting a sustainable energy structure, preserving the environment, responding to climate change challenges, and advancing economic prosperity. The identified regional trends and disparities underscore the importance of targeted policies and interventions to ensure a more equitable and sustainable renewable energy landscape in China.

6 | CONCLUSIONS

The object of investigation was dimensions that impact renewable energy efficiency in China. The research employed a diverse array of methodologies, including the ultraefficient SBM model for assessing renewable energy development efficiency, the Dagum-Gini coefficient decomposition process to analyse interregional variations in renewable energy efficiency, nuclear density estimation to examine dynamic distribution patterns, a Markov model for forecasting renewable energy development efficiency, and Tobit models to evaluate the factors influencing renewable energy outcomes. The empirical findings confirm that there is a widening disparity in the development of renewable energy across regions in China, with a trend of fluctuation over time. Interregional variances have been identified as the primary cause of these disparities. The eastern region exhibits polarization, while the northeast region does not, and the middle and western areas show improvement and a narrowing of absolute differences in renewable energy development. Additionally, factors such as economic development, green finance, technological progress, urbanization rate, and economic openness positively contribute to renewable energy efficiency. Moreover, China's renewable energy is developing at a higher level, in turn promoting sustainable energy development. Given the overhead themes, the following policy implications could be outlined:

1. To build a shared vision of the environment and energy and strengthen the division of labour and cooperation between provinces and regions. While boosting the overall efficiency of the development of renewable energy, we should narrow regional differences. Renewable energy development efficiency is higher in provinces that should continue to deepen basic research and scientific and technological innovation. At the same time, the efficiency of renewable energy development allows lower regions to take measures to local conditions to help drive policies. Renewable energy development efficiency is higher, and provinces should also actively combine their resource endowment and advantageous positive resource development.
2. Encourage green finance and expand financing channels for the renewable energy industry. Actively guide the expansion of green credits. Green bonds provide recognition and financial support for renewable energy enterprises, especially private enterprises. Hasten the erection of an integrated carbon pecuniary trading marketplace nationwide and gradually realize integration with the international carbon financial market (Azhgaliyeva et al., 2020; Hu et al., 2022)
3. Technological innovation is crucial to increasing the competence of renewable energy development (Østergaard et al., 2020). The government policy of renewable energy development of subsidy design and subsidies is conducive to technological innovation. Modern information technology and material technology should be strengthened. Internet technology development in large-scale energy storage, new energy materials, and other renewable energy development in critical areas of technical breakthroughs gradually improves the low-carbon energy alternative to traditional energy (fossil fuels) and encourages the continuous progress of renewable energy efficiency.

Despite the valuable findings, this study has several limitations that should be considered in future investigations. This study focuses specifically on the regional context of renewable energy development in China. Therefore, the findings may not be directly applicable to other countries or regions with different socioeconomic, political, and environmental conditions. This study identifies several factors that impact renewable energy efficiency, including economic development, green finance, technological progress, urbanization rate, and economic openness. However, it is important to note that the identified associations do not necessarily imply causality, and further research is needed to establish causal relationships between these factors and renewable energy efficiency. While the study provides valuable insights into the dimensions impacting renewable energy efficiency in the Chinese context, it is essential to acknowledge these limitations and consider them when interpreting the results and applying them to other contexts. Further research and analysis are necessary to broaden the understanding of the complex relationship between renewable energy efficiency and its influencing factors. In addition, considering the paper by Honma and Hu (2008), DEA allows considering not only technical efficiency scores within the assessment of energy efficiency. In this case, further studies should incorporate different methods to calculate energy efficiency, which improves the empirical justification of the results.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in the China Statistical Yearbook, China Urban Statistical Yearbook and the data and statistical bulletins released by the provincial statistical bureaus.

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