Efficiency assessment of green technology innovation of renewable energy enterprises in China: A dynamic data envelopment analysis considering undesirable output

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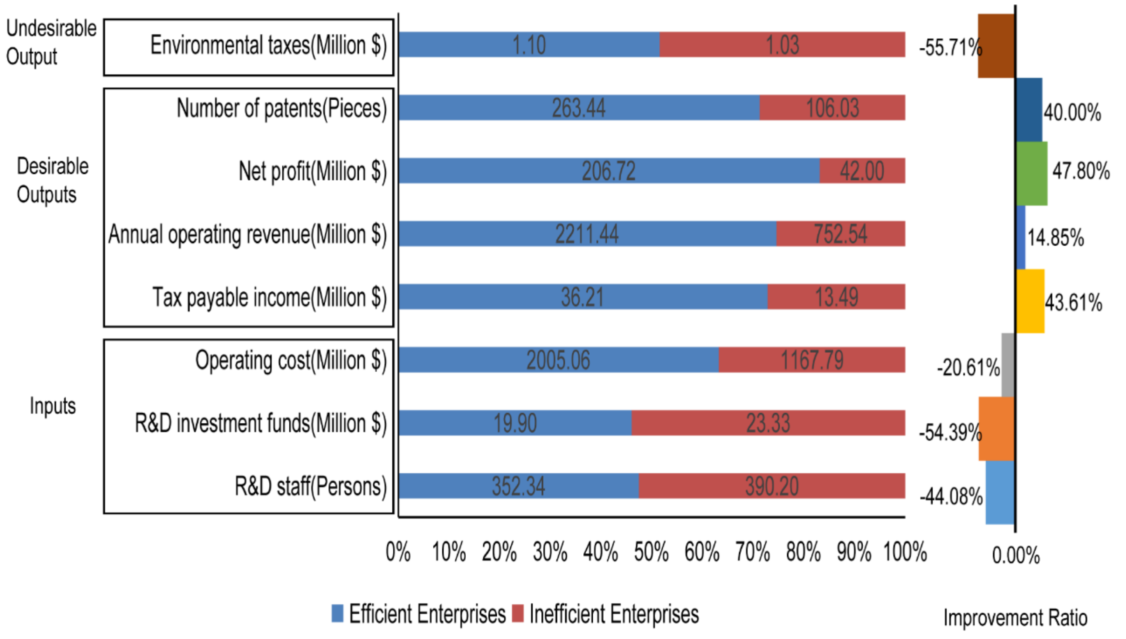
Abstract: The rapid development of renewable energy enterprises has produced important benefits for contemporary efforts to address serious environmental pollution and depletion of fossil energy resources. However, the environmental pollution that exists in the production and operation of enterprises has been ignored, and so an objective evaluation of this issue is becoming urgent. This paper established an evaluation index system for green technology innovation efficiency, and used dynamic Data Envelopment Analysis (DEA) considering undesirable output to measure the green technology innovation efficiency of renewable energy enterprises, and the improvement potential of ineffective enterprises was put forward. The results show that: (1) The green technology innovation of renewable energy enterprises needs to be greatly improved. The average efficiency score of sample was 0.385 over four years, and only 16 enterprises were found to operate effectively; (2) When effective and inefficient DMUs were compared, the latter were found to have significant output shortfalls, especially in environmental tax, and were found to show an improvement potential of 55.71 percent; (3) The efficiency analysis of different types of renewable energy enterprises found that the green technology innovation efficiency score of nuclear energy enterprises was the highest, and rapidly rose; (4) The green technology innovation efficiency of renewable energy enterprises in the western region greatly exceeded the efficiency of the eastern and central regions. The efficiency evaluation results could not only provide a guidance for central and local governances to optimize the structure of renewable energy sector, but also potentially provide a reference for the operation and management of renewable energy enterprises in China.

Keywords: Green Technology Innovation, Efficiency assessment, Data envelopment analysis, Renewable Energy Enterprises

Graphic abstract



1、Introduction

In recent decades, the development and utilization of renewable energy has received growing attention all over the world. Renewable energy enterprises are a strategic emerging industry that China is vigorously developing, and their future prospects in the country look promising. ‘Guiding Opinions on Energy Work in 2018’ , which was issued by the National Energy Administration of China (2018), proposed to accelerate the development of renewable energy, and as a result the proportion of non-fossil energy consumption increased to about 14.3%. It has been estimated that non-fossil energy will account for 20% of primary energy consumption by 2030. The substitution of renewable energy has become increasingly prominent.

However, it has been commonly found that the production of renewable energy is not completely clean. Renewable energy enterprises are essentially manufacturing industries, but the environmental pollution problems that emerge from the production process is often ignored (Li et al. 2019). For example, many studies showed that the process of photovoltaic cell production produces a lot of pollutants (Hou et al. 2016). Besides, other forms of renewable energy, such as biomass, geothermal, nuclear and wind energy, also lead to environmental pollution problems in the production stage (Jacobson 2009).

In line with ‘the Paris climate change agreement’, China’s manufacturing sector should make large-scale changes and work towards a cleaner production. The ‘Made in China 2025’ (2015) initiative sought to comprehensively upgrade the country’s economic performance and focused on innovation-driven and green development. Green technology innovation applies ecological-economic principles to save resources and energy, eliminate or reduce environmental pollution and degradation and achieve long-term sustainable development that produces economic, environmental and social benefits (Zhou 2014). In comparison with traditional technologies, green technology innovation emphasizes coordinated economic and environmental development (Braun and Wield 1994). Researchers who have engaged with green technology innovation evaluation have produced results with important theoretical and practical implications. Examples include regional green technology innovation efficiency (Luo and Liang 2016), green technology innovation efficiency in high-end manufacturing industry (Li et al. 2018) and factors influencing green technology innovation (Guo et al. 2018), and so on. Green technology innovation has been a new trend of technological innovation development and an effective way to achieve sustainable development. Therefore, the efficiency of green technological innovation in renewable energy enterprises is a subject that deserves a more deeply discussion.

A few studies refer to the technological innovation efficiency of renewable energy enterprises. Renewable energy mainly includes biomass, geothermal, hydrogen, nuclear, ocean, solar and wind energy (Zeng et al. 2019). Most renewable energy studies have focused at a macro-level, such as an industry or geographic zone. Wang et al (2020) gave a comprehensive evaluation of China’s regional renewable energy development. Lin and Xu (2018) used the vector autoregressive (VAR) model to examine the main driving forces of the renewable energy industry. Fewer studies have examined micro-level enterprises, such as renewable energy enterprises. Zhang et al (2016) conducted a comprehensive analysis and evaluation of the operating performance of 58 domestic photovoltaic enterprises by applying the DEA method, and found that all Chinese photovoltaic enterprises have lower operating performance because of lower technical efficiency. Zhao and Wei (2019) measured the technical efficiency of China's wind power enterprises by applying DEA, and analyzed technical differences in different regions. Li and Liu (2018) evaluated the efficiency of enterprise technological innovation by using the research and development (R&D) data of 20 new energy vehicle enterprises in China. These studies do not analyze the gaps in green technology innovation efficiency of different types of renewable energy enterprises. Wang et al (2016) assessed the innovation efficiency of the technology research and development and marketing process of 38 Chinese renewable energy enterprises in the period 2009-2013 by applying a non-radial data envelopment analysis method. Zeng et al (2018) evaluated the investment efficiency of the new energy industry in China. Çelikbilek and Tüysüz (2016) established a DEA model to analyze the overall efficiency of the different forms of renewable energy. Zeng et al (2020) assessed the comprehensive performances of different renewable energy schemes by using DEA method. Existing studies on renewable energy mainly focused on its economic and social dimensions, while ignoring environmental factors. The problem of environmental pollution in the production and operation of renewable energy enterprises in China has not been studied. What’ s more, quantifying potential improvements in each indicator is critical to supporting the decision-making process (Jiang et al. 2020). Previous research mainly focused on efficiency evaluation and failed to provide improvement suggestions for each enterprise, for lacking further analysis in input excesses and output shortfalls. Therefore, it is necessary to analyze the current situation and deficiency of green technology innovation efficiency in renewable energy enterprises to make up for this research gap. Given the critical role of renewable energy enterprises in cleaner production and the significance of green technology innovation, this paper measured the green technology innovation efficiency of China’ s renewable energy enterprises by applying the dynamic SBM (Slacks-Based Measure) model and makes up for this research gap.

Data Envelopment Assessment (DEA) has been widely used in the performance evaluation of various productive activities (Mohammadi et al. 2011). This method obtains the relative efficiency of decision-making units (DMUs) with multiple inputs and multiple outputs based on linear programming (Mousavi-Avval et al. 2011). One of the most significant advantages of this method is that it does not assume a correlation between input and output indicators (Hosseinzadeh-Bandbafha et al. 2016), and this means the evaluation results are objective. However, the traditional DEA model is inadequate for performance evaluation when the development of a company is a dynamic process that extends across more than one period, and this is because the traditional model does not consider operational efficiency across different periods (Alizadeh et al. 2020). The dynamic SBM model proposed by Tone and Tsutsui (2010) perfectly solved this problem because it gives a dynamic evaluation and incorporates the carry-over terms in the model. Dynamic SBM helps decision-makers to understand the effect of past decisions on future performance.

Green technology innovation efficiency was defined here as the input-output efficiency of green technology innovation activities (Lin et al. 2018). This paper selected 74 renewable energy enterprises as samples to evaluate green technology innovation efficiency. The purpose of the study is (1) to evaluate the efficiency of green technology innovation in renewable energy enterprises in China; (2) to identify the potential for improvement in inefficient renewable energy enterprises. The results of this paper can help the government departments and corporate administrators analyze the current situation of green technology innovation in renewable energy enterprises and put forward the improved policies that will effectively promote the green development of renewable energy enterprises in China.

2、Methodology and Data

2.1 Dynamic SBM model

DEA is a method to evaluate the relative efficiency of decision making units (DMUs) with various input and output indicators (Charnes et al. 1978). Traditional DEA models measure the relative efficiency of DMUs in a specific period but cannot evaluate the performance of DMUs over time (Kaleibari et al. 2016). To deal with this concern, some studies used the Malmquist Productivity Index (Xie et al. 2021) and Malmquist-Luenberger Productivity Index (Shen et al. 2019) to evaluate performance in two consecutive periods. The Malmquist Index neglects the carry-over activities between two consecutive terms in dynamic evaluation. When inter-relations of consecutive periods should be taken into account for efficiency analysis, then dynamic DEA must be used (Kao 2013).

Based on the traditional DEA, the dynamic SBM model proposed by Tone and Tsutsui (2010) gives a dynamic evaluation and incorporates the carry-over terms in the model. Many scholars have done some research and achieved certain results (Zhou et al. 2008). Li (2016) formulated an input-orientated dynamic SBM model to measure the operational efficiency of Chinese PV producers. The technological innovation of enterprises is a dynamic process. Therefore, based on the traditional DEA model, this paper will use the dynamic SBM model to comprehensively evaluate the efficiency of green technology innovation in renewable energy enterprises.

Suppose there are n DMU_s (j=1, 2, …, n) over T periods (t=1, 2, …, T). At each period, DMUs use m inputs (i=1, 2, …, m) and i carry-over terms (i=1, 2, …, ngood) to produce s outputs (i=1, 2, …, s). Let x_{iot}, y_{iot} denote the observed input and output values of DMU j at period t, respectively. The notation z_{ijt}^{good} (i=1, 2, …, ngood; j=1, 2, …, n; t=1, 2, …, T) denotes the good link (desirable carry-over) values where ngood is the number of good links. The dynamic SBM model is extended from the slacks-based measure (SBM) framework proposed by Tone (2001) and Pastor (1999). The non-oriented models aim to reduce input-related factors and to enlarge output-related factors simultaneously (Tone and Tsutsui 2010). For the sake of our research, we define the non-oriented efficiency measure by solving program below:

$$\rho_o^* = min\frac{\frac{1}{T}\sum_{t=1}^{T} w^t\left[1-\frac{1}{m}\left(\sum_{i=1}^{m}\frac{w_i^- s_{it}^-}{x_{iot}}\right)\right]}{\frac{1}{T}\sum_{t=1}^{T} w^t\left[1+\frac{1}{s+ngood}\left(\sum_{i=1}^{s}\frac{w_i^+ s_{it}^+}{y_{iot}}+\sum_{i=1}^{ngood}\frac{s_{it}^{good}}{z_{iot}^{good}}\right)\right]} \quad (1)$$

The continuity of link flows (carry-overs) between terms t and t+1 can be guaranteed by the following condition:

$$\sum_{j=1}^{n} z_{ijt}^{\alpha}\lambda_j^t = \sum_{j=1}^{n} z_{ijt}^{\alpha}\,\lambda_j^{t+1}(\forall i; t = 1,\cdots,T-1\ ) \quad (2)$$

where the symbol α stands for good, bad, free or fix. This constraint is critical for the dynamic model, since it connects term t and term t+1 activities.

Using these expressions for production, we can express DMU$_o$ (o=1, ……, n) as follows:

$$x_{iot} = \sum_{j=1}^{n} x_{ijt}\lambda_j^t - s_{it}^-\,(i = 1,\cdots,m; t = 1,\cdots,T)$$

$$y_{iot} = \sum_{j=1}^{n} y_{ijt}\lambda_j^t + s_{it}^+\,(i = 1,\cdots,s; t = 1,\cdots,T)$$

$$z_{iot}^{good} = \sum_{j=1}^{n} z_{ijt}^{good}\,\lambda_j^t - s_{it}^{good}\,(i = 1,\cdots,ngood; t = 1,\cdots,T)$$

$$\sum_{j=1}^{n}\lambda_j^t = 1(t = 1,\cdots,T)$$

$$\lambda_j^t \geq 0, s_{it}^- \geq 0, s_{it}^+ \geq 0, s_{it}^{good} \geq 0 \quad (3)$$

where s_{it}^-, s_{it}^+, s_{it}^{good} are slack variables denoting, respectively, input excess, output shortfall, link shortfall. Using an optimal solution$\left(\{\lambda_0^{t*}\},\{s_{ot}^{-*}\},\{s_{ot}^{+*}\},\{s_{ot}^{good*}\}\right)$ to (1), (2) and (3) we define the non-oriented term efficiency as follows:

$$\rho_{ot} = min\frac{1-\frac{1}{m}\left(\sum_{i=1}^{m}\frac{w_i^- s_{iot}^{-*}}{x_{iot}}\right)}{1+\frac{1}{s+ngood}\left(\sum_{i=1}^{s}\frac{w_i^+ s_{it}^{+*}}{y_{iot}}+\sum_{i=1}^{ngood}\frac{s_{iot}^{good*}}{z_{iot}^{good}}\right)}(t = 1,\cdots,T) \quad (4)$$

The overall efficiency during the whole period is the average of the term efficiency, which is described as follows:

$$\rho_o^* = \frac{1}{T}\sum_{t=1}^{T}\rho_{ot}^* \quad (5)$$

The non-oriented overall efficiency (ρ_o^*) is a ratio between 0 and 1. If $\rho_o^* = 1$, DMUo is considered non-oriented overall efficient. If $\rho_{ot}^* = 1$, then DMU$_o$ is considered to be non-oriented term efficient for period t. Moreover, DMU_o is overall efficient if and only if $\rho_{ot}^{*} = 1$ for all the periods.

2.2 Inputs and outputs

Reasonable inputs and outputs were selected to accurately assess the relative efficiency of the DMUs. In order to evaluate the efficiency of green technology innovation in renewable energy enterprises, the index system is constructed from many dimensions, such as economy, society and environment. The minimum number of indicators is selected to ensure the integrity of the evaluation elements. After the conducting correlation analysis, we found a strong correlation between operating cost and annual operating revenue. But sensitivity analysis showed that operating cost or annual operating revenue have little effect on the efficiency of green technology innovation. We hoped to get the potential improvement value of operating cost and annual operating revenue, and we kept two indicators.

Investment in green technology innovation activities in the manufacturing industry includes research and development (R&D) personnel input and R&D expenditure. Many scholars regarded that the funding that enterprises commit to R&D has the most direct impact on green technology innovation in enterprises (Zhong et al. 2011). For R&D expenditure, this paper selected the capital expenditure in R&D as the investment index of green technology innovation (Sun et al. 2017). R&D personnel specialize in R&D activities, including the whole process in green technology innovation activities. The labor cost that the enterprise pays for R&D can be measured by the data of the personnel engaged in R&D (Becheikh et al. 2006). Therefore, this study used R&D costs as the financial input and the number of R&D staff as the human resource input (Lin et al. 2018). The operating cost of an enterprise is a factor that directly influences its business activities, and operating cost are therefore an important input variable that is used to evaluate green technological innovation (Luo and Liang 2016).

Output indicators can be divided into knowledge output and product economic output. Patent is the most direct reflection of technology innovation in a certain period. It takes a long time to progress from patent application to authorization. Instead of patent grants, the number of patent applications reflects the true output level of technology innovation activities in this period (Luo et al. 2019). Therefore, we chose the number of patent applications made by enterprises as a good proxy indicator for R&D outputs. In referring to indicators used by previous research (Li and Liu 2018), we selected annual operating income, net profit and tax payable as indicators of economic and social output.

In the selection of green output variables, variables such as carbon emissions, environmental pollution index, three waste emissions, total industrial water consumption, smoke and dust emissions, and total SO_2 emissions have been frequently selected as environmental variables (Bai et al. 2018). Due to the difficulty of measuring enterprises' environmental indicators, we creatively selected the sewage charges or environmental taxes as the undesirable outputs of renewable energy enterprises. Both the sewage charges and environmental taxes have been mentioned in the annual reports of listed enterprises.

Environmental regulations have both a positive “compensation effect” (Lee et al. 2010) and a negative “crowding-out effect” (Filbeck and Gorman 2004) on enterprise innovation. Environmental regulation measures require enterprises to carry out technological innovation and improve production processes. Meanwhile, environmental pollution control requires a large amount of capital, which tends to pressurize an enterprise’s R&D funds. This paper regards environmental regulation as an undesirable output of green technology innovation, which has a reasonable theoretical basis.

2.3 Data source

Based on the data available and complete, we extracted data about 74 renewable energy enterprises from 2015 to 2018. In referring to the ‘Industry Classification Guidelines of Listed Companies’ published by China Securities Regulatory Commission, this paper selected renewable energy enterprises and removed enterprises with negative total profits and those marked with a ‘delisting’ risk during this period. According to the remaining data ,74 renewable energy enterprises were selected. All 74 sample enterprises were listed on China’s Shanghai and Shenzhen Stock Exchange, and are engaged in the production and manufacture of photovoltaic, wind, hydro, nuclear, and biomass energy (Table 1 sets out the sample enterprises). The selected samples are all listed enterprises, which are representative and have an important research significance. The data for input and output variables were taken from the annual reports of listed enterprises, the Wind database, and the China Stock Market and Accounting Research Database (CSMAR). The number of enterprises’ s annual patent application, meanwhile, was taken from the Chinese patent database. Table 2 presents the specific input-output variables and data sources.

Table 1 Sample Enterprises

No.	Stock code	No.	Stock code	No.	Stock code	No.	Stock code	No.	Stock code
1	601678.SH	16	002729.SZ	31	600184.SH	46	600482.SH	61	600796.SH
2	600960.SH	17	300092.SZ	32	600151.SH	47	002163.SZ	62	000601.SZ
3	002167.SZ	18	002358.SZ	33	002056.SZ	48	600516.SH	63	600111.SH
4	600746.SH	19	600458.SH	34	600485.SH	49	002318.SZ	64	000786.SZ
5	600160.SH	20	600152.SH	35	600220.SH	50	600328.SH	65	300034.SZ
6	000697.SZ	21	000539.SZ	36	600586.SH	51	300004.SZ	66	600259.SH
7	000723.SZ	22	600192.SH	37	002516.SZ	52	603333.SH	67	002002.SZ
8	002709.SZ	23	600112.SH	38	601012.SH	53	002366.SZ	68	600432.SH
9	002386.SZ	24	000970.SZ	39	000815.SZ	54	601985.SH	69	603113.SH
10	002648.SZ	25	600163.SH	40	002050.SZ	55	000990.SZ	70	300072.SZ
11	002125.SZ	26	002046.SZ	41	000533.SZ	56	600538.SH	71	000825.SZ
12	600550.SH	27	600207.SH	42	600089.SH	57	600864.SH	72	600281.SH
13	002478.SZ	28	000969.SZ	43	002623.SZ	58	600475.SH	73	600792.SH
14	600256.SH	29	601991.SH	44	300125.SZ	59	002630.SZ	74	002053.SZ
15	600619.SH	30	603806.SH	45	002189.SZ	60	002201.SZ		

Table 2 List of Variables

Type	Variables	Source
Inputs	R&D staff R&D investment funds Operating cost	Annual reports of listed enterprises; Wind database; CSMAR database
Desirable outputs	Number of patents	China Patent Database
	Tax payable income Annual operating revenue Net profit	Annual reports of listed enterprises; Wind database; CSMAR database
Undesirable output	Sewage charges or environmental taxes	Annual report of listed enterprises

3. Discussion

3.1 Overall efficiency analysis

In this study, the dynamic SBM model was established by MaxDEA Ultra 8 (No 812-182) software. This model can consider time change and carry-over factors, and its results are more accurate and reliable than those provided by the traditional SBM model (Kao 2013). In the period 2015-2018, the average efficiency score (for 74 samples) was 0.385, and only 16 enterprises were found to operate effectively.

Green technology innovation efficiency is defined as the product of pure technical efficiency and scale efficiency, and it is a comprehensive evaluation of the DUMs' resource allocation capability and resource utilization efficiency (Li et al. 2017). Figure 1 shows that, in the period 2015-2018, the efficiency of green technology innovation generally initially increased and then decreased. Efficiency peaked in 2016 and declined afterwards.

Pure technical efficiency was the production efficiency affected by factors such as management and technology (Li et al. 2017). Pure technical efficiency similarly initially increased and then decreased in the relevant period, and in other respects approximated to the green technology innovation efficiency trend. This showed that the overall level of technical and management efficiency declined. Scale efficiency referred to the production efficiency affected by scale factors, and reflected the gap between the actual scale and the optimal production scale (Li et al. 2017). The overall scale efficiency of renewable energy enterprises in China has been closer to the optimal production scale. It is also consistent with the results of Xu (2018).

A series of favorable industrial policies, including the 'Renewable Energy Law' and the 'National Renewable Energy and New Energy National Science and Technology Cooperation Plan') (2015), established an economic environment that would support renewable energy enterprises. Therefore, Chinese enterprises that sought to enter the renewable energy field would enjoy clear policy advantages, and this would help to optimize the overall scale of the renewable energy enterprises.

The key and core technologies of China' s renewable energy enterprises were highly dependent on foreign countries, which is due to the lack of independent innovation ability of Chinese enterprises. The core technology bottleneck was the key obstacle that hindered the development of China's renewable energy enterprises. Therefore, the efficiency of green technology innovation in Chinese renewable energy enterprises mostly depended on scale efficiency, which is consistent with the result measured of Zhao (2019).

With regard to application structure, renewable energy lacked sufficient application channels. In 2018, the amount of abandoned water electricity was about 69.1 billion kWh / year; the amount of abandoned wind electricity was 27.7 billion kWh / year; the amount of abandoned photovoltaic power was 5.49 billion kWh / year; and the amount of abandoned electricity was still high. Figure 2 showed the situation of China's renewable energy abandoned power. To address this situation, China's renewable energy enterprises were adjusting their industrial structure (Lin and Xu 2018). Green technology innovation shifted from a reliance on scale to a technological emphasis. This is confirmed that renewable energy enterprises needed to strengthen their investment in technology and management to ensure their long-term development.

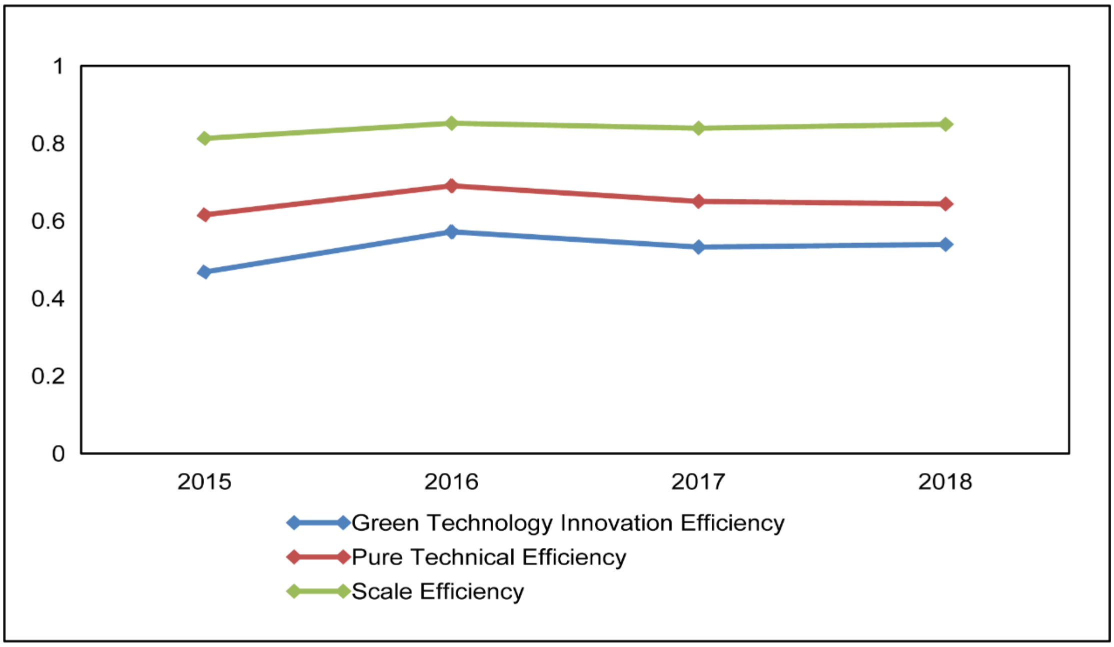


Fig.1 Changes in Green Technology Innovation Efficiency

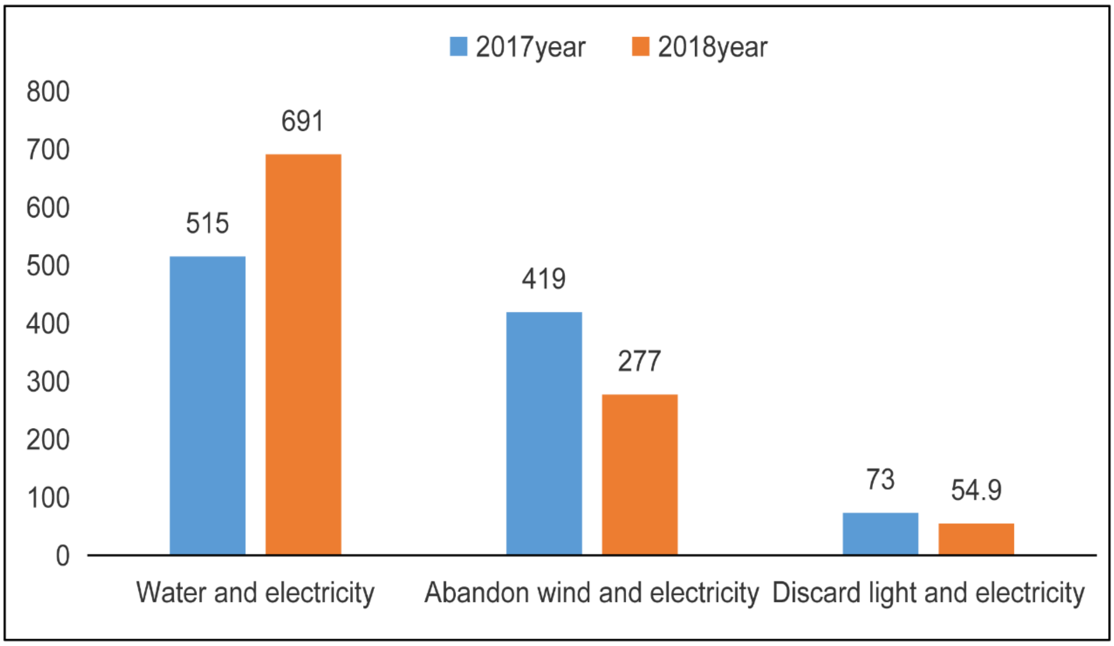


Fig.2 Abandoned electricity of major new energy sources in China (Unit: 100 million kWh)

Source: National Energy Administration; Foresight Industry Research Institute

3.2 Potential improvement

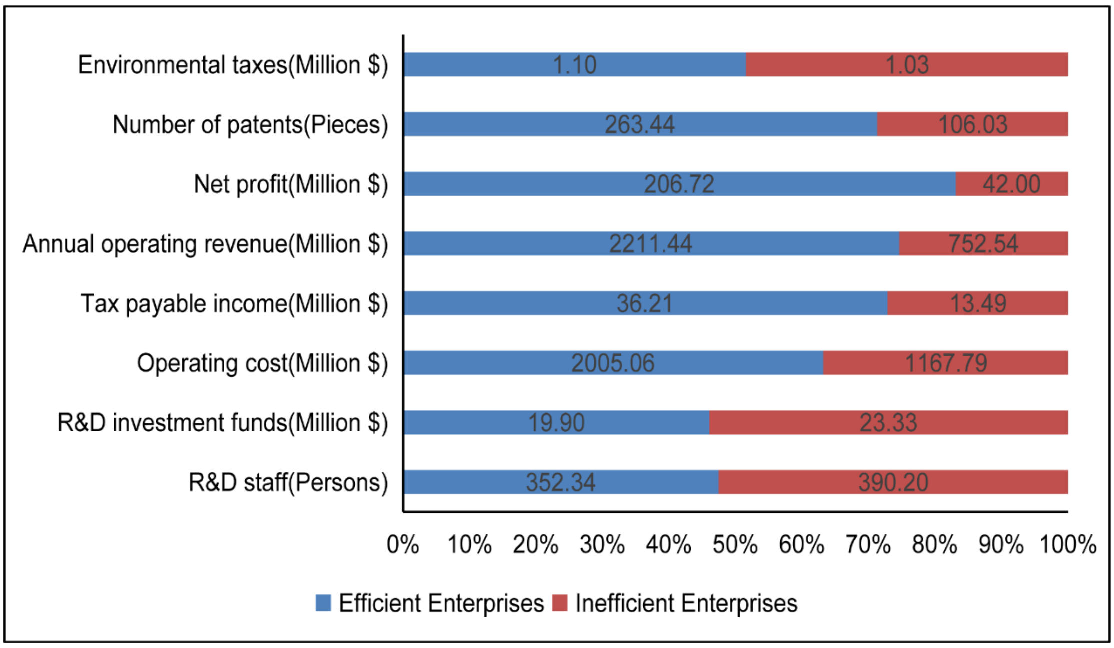


Fig.3 Comparison of eight variables in efficient and inefficient enterprises.

Figure 3 provided a statistical comparison of efficient and inefficient enterprises, and showed that the inputs and undesirable output of efficient enterprises are obviously lower when compared against inefficient enterprises. The average R&D investment funds of efficient enterprises were 131.42 million CNY (around US $19.9 million), while that of inefficient enterprises was 1554.07 million CNY (around US $23.33 million). Efficient enterprises recorded a net profit of 1365.16 million CNY (around US $206.72 million), which was far higher than inefficient enterprises (277.36 million CNY, around

US $42.0 million). Moreover, there was no significant difference in environment taxes, as the environmental efficiency of enterprises is generally a weakness.

In addition to providing overall efficiency scores, software MaxDEA can also provide target improvement for each DUM, including all inputs and outputs (Cheng et al. 2020). In other words, taking efficient samples as benchmark, it can quantify potential improvement of each item for inefficient DMUs to improve scores of inefficient enterprises. Previous studies have analyzed the efficiency of green technology innovation in enterprises, but there is no further optimization of input excesses and output shortfalls. This paper has overcome the deficiency and obtained more scientific and useful assessment results. The results of improvement potential are shown in Table 3.

Table 3 The improvement potential of all Enterprises in this study

	Origin	Projection	Improvement	Improvement ratio
R&D staff (persons)	431	241	-190	-44.08%
R&D investment founds（million USD）	28.00	12.77	-15.23	-54.39%
Operating cost（million USD）	1155.55	917.39	-238.16	-20.61%
Tax payable income (million USD)	19.95	28.65	8.70	43.61%
Annual operating revenue (million USD)	1252.03	1437.94	185.91	14.85%
Net profit (million USD)	96.81	143.09	46.28	47.80%
Number of patents(pieces)	70	98	28	40.0%
Environmental tax (million USD)	0.70	0.31	-0.39	-55.71%

Note: Negative values in improvement represent input excesses or undesirable output excesses that should be reduced, positive values represent the desirable output shortfalls that need to be made up for.

Under the current output level, ineffective renewable energy enterprises had diverse levels of excess input, specifically R&D staff, R&D investment funds and operating costs. In the case of the 74 enterprises, R&D staff, R&D funds and operating costs could be respectively reduced by 190 employees, 100.58 million CNY (around US $15.23 million) and 1572.78 million CNY (around US $238.16 million). Under the current input level, inefficient renewable energy enterprises focused too much on economic income, but ignored environmental benefits. For undesirable output, environmental taxes could be reduced by 2.58 million CNY (around US $0.39 million).

Overall, according to the improvement ratio, there is substantial room for improvement in both input and output indicators. China's renewable energy enterprises could improve the efficiency of green technology innovation by improving the existing deficiencies, which would promote the coordinated development of the economy, environment and society.

3.3 Analysis of efficiency of different types of renewable energy enterprises

Due to the differences between enterprises, the changes in green technology innovation efficiency of different types of renewable energy enterprises are closely related to the characteristics of enterprises itself. Therefore, it was necessary to analyze the differences between green technology innovation efficiency from the perspective of renewable energy types. This paper divided the sample enterprises into 6 types in accordance with production types and the production products of each renewable energy enterprise: energy storage, wind energy, photovoltaic, nuclear energy, biomass energy and new materials.

Table 4 showed the number of samples whose green technology innovation efficiency reached the effective value in the period 2015-2018. Of these, enterprises with efficient green technology innovation efficiency values were relatively small in number. In the given period, the total fluctuated greatly, attesting to a clear instability.

Figure 4 and Figure 5 showed the trend of changes in the green technology innovation efficiency of Chinese renewable energy enterprises over the past four years. Energy storage, photovoltaic and new materials enterprises showed a tendency to initially rise and then decrease in the period, and peaked between 2016 and 2017. Nuclear power enterprises rose rapidly over the four-year period, which is consistent with the findings of Wang (2016). However, the development of green technology in biomass energy enterprises was slow, and little research has engaged enterprises of this kind. The efficiency evaluation results could help government departments to analyze the current situation of green technology innovation in renewable energy enterprises and optimize the structure of renewable energy sector. A renewable energy ‘Guidance Catalogue for Industrial Structure Adjustment’ (2019), which was issued by the National Development and Reform Commission , highlighted improvements in the technical level of renewable energy as a top priority. However, China's renewable energy enterprises will have a substantial distance to go before "innovation" and "green" can be achieved simultaneously.

Table 4 Number of enterprises with Score = 1

		2015	2016	2017	2018
Type	Quantity	Score=1	Score=1	Score=1	Score=1
Stored Energy	11	2	2	2	3
Wind Energy	15	6	6	7	8
Photovoltaic	21	7	8	6	6
Nuclear Energy	7	2	4	4	4
Biomass Energy	8	0	2	0	3
New Material	12	5	5	4	3
Total	74	22	27	23	27

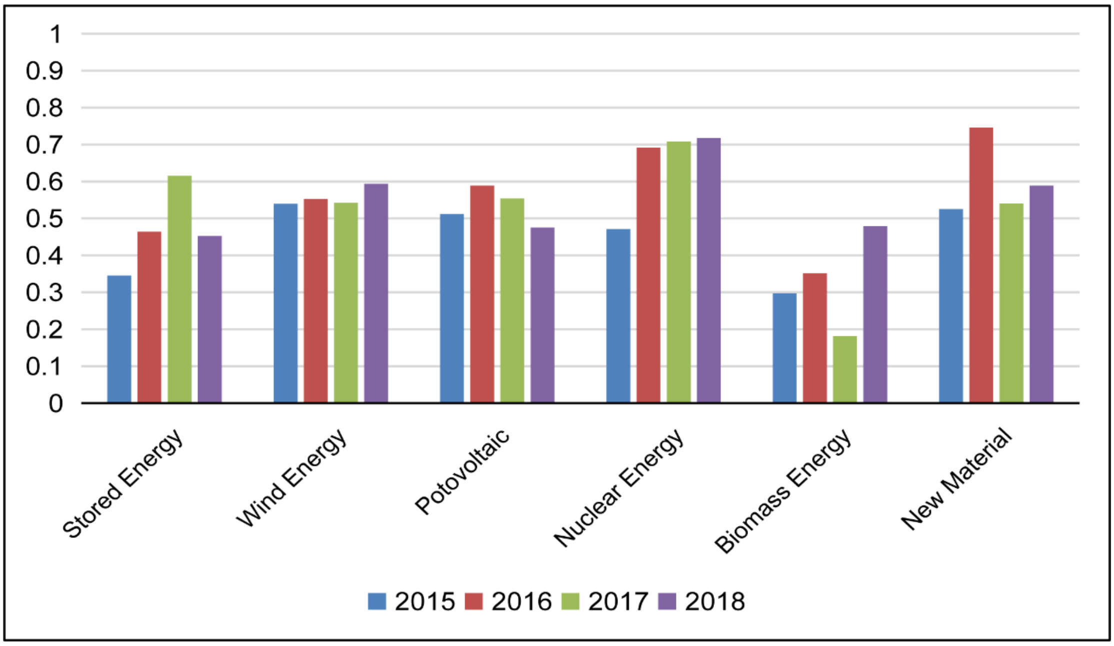


Fig.4 Efficiencies for different types of renewable energy enterprises

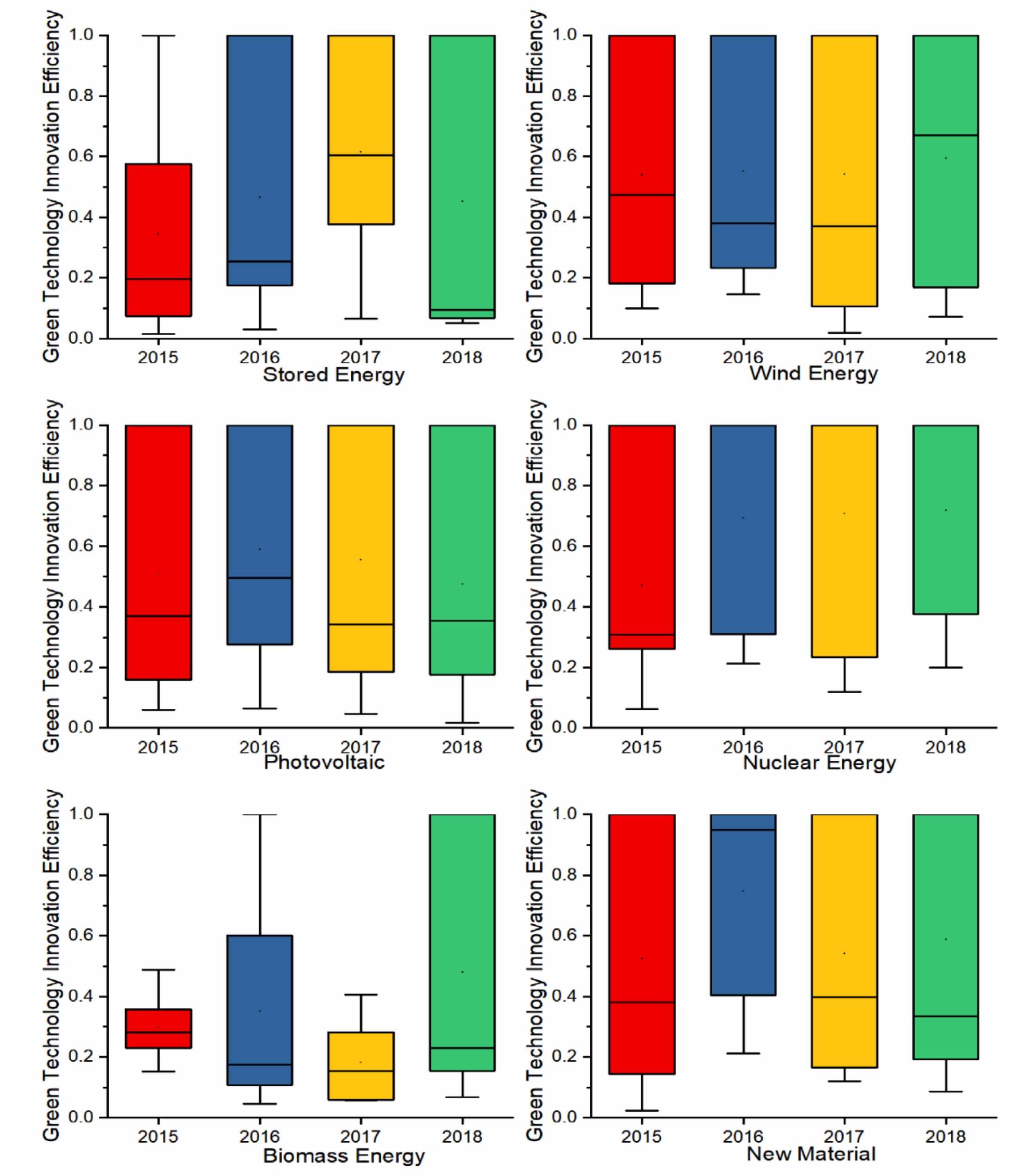
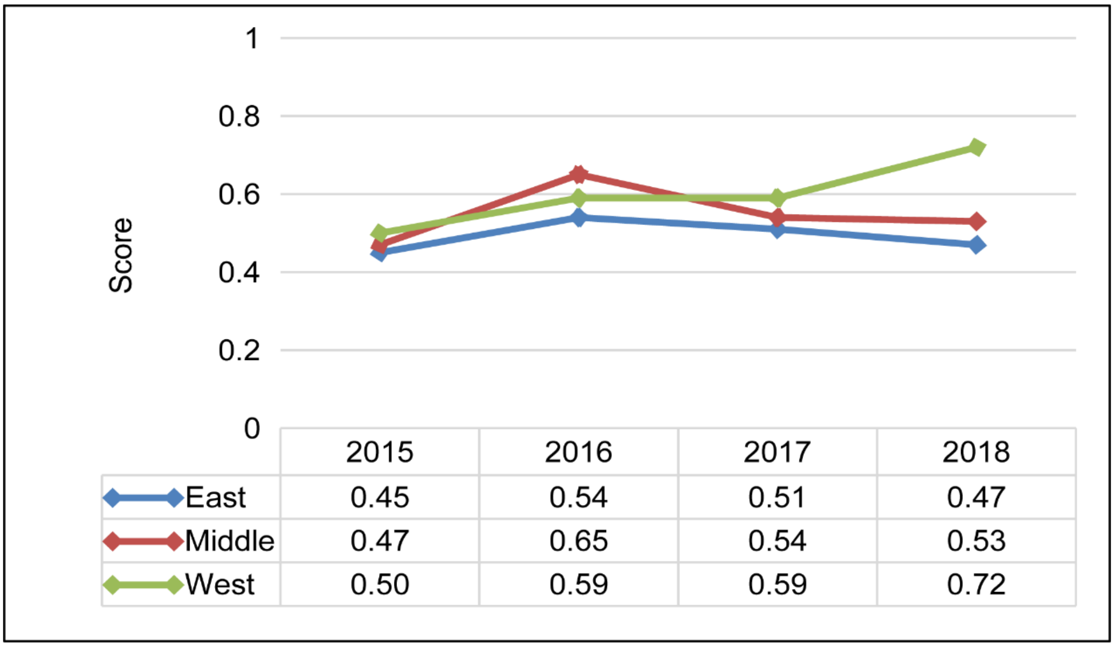


Fig.5 Boxplots of the efficiency of different renewable energy enterprises

3.4 Analysis of regional differences in renewable energy enterprises

This paper referred to the criteria for the division of economic regions that is outlined in the regional coordinated development strategy, and classified the sample enterprises in accordance with their location and therefore divided them into eastern, central and western regions. Figure 6 showed the green technology innovation efficiency levels in the three regions. This figure clarified that the efficiency of the three regions was basically the same in 2015. In the period since 2017, however, the efficiency of the western region has gradually increased, while gradually declining in the eastern and central regions. The efficiency of green technology innovation in the western region has greatly surpassed that in the eastern and central regions. Zhao (2019) similarly drew this conclusion, and attributes it to resource advantages, greater R & D investment and higher levels of technological progress. According to the distribution of green technology innovation efficiency changes, government departments could implement regional renewable energy policies for different regions.

Current tendencies suggest this trend will persist into the future. The ‘promotion in the rise’ strategy has contributed to rapid green technology innovation efficiency improvements in recent years. This was because enterprises in the western region can take advantage of low labor costs, low competitive pressure and outstanding regional advantages (Dong and Shi 2019). In addition, they have also benefitted from rich resources reserve in the region, such as wind, geothermal and solar energy. Renewable energy enterprises such as photovoltaic and wind power generation were cited in the Catalogue of Encouraging Industries in the Western Region that was issued by the National Development and Reform Commission. The Chinese government’ s support for the construction of the western region is conducive to the development of renewable energy enterprises.



	2015	2016	2017	2018
East	0.45	0.54	0.51	0.47
Middle	0.47	0.65	0.54	0.53
West	0.50	0.59	0.59	0.72

Fig.6 Comparison chart of efficiency by region

4、Conclusions and recommendations

With the rapid development of renewable energy enterprises in China, the environmental pollution in the production and operation of enterprises are gradually prominent. However, the issues have been ignored, and a comprehensive, quantitative and objective evaluation of them is becoming urgent. DEA is considered as an effective performance evaluation tool to solve this problem. In this paper, 74 renewable energy enterprises were evaluated by the dynamic SBM model from multiple dimensions including economy, environment and society.

The main results are as follows: (1) the average efficiency score of samples was 0.385 over four years, of which only 16 enterprises operate effectively; (2) compared with the effective DMUs, the inefficient DMUs had significant shortfalls in the outputs, especially in environmental tax, with the improvement potential of 55.71%; (3) different types of renewable energy enterprises showed significant differences in green technology innovation efficiency. Among them, the green technology innovation efficiency of nuclear energy enterprises is the largest, and it also rise rapidly; (4) the green technology innovation efficiency of renewable energy enterprises in the western region has far exceeded the efficiency of counterparts in the eastern and central regions.

Based on the results above, the targeted recommendations are presented as follows to improve the efficiency of green technology innovation in renewable energy enterprises: (1) the government must put forward policies to encourage green technology research and development; (2) the government should try to narrow the gap between the eastern, central and western regions and promote the coordinated development of all types of renewable energy enterprises; (3) enterprises should continue to strengthen the awareness of environmental protection, from the traditional "governance"-based end of governance to "prevention"-based clean production changes.

The dynamic SBM model applied to this paper identifies effective DMUs as the best practices, calculating slack improvement value of inputs and outputs to maximize the efficiencies of inefficient enterprises. There is no doubt that the methodology and applications in this study are useful for government departments and enterprise managers. It can help government and enterprise managers to evaluate the green technology innovation and realize the effective improvement of renewable energy enterprises.

The dynamic SBM model was used to evaluate the green technology innovation efficiency for four consecutive years, which is more comprehensive and accurate than the static efficiency value analysis. On the other hand, it is worth noting that DEA can only effectively assess the relative, and not absolute, efficiency. In addition, this paper has not analyzed the potential factors affecting the efficiency of renewable energy enterprises. Therefore, further research can combine the DEA with the regression method to analyze how internal and external factors influence efficiency value.

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Authors' contributions

Tingting Jiang: Conceptualization, Writing- Reviewing and Editing, Resources, Supervision

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