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Analysis of Spatial and Temporal Differences in the Efficiency of Rural Renewable Energy and Influencing Factors

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Abstract

This paper takes the rural areas of 27 provinces in China from 2009 to 2020 as the research object. Based on the Super-SBM model and the GML index, the efficiency of rural renewable energy is calculated and analyzed from both static and dynamic perspectives. Subsequently, the spatial differences among regions and the sources of these differences are analyzed using the Dagum Gini coefficient method. Finally, the panel Tobit model is used for the analysis of influencing factors. The research results show: (1) Within the study range, the efficiency of renewable energy shows significant spatio-temporal heterogeneity; the GML index presents a U-shaped characteristic, with slight declines in 2015 and 2016, and stable growth in other periods. (2) Regional differences are the main source of overall differences, but they show a gradually decreasing trend, indicating that the imbalance in the development of renewable energy in various regions in China has improved. (3) Economic level, education level, and power infrastructure have significant positive effects on the efficiency of renewable energy, while urbanization level is significantly negatively correlated with the efficiency of rural renewable energy. The impact is complex, and the effect of green finance is not significant.

Keywords

Rural Renewable Energy Efficiency; Inter - Provincial Differences; Super - SBM Model.

1. Introduction

Rural energy plays a crucial role in promoting sustainable agricultural development, enhancing farmers' quality of life, and facilitating the diversification of rural economies. It directly relates to the daily needs of rural residents and is a key factor in promoting the application of modern agricultural technologies and improving agricultural production efficiency. However, there are still many problems with rural energy, such as low commercialization degree of energy and low consumption levels and electrification rates. Many farmers still rely on straw and firewood, with the energy structure dominated by coal and biomass energy (Liu, 2011). The utilization methods of energy are relatively simplistic, and various problems follow. Firstly, the combustion of fossil energy, straw, and firewood will emit a large amount of pollutants such as smoke dust, sulfur dioxide, and nitrogen oxides. At the same time, coal mining and excessive collection of firewood will cause damage to the ecological environment, and the combustion of solid fuels poses a direct threat to human health (Li, 2020). Taking effective measures to reduce the use of solid fuels and promote clean energy is of vital importance for improving indoor air quality and reducing health risks.

Driven by multiple demands, the development of renewable energy has become a key to driving new growth in rural economies. The "13th Five-Year Plan" has also included agricultural and rural energy conservation and emission reduction in the key areas of energy conservation and emission reduction. However, the development of rural renewable energy still faces some problems. Compared with fossil energy and biomass energy, which are relatively easy to obtain, the development of renewable energy has high initial costs and infrastructure construction requirements, and the investment recovery period is also very long, which restricts its large-scale application. At the same time, renewable energy is highly dependent on infrastructure, and the infrastructure in rural areas is relatively weak. During the construction of new energy projects, due to factors such as market demand and electricity prices, renewable energy power may be abandoned or wasted. At this time, accurately depicting the utilization of renewable energy in rural areas and exploring how to improve the efficiency of renewable energy becomes the key to solving the problem.

Therefore, this study will explore the following contents: Firstly, a Super-SBM model considering non-desired outputs will be constructed to calculate the efficiency of rural renewable energy. Combined with the GML index, an overall analysis of the dynamic change trend of rural renewable energy efficiency in China will be conducted. Subsequently, the Dagum Gini coefficient method will be used to analyze the spatial differences in renewable energy efficiency across the country and in the six administrative regions, revealing the sources of overall differences. Finally, by means of the panel Tobit model, the influencing factors of China's renewable energy development will be analyzed from aspects such as green finance, economic development level, urbanization level, education level, and power infrastructure.

The structure of this study is as follows: Literature review - Reviewing the measurement methods and influencing dimensions of rural renewable energy efficiency; Research methods - Describing the methods used and data sources; Results - Describing and analyzing the calculation results; Conclusion - Summarizing the core results of the study and providing corresponding policy recommendations.

2. Literature Review

Renewable energy efficiency is proposed based on energy efficiency. As one of the main ways to reduce ecological footprint, renewable energy is a key to balancing economic development and environmental protection. With policy guidance and efforts from multiple parties, it is currently in a stage of rapid development. The power generation scale is increasing year by year. Some scholars, based on the research method of energy efficiency, have begun to explore the connotation and significance of renewable energy efficiency. Qin & Wang (2021) pointed out in their research at the National Renewable Energy Laboratory of the United States that renewable energy efficiency discusses how to achieve the best environmental protection with less natural resource input to produce a larger economic output. Chen et al. (2022) proposed that with a well-developed financial system, investment in renewable energy research and development can be increased, and it is expected that this will have a positive promoting effect on improving energy efficiency. Renewable energy efficiency is gradually entering the public's view.

With the enrichment of its connotation, the methods that can be used to calculate renewable energy efficiency have also gradually diversified. Among them, DEA is the most widely applied and accepted method in efficiency research-related literature. Farrell (1957) proposed Data Envelopment Analysis (DEA) as a non-parametric method, which shows unique advantages. It can establish connections between multiple decision-making units and judge the optimal individual results. Early on, the basic DEA model, namely the radial model, was often used, but it had problems such as lacking flexibility in weight determination, all DMUs being judged as DEA efficient, and ignoring some weakly efficient situations. Researchers proposed many methods, including the SBM model based on slack variable measurement, the RAM model, the window DEA model, and the Super-DEA model. Li et al. (2022) analyzed the panel data of 36 countries from 2009 to 2018 and used the Super-DEA model and the Malmquist index to estimate the efficiency of renewable energy power generation (PGE). Wu (2023) evaluated the impact of China's investment in energy technology on economic growth and environmental improvement, using the Super-SBM model to measure the green energy efficiency of 30 provinces in China from 2010 to 2019.

After studying the measurement of renewable energy efficiency, many scholars will choose to analyze the influencing factors of the efficiency value, thereby proposing targeted paths for the improvement of renewable energy. The main influencing factors include green finance, economic development level, FDI (foreign direct investment), industrial structure, transportation infrastructure, technological innovation, urbanization, power grid conditions, carbon emission levels, and other factors. Li et al. (2022) explored the determinants of renewable energy power generation efficiency in various countries through a random forest regression model. The results showed that carbon emission levels and industrial structure had the greatest impact on power generation efficiency, followed by power structure, technological level, and economic conditions. Su et al. (2023) empirically studied the driving factors of efficiency levels using the Tobit model. Government intervention degree, innovation level, green finance, economic development level, transportation infrastructure, industrial structure, and renewable energy efficiency were significantly positively correlated. Liu & Chen (2023) used the Tobit model to explore the impact effect of rural infrastructure on the level of agricultural and rural modernization. The results showed that water conservancy and power infrastructure had a positive effect, while transportation infrastructure had a negative effect.

In conclusion, compared with numerous studies related to energy efficiency, research on the efficiency of renewable energy sources is still relatively scarce. Moreover, the relevant studies mainly focus on a specific industry at the national, provincial or regional level of each country. Currently, there is still a certain lack in the research on the efficiency of renewable energy in rural areas. However, as a major agricultural country, the importance of rural renewable energy is beyond doubt. Therefore, based on previous studies, this paper conducts research on the efficiency of renewable energy in rural areas.

3. Research Methods

3.1. Super - SBM Model based on Undesirable Outputs

In order to solve the problem that it is impossible to further distinguish effective decision-making units (DMUs), Tone (2002) defined the super-efficiency SBM model based on the SBM model. To effectively distinguish the efficiency differences among different decision-making units, the formula is as follows:

$$min\sigma = \frac{1+\frac{1}{m}\sum_{i=1}^{m}\frac{S_i^-}{y_{yk}}}{1+\frac{1}{S_1+S_2}\left(\sum_{r=1}^{S_1}\frac{S_r^+}{y_{yk}}+\sum_{t=1}^{S_2}\frac{S_t^{b-}}{b_{tk}}\right)} \tag{1}$$

$$\begin{cases} \sum_{j=1,j\neq k}^{n} x_{ij}\lambda_j - S_i^- \leq x_{ik} \\ \sum_{j=1,j\neq k}^{n} y_{rj}\lambda_j + S_i^+ \geq y_{rk} \\ \sum_{j=1,j\neq k}^{n} b_{tk}\lambda_j + S_i^{b-} \geq b_{tk} \\ 1+\frac{1}{S_1+S_2}\left(\sum_{r=1}^{S_1}\frac{S_r^+}{y_{yk}}+\sum_{t=1}^{S_2}\frac{S_t^{b-}}{b_{tk}}\right) > 0 \end{cases} \tag{2}$$

In Equation (2),σrepresents the sought efficiency value, while x_{ij}, y_{rj}, b_{tk} are the elements in the corresponding input, expected output and non-expected output matrices. S^-- and S^+ are the slack variables for input and output respectively. n denotes the number of decision-making units (DMUs), each of which is composed of three types of factors: m (input), S_1 (expected output) and S_2 (non-expected output). In the matrix, λ is the weight vector.

3.2. GML Index Model

To avoid the drawbacks of the ML index, such as the lack of transitivity and the possibility of unsolvable problems, Oh (2010) proposed the GML index model based on the global reference set. This paper conducts research by applying the GML index model. The GML index and its decomposition formula are as follows:

$$GML^{t,t+1} = GMLEC^{t,t+1} \times GMLTC^{t,t+1} \tag{3}$$

$$GML^{t,t+1} = \frac{1+\vec{D}_0^G(x^t,y^t,b^t;g^t)}{1+\vec{D}_0^G(x^{t+1},y^{t+1},b^{t+1};g^{t+1})} \tag{4}$$

$$GMLEC^{t,t+1} = \frac{1+\vec{D}_0^t(x^t,y^t,b^t;g^t)}{1+\vec{D}_0^{t+1}(x^{t+1},y^{t+1},b^{t+1};g^{t+1})} \tag{5}$$

$$GMLTC^{t,t+1} = \frac{1+\vec{D}_0^G(x^t,y^t,b^t;g^t)}{1+\vec{D}_0^t(x^{t+1},y^{t+1},b^{t+1};g^{t+1})} \times \frac{1+\vec{D}_0^{t+1}(x^t,y^t,b^t;g^t)}{1+\vec{D}_0^G(x^{t+1},y^{t+1},b^{t+1};g^{t+1})} \tag{6}$$

In the above formula, $\vec{D}_0^G(\bullet)$ is the global directional distance function. In this paper, we need to asymmetrically handle the expected output and the non-expected output. Therefore, it is set as $g = (y, -b)$, thereby achieving the goal of maximizing the reduction of non-expected output while increasing the expected output. To sum up, this paper selects the GML index model to explore the dynamic change trend of the efficiency of rural renewable energy in China.

3.3. Dagum Gini Coefficient

Taking into account the issue of overlapping among different data sets, Dagum (1997) first proposed the Dagum-Kini coefficient. The overall degree of difference can be decomposed into three components: intra-group difference degree, inter-group difference degree and the density of super-variables, and has been widely applied.Dagum (1997) decomposed the Dagum Gini coefficient into the following three parts:

$$G = \sum_{j=1}^{k} G_{jj}\, p_j s_j + \sum_{j=1}^{k} G_{jh}\, p_j s_h D_{jh} + \sum_{j=1}^{k} \sum_{h\neq j} G_{jh}\, p_j s_h (1 - D_{jh}) \tag{7}$$

$$G = G_w + G_{nb} + G_t \tag{8}$$

Here, $p_j = n_j/n$ represents the proportion of the sample size n_j in the sample capacity n within the j group, and $sh \equiv n_h\bar{y}_h/n\bar{y}$ represents the proportion of the renewable energy efficiency of h group among all the sample efficiency values within the sample. From $\sum_j \sum_h p_j s_h = 1$, it can be known that the overall Dagum Gini coefficient is the weighted average of the inter-group (intra-group) Gini coefficients G_{jh} of all pairwise combinations of the groups, and the corresponding weights are $p_j s_h$. G_w represents the total contribution of the differences in sample efficiency values within each group to the overall difference, and $G_{gb} = G_{nb} + G_t$ represents the total contribution of all inter-group differences. D_{jh} represents the relative influence between the j region and the h region, and its calculation formula is:

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

$$d_{jh}=\int_0^{\infty} d\,F_j(y)\int_0^{y}(y-x)d\,F_h(x) \tag{10}$$

$$p_{jh}=\int_0^{\infty} d\,F_h(y)\int_0^{y}(y-x)d\,F_j(x) \tag{11}$$

Here, d_{jh} denotes the average of the aggregated values of $y_{ji}-y_{hr}>0$ across all j group and the h group. It can be estimated using the average of the aggregated values of $y_{hr}-y_{ji}>0$ across all j group and the h group. It can be estimated using the same weighting as d_{jh}, with the weighted average of sample values. D_{jh} represents the proportion of the net influence between groups, which is $d_{jh}-p_{jh}$ relative to its maximum possible value $d_{jh}+p_{jh}$. It holds that $d_{jh}+p_{jh}$, and its range is limited to [0,1]. It takes the value of 0 when $\bar{y}_j=\bar{y}_h$, and when there is no overlap between the j group and the h group. Therefore, G_{nb} can represent the contribution of the regional difference net value, and G_t can represent the contribution of the regional supervariation density.

3.4. Tobit Regression Model

The efficiency values calculated by the Super - SBM model usually range from 0 to 2, which are censored data. The Tobit model can take into account the existence of upper and lower bounds of the dependent variable. By using the Tobit model, a more scientific and reasonable empirical analysis of relevant influencing factors can be carried out. Therefore, this paper chooses to use the Tobit model for regression. The basic form of the Tobit model is:

$$\begin{gathered} y_i^*=\beta x_i+\varepsilon_i, i=1,2,\dots,n, \varepsilon_i\sim(0,\sigma^2) \\ y_i=y_i^*, y_i^*>0 \\ y_i=0, y_i^*\leq 0 \end{gathered} \tag{12}$$

Based on this, the regression model for this article is constructed as follows:

$$EFF_{it}=c+\beta_1 LS_{it}+\beta_2 RJ_{it}+\beta_3 CH_{it}+\beta_4 SJ_{it}+\beta_5 DL_{it}+\varepsilon_{it} \tag{13}$$

In the constructed regression model, EFF_{it}_it represents the rural renewable energy efficiency measured by DEA, β_1, β_2, β_3, β_4, $\beta_5$are the regression coefficients of each explanatory variable, ε_{it} is a random variable, and c is a constant term. i and t represent each province and each period respectively, and their value ranges are: $i=1,2,\dots,27, t=2009,\dots,2020$.LS indicates the green finance index, RJ indicates the economic development level, CH indicates the urbanization level, SJ indicates the education level, and DL indicates the power infrastructure.

3.5. Indicator Selection and Data Sources

To better estimate the renewable energy efficiency in rural areas of 27 provinces and autonomous regions in China, this paper refers to the indicators in previous literature (Su, 2023; Cai, 2022) and combines the actual situation of renewable energy in rural areas to construct an input, desirable output, and undesirable output indicator system for measuring the renewable energy efficiency in rural areas, as shown in Table 1.

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Table 1. Rural Renewable Energy Efficiency Input-Output Index System

Index system	Variable	Measurement method
Input	Fixed assets	capital stock in rural areas
	Labor force	Number of employees
	Energy input	Annual electricity consumption in rural areas
	renewable energy Investment	Renewable energy power generation volume
Expected output	Economic output value	Total output value of agriculture, forestry, animal husbandry and fishery
Unanticipated output	Carbon emissions	Carbon emissions from energy consumption

Fixed asset investment: In this paper, the "perpetual inventory method" is used to estimate the actual capital stock of rural areas in each province and city every year. The calculation method is:

$$K_{i,t} = I_t^i + (1-\delta)K_{i,t-1} \tag{14}$$

Here, $K_{i,t}$ and $K_{i,t-1}$ represent the capital stock of region i in the t and t+1 years respectively, δ is the depreciation rate of fixed assets, and $I_t^i$is the investment of region i in the t year. In this paper, δ is set at 10.96%, and the base period is 2000. The initial capital stock of each province is calculated as the ratio of the total fixed capital formation in 2001 to the average depreciation rate of 10.96% and the average investment growth rate from 2001 to 2005 for each province. (Shan, 2008); labor input: To ensure the availability and comparability of the data used, this study selects the total number of employees in the primary industry as an indicator to measure labor input for relevant calculations; energy input: It is measured by annual electricity consumption. Energy input is a basic factor for evaluating economic development and sustainability. The electricity consumption is chosen for measurement because there is a close relationship between electricity consumption and broader energy demand in the economic system; renewable energy input: It is represented by the electricity generation from renewable energy. Based on the common types of renewable energy in rural areas at present, the four types of energy with the largest proportion in rural renewable energy, namely hydropower, wind power, solar power and biogas, are selected as the objects of investigation (Hong, 2020).

Given the diversity of geographical environments and the emphasis of agricultural development in rural areas of China, this paper decides to use the total output value of agriculture, forestry, animal husbandry and fishery in each region as the desired output for evaluating the rural economic level, and takes CO_2 emissions as the undesired output indicator. The specific calculation formula is as follows:

$$CO_2 = \sum_{i=1}^{8} CO_{2,i} = \sum_{i=1}^{8} E_i \times NCV_i \times CC_i \times COF_i \times \frac{44}{12} \tag{15}$$

Among them, CO2 represents the emissions of each province, i represents various types of fossil energy, including raw coal, diesel, gasoline, kerosene, coke, fuel oil, natural gas, and liquefied petroleum gas. E_i is the consumption of the i type of energy, NCV_i is the average lower calorific value, CC_i is the carbon content of the i type of energy, COF_i is the carbon oxidation of the i type of energy, and 44/12 is the mass ratio of a carbon dioxide molecule to a carbon element.Since this paper focuses on renewable energy in rural areas, the urbanization ratios of Beijing, Shanghai, and Tianjin exceed 85%, and the data magnitude differs significantly from

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other research object, regions such as Beijing, Shanghai, Tianjin, Tibet, Hong Kong, Taiwan, and Macau are excluded from the research scope.The provinces and cities within the research scope are divided into six regions for research, as shown in Table 3.The relevant data are obtained from the "China Statistical Yearbook", "China Energy Statistical Yearbook", "China Rural Statistical Yearbook", "China Rural Energy Yearbook", and the statistical yearbooks of each province. The missing data are supplemented by interpolation.

Table 2. Division of Six Administrative Regions

Zoning	Province
Northeast China	Liaoning, Jilin, Heilongjiang
North China	Hebei, Shanxi, NeiMonggu
East China	Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong
South and Central China	Guangdong, Guangxi, Hainan, Henan, Hubei, Hunan
Northwest	Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang
Southwest China	Chongqing, Sichuan, Guizhou, Yunnan

3.6. Identification of Influencing Factors

In the regression model constructed in this paper, the rural renewable energy efficiency calculated by the Super - SBM model above is used as the explained variable, and there are a total of 5 explanatory variables, namely green finance, economic development level, urbanization, education level, and power infrastructure. Green finance can promote the establishment of green industry investment funds, optimize and integrate the green credit support system, encourage the innovation of green financial products, and comprehensively support the development of rural renewable energy, thus having a certain impact on the development of rural renewable energy. Based on existing research, this paper selects the following indicator system to systematically evaluate the development level of green finance in each province. The indicator weights are calculated by the entropy weight method. The core variables and measurement methods of the green finance development index are shown in Table 3 (Bu, 2024).

Table 3. Green Finance Index System

Primary indicator	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 securities	The market capitalization of the six major energy-intensive A-share companies / The total market capitalization of A-shares
Green Insurance	The ratio of agricultural insurance premium income to the total premium income of property insurance business
Green investment	The ratio of environmental pollution control investment to GDP
Carbon finance	Carbon dioxide emissions

Differences in the economic levels of various samples may lead to disparities in renewable energy efficiency. In this paper, the logarithm of the per capita gross output value of agriculture, forestry, animal husbandry, and fishery in rural areas is used as a measure of the economic development level. The continuous advancement of urbanization (CH) may lead to an increase in machinery use, a rapid rise in diesel consumption, and a reduction in available rural land. On the other hand, population migration can promote the increase and establishment of farmers' environmental protection behaviors and awareness. The overall impact is rather complex. In this paper, the proportion of the permanent urban population in the total population is mainly used to represent the urbanization level. The education level (SJ) of rural residents affects their access to renewable energy knowledge, application of technologies, and understanding and implementation of policies, which is an important influencing factor in the development of rural renewable energy. In this paper, the average years of education in rural areas of each province is used to represent the rural education level. The main calculation formula is as follows:

$$SJ_{ij} = \frac{(A_{ij}+B_{ij}\cdot 6+C_{ij}\cdot 9+D_{ij}\cdot 12+E_{ij}\cdot 16)}{F_{ij}} \quad (16)$$

Herein, SJ_{ij} represents the average years of education received by the population in Province i in the year j, A_{ij} denotes the number of $i$lliterates in Province i in the year j, B_{ij} indicates the number of people with primary school education in Province i in the year j , C_{ij} signifies the number of people with junior high school education in Province i in the year j, D_{ij} represents the number of people with high school and technical secondary school education in Province i in the year j, E_{ij} indicates the number of people with college and undergraduate education qualifications in Province i in the year j, and F_{ij} stands for the total population aged 6 and above in Province i in the year j.

Power infrastructure (DL) has a significant impact on the development of rural renewable energy. By strengthening power grid construction and renovation, the power transmission capacity, power supply quality, and power supply reliability of the grid can be improved, ensuring the stable supply of rural renewable energy. At the same time, a complete power infrastructure can reduce the development cost of rural renewable energy. This paper refers to Liu Juan's approach in 2023 and uses the per capita electricity consumption in rural areas as an indicator to measure rural power infrastructure (Liu, 2023). The relevant data are sourced from the "China Statistical Yearbook", "China Rural Statistical Yearbook", "China Industrial Statistical Yearbook", Wind database, "China Ecological Environment Statistics Yearbook", "China Insurance Yearbook", "China Energy Statistical Yearbook", and the statistical yearbooks of various provinces. The specific variables and descriptions are shown in Table 4.

Table 4. Influencing Factors of Renewable Energy Efficiency and Their Descriptions

Variable	Code	Explanation
Renewable energy efficiency	EFF	Above text yields
Green Finance	LS	Entropy Weight Method
Economic development level	RJ	Output value of agriculture forestry, animal husbandry and fishery / rural population
Urbanization level	CH	Urban population/total population
Educational attainment	SJ	Average years of education
Electric power infrastructure	DL	Rural electricity consumption / Rural population

4. Results

The efficiency values calculated by the Super - SBM model with non - desirable outputs are presented in Table 5. In this paper, to better analyze the nationwide differences in rural renewable energy efficiency, we categorize it into three levels-high, medium, and low-based on the disparities among provinces and autonomous regions. The high - efficiency range is [1,+∞), the medium - efficiency range is [0.5,1), and the low - efficiency range is [0,0.5).Overall, due to variances in rural renewable energy resource endowments, economic development levels, and policies across different provinces and autonomous regions, there are significant differences in the calculated development efficiency of rural renewable energy.

In Jiangsu, Shandong, Qinghai, Ningxia, Inner Mongolia, Heilongjiang, Liaoning, Guangxi, and Hainan, the annual development efficiency of rural renewable energy is greater than 1. This indicates that, considering non - desired outputs, these provinces are on the efficient frontier, meaning that the renewable energy in the rural areas of these provinces has been relatively fully developed and utilized. Qinghai, Ningxia, and Inner Mongolia are relatively representative. These three provinces have superior geographical locations, and the development of renewable energy is uniquely advantaged. The abundant land resources and strong solar radiation bring huge potential for solar energy development. At the same time, the northwest region has a plateau landform with relatively small surface undulations, making it one of the regions with the richest wind energy resources in China. Inner Mongolia, in particular, is known as the "Three Gorges of Wind Power." In addition, it also benefits from national policy support, with the key development and construction of several large - scale clean energy bases [82]. Sometimes, the distribution of renewable resource power generation equipment is not completely consistent with the distribution of renewable resources. Thanks to their strong economic foundations and the advantages of relevant local policies, Shandong and Jiangsu still have a large number of solar power plants despite not having particularly abundant solar resources. Key indicators such as the installed capacity ratio and power generation ratio are far ahead in the same region (Wang et al., 2020).

Table 5. Calculation Results of Rural Renewable Energy Efficiency from 2009 to 2020

Province	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Hebei	0.588	0.645	0.615	0.560	0.480	0.458	0.445	0.305	0.290	0.344	0.351	0.414
Shanxi	0.316	0.335	0.336	0.324	0.318	0.308	0.308	0.299	0.323	0.327	0.430	1.037
NeiMonggu	1.148	1.229	1.234	1.225	1.209	1.187	1.185	1.200	1.218	1.259	1.173	1.230
Liaoning	1.114	1.123	1.109	1.074	1.104	1.100	1.139	1.035	1.090	1.051	1.059	1.130
Jilin	1.282	1.238	1.276	1.300	1.014	1.010	0.794	0.586	0.571	0.626	0.651	0.843
Heilongjiang	1.141	1.142	1.159	1.202	1.225	1.235	1.248	1.273	1.340	1.298	1.313	1.291
Jiangsu	1.060	1.058	1.088	1.092	1.091	1.091	1.087	1.172	1.149	1.099	1.096	1.106
Zhejiang	0.301	0.324	0.363	0.337	0.357	0.323	0.391	1.008	1.017	1.030	1.041	1.041
Anhui	0.639	0.696	0.682	0.692	0.582	0.579	0.544	0.704	0.689	0.578	0.615	0.785
Fujian	0.524	0.568	0.659	0.643	1.087	1.127	1.147	1.093	1.088	1.099	1.119	1.157
Jiangxi	0.753	1.029	1.005	1.049	1.013	1.011	0.698	0.748	0.705	0.515	0.518	0.668
Shandong	1.201	1.138	1.146	1.209	1.111	1.133	1.137	1.101	1.094	1.164	1.138	1.012
Henan	1.043	1.206	1.042	1.032	1.010	1.007	1.004	1.049	1.018	0.784	1.012	1.104
Hubei	1.080	1.092	1.102	1.064	1.016	1.005	0.618	0.697	0.667	0.620	0.651	0.685
Hunan	1.046	1.059	1.040	1.022	0.526	0.506	0.467	0.370	0.357	0.356	0.492	1.011
Guangdong	0.391	0.379	0.418	0.386	0.373	0.380	0.359	0.542	0.407	0.463	0.544	0.628
Guangxi	1.321	1.244	1.253	1.174	1.231	1.144	1.139	1.111	1.153	1.179	1.221	1.225
Hainan	1.823	1.663	1.659	1.440	1.464	1.529	1.452	1.453	1.458	1.389	1.446	1.277
Chongqing	0.370	0.371	0.418	0.423	0.547	0.525	0.533	0.610	0.618	0.688	1.001	1.077
Sichuan	1.022	0.685	1.009	1.015	0.604	0.565	0.575	1.052	1.062	1.035	1.054	1.098
Guizhou	0.278	0.270	0.280	0.288	0.302	0.320	0.316	0.420	0.420	0.465	0.470	0.493
Yunnan	0.335	0.327	0.358	0.371	0.367	0.346	0.339	0.353	0.341	0.353	0.396	0.550
Shanxi	0.357	0.400	0.441	0.453	0.493	0.478	0.504	0.519	0.538	0.528	0.484	0.675
Gansu	0.342	0.364	0.348	0.371	0.390	0.374	0.377	0.307	0.325	0.328	0.335	0.375
Qinghai	1.683	1.629	1.597	1.590	1.598	1.557	1.445	1.444	1.403	1.416	1.385	1.438
Ningxia	1.580	1.647	1.854	1.664	2.092	2.209	2.238	1.958	1.574	1.804	1.805	2.128
Xinjiang	0.661	1.058	0.849	0.731	0.612	0.573	0.535	0.501	0.484	0.493	0.498	0.559

Fujian, Zhejiang, Jilin, Sichuan, Chongqing, Jiangxi, Xinjiang, Hubei, Hunan, Anhui, Henan are at the medium level. Among them, Xinjiang is also located in the northwest region, but the efficiency level is not significantly improved mainly due to the problems of wind and solar energy abandonment. Currently, the proportion of flexible regulation of energy in China is relatively low. There are deficiencies in the construction of cross-provincial and cross-regional power transmission channels in the northwest region. Meanwhile, the growth of electricity demand in China is gradually slowing down, and the problems of wind and solar energy abandonment are prominent. As shown in Table 6, the wind and solar energy abandonment rates in Gansu and Xinjiang are around 20% to 30%. There is still room for improvement in the development and utilization of renewable energy (Xu et al., 2018). Hebei, Shanxi, Guangdong, Guizhou, Yunnan, Shaanxi, Gansu are at the low efficiency level. Among them, Shanxi is responsible for transporting energy to multiple provinces across the country. Coal mines are mostly located in rural areas, and the mining process and the high proportion of traditional fossil energy consumption have brought about a large amount of unwanted output, which has led Shanxi to be one of the provinces with the highest energy consumption per unit of GDP. The efficiency of rural renewable energy utilization is poor (Chen et al., 2021).

Table 6. The Rate of Waste Generation from Solar and Wind Energy

Region	Abandoned Photovoltaic Rate	Abandoned Wind Rate
Shaanxi	13.0%	7.3%
Gansu	20.8%	32.7%
Qinghai	6.2%	0.0%
Ningxia	6.4%	4.8%
Xinjiang	21.6%	29.8%
Total	14.1%	24.6%

Subsequently, the dynamic changes in the efficiency of rural renewable energy development were studied through the GML index model. The results are shown in Figure 1. The overall trend is close to a U-shape. After experiencing a negative growth in 2015, it achieved stable growth again. This phenomenon may be due to the fact that although renewable energy development was rapid during the period from 2009 to 2015, there were still internal problems. Due to weak infrastructure and limited electricity demand, during the construction of new energy projects, factors such as market demand and electricity prices may lead to the abandonment or waste of renewable energy power in rural areas (Jia et al., 2021). Since 2016, the government has introduced some policies, focusing on addressing two prominent problems of renewable energy: the increasingly prominent subsidy funding gap and insufficient consumption capacity. For rural areas, the government has also proposed several policies regarding the continuous upgrading and transformation of rural power grids, such as the "New Rural Power Grid Upgrade Project Management Measures" released in 2016. These policies have effectively alleviated the problem of renewable energy power consumption and enabled the GML index of renewable energy utilization efficiency to achieve stable growth (Tu et al., 2020).

Based on the Dagum Gini coefficient, the degree of inter-group differences among the six major administrative regions in China was calculated, and the calculation results of several key years were presented in Figure 2. As can be seen from the figure, the shaded area has shrunk since 2015, indicating that the imbalance in the development of renewable energy among different regions in China has improved. In the early stage of development, due to differences in resource endowment, economy, and technology, the development sequence of each region was different. With the introduction of a series of universal and guiding policies by the country to ensure that all regions could obtain corresponding support and development opportunities, the technologies of hydropower, wind power, and photovoltaic power generation have become

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more mature and easier to promote, promoting the balanced and high-quality development of renewable energy in China.

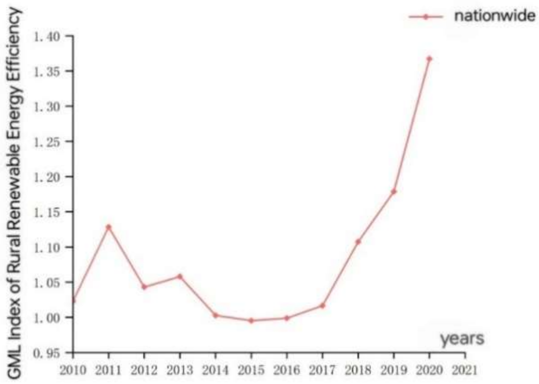

Figure 1. Graph of the change in the GML index of rural renewable energy efficiency

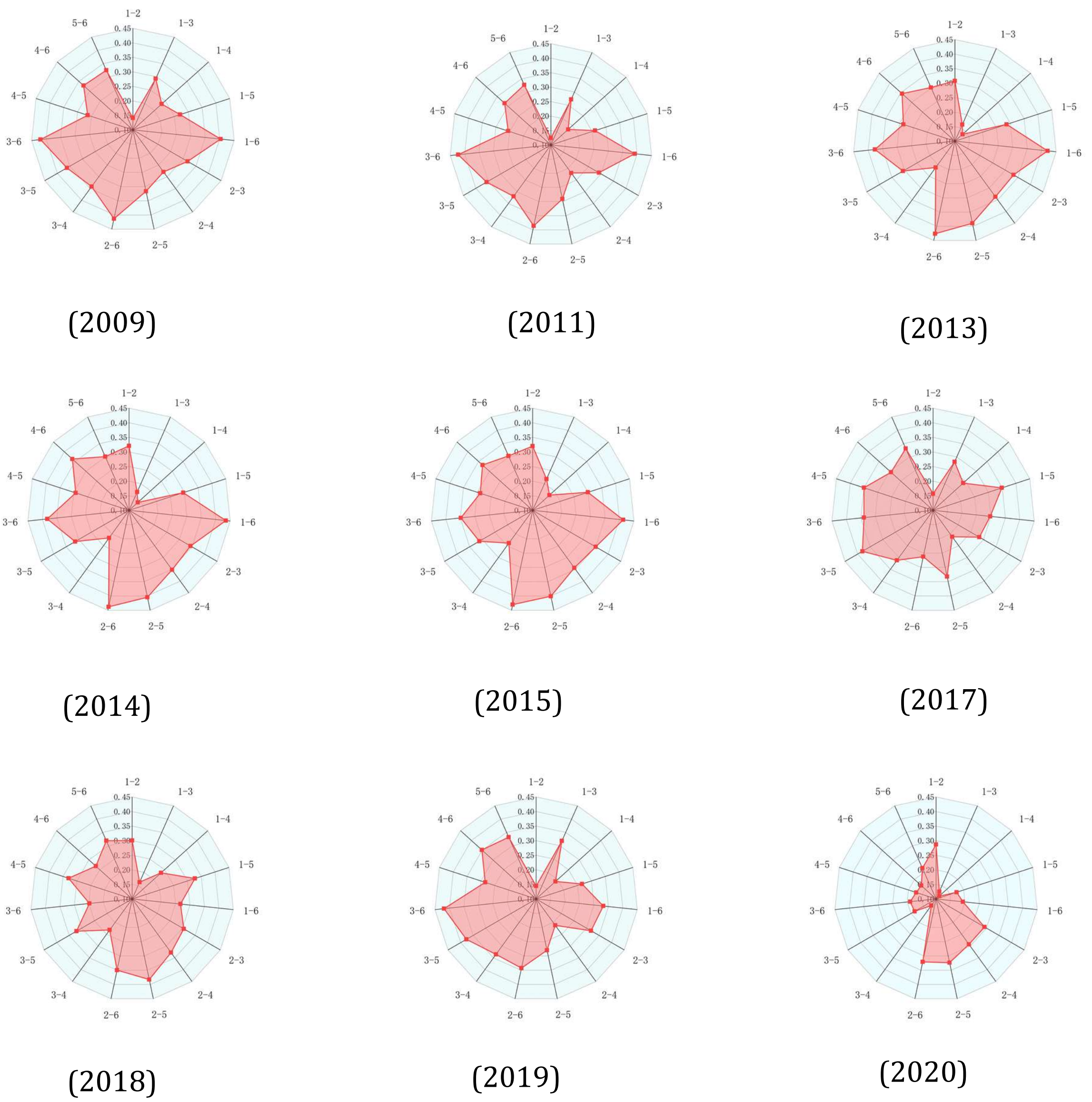

Figure 2. Diagram of Changes in Inter - group Differences

From the specific values of the inter-group differences, the sample values of the western region and other regions are exactly ranked in the top six. The average inter-group differences among Northeast, North China, East China, Central South, and Southwest regions are 0.360, 0.373, and 0.364 respectively. The average inter-group differences among North China, East China, and Northwest regions are 0.326 and 0.328 respectively. From 2005 to 2020, the resource endowment of the western region was significantly stronger than that of other regions, and the consumption of renewable energy in each region showed a trend of gradually decreasing from the west to the central and then to the east (Li et al., 2024). This led to different development paths for the western region from other regions, ultimately resulting in relatively large differences between them.

Secondly, the overall differences in the efficiency of rural renewable energy can be decomposed into three components: intra-group contribution, net inter-group contribution, and cross-regional density. The calculated values and contribution rates of each component are shown in Figure 3. It can be seen that the inter-group differences are the main source of the overall differences in the efficiency of rural renewable energy across different regions in China. Among them, the super-variable density among different regions shows a gradually increasing trend.

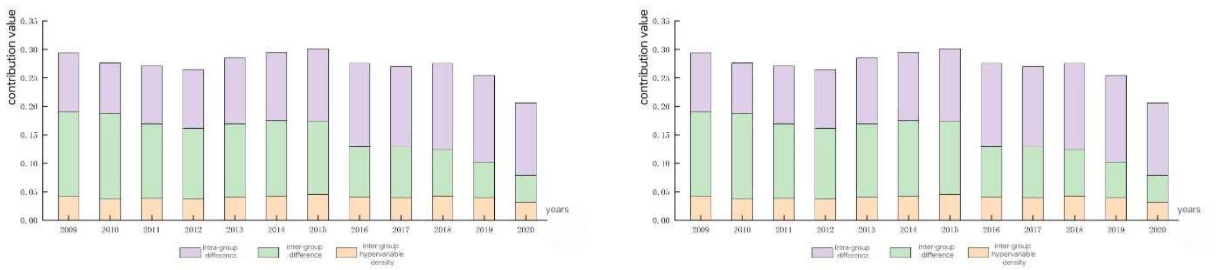

Figure 3. Spatial Differences and Sources of Rural Renewable Energy Efficiency

Although polarization characteristics are observed in the overall situation and in many regions, the distribution interval of efficiency values has been continuously shifting to the right. By the end of the sample period, i.e., in 2020, the values clustered in a relatively high range with a distinct peak. This may be because the "Implementation Opinions on Accelerating Energy Development and Construction in Poverty - Stricken Areas to Promote Poverty Alleviation" stated that by 2020, rural power for motive use would be basically fully covered, and the construction of photovoltaic poverty alleviation projects for 2 million registered poor households would be completed. China achieved this goal in 2020, with rural areas basically achieving full coverage of stable and reliable power supply services. The photovoltaic poverty alleviation projects have made substantial progress, and the utilization of renewable energy has reached a new level. The overall extensibility has contracted, the absolute gap has decreased, the level of differentiation within the region has declined, and the development trend is favorable. However, although the efficiency values in North China and East China have increased, their extensibility has expanded. Moreover, the North China region has obvious spatial polarization characteristics, with a relatively high overall level of differentiation, which is worthy of attention.

This paper uses Stata18 to conduct a Tobit regression on the influencing factors of rural renewable energy efficiency. Taking the rural renewable energy efficiency value as the dependent variable, and the green finance index, economic development level, urbanization level, education level, and power infrastructure as independent variables, the regression results are shown in Table 9:

Table 7. Tobit Regression Results of Influencing Factors

Variable	Coef.	Std.Err.	z	P>|z|	[95% conf.	interval]
LS	0.0131955	0.04843	0.27	0.785	-0.081723	0.1081138
CH	-0.0220228***	0.00554	-3.98	0.000	-0.032874	-0.0111718
RJ	0.285247***	0.07501	3.80	0.000	-0.138224	0.43227
SJ	0.0716257*	0.03719	1.93	0.054	-0.001280	0.144531
DJ	0.8344525***	0.24570	3.40	0.001	-0.352904	1.316001
_cons	-0.0842112	0.34948	-0.24	0.810	-0.769180	0.6007576
Note: *,**,*** respectively indicate significance levels of 10%, 5% and 1%.						

According to the regression results, among the five explanatory variables, four are significant. Firstly, the urbanization level is significantly negatively correlated with rural renewable energy efficiency. As mentioned earlier, the impact of the urbanization level on renewable energy efficiency is complex and multi - faceted, which can also be reflected in the regression coefficient. The regression coefficient of the urbanization level on renewable energy efficiency is at the lowest level among all variables, indicating that although the negative impact is significant, its degree is not high. During the process of urbanization, on the one hand, it brings negative effects such as labor force loss, increased use of fossil energy, and the squeezing of the living space of renewable energy. On the other hand, it also has positive effects such as enhanced environmental awareness and improved infrastructure. We should leverage strengths and avoid weaknesses, pioneer the implementation of a new type of urbanization, promote the intensive use of resources, and achieve an improvement in rural renewable energy efficiency and rural green and sustainable development. Secondly, the economic development level, education level, and power infrastructure hypothesis show a significant positive impact, which is in line with expectations. The economic development level has the highest coefficient among several variables, indicating a relatively large impact. This shows that the investment, technology - introduction capabilities, and the increase in farmers' energy demand accompanied by economic development can effectively promote the development of rural renewable energy efficiency. The education level has a significant positive impact on the development of renewable energy efficiency and is an important driving factor for renewable energy efficiency. The continuous improvement of power infrastructure can lay a solid foundation for the development of renewable energy and is an important guarantee for ensuring the stable supply of renewable energy. Finally, the green finance index has a certain positive impact on renewable energy efficiency, but it is not significant. This may be because current green finance products are mainly targeted at the construction of large - scale rural renewable energy projects, mostly in the rural photovoltaic industry, which is not conducive to comprehensive development. Secondly, the publicity and promotion of green finance in rural areas have not been effective, the popularization of green finance knowledge is at a low level, and extensive demonstration and implementation have not been carried out in rural areas. Therefore, there is still great room for development in rural areas (Pang et al., 2023).

5. Conclusion

This paper first takes the provincial - level renewable energy efficiency in China from 2009 to 2020 as the research object. Based on the Super - SBM model considering undesirable outputs, it calculates the rural renewable energy efficiency. Subsequently, combined with the GML index, it analyzes the characteristics of static and dynamic efficiency. Then, through the Dagum Gini coefficient method and the kernel density estimation method, it explores the spatial differences and dynamic changes of rural renewable energy efficiency. Finally, it conducts an analysis of influencing factors with the help of the panel Tobit model. The empirical results confirm that:

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The rural renewable energy efficiency exhibits significant spatio - temporal heterogeneity due to differences in resource endowments, economic levels, geographical locations, development strategies, and policies. During the study period, the GML index of rural renewable energy efficiency shows a U - shaped characteristic. After the state introduced a series of policies regarding the consumption of renewable energy in 2016, it achieved stable growth again. The overall inter - group difference value at the national level has decreased, and the unbalanced development of renewable energy in various regions has improved to some extent. The inter - regional difference has always been the main source of the overall difference. Although polarization characteristics exist in the overall situation and in many regions, the distribution interval of efficiency values continuously shifts to the right, showing an upward trend. The extensibility of North China and East China has expanded, and North China has obvious spatial polarization characteristics, which is worthy of attention. The economic level, education level, and power infrastructure have a significant positive impact on renewable energy efficiency. The urbanization level is significantly negatively correlated with rural renewable energy efficiency, but the regression coefficient is at the lowest level, indicating a relatively complex impact. Green finance has a certain positive impact, but the effect is not significant. Based on the above conclusions, this paper puts forward the following policy recommendations to provide a theoretical reference for policymakers to formulate policies to improve the renewable energy efficiency at the national and regional levels.

(1)Construct a green financial system to support the development of rural renewable energy. The development of green finance in rural areas can be promoted from the following aspects: actively guide the establishment of green industry investment funds; improve the green credit support system in terms of loan terms and the design of financing models to provide financing guarantees for rural renewable energy projects; encourage and guide the innovation of green financial products, and explore the issuance mechanism of special bonds for rural renewable energy through methods such as "investment - loan linkage and combination of equity and debt"; vigorously develop green insurance products to provide a solid guarantee for the construction of rural renewable energy projects.

(2)Promote technological progress and popularize the application of new technologies. Integrate hard and soft technologies well to achieve the R & D and innovation capabilities of "hard" technologies and the orderly improvement of "soft" technologies. At the level of hard technologies, technological progress requires the government to take the lead, increase capital investment in technological innovation, and facilitate cooperation between renewable energy enterprises, relevant research institutions, and universities to solve bottleneck problems. At the level of soft technologies, promote the development process of hard technologies and their effective application in rural areas by optimizing systems, management, etc. Improve the construction of energy development systems, increase the proportion of renewable energy in rural energy consumption, and pave the way to enhance the local acceptance of new technologies.

(3)Attract rural elites to return to their hometowns and optimize rural grass - roots organizations. Local governments can vigorously implement the "Elite Return" plan, introduce preferential policies, and provide support for returning elites. Build platforms such as return - to - hometown entrepreneurship parks and agricultural innovation bases to provide room for the returning youth to display their talents. Hold hometown - affection talks, rural cultural festivals and other activities to enhance their sense of belonging and identity to their hometowns. Additionally, cultivate new - type farmers with knowledge and skills to help local farmers better understand and apply renewable energy policies, knowledge, and technologies.

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