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Efficiency Evaluation and Comparative Study of Regional Wind Power Industry in China Based on CO2 Emission Reduction

Fang-rong Ren[1]* , Ze Tian [2], Qin-wen Xiao [1] , and Tai-Yu Lin [3]

[1] Business School, Hohai University, No.8 Focheng West Road, Nanjing 211100, China, 180213120008@hhu.edu.cn; xqw19951105@hhu.edu.cn;

* Correspondence: 180213120008@hhu.edu.cn

[2] School of Business Administration, No.200 Jinling North Road, Hohai University, Changzhou 213022, China, tianze21@126.com ;

- [3] Department of Economics, Soochow University, No.56, section 1, Guiyang Street, Zhongzheng
- District, Taipei 10048, Taiwan; eickyla@gmail.com

Corresponding author:

Name: Fangrong Ren

Postal address：Business School, Hohai University, No.8 Focheng

West Road, Nanjing 211100, China.

E-mail: 180213120008@hhu.edu.cn

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Abstract: In 2015, the new installed capacity of global renewable energy power generation exceeded the newly installed capacity of conventional energy power generation, marking a structural change in the construction of the global power system. With the continuous improvement of wind energy utilization technology, the global wind power industry has developed rapidly in recent years. The world's available wind energy is 20 billion kilowatts and has become one of the most economical green power. In China, wind power has become the third largest source of electricity, with the installed capacity increasing from 3.1% in 2010 to 9.2% in 2017. In 2017, China's new installed capacity was 19,660 MW, accounting for 37.45% of the world's new installed capacity. This paper evaluates and compares the efficiency of wind power industry in the four regions of eastern, central, western and northeastern China through EBM models based on radial and non-radial factors. This paper discusses the contribution of China's wind power industry to CO_2 emission reduction from the relationship between installed capacity efficiency and CO_2 emission reduction efficiency. The conclusions show that the overall efficiency score and ranking of wind power in 2013-2017 is the best in the eastern region, followed by the northeast region and the western and central regions.

Keywords: CO_2 emission reduction, wind power industry, EBM, efficiency evaluation

1. Introduction

Reducing the burning of fossil energy and accelerating the development and utilization of renewable energy have become the consensus of all countries in the world. In 2015, the newly added capacity of renewable energy power generation in the world exceeded the newly installed capacity of conventional energy power generation for the first time, marking a structural change in the construction of the global power system. In 2017, the amount of new renewable energy generated has reached 70% of the net increase in global power generation.

According to relevant estimates, the total amount of wind energy in the world is about 130 billion kilowatts, of which 20 billion kilowatts of wind energy is available, which is 10 times larger than the total amount of water energy that can be developed and utilized on the earth, up to 53 trillion kWh per year. At the end of the 19th century, Denmark began to use wind energy to generate electricity. At present, wind power, as a mature technology and environmentally friendly renewable energy, has been developed and applied on a large scale in the world. In 2019, the cost of the world's lowest cost wind power project is expected to reach or even be less than 3 cents / kWh, making it one of the most economical green power.

China has large reserves of wind energy and a wide distribution. The wind energy reserves on land alone are about 253 million KW. In April 2019, the Global Wind Energy Council (GWEC) released the latest "2018 Global Wind Report" (GWEC Global Wind Report 2018), showing that the new installed capacity of the global wind energy industry in 2018 is 51.3 GW. China became the first country to enter the 200GW club for wind power installations, with a total installed capacity of 221GW. On the one hand, the scale of installed capacity has been maintaining a rapid momentum, which is followed by the shutdown, abandonment and the lack of wind power consumption in some areas. In 2018, China's wind curtailment was 27.7 billion kWh.

The main directions of research on wind power efficiency are as follows: The first is the study of the relationship between wind power and energy consumption, such as Leao et al. [1], Tan et al. [2], Yang et al. [3], Yang et al. [4], Dawn et al. [5] and Gao et al. [6]; the second is policy development and development strategy research in the wind power industry, such as Yu et al. [7], Zhang [8], Tan et al. [9], Motie et al. [10] , Yu et al. [11] , Li et al. [12] and Kazimierczuk [13]; and the third, studies on the efficiency of wind power utilization, such as Lu et al. [14], Kaldellis [15], Katinas et al. [16], Pieralli et al. [17], Liu et al. [18], Saglam [19] and Zhao [20] .

Previous studies have explored wind power policies, efficiency assessments and environmental impacts, and lacked research on the relationship between clean wind power and CO_2 emissions reduction. The research method is dominated by linear or nonlinear methods (SBM). However, the linearity does not consider the Slack factor, and the nonlinearity lacks the linear characteristics. This paper evaluates and compares the efficiency of wind power industry in the four regions of eastern, central, western and northeastern China through the EBM model based on linear and nonlinear factors, and discusses the contribution of China's wind power industry to CO_2 emission reduction from the relationship between installed capacity efficiency and CO_2 emission reduction efficiency.

The organization of this paper runs as follows. Section 2 is the literature review. Section 3 covers the research method. Section 4 presents the empirical results and discussions. Section 5 is conclusions.

2. Literature review

Some scholars have studied the relationship between wind power and power systems, energy consumption, and the environment. Leao et al. [1] argue that wind energy used on the grid on a large scale, bringing many changes to the planning and operation of power systems, transmission and distribution infrastructure, wind power reserves and forecasts, and energy markets. Tan et al. [2] analyzed the policy orientation, existing problems, and operational efficiency and grid integration standards of wind power manufacturing in China from a macro perspective. The results show that the use of wind power can save standard coal consumption and effectively reduce emissions. Yang et al.[3]found that wind power is more competitive in terms of energy conservation and emission reduction than other power generation systems. If the recovery of the wind turbine disassembly stage is taken into account, energy savings of 46.7% and material recovery rate of 0.467 can be achieved. Yang et al. [4] conducted a quantitative study on the synergistic effects of wind power penetration and energy efficiency in China. Dawn et al. [5] described the promotion policies adopted by the Indian government to rationally utilize renewable energy sources and expand domestic energy security. Gao et al. [6] found that desert wind farms have the least impact on the environment, followed by grassland and woodland wind farms.

Many scholars are committed to policy development and strategy research in the wind power industry. Yu et al. [7] believe that the Spanish electricity market implements a wind energy convertible electricity price policy, which can provide greater flexibility for wind power companies to operate wind power assets, and provide options for coordinating wind power seasonality, power demand and electricity price changes. Zhang et al. [8] studied China's wind power policy from 2005 to 2011 and found that the achievements of China's wind power generation can be attributed to the political motives and institutional arrangements and institutional changes of the Chinese government. Hou [21] used the system dynamics model of wind power to simulate wind power policy results based on complex systems. Tan et al. [9] analyzed the utilization status of renewable energy resources such as wind energy in China, and proposed some improvement measures. Motie et al. [10] innovatively proposed the use of grid-connected electric vehicles and wind resources to address financial support issues in a competitive environment. Yu et al. [11] believe that China's wind energy utilization efficiency is low in the past decade, and it is imperative to introduce reforms in the power industry such as retail-side competition. Li et al. [12] applied the fitting method, game theory and empirical analysis to discuss 134 China's onshore wind power policies from 2005 to 2015. The results show that China's wind power policy has problems such as unreasonable planning, imperfect support policies, immature trading systems, and uncoordinated actions of stakeholders. Kazimierczuk [13] reviewed recent developments and policy frameworks for wind energy in Africa. Park et al. [22] believed that the geographical conditions of South Korea make large offshore wind farm projects relatively independent of various factors. Gupta et al. [23] analyzed the relationship between fiscal mechanisms and wind power capacity in 15 countries and 10 states in the United States from 2006 to 2017. Shen et al. [24] found that different levels of government exercise approval power will affect the growth of regional wind power installed capacity. Lin et al. [25] showed that the demand-pull policy promotes wind power technology innovation through the on-grid tariff policy, and the higher the wind power on-grid tariff, the larger the wind power technology patent stock. Zhang [26] determined the causal relationship between energy intensity targets and wind power generation capabilities. The results showed that mandatory energy goals can promote the development of renewable wind energy in the provinces.

In the research of efficiency/level of wind power utilization, many scholars use the empirical methods such as DEA and factor analysis to measure. Lu et al. [14] proposed that wind energy efficiency, yield and maintenance factor can be used as evaluation indicators to establish a comprehensive evaluation system. According to Kaldellis [15], compared with traditional power plants and photovoltaic power plants, wind energy have advantages. Katinas et al. [16] calculated the wind energy efficiency of the capacity factor C-P of large wind turbines installed in different regions of Lithuania. Pieralli et al. [17] analyzed the production losses of 19 wind turbines in four wind farms in Germany and found that losses accounted for 27% of the maximum electricity production. Liu et al. [18] used the data envelopment analysis model to analyze the efficiency of the wind power industry from 2008 to 2012 and found that the performance of the wind power industry is on the rise. Feng et al. [27] introduced and evaluated the distribution of wind resources in China. The wind power generation base of 10gw scale was introduced in detail, and the wind power equipment manufacturers were evaluated. Fan [28] combined with wind power basic indicators, development scale indicators and utilization efficiency indicators to build wind power utilization indicators. The results show that the total utilization level of wind power in China is comparable to that of the United States. Ewertowska et al. [29] introduce a method that combines DEA, LCA, and stochastic modeling to assess the environmental efficiency of a product under uncertainty. It proves that there may be significant differences in efficiency scores between nominal and random conditions. Saglam [19] evaluated the relative efficiency of wind power performance in 39 states. The results show that more than half of the states are operating wind power efficiently. Tobit regression shows that early installed wind power is more costly and less productive than currently installed wind power. Zhao and Zhen [20] measured the technical efficiency of Chinese wind power enterprises. The results show that the wind power industry has inefficiencies caused by uneconomic scale.

The main differences between this study and other studies are: 1. Using the combination of radial and non-radial EBM, the wind power efficiency of 30 provinces in 4 regions of China is evaluated and compared, and the method selection is improved and breakthrough. 2. Using wind power generation and CO_2 emission reduction as output indicators, it can more effectively evaluate the power generation efficiency and environmental efficiency of wind power, the relationship between wind power input and output and environmental benefits.

3. Research Method

Charnes et al. [30] developed the CCR DEA model with a constant returns scale assumption, after which Banker et al. [31] extended these a variable returns scale assumptions to propose a BCC model that measured technical efficiency and scale efficiency. However, as both CCR and BCC were radial DEA models that ignore non-radial slacks when evaluating efficiency values, Tone [32] proposed the non-radial estimation methods to present SBM(slack Decision-Making Unit) efficiency values of between 0 and 1. However, as the SBM was a non-radial DEA model, it failed to consider the radial characteristics; that is, it ignored the characteristics that had the same radial proportions. To address the shortcomings in both the radial and non-radial models, Tone and Tsutsui [33] then proposed the EBM (Epsilou-Based Measure) DEA model, that was input-oriented, output-oriented, and non-oriented,

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and was able to resolve the shortcomings in radial and non-radial DEA models.

Tone and Tsutsui's [33] EBM DEA description for the basic model and solutionwas as follows:

Non-oriented EBM

Suppose there are n DMU, where $DMU_j = (DMU_1, DMU_2, \ldots\ldots, DMU_k, \ldots\ldots, DMU_n)$. m kinds of inputs $X_j = (X_{1j}, X_{2j}, \ldots\ldots, X_{mj})$, and s outputs $Y_j = (Y_{1j}, Y_{2j}, \ldots\ldots, Y_{sj})$, The efficiency value of DMU :

$$K^* = \min_{0,\eta,\lambda,s^-,s^+} \frac{\theta - \mathcal{E}_x \sum_{i=1}^{m} \frac{w_i^- s_i^-}{x_{i0}}}{\eta + \mathcal{E}_y \sum_{i=1}^{s} \frac{w_i^+ s_i^+}{y_{i0}}}$$

Subject to $\theta X_0 - X_\lambda - S^- = 0,$ (1)

$\eta Y_0 - Y_\lambda + S^+ = 0,$

$\lambda_1 + \lambda_2 + \cdots + \lambda_n = 1$

$\lambda \geq 0,\ \ S^- \geq 0,\ \ S^+ \geq 0.$

Y : DMU output,

X : DMU input,

S^- : slack variable,

S^+ : surplus variable,

W^- : the weight of the input I, $\sum W_i^- = 1\ \ (\forall_i\ \ W_i^- \geq 0)$,

W^+ : the weight of the output S,$\sum W_i^+ = 1\ \ (\forall_i\ \ W_i^+ \geq 0)$,

$\mathcal{E}_x$: The set of radial θ and non-radial slack,

$\mathcal{E}_y$: The set of radial η and non-radial slack,

If DMU0 $K^* = 1$ is the best efficiency for a Non- oriented EBM, if an inefficient DMU wants to achieve an appropriate efficiency goal, the following adjustments are needed:

$$X_0^* = X\lambda^* = \theta^* X_0 - S^{-*}$$

$$Y_0^* = Y\lambda^* = \eta^* y_0 + S^+ \quad (2)$$

3.1 Generating equipment availability hour, installed capacity, electric energy production and CO_2 emission reduction production efficiency indices

Total-factor energy efficiency index is used in this paper to overcome any possible bias in the traditional energy efficiency indicators. For each specific evaluated municipality or province, the generating equipment availability hour(GEAH), installed capacity, electric energy production(EEP),and CO_2 emission reduction (CO_2 ER)were calculated using Equations (3) - (6).

$$GEAH=\frac{\text{Target GEAH input (i,t)}}{\text{Actual GEAH input (i,t)}} \quad (3)$$

$$\text{Installed capacity}=\frac{\text{Target Installed capacity input (i,t)}}{\text{Actual Installed capacity input (i,t)}} \quad (4)$$

$$EEP=\frac{\text{Actual EEP desirable output (i,t)}}{\text{Target EEP desirable output (i,t)}} \quad (5)$$

$$CO_2\ ER=\frac{\text{Actual } CO_2 \text{ ER desirable output (i,t)}}{\text{Target } CO_2 \text{ ER desirable output (i,t)}} \quad (6)$$

If the target GEAH and Installed capacity input equal the actual input , then the GEAH and Installed capacity efficiencies equal 1, indicating overall efficiency. If the target GEAH and Installed capacity input is less than the actual input, then the GEAH and Installed capacity efficiencies are less than 1, indicating overall inefficiency.

If the target EEP and CO_2 ER desirable output is equal to the actual EEP and CO_2 ER desirable output, then the EEP and CO_2 ER efficiencies equal 1, indicating overall efficiency. If the actual EEP and CO_2 ER desirable output is less than the target EEP and CO_2 ER desirable output, then the EEP and CO_2 ER efficiencies are less than 1, indicating overall inefficiency.

3.2 Data sources and description

This paper collects data from 30 provincial-level administrative regions in China between 2013 and 2017. The eastern region includes Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan. The central region includes Shanxi, Anhui, Jiangxi, Henan, Hubei, and Hunan. Western regions include Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang. Northeast China includes Liaoning, Jilin and Heilongjiang.

The input indicator variables used in this study were labor, generating equipment availability hour, installed capacity, the output indicator was electric energy production, and CO_2 emission reduction. (Table 1)

Table 1 input and output variables

Input variables	Output variables	Data sources
Labor		China electric power yearbook 2013-2017
Generating equipment	Electric energy production	China's national bureau of statistics
availability hour	CO_2 emission reduction	China clean development mechanism network
Installed capacity		Other related journals and websites

Input variables:

Labor input (lab): employees; Since there is no separate statistics on the number of employees in the wind power industry, the employment of urban units in the production and supply industries of electricity, gas and water is used instead. This study used the number of employees in each municipality/province at the end of each year; unit :Ten thousand people.

Generating equipment availability hour: the number of operating hours calculated by dividing the generating capacity of the reporting period by the capacity of the equipment; unit :Hours.

Installed capacity: The sum of the rated effective power of the generator set actually installed; unit : MKW.

Output variable:

Electric energy production: the amount of electrical energy produced by a generator through energy conversion; unit: KWh **.**

CO_2 emission reduction： Based on the CO_2 generated by thermal power generation under the same generating capacity, the generating capacity is converted into standard coal, and the one-degree power consumes 360 grams of standard coal.1 ton of raw coal =0.714 tons of standard coal. Carbon dioxide emission coefficient per ton of raw coal is 1.9003kg-co_2/kg. Therefore, the formula is: CO_2 emission reduction= power generation* 0.36/0.714*1.9003/10; unit: Mt.

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4. Results and Discussion

4.1 Statistical analysis of input-output indicators

Figure 1 shows the wind power installed capacity, the number of hours of use in the sub-region, the number of employees, and the amount of wind power generation and CO_2 emission reductions produced. The average, maximum and standard deviation of wind power installed capacity are increasing year by year. The average value of labor has declined. The average of the hours of use by region is the lowest in 2015.

Among the two factors of output, the average value, maximum value and standard deviation of wind power generation and CO_2 emission reduction have shown a significant upward trend. From the statistical characteristics of output indicators, the capacity of the wind power industry is growing rapidly.

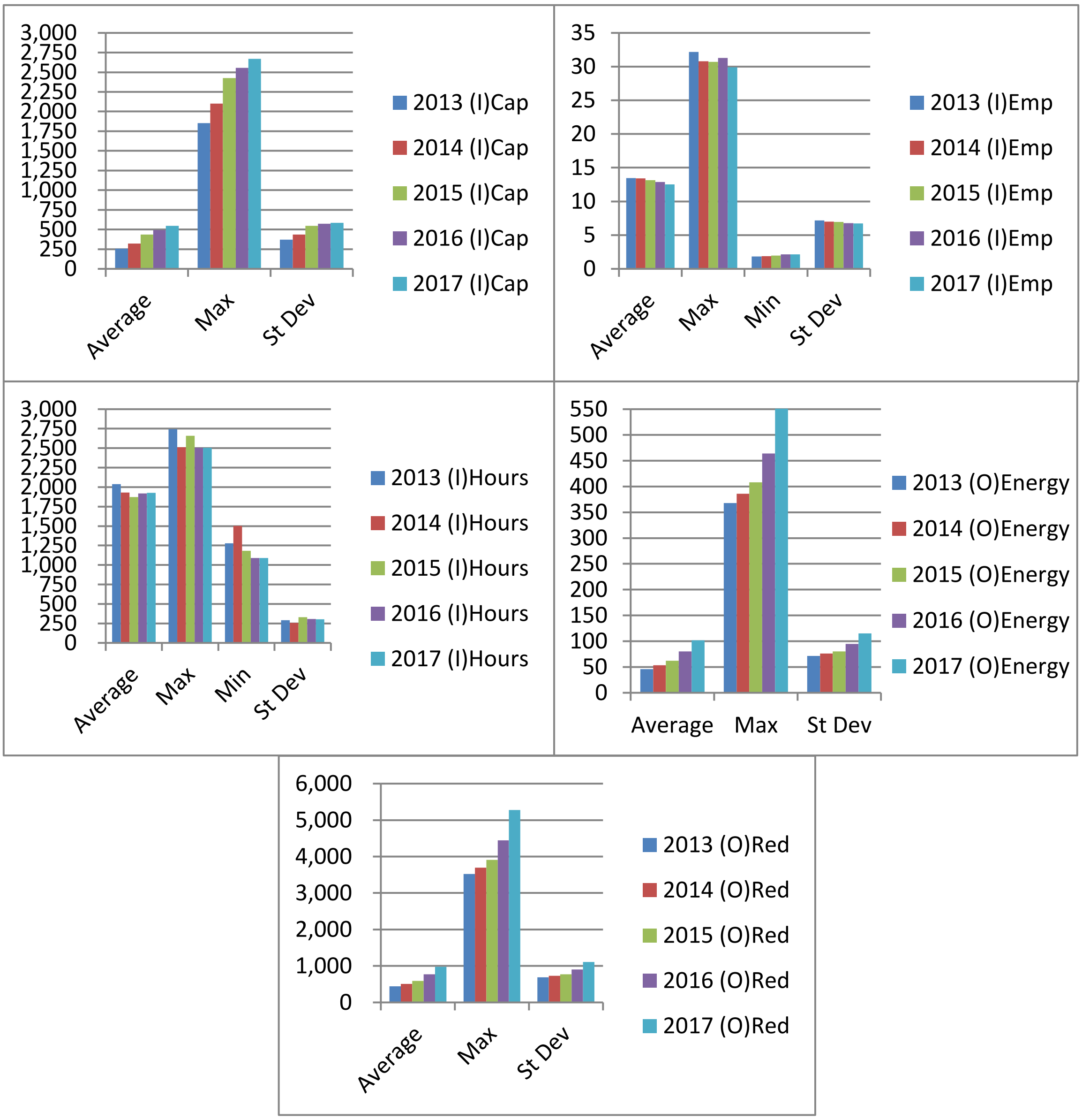

Figure 1. Statistical description of input and output variables by year

4.2 2013-2017 overall efficiency score ranking

From Table 2 shows China's four regions have efficiency scores and rankings. Both Fujian and Inner Mongolia have overall efficiency score of 1, indicating that these provinces and cities have no room for improvement.

1. From the eastern region, Beijing dropped by 12 places in five years, Tianjin ranked 8 places, Zhejiang dropped 13 places, and Shandong and Hainan dropped by 9. The average wind power efficiency in Beijing for five years is the lowest in the eastern region, only 0.4942. The overall efficiency score of Fujian is 1 and the remaining 8 provinces and cities are concentrated between 0.59 and 0.78. The ranking of Jiangsu has risen. The Hebei ranking has not changed, and the efficiency value has increased from 0.646 to 0.93.

2. From the central region, Shanxi, Hubei and Hunan have significantly improved their overall efficiency scores and rankings. Hunan's efficiency improvement is the most obvious. The ranking increases from 25 to 15 and the overall efficiency score increases from 0.362 to 0.634. The overall efficiency rankings of Anhui and Jiangxi are stable, with a slight increase in scores. The only decline in the overall efficiency ranking in the central region is in Henan, from 21 in 2013 to 29 in 2017. The difference in wind power efficiency values is small.

3. The provinces with the highest efficiency scores and rankings in the western region accounted for the majority, namely Guizhou, Ningxia, Sichuan, Xinjiang, Yunnan and Chongqing. Xinjiang has risen by as many as 14 places, and the efficiency value has increased from 0.443 to 0.843. The overall efficiency rankings in Gansu and Guangxi have declined. The overall efficiency rankings of Inner Mongolia, Qinghai and Shaanxi are stable.

4. The overall efficiency score and ranking in the northeast increases. Jilin has risen from 18 in 2013 to 12 in 2017. The most significant increase in efficiency is in Liaoning, which increases from 0.569 to 0.825.

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Table 2 Overall efficiency and ranking

Region	No.	DMU	2013 Rank	2013 Score	2014 Rank	2014 Score	2015 Rank	2015 Score	2016 Rank	2016 Score	2017 Rank	2017 Score	AVE. score
Eastern region	1	Beijing	16	0.475	18↓	0.523	24↓	0.504	30↓	0.502	28↑	0.467	0.4942
	2	Tianjin	8	0.605	10↓	0.604	14↓	0.571	16↓	0.688	16-	0.634	0.6204
	3	Hebei	5	0.646	6↓	0.694	4↑	0.732	5↓	0.922	5-	0.930	0.7848
	4	Shanghai	6	0.629	12↓	0.578	19↓	0.541	11↑	0.733	8↑	0.768	0.6498
	5	Jiangsu	15	0.512	7↑	0.677	10↓	0.611	10-	0.745	11↓	0.700	0.649
	6	Zhejiang	10	0.547	15↓	0.551	22↓	0.522	13↑	0.715	23↓	0.603	0.5876
	7	Fujian	1↑	1.000	1-	1.000	1-	1.000	1-	1.000	1-	1.000	1
	8	Shandong	11	0.537	11-	0.604	6↑	0.694	8↓	0.761	20↓	0.619	0.643
	9	Guangdong	17	0.471	14↑	0.552	8↑	0.642	12↓	0.729	19↓	0.624	0.6036
	10	Hainan	13	0.525	16 ↓	0.526	11↑	0.594	17↓	0.682	22↓	0.613	0.588
Central region	1	Shanxi	12	0.536	9↑	0.618	7↑	0.645	7-	0.776	9 ↓	0.756	0.5997
	2	Anhui	19	0.445	20 ↓	0.515	13↑	0.574	9↑	0.746	18 ↓	0.631	0.5114
	3	Jiangxi	23	0.406	24 ↓	0.457	25 ↓	0.481	20↑	0.654	24 ↓	0.603	0.448
	4	Henan	21	0.413	25 ↓	0.444	26 ↓	0.409	23↑	0.612	29 ↓	0.422	0.422
	5	Hubei	24	0.386	17↑	0.524	16↑	0.550	18 ↓	0.672	17↑	0.632	0.4867
	6	Hunan	25	0.362	29 ↓	0.357	23↑	0.519	15↑	0.698	15-	0.634	0.4127
Western region	1	Gansu	7	0.623	22 ↓	0.505	20↑	0.533	29 ↓	0.539	13↑	0.648	0.5696
	2	Guangxi	22	0.411	26 ↓	0.424	28 ↓	0.402	22↑	0.630	26 ↓	0.537	0.4808
	3	Guizhou	28	0.238	30 ↓	0.266	27↑	0.406	21↑	0.634	21-	0.618	0.4324
	4	Neimenggu	1	1.000	1-	1.000	1-	1.000	1-	1.000	1-	1.000	1
	5	Ningxia	4	0.828	5 ↓	0.720	5-	0.700	1↑	1.000	1-	1.000	0.8496
	6	Qinghai	29	0.193	27↑	0.411	18↑	0.543	28 ↓	0.572	30 ↓	0.406	0.425
	7	Shaanxi	26	0.294	23↑	0.498	21↑	0.531	24↓	0.603	27↓	0.522	0.4896
	8	Sichuan	30	0.154	28↑	0.363	29↓	0.387	25↑	0.602	25-	0.540	0.4092
	9	Xinjiang	20	0.443	4↑	0.727	17↓	0.548	14↑	0.704	6↑	0.843	0.653
	10	Yunnan	3	0.892	1↑	1.000	9↓	0.640	1↑	1.000	1-	1.000	0.9064
	11	Chongqing	27	0.267	21↑	0.512	30↓	0.340	26↑	0.583	14↑	0.644	0.4692
Northeast region	1	Heilongjiang	14	0.520	13↑	0.573	12↑	0.580	19↓	0.668	10↑	0.714	0.611
	2	Jilin	18	0.468	19↓	0.521	15↑	0.551	27↓	0.574	12↑	0.668	0.5564
	3	Liaoning	9	0.569	8↑	0.653	3↑	0.823	6↓	0.824	7↓	0.825	0.7388

Notes: " ↑ " , " ↓ " and "-" respectively indicate that the province's efficiency rankings in the current year have risen, fallen or remained the same as in the previous year;

The data are from the authors' collection.

4.3Rank of efficiency scores for each indicator

Table 3 shows the installed efficiency and CO_2 emission reduction efficiency scores for the four regions during 2013-2017. In addition to Ningxia, the installed capacity efficiency rankings of the provinces are almost the same as the CO_2 emission reduction efficiency rankings. The rapid development of the wind power industry has a clear positive relationship with CO_2 emission reduction.

4.3.1 Installed capacity efficiency

The average installed capacity efficiency in the eastern region decline, and the average installed capacity efficiency in the western region increase, while the average installed capacity efficiency in the central and northeastern regions is less obvious. The average installed capacity efficiency in the eastern region is the highest among the four regions, followed by the northeast region and the central region. The average installed capacity in the western region is the least efficient.

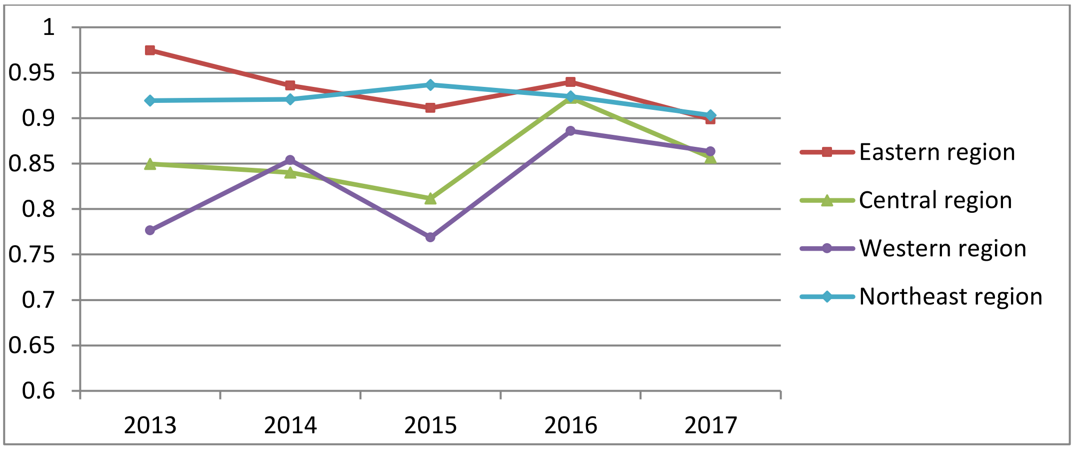

Figure 2. Efficiency values of installed capacity in various regions by year

In the eastern region, Zhejiang Province has the highest installed capacity efficiency and the most stable performance, and the efficiency value is stable at 1 Beijing has the lowest annual average installed capacity efficiency, and the efficiency value has decreased year by year, from 0.928 in 2013 to 0.759 in 2017. Beijing's land is less for wind farm construction, resulting in a relatively small installed capacity. Although the other eight eastern provinces have relatively high efficiency values, they all show a downward trend. The eastern region is close to the sea, rich in wind energy resources, and has the advantage of developing offshore wind power.

In the central region, Shanxi's installed capacity efficiency is the best, with a five-year average of 0.9586. This is closely related to Shanxi's energy transformation in recent years. Henan has the lowest efficiency value and ranks 27th in the country. The installed capacity in the central region increase and reached its highest efficiency in five years in 2016.

The western region is China's second-largest wind energy resource area, under the westerly winds all year round. The effective wind power occurrence time percentage is about 70%, and the wind speed greater than or equal to 3 m/s is more than 5000h for the whole year, and the wind speed greater than or equal to 6m/s is more than 2000h. The installed capacity efficiency of Inner Mongolia is 1 for five years. Qinghai, Sichuan, Shaanxi and other efficiency averages ranked 20th in the country. The efficiency values of Gansu, Guizhou and Ningxia declined in 2017. This is inconsistent with the conditions of superior wind energy resources in the western region. The investment in wind farm construction in the region is high, some wind farms are abandoned.

In the northeastern region, the installed capacity efficiency of Liaoning has increased year by year, and the stability value is 1 from 2015 to 2017. Heilongjiang and the eastern part of Jilin are the third largest wind energy resource area in China. The wind energy density is above 200W/m2, and the annual accumulated hours of wind speed greater than or equal to 3m/s and 6m/s are 5000-7000h and 3000h respectively. The installed capacity efficiency of these two provinces is declining year by year, which is undoubtedly a waste of wind energy resources.

4.3.2 Carbon reduction efficiency

The trend of the average carbon emission reduction efficiency in the four regions is similar to that of the average installed capacity efficiency. The average carbon emission reduction efficiency is above 0.8 (see Figure 3). The average carbon emission reduction efficiency values in the eastern and northeast regions exceeded 0.9 in 5 years, and the improvement space is small. The average carbon emission reduction efficiency in the central and western regions has increased slightly, and the gap between the average carbon emission efficiency in the eastern and northeast regions is narrowing.

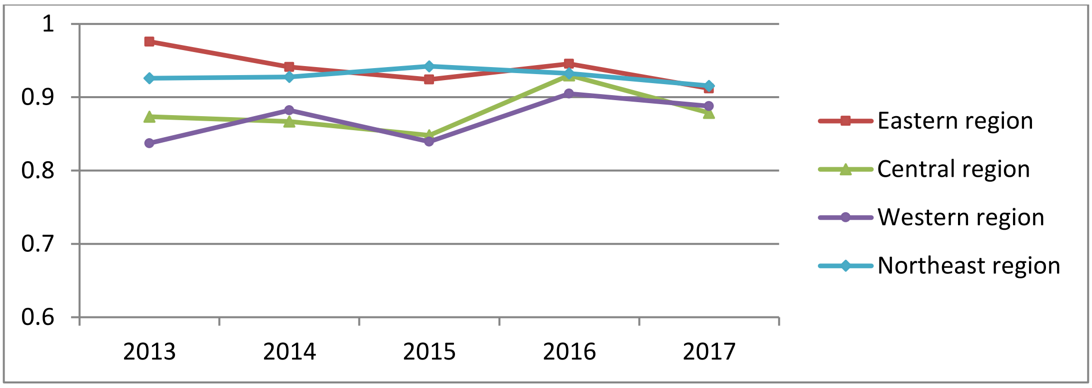

Figure 3. Carbon reduction efficiency in various regions by year

Emission reduction efficiency of CO_2 in the eastern region declines in 2017 compared to 2013. Zhejiang and Hainan do not maintain optimal efficiency. Fujian's efficiency value is 1 for five years, and Hebei reaches 1 in 2017. Except for Beijing, the average efficiency of the remaining nine provinces is above 0.9. The electricity demand market in the eastern region is huge, and the wind power that can grow rapidly will lead to a large amount of CO_2 emission reduction. Therefore, the carbon emission reduction efficiency in the eastern region is higher than other regions.

In the central region, the CO_2 emission reduction efficiency of Jiangxi, Hubei and Hunan increases significantly in 2017 compares with 2013. The decline is more obvious in Anhui and Henan. The average CO_2 emission reduction efficiency of the four provinces ranked 20th in the country. In the northeast, Liaoning's CO_2 emission reduction efficiency has improved significantly. After reaching 1 in 2015, it maintained a stable and optimal state. The CO_2 emission reduction efficiency values of Heilongjiang and Jilin decrease slightly.

The provinces with the best CO_2 emission reduction efficiency in the western region are Inner Mongolia, Yunnan and Ningxia. The mean values of efficiency are 1, 0.991 and 0.98, respectively, ranking 1, 3 and 6. The CO_2 emission reduction efficiency value and ranking in the western region are very different. In addition to the above three provinces, the remaining provinces in the region ranked after 19 countries nationwide. Although the CO_2 emission reduction efficiency in the western region is not well ranked, the efficiency values of the six provinces have increased significantly.

4.3.3 Relationship between installed capacity efficiency and carbon emission reduction efficiency

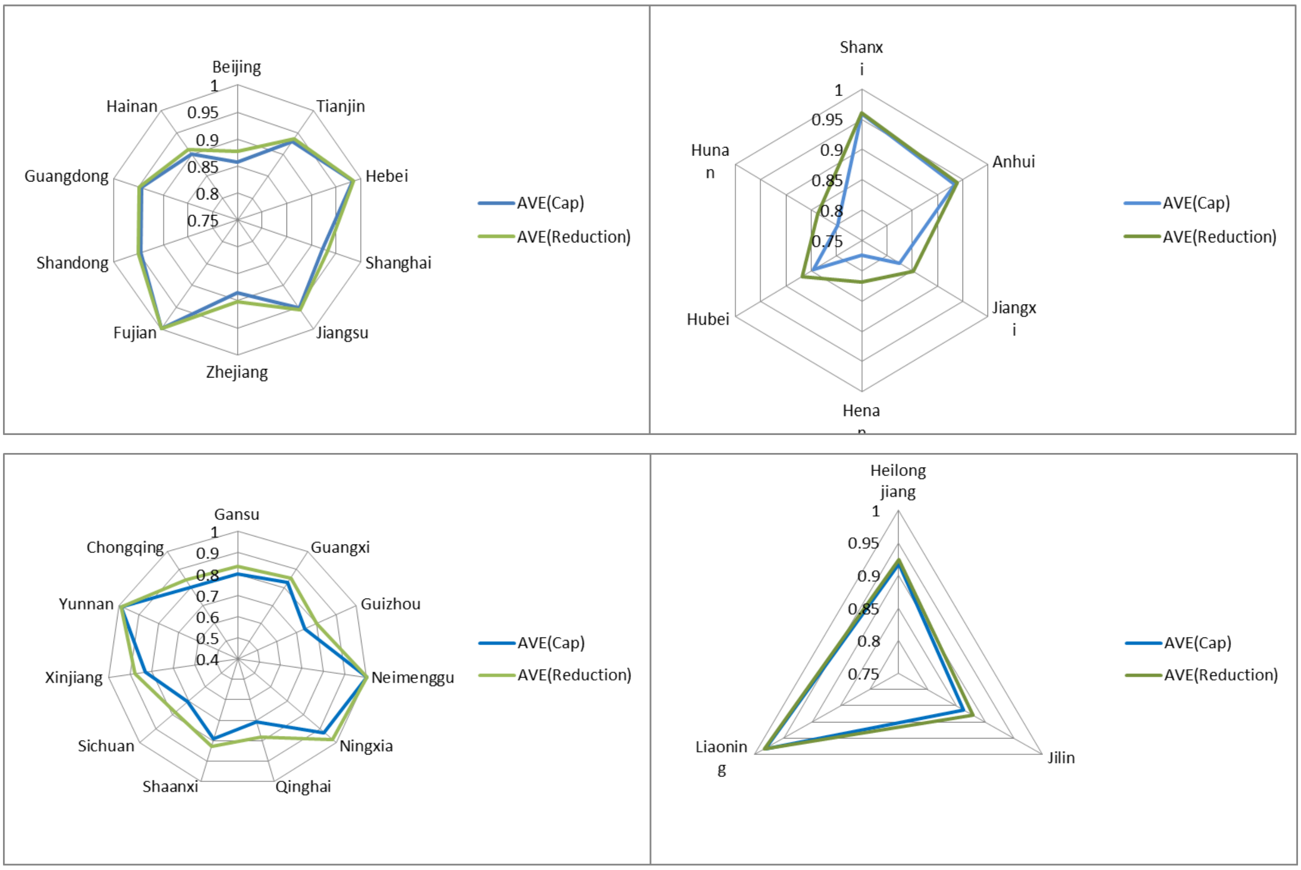

Figure 4. Average installed capacity efficiency and average annual carbon emission reduction efficiency in various regions

Annual average installed capacity efficiency is generally less than annual average carbon emission reduction efficiency, but the relationship between them is very consistent (see Figure 4). The annual average installed capacity efficiency of the eastern and northeastern provinces is close to the annual average carbon emission reduction efficiency, and the efficiency values are all greater than 0.8. The central and western regions have large differences within the region, with provinces with annual average efficiency values close to or equal to 1, such as Yunnan, Inner Mongolia, and Shanxi. Sichuan, Guizhou, and Henan have annual average efficiency values between 0.7 and 0.8.

The annual average installed capacity efficiency and annual carbon emission reduction efficiency of Beijing and Zhejiang in the eastern region are significantly different from those in other provinces. Explain that although the installed capacity of these two provinces is low, there is still room for improvement in the investment of wind power generators. Increasing the installed capacity of the two provinces will help

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promote carbon emission reduction. The annual installed capacity efficiency and annual carbon emission reduction efficiency of Sichuan, Qinghai, Hunan, and Henan in the central and western regions are very different, and the difference in efficiency values is close to 0.1.

In recent years, China has actively developed the wind power industry. However, the economic development in the central, western and northeastern regions is slower than in the eastern regions, and the electricity demand market is smaller and the resident population is smaller. Wind power is still weak in local competitiveness. The difficulty of wind power storage and transportation brings difficulty to the eastern market, so many wind farms have been abandoned. There is a large room for improvement in installed capacity efficiency and carbon emission reduction efficiency in the central, western and northeastern regions.

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Table 3 2013-2017 installed efficiency and CO_2 emission reduction efficiency score

			Installed capacity							CO_2 emission reduction						
Region	No.	DMU	2013	2014	2015	2016	2017	AVE	Rank	2013	2014	2015	2016	2017	AVE	Rank
Eastern region	1	Beijing	0.928	0.911	0.878	0.807	0.759	0.8566	18	0.933	0.918	0.891	0.838	0.806	0.8772	18
	2	Tianjin	0.994	0.928	0.894	0.939	0.890	0.929	11	0.994	0.933	0.904	0.943	0.901	0.935	12
	3	Hebei	0.973	0.962	0.988	1.000	1.000	0.9846	4	0.973	0.963	0.989	1.000	1.000	0.985	4
	4	Shanghai	1.000	0.926	0.781	0.915	0.993	0.923	13	1.000	0.931	0.820	0.922	0.993	0.9332	13
	5	Jiangsu	0.961	1.000	0.960	0.981	0.859	0.9522	7	0.962	1.000	0.962	0.981	0.876	0.9562	8
	6	Zhejiang	1.000	0.896	0.751	0.905	0.872	0.8848	16	1.000	0.906	0.801	0.914	0.887	0.9016	16
	7	Fujian	1.000	1.000	1.000	1.000	1.000	1	1	1.000	1.000	1.000	1.000	1.000	1	1
	8	Shandong	0.946	0.938	0.999	0.982	0.862	0.9454	8	0.948	0.942	0.999	0.983	0.879	0.9502	9
	9	Guangdong	0.946	0.951	1.000	0.960	0.865	0.9444	9	0.949	0.953	1.000	0.961	0.881	0.9488	10
	10	Hainan	1.000	0.847	0.861	0.906	0.887	0.9002	15	1.000	0.867	0.878	0.914	0.898	0.9114	15
Central region	1	Shanxi	0.961	0.952	0.941	0.982	0.957	0.9586	6	0.962	0.954	0.944	0.982	0.958	0.96	7
	2	Anhui	0.939	0.926	0.957	0.974	0.875	0.9342	10	0.942	0.931	0.959	0.975	0.889	0.9392	11
	3	Jiangxi	0.816	0.808	0.782	0.859	0.860	0.825	22	0.845	0.839	0.821	0.876	0.877	0.8516	22
	4	Henan	0.848	0.799	0.680	0.851	0.693	0.7742	27	0.868	0.833	0.758	0.870	0.765	0.8188	27
	5	Hubei	0.787	0.869	0.769	0.925	0.877	0.8454	19	0.824	0.885	0.813	0.931	0.890	0.8686	20
	6	Hunan	0.747	0.685	0.741	0.942	0.878	0.7986	25	0.798	0.761	0.794	0.945	0.891	0.8378	24
Western region	1	Gansu	0.921	0.766	0.752	0.740	0.831	0.802	23	0.926	0.810	0.801	0.793	0.855	0.837	25
	2	Guangxi	0.875	0.822	0.739	0.886	0.814	0.8272	21	0.889	0.849	0.793	0.897	0.843	0.8542	21
	3	Guizhou	0.619	0.592	0.756	0.911	0.825	0.7406	28	0.724	0.710	0.804	0.919	0.851	0.8016	28
	4	Neimenggu	1.000	1.000	1.000	1.000	1.000	1	1	1.000	1.000	1.000	1.000	1.000	1	1
	5	Ningxia	1.000	0.961	0.678	1.000	1.000	0.9278	12	1.000	0.962	0.938	1.000	1.000	0.98	6
	6	Qinghai	0.490	0.810	0.775	0.835	0.628	0.7076	29	0.662	0.840	0.816	0.858	0.729	0.781	30

	7	Shaanxi	0.735	0.827	0.763	0.872	0.759	0.7912	26	0.790	0.853	0.809	0.887	0.806	0.829	26
	8	Sichuan	0.456	0.732	0.697	0.837	0.814	0.7072	30	0.647	0.789	0.768	0.860	0.843	0.7814	29
	9	Xinjiang	0.793	0.974	0.667	0.796	0.922	0.8304	20	0.829	0.974	0.795	0.857	0.928	0.8766	19
	10	Yunnan	1.000	1.000	0.953	1.000	1.000	0.9906	3	1.000	1.000	0.955	1.000	1.000	0.991	3
	11	Chongqing	0.655	0.911	0.675	0.866	0.903	0.802	23	0.743	0.918	0.755	0.882	0.911	0.8418	23
Northeast region	1	Heilongjiang	0.940	0.926	0.919	0.927	0.876	0.9176	14	0.943	0.931	0.925	0.932	0.890	0.9242	14
	2	Jilin	0.873	0.872	0.891	0.845	0.833	0.8628	17	0.888	0.887	0.902	0.866	0.857	0.88	17
	3	Liaoning	0.945	0.964	1.000	1.000	1.000	0.9818	5	0.947	0.965	1.000	1.000	1.000	0.9824	5

Notes: The data are from the authors' collection.

5. Conclusion

This study uses the data from 2013 to 2017 to measure the wind power generation efficiency of 30 provinces in China, and analyzes the wind power generator capacity, wind power generation, and carbon emission reduction in the four regions. The results are as follows:

1. From the overall efficiency scores and rankings of wind power generation, the eastern and northeastern regions perform better, the western region is normal, while the central region has the lowest overall efficiency score and ranking. The overall efficiency score and ranking in the eastern region show a downward trend. The Northeastern region's average overall efficiency score in 2017 ranked first.

2.。The average installed capacity efficiency of the eastern provinces is the highest in four regions but with a downward trend. The average installed capacity in the western region has the lowest efficiency but an upward trend. The average installed capacity efficiency in the central and northeastern regions is not significantly changed. The trends in power generation efficiency and carbon emission reduction efficiency and the efficiency of installed capacity in each province are basically similar.

3. The annual average installed capacity efficiency and the annual average carbon emission reduction efficiency of the provinces in the eastern and northeastern regions are smaller; the regional differences between the central and western regions are larger.

Based on the above research conclusions, combined with the actual situation of each region, the following countermeasures are proposed for each province and city to improve wind power generation efficiency and carbon emission reduction efficiency:

1. Analyze the demand and wind energy resources of each province, select the most suitable wind power generation area, increase the average installed density of wind farms, and save resources. Large wind farms can be built in areas with abundant wind energy resources, the southeast coast and its islands, Inner Mongolia and northern Gansu, Heilongjiang and eastern Jilin, and the Liaodong Peninsula coastal and Qinghai-Tibet Plateau. South East can develop offshore wind power.

2. The long-term planning and short-term construction of the wind power industry should be coordinated. At present, the capacity of the power grid is insufficient, the construction period of the wind farm is not matched, and the wind power is unstable, resulting in serious wind farm disposal. The areas rich in wind energy are distributed in the western regions with low economic development, such as Xinjiang, Weibei, Gansu, Inner Mongolia, etc. Due to the constraints of economic development level and population

density, the phenomenon of oversupply in the local wind farms has occurred. Northeastern energy consumption is dominated by thermal power, and there is almost no room for wind power consumption. In the long run, consideration should be given to increasing the space of the local electricity market, while developing wind power technology and increasing the storage and transportation capacity of wind power.

3. Increase investment in wind power technology. The technology of China's wind power industry is still not mature, large-scale generator sets rely on imports, and wind power costs are high. Strengthening the research and development of wind power core technology and self-produced reliable wind power equipment can reduce the construction cost of wind farms. Due to the intermittent and random effects of wind energy, wind power generation is unstable and requires large-scale power storage technology. Optimizing wind power generation, developing energy storage technologies and wind power grid-connected technologies have an important role in the development of the wind power industry.

4. The government should formulate wind power incentive policies for taxation and finance. The policy of adopting the lowest protection price of electricity encourages the use of wind power. As the scale of the wind power industry expands and the income increases, the minimum protection price is lowered year by year. A policy of a guided and legally valid French regulation such as a quota system. China can learn from countries such as Denmark give wind power companies a certain amount of economic subsidies, and impose certain taxes on coal-fired power generation and CO_2 emissions.

5.Standardize the technical standards of the wind power industry and gradually adjust the price control system. Wind power companies have a lot of waste due to poor management and immature technology. In some areas, the technical level is limited, resulting in potential safety hazards, resulting in a decline in profits and hindered industrial development. Market control enables electricity prices to reflect the supply and demand of the market and promote the sound development of the wind power industry.

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