Comparison and Optimization of energy efficiency between Hydropower and thermal power in China

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Abstract

Background: As the two main forces of China's power electricity, the energy generation efficiencies of thermal power and hydropower are important factors affecting energy conservation and emissions reduction.

Methods: Considering regional differences and multiple effective decision-making units, this research uses the meta-frontier super-efficiency slack based measure model to comprehensively evaluate the efficiencies of hydropower and thermal power generation in China, with CO_2 emissions of thermal power generation as its undesirable output.

Results: The average group efficiency of thermal power generation in the central region have greatly improved, and the eastern and western regions also show an upward trend, whereas there is a slight downward trend for hydropower in the three regions. The hydropower technological gaps in the three regions have slightly expanded, but the thermal power technology gaps in the east, the central, and the west have gradually narrowed, indicating that the thermal power industry is generally mature, and CO_2 emission control and treatment have made some progress. From the perspective of input-output non-efficiency level, the undesirable output CO_2 of thermal power energy efficiency in the eastern, central, and western regions is surplus, and the redundancy of equipment utilization hours, energy input, and installed capacity in the western region are all high, but generation in the western region is insufficient, leading to relatively low efficiency of thermal power generation there. In the east, the redundancy of equipment utilization hours, number of employees, and installed capacity are all high, and the generation of hydropower in the east and the central is insufficient, leading to relatively low efficiency of hydropower in these two regions.

Conclusions: There are regional differences in the efficiencies of hydropower and thermal power generation in China. The thermal power industry is becoming mature, but its CO_2 emissions should be reduced, and the hydropower industry needs further policies support according to local conditions to improve energy efficiency and achieve green development.

Key words: Energy Efficiency; Hydropower; Thermal Power; CO_2; Super-Efficiency Slack Based Measure Model; Meta-frontier

1 Introduction

With the greater urbanization and industrialization of China, the demand for energy consumption is also increasing, leading to higher carbon emissions. At the same time, the ecological environment is facing severe pressure, which makes energy conservation and carbon emissions reduction the clear focus of China's government and its citizens. The report of the 19th National Congress of the Communist Party of China highlighted the revolution of the production and consumption of electricity energy to promote green development. The key point is how to promote high-quality and efficient electric power production and reduce carbon emissions.

In order to promote the construction of ecological civilization and realize green development, the China government formulated 《Environmental Protection Tax Law》 (Draft) in 2016, proposing to levy environmental protection taxes on air pollutants, water pollutants, solid wastes, and noise. One of the main sources of air pollution is coal, and coal-fired power generation is currently the main form of production in the country's power industry. In 2017, China's total power generation reached 6417.1 billion kWh, of which thermal power generation and hydropower generation accounted for 70.99% and 18.59%, respectively. And in 2017, China's installed power generation capacity hit 1777.08 million KW, an increase of 7.67% over the previous year. And the installed power generation capacity of thermal power and hydropower accounted for 62.18% and 19.33%, respectively. Although hydropower has received much attention and development, its proportion of power generation and installed capacity is smaller than that of thermal power, meaning that its development scale is currently not as good as thermal power. In order to implement the development concepts of innovation, coordination, greenness, openness, and sharing and to accelerate the construction of China's ecological civilization, it is necessary to adjust the structure of electric energy production, optimize and improve the efficiency of thermal power energy, and continuously increase the proportion of clean energy such as hydropower and wind power. Thus, research on China's thermal power and hydropower energy efficiency evaluation and regional comparative analysis are of great theoretical value and practical significance. The clean characteristics of hydropower offer a good promotion effect on energy conservation and emissions reduction and provide a way to improve the energy structure.

Regarding the study of energy efficiency, first, most research objects use the concept of total energy to perform efficiency calculations, and more specifically it is necessary to examine the industry efficiency issues of thermal power generation and hydropower generation. Some scholars have conducted research on the efficiency of thermal power generation as a research object, while others have studied the efficiency of hydropower generation, but they lack a comparative analysis of the power generation efficiency of traditional energy sources like thermal power and new energy sources like hydropower. Second, in studies of thermal power generation efficiency, there are more micro-level efficiency calculations for thermal power companies or power plants, with relatively few macro-level thermal power efficiency calculations considering regional differences. Moreover, the analysis does not solve the problem of distinguishing the efficiency of an effective decision-making unit (DMU). It is thus necessary to consider incorporating carbon dioxide emissions from thermal power generation in China's provinces as an undesirable output to reflect the energy efficiency of regional thermal power generation more realistically and comprehensively, to compare and observe the efficiency differences between hydropower and thermal power more realistically.

The academic contributions of this paper are as follows. (1) By considering regional differences, hydropower, and thermal power efficiencies in different regions of China are calculated and evaluated in a systematic and comprehensive way, which can be more effectively and efficiently analyze the efficiencies of these two forms of power. (2) This study sorts multiple effective decision-making units in the measurement results of thermal and hydropower energy efficiencies, compares and analyzes the two efficiencies, and considers the input-output indicators more comprehensively. To consider the environmental impact of thermal power generation, we include CO_2 emissions from thermal power generation as an undesirable output.

2 Literature Review

With the development of China's economy, the requirements for energy continue to increase, and green energy development has become an important trend. In recent years, China's clean energy industry, including hydropower, wind power, solar energy, biomass energy, and nuclear energy, has developed rapidly and achieved large-scale development. In addition, the proportion of clean energy consumption in total energy consumption is still rising. This has prompted many scholars to pay more and more attention to clean energy and its efficiency.

Scholars use a variety of research methods to study different industries, including different types of energy use and impact issues. Some scholars use the LMDI method to decompose and study the influencing factors of energy or carbon emissions, such as Liu et al. [1] and Wang and Zhou [2]. Others have adopted econometric methods, such as Meng et al. [3], using polynomial functions and PLS (Partial Least Squares) algorithms to evaluate the effect of market reforms in China's thermal power industry in 2003. Empirical results show that the reforms made the thermal industry's "natural" power generation efficiency curve suddenly shift down by 0.142kw h/kg SCE (standard coal equivalent), causing a waste of 555.8 million tons of standard coal in 2003-2012. The generation efficiency of China's thermal power industry has decreased since the reform, mainly due to the failure to implement electricity price tendering. Li et al. [4] proposed a new method of mixing the multiple regression model with the generalized autoregressive conditional heteroscedasticity (GARCH) model when evaluating the energy efficiency of thermal power plants in China. Most scholars use the DEA method to analyze and evaluate energy and environmental efficiency, such as DEA and Malmquist index by Dyckhoff et al. [5], Perez et al. [6], SBM-DEA by Choi et al. [7], and meta-frontier by Battese et al. [8] and Beltrán-Esteve et al. [9].

The DEA model was originally proposed by Charnes, Cooper and Rhodes in 1978 [10] and was used by scholars to evaluate energy and environmental efficiency. Tone (2001) then proposed the SBM model [11], which is a DEA model that considers input and output slack and an efficiency evaluation method that takes on undesirable output indicators. The research objects can be divided into regional-/macro-level and company-/micro-level studies. At the company-/micro-level aspect, Moon et al. [12] used a two-stage DEA model to analyze the efficiency of energy-intensive manufacturing companies in South Korea.

For regional-/macro-level energy efficiency, Mei et al. [13] used the meta-frontier slack-based measure method to conduct an empirical analysis of regional environmental efficiency on China's sulfur dioxide emissions and chemical oxygen demand (COD) from 2000 to 2011. The results showed that excessive emission pollution is the main cause of low environmental efficiency, and there are differences in environmental efficiency in the eastern, central, and western regions. Bi et al. [14] utilized a slack-based measure approach to study the impact of environmental regulations on the energy efficiency of thermal power generation in China. Their study found that energy efficiency and environmental efficiency are relatively low and have distinct regional characteristics. Song et al. [15] employed the slack-based endogenous directional distance function (SBEDDF) model to evaluate the environmental impact of China's power generation industry. Results show that the environmental efficiency of China's thermal power industry is low, and that the gap between different regions is large. During the period 2006-2012, environmental efficiency increased by 47%. The best way to reduce emissions is unique to each region. Li and Shi [16] proposed an improved Super-SBM model with bad output, which can reasonably distinguish multiple effective decision-making units, make the efficiency ranking more effective, and apply it to measuring the energy efficiency of China's industrial sector. When comparing and analyzing the energy efficiency of thermal power and hydropower, more real and effective calculations need to be considered, and attention should focus on the regional differences and rankings of effective decision-making units (DMUs).

With the development of new energy, attention has been paid more to the energy efficiency of hydropower. For example, Barros [17] used the data envelopment analysis (DEA) method to measure and decompose the efficiency of EDP (the Portugal Electricity Company) hydroelectric energy generating plants, showing that hydropower stations have improved in terms of technical efficiency and technological progress. Barros et al. [18] employed the Virtual Frontier Dynamic Range Adjusted Model (VDRAM) DEA method to evaluate the efficiency of the Angolan hydropower plants. The study considered that efficiency analysis is important and can promote the level of energy utilization in order to achieve good management and sustainable development.

Considering undesired output when assessing energy efficiency can reflect the requirements for green development of energy, making efficiency measurement more real and effective. Scholars have taken diversified input-output indicators in energy efficiency calculations, but they have common points, such as [3], [7], [14], [15], and [19]. The input indicators mostly are labor and capital, but special input indicators of raw materials and equipment are also considered. In addition, output indicators are mostly production volume, GDP, etc. and include undesirable output that is unfavorable to the environment, including most selected CO_2 emissions, such as [20], [21] [22], [23], and [24].

We find that there are few studies on the calculation of hydropower efficiency, but relatively more research on the efficiency of thermal power. Research at the micro-level (firms or plants) is more abundant, and thus research at the regional level still needs to be further explored. Moreover, there are fewer comparative studies on energy efficiency of hydropower and thermal power. Wang et al. [25] believed that although hydropower and thermal power constitute the two pillars of China's electricity supply, the relationship between the two needs to be further studied. They aimed to reveal the relationship between the two under the framework of the autoregressive distributed lag (ARDL) model, which can provide a useful enlightenment to consider regional hydropower and thermal power efficiency calculations and compare them.

The various DEA methods chosen by scholars are mainly based on their research purposes and actual conditions. These studies lay a foundation for innovation in this paper for constructing and using the Meta-SE-SBM-Undesirable model by considering regional differences in the efficiency calculation of thermal power and hydropower. However, most studies in the literature have the following limitations. (1) Simple analysis and evaluation of thermal power or hydropower efficiency are performed, and most of them are concentrated at the level of power plants or power generation companies. There is a lack of more macro-level regional thermal power and hydropower efficiency calculations and a comparative analysis of the two. Regional development differences are considered so that the efficiency value will not be overestimated. (2) A more realistic and effective efficiency measurement of thermal power and hydropower generation methods is needed, and multiple effective decision-making units should be ranked. Comparative studies are relatively lacking, and more comprehensive input-output indicators are required.

3 Methods

3.1. SE-SBM model

The Slack Based model (SBM) was proposed by Tone (2001) [11] and is a DEA model that considers slack improvement. It can solve the problem that the radial model does not include slack variables in non-efficiency measurements. The super-efficiency SBM model (SE-SBM) also solves the problem of differentiating effective decision unit (DMU) efficiency and at the same time incorporates undesirable outputs into the measurement system [26], which can more realistically and comprehensively reflect regional energy efficiency.

$$min\rho = \frac{1+\frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{ik}}}{1-\frac{1}{q_1+q_2}\left(\sum_{r=1}^{q_1}\frac{s_r^{g+}}{y_{rk}^g}+\sum_{r=1}^{q_2}\frac{s_t^{b-}}{y_{rk}^b}\right)} \tag{1}$$

$$s.t.\ \sum_{j=1,j\neq k}^{n} x_{ij}\lambda_j - s_i^- \leq x_{ik},\ \sum_{j=1,j\neq k}^{n} y_{rj}\lambda_j + s_r^{g^+} \geq y_{rk}^g,\ \sum_{j=1,j\neq k}^{n} y_{tj}^b - s_t^{b^-} \leq y_{tk}^b$$

$$1-\frac{1}{q_1+q_2}\left(\sum_{r=1}^{q_1}\frac{s_r^g}{y_{rk}^g}+\sum_{r=1}^{q_2}\frac{s_r^b}{y_{rk}^b}\right) > 0,\ s^- > 0,\ s^b > 0,\ s^g > 0, \lambda > 0$$

$$i = 1,2,\dots m;\ r = 1,2,\dots q;\ j = 1,2,\dots n(j \neq k)$$

In the SE-SBM model (Eq. (1)), it is assumed that there are n decision-making units, and each decision-making unit has m inputs (x), s_1 desirable output (y^g), and s_2 undesirable output (y^b). We define matrices X, Y^g, and Y^b and $X=[x_1, x_2,\cdots x_n]$, $Y^g=[y_1^g,\ y_2^g,\cdots\ y_n^g]$, $Y^b=[y_1^b,\ y_2^b,\cdots\ y_n^b]$. In addition, s is the amount of slack in the input and output, λ is the weight vector, and the objective function is ρ, whose value is between 0 and 1. Here, x_{ij} is the i^{th} input of the j^{th} DMU, and y_{rj} is the r^{th} output of the j^{th} DMU.

3.2. Meta-frontier and technology gap ratio

Battese et al. [27] proposed a Meta-frontier Production Function, while O'Donnell et al. [28] further established a meta-boundary framework based on DEA. Suppose that the production fronts of group g are included in the meta-boundary. The efficiency under the group boundary is greater than the efficiency under the meta-boundary. The ratio of the two frontiers is called the technology gap ratio (TGR) as follows:

$$TGR = \frac{\rho^*}{\rho_0^{*g}} \tag{2}$$

In formula (2), the larger TGR is, the closer the production technology used by the decision-making unit is to the frontier of production technology.

3.3. Meta-SE-SBM undesirable model

We refer to the super-efficient SBM model proposed by Huang [29], which considers the meta-frontier and undesirable output. Assume that the number of decision-making units is N, and they are divided into H groups (H>1) according to some heterogeneous characteristics. Define the number of DMUs in the h group as N_h, and then $\sum_{h=1}^{H} N_h = N$. Assume that each decision-making unit (DMU) has three types of input and output variables: inputs, desirable outputs, and undesirable outputs, which are expressed as: $x = [x_1, \ x_2, \cdots, \ x_M] \in R_+^M$, $y = [y_1, \ y_2, \cdots, \ y_R] \in R_+^R$, $b = [b_1, \ b_2, \cdots, \ b_J] \in R_+^J$, and M, R, and J represent the number of three types of variables in turn. When considering both undesirable output and heterogeneous technologies, the efficiency of the k^{th} group of the o^{th} decision-making unit ($o = 1, 2, ..., N_k$; $k = 1, 2, ..., H$) for the non-directed and non-radial SBM of the meta-frontier formed by all groups can be obtained by solving the following plan.

$$\rho_{ko}{}^{Meta*} = min \frac{1+\frac{1}{M}\sum_{m=1}^{M}\frac{s_{mko}^{x}}{x_{mko}}}{1-\frac{1}{R+J}(\sum_{r=1}^{R}\frac{s_{rko}^{y}}{y_{rko}}+\sum_{j=1}^{J}\frac{s_{jko}^{b}}{b_{jko}})} \quad (3)$$

$$s.t.\ \ x_{mko} - \sum\nolimits_{h=1}^{H}\sum\nolimits_{n=1,n\neq 0\ if\ h=k}^{N_h} \xi_n^h x_{mhn} + s_{mko}^{x} \geq 0$$

$$\sum\nolimits_{h=1}^{H}\sum\nolimits_{n=1,n\neq 0\ if\ h=k}^{N_h} \xi_n^h y_{rhn} - y_{rko} + s_{rko}^{y} \geq 0$$

$$b_{jko} - \sum\nolimits_{h=1}^{H}\sum\nolimits_{n=1,n\neq 0\ if\ h=k}^{N_h} \xi_n^h b_{jhn} + s_{jko}^{b} \geq 0$$

$$1 - \frac{1}{R+J}(\sum\nolimits_{r=1}^{R}\frac{s_{rko}^{y}}{y_{rko}} + \sum\nolimits_{j=1}^{J}\frac{s_{jko}^{b}}{b_{jko}}) \geq \varepsilon$$

$$\xi_n^h, s^x, s^y, s^b \geq 0$$

$$m = 1,2, \ldots, M; r = 1,2, \ldots, R; j = 1,2, \ldots, J$$

In Equation (3), ξ is a non-negative weight vector, ε is a non-Archimedean infinitely small, and s^x, s^y, and s^b are slack variables of the input, desirable output, and undesirable output of DMU_{ko}, respectively. The constraint $1 - \frac{1}{R+J}(\sum_{r=1}^{R}\frac{s_{rko}^{y}}{y_{rko}} + \sum_{j=1}^{J}\frac{s_{jko}^{b}}{b_{jko}}) \geq \varepsilon$ is added here to ensure that the denominator of the objective function is not zero. If we assume variable returns-to-scale (VRS), then we need to add the constraint $\sum_{h=1}^{H}\sum_{n=1,n\neq 0\ if\ h=k}^{N_h}\xi_n^h=1$ here.

3.4. Data sources and description

Due to the lack of statistical data, this study does not consider Hong Kong, Macau, Taiwan, and Tibet as decision-making units (DMUs). In order to consider regional differences, following Liu et al. [20], this study divides 30 provinces and cities in China into three major regions. The eastern region group includes Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan, for a total of 11 provinces; the central region group includes Shanxi, Inner Mongolia, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei, Hunan, and Guangxi, for a total of 10 provinces; and the western region group includes Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang, for a total of 9 provinces. This study uses the latest data representing China's provinces in measuring thermal power efficiency and takes the latest data from 28 provinces (excluding Shanghai and Tianjin) for measuring hydropower efficiency. Shanghai's hydropower generation has shown zero over the years, while Tianjin's hydropower indicators are lacking. Therefore, Shanghai and Tianjin are not considered when calculating hydropower efficiency. The data come from China Statistical Yearbook [30], China Energy Statistical Yearbook [31], and China Electric Power Statistical Yearbook [32], and relevant data for 2013 and 2017 are collected. The input and output variables are as follows.

Input indicators: ①Employees of urban units in the production and supply of electricity, gas, and water are the proxy variable for labor input in the hydropower and thermal power industries; the unit is 10,000 people; ②Installed capacity represents the investment scale; the unit is 10,000 KW; ③Hours are used to indicate the effective utilization rate of the equipment; the unit is h; ④ Energy input has a unit of 10,000 tons; the data of thermal power input are from the fossil fuel data of the thermal power industry provided by China Energy Statistics Yearbook [31], mainly including coal, oil, and natural gas; the unit is 10,000 tons of standard coal. Hydropower energy input data are obtained according to the China Electric Power Yearbook [32], and the unit is 10,000 tons of standard coal.

Desirable output indicator: We take the amount of power generation as an important indicator to measure the output of power generation; the unit is 100 million kilowatt hours (KWH).

Undesirable output indicator: Due to the characteristics of clean energy, hydropower does not consider undesirable output. In the calculation of thermal power efficiency, CO_2 emissions from thermal power generation are selected as undesirable output, and the unit is 10,000 tons. According to Liu et al. [33] and Qin et al. [24], and based on the fossil fuel energy consumption data of the thermal power industry at the provincial level, we estimated the carbon dioxide emissions of thermal power generation in China's provinces in 2013 and 2017. The formula is as follows:

$$C_{\mathrm{it}} = \sum E_{\mathrm{ijt}} \times CEF_j \times COR_j \times \frac{44}{12} \tag{4}$$

Among the variables above, C_{it} is the carbon dioxide emissions caused by the energy consumption of thermal power generation in area i in one year; E_{ijt} is the j-type energy consumption consumed by thermal power generation in area i; CEF_j represents the carbon emission factor; COR_j represents the rate of carbon oxidation; and the coefficients of the two are from the research of Liu et al. [33] and Qin et al. [24].

4 Results and Discussion

4.1. Input-output indicator statistics

Table 1 summarizes the descriptive statistics of the mean, standard deviation, maximum, and minimum of the input variables, desirable output variables, and undesirable output variables used in the model.

Table 1. Statistical presentation of input-output variables of thermal power

Variable		Mean	Std.	Max	Min
Descriptive analysis of thermal power					
Input	installed capacity	3290.42	2406.95	10335.00	235.00
	energy	4660.97	3714.04	15427.17	515.66
	hour	4450.53	895.96	6173.00	1405.00
	labor	12.99	7.04	32.18	1.85
Output	generation	1575.70	1395.59	7555.00	136.00
Undesirable output	CO_2	11424.99	9126.17	38179.86	1212.11
Descriptive analysis of hydropower					

Input	installed capacity	1110.40	1589.65	7714.00	43.00
	energy	1123.53	1872.87	9236.01	12.28
	hour	2653.93	1152.39	4599.00	355.00
	labor	13.59	6.90	32.18	1.85
Output	generation	371.15	634.39	3164.00	4.50

The trend of CO_2 emissions in the thermal power industry needs some attention. Figure 1 shows the CO_2 emissions from thermal power generation in China's provinces in 2013 and 2017. We see that CO_2 emissions are on the rise, and the issue of CO_2 from thermal power generation does require improvement. The energy efficiency calculation of thermal power generation must also consider CO_2 emissions to be more realistic.

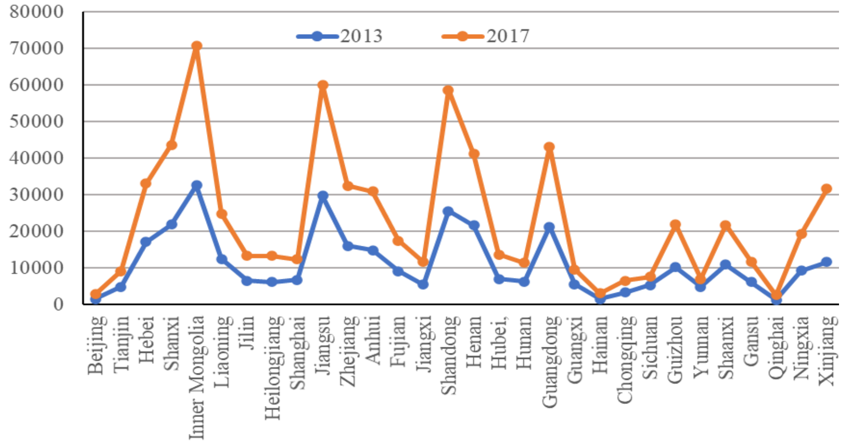


Figure 1. Regional CO_2 emissions in China in 2013 and 2017

Note: The data source comes from the authors' collection.

4.2. Meta- and group efficiency scores and ranks of thermal power and hydropower

MaxDEA Pro 7.0 software was used to measure the energy efficiency of thermal power and hydropower in China's provinces and cities in 2013 and 2017 in this paper, and output-oriented and non-radial types were selected in the efficiency measurement. Among them, in the measurement of thermal power energy efficiency, the ratio of desirable output to undesirable output is set to 1: 1; that is, CO_2 emissions and thermal power generation are placed in the same position.

Table 2 shows the meta-efficiency scores of thermal power and hydropower in China's provinces in 2013 and 2017. In 2017, thermal power's meta-efficiency scores for Beijing, Jiangsu, Ningxia, Shandong, Hebei, Jiangxi, Zhejiang, and Inner Mongolia are all higher than 1, while hydropower's meta-efficiency scores for Yunnan, Jiangsu, Sichuan, Gansu, Shaanxi, Hubei, and Xinjiang are higher than 1. Moreover, we find that the hydropower and thermal power meta-efficiency scores of Jiangsu are both higher than 1 in 2017. The analysis is as follows.

Table 2. Meta-efficiency scores and ranks of thermal power and hydropower in 2013 and 2017

DMU	Thermal power				Hydropower			
	2013		2017		2013		2017	
	Rank	Meta	Rank	Meta	Rank	Meta	Rank	Meta

Beijing	20	0.2716	1	1.3193	5	1.1656	15	0.8217
Tianjin	15	0.3604	14	0.9272	-	-	-	-
Hebei	14	0.3657	5	1.0226	27	0.8897	27	0.5852
Liaoning	16	0.2951	25	0.8494	16	0.9743	25	0.6311
Shanghai	8	0.4447	9	0.9883	-	-	-	-
Jiangsu	3	0.5064	2	1.1146	23	0.9368	2	1.3506
Zhejiang	9	0.4363	7	1.0211	8	1.0164	21	0.7283
Fujian	13	0.3853	16	0.9173	9	1.0111	19	0.7633
Shandong	5	0.4928	4	1.0381	28	0.8475	28	0.3363
Guangdong	7	0.4673	10	0.9839	11	0.9867	24	0.6594
Hainan	18	0.2824	23	0.8711	7	1.0234	8	0.9874
Eastern group average	2	0.3916	1	1.0048	2	0.9835	3	0.7626
Shanxi	6	0.4840	22	0.8736	22	0.9426	18	0.7830
Inner Mongolia	4	0.5027	8	1.0055	21	0.9486	26	0.6198
Jilin	28	0.1883	30	0.7584	10	0.9873	20	0.7485
Heilongjiang	26	0.2002	26	0.8346	24	0.9363	16	0.8159
Anhui	12	0.4103	11	0.9719	19	0.9497	22	0.7203
Jiangxi	27	0.1917	6	1.0219	14	0.9769	23	0.6871
Henan	10	0.4310	15	0.9269	13	0.9833	14	0.8528
Hubei	21	0.2426	12	0.9653	6	1.0403	6	1.0184
Hunan	24	0.2094	13	0.9302	15	0.9758	17	0.7878
Guangxi	1	1.8055	20	0.8945	12	0.9867	12	0.9139
Central group average	1	0.4666	2	0.9183	3	0.9727	2	0.7947
Chongqing	25	0.2024	21	0.8771	26	0.9184	13	0.9037
Sichuan	29	0.1721	18	0.8977	4	1.2139	3	1.2117
Guizhou	19	0.2824	27	0.8262	17	0.9552	11	0.9192
Yunnan	30	0.1636	29	0.8037	1	1.6576	1	1.6925
Shaanxi	17	0.2896	17	0.9142	20	0.9487	5	1.0476
Gansu	23	0.2293	24	0.8540	3	1.2182	4	1.0781
Qinghai	22	0.2375	28	0.8192	2	1.4576	9	0.9642
Ningxia	2	0.5602	3	1.0570	18	0.9530	10	0.9460
Xinjiang	11	0.4139	19	0.8973	25	0.9256	7	1.0156
Western group average	3	0.2834	3	0.8829	1	1.1387	1	1.0865
Total mean	-	0.3842	-	0.9394	-	1.0295	-	0.8782

The meta-efficiency scores reflect the thermal power efficiency and hydropower efficiency of China's provinces without considering group differences. According to the calculation results in Table 2, the specific analysis runs as follows. Regarding the eastern provinces, thermal power generation meta-efficiency of Tianjin, Shanghai, Jiangsu, Zhejiang, and Shandong maintained relatively stable rankings, and Beijing and Hebei have greatly increased their rankings. Compared with 2013, Beijing's meta-efficiency of thermal power increased by 19 places in 2017, as its meta-efficiency score rose from 0.2716 to 1.3193. On the contrary, Liaoning showed a significant decline. The eastern provinces of Hebe, Shandong, and Hainan have maintained a relatively stable ranking of hydropower meta-efficiency, while Jiangsu's ranking has greatly increased. Compared with 2013, the meta-efficiency of Jiangsu's hydropower rose 21 places in 2017, as its efficiency value increased from 0.9368 to 1.3506. The hydropower meta-efficiency of Zhejiang, Guangdong, and Fujian declined significantly. Moreover, Shandong's thermal power and hydropower meta-efficiency rankings have been stable.

Regarding the central region provinces, Jilin, Heilongjiang, and Anhui have maintained a relatively stable ranking in terms of thermal power generation meta-efficiency. Compared with 2013, Jiangxi's thermal power meta-efficiency ranking in 2017 increased by 21 places, as its meta-efficiency value rose from 0.1917 to 1.0219. By contrast, Guangxi and Shanxi declined significantly. Anhui, Henan, Hubei, Hunan, and Guangxi have maintained a relatively stable hydropower generation meta-efficiency ranking, while the rankings of Jilin and Jiangxi have fallen. Anhui's rankings of thermal power and hydropower meta-efficiency have remained stable.

For the western provinces, Yunnan, Shaanxi, Gansu, and Ningxia have all maintained relatively stable rankings in terms of meta-efficiency of thermal power generation. Compared with 2013, Sichuan's thermal power generation meta-efficiency ranking increased by 11 places in 2017, as its efficiency value rose from 0.1721 to 0.8977. However, Guizhou and Xinjiang declined. Yunnan and Gansu have maintained a relatively stable ranking of hydropower generation meta-efficiency, and Xinjiang has risen. Compared with 2013, Xinjiang's ranking increased by 18 places in 2017, as its meta-efficiency score rose from 0.9256 to 1.0156, but Qinghai's ranking dropped. In summary, the hydropower and thermal power generation meta-efficiency rankings of Yunnan and Gansu have remained stable.

Figure 2 shows the average meta-efficiency values of hydropower and thermal power generation in the eastern, central, and western provinces in 2013 and 2017. Comparing 2013 and 2017, the average meta-efficiency values of thermal power generation in the three regions all showed a significant upward trend. In 2017, the average thermal power generation meta-efficiency ranking was Eastern > Central > Western; the average meta-efficiency value of hydropower generation in the eastern and central regions showed a significant downward trend, and the western region has shown a slight downward trend. In 2017, the meta-efficiency ranking of hydropower generation was West > Central > East. In summary, the difference in the meta-efficiency value of thermal power generation in all provinces is shrinking, while the difference in the meta-efficiency value of hydropower generation is expanding. Therefore, the development of the hydropower industry should employ measures to suit local conditions, formulate sustainable policies for the power industry, and promote efficient and green development of the hydropower and thermal power industries in each province.

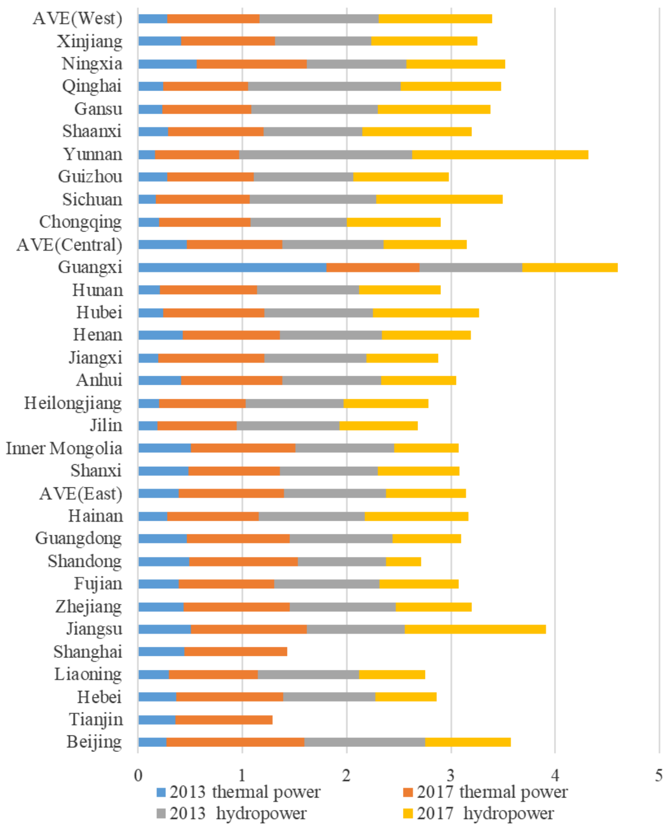


Figure 2. The thermal power and hydropower meta-efficiency scores in eastern, central, and western regions

Note: The data source comes from the authors' collection.

Figure 3 shows the comparison of the group score and the meta score of thermal power generation in China's provinces in 2013 and 2017. The group efficiency reflects the relative efficiency of each province in its group, excluding variations caused by group differences. The specific analysis is as follows. The group efficiency of the provinces such as Beijing, Jiangsu, and Zhejiang in the eastern region has been greater than 1, and the group efficiency of the provinces such as Chongqing, Shaanxi, Ningxia, and Xinjiang in the western region has also been greater than 1, indicating that these provinces are at the efficient production frontier. The thermal power generation group efficiency of Jilin in the central region in 2013 and 2017 is the lowest, but the gap between the thermal power group efficiency and the meta-efficiency of each province is gradually narrowing.

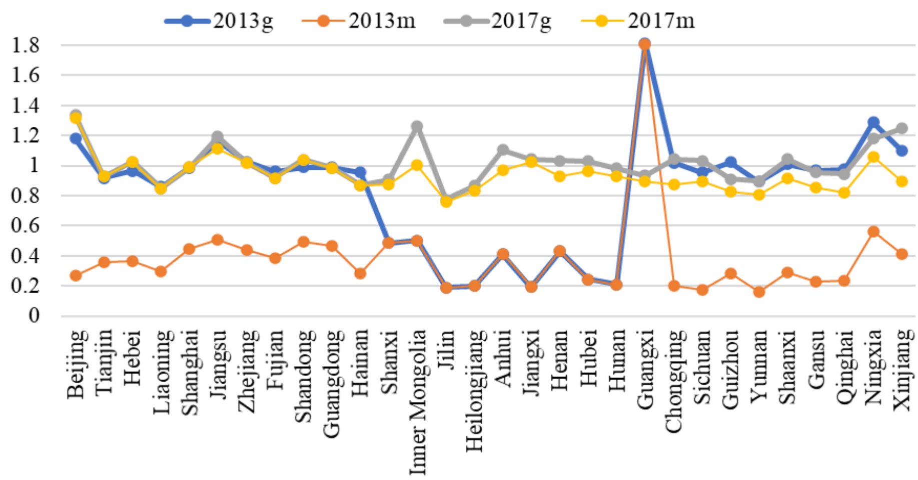


Figure 3. China's provincial group and meta-efficiency scores of thermal powers in 2013 and 2017

Note: The data source comes from the authors' collection.

Figure 4 shows the comparison results of thermal power generation group efficiency and meta-efficiency in the eastern, central, and western regions in 2013 and 2017. Specifically, in 2013 the average thermal power generation group efficiency of the three regions was 0.9992, 0.4674, and 1.0253, respectively. There are large regional differences in efficiency values, and there is room for improvement in the thermal power generation efficiency of the central region. In comparison, in 2017 the average group efficiency of thermal power generation was 1.0143, 0.9939, and 1.0279, respectively. The average group efficiency of the central region has greatly improved, and the eastern and western regions are also on the rise. Regarding the average thermal power group efficiency ranking, the western region is currently ranked first, followed by the eastern region, and then the central region. The above results show that the development of the thermal power generation industry in the eastern, central, and western regions is gradually mature and stable.

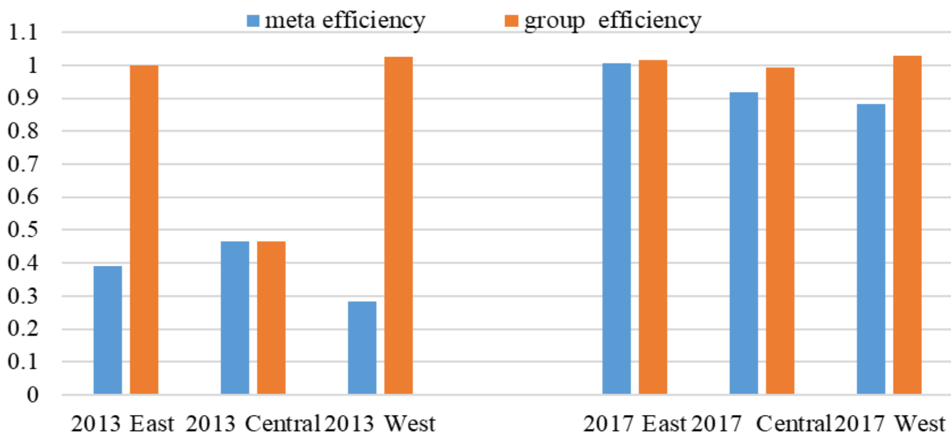


Figure 4. China's east, central, and west regional group, and meta-efficiency scores of thermal powers in 2013 and 2017

Note: The data source comes from the authors' collection.

Figure 5 shows the comparison between the group score and the meta-score of hydropower generation in China's provinces in 2013 and 2017. In terms of hydropower generation, the group efficiency of Zhejiang, Fujian, and Hainan in the eastern region has been greater than 1, and the group efficiency of Sichuan, Yunnan, Shaanxi, and Gansu in the western region has been greater than 1. Only Hubei's group efficiency in the central region has been greater than 1. Lastly, Shandong's hydropower generation group efficiency was the lowest in 2013 and 2017.

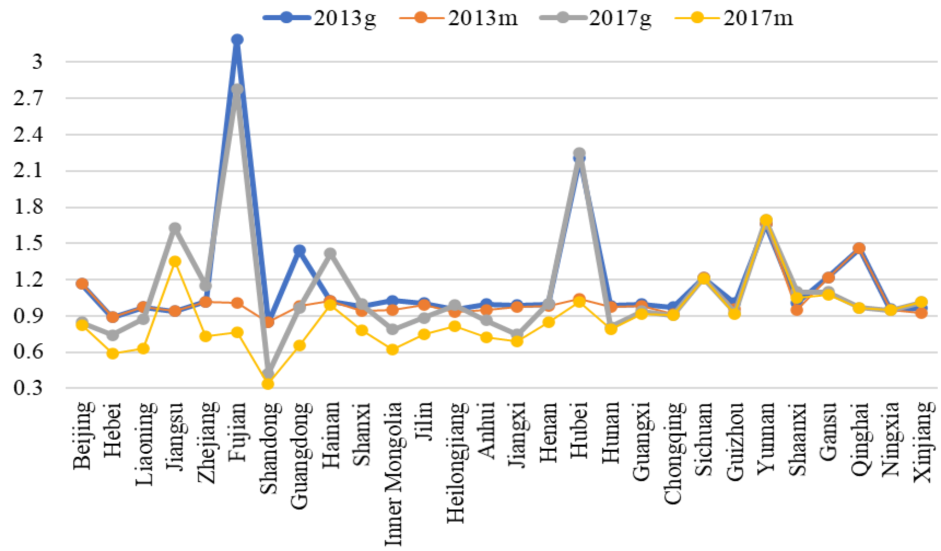


Figure 5. China's provincial group and meta-efficiency scores of hydropower in 2013 and 2017

Note: The data source comes from the authors' collection.

Figure 6 shows the comparison results of the group efficiency and meta-efficiency of hydropower generation in the eastern, central, and western regions of China in 2013 and 2017. Among them, the average hydropower generation group efficiency of the three in 2013 was 1.2759, 1.1135, and 1.1614, respectively, the difference in the average group efficiency values between the three major regions is relatively small, and the efficiency values are relatively high. In 2017, the average group efficiency of hydropower generation in the three regions was 1.2026, 1.0269, and 1.0956, respectively, and the average group efficiency values of the three major regions show a slight downward trend. In terms of average hydropower generation group efficiency rankings, the rankings of first (east), second (west), and third (central) have not changed and are relatively stable. We can see that the hydropower generation technology in the east, central, and western regions needs to be further improved, and the development of the hydropower generation industry needs continuous encouragement and promotion.

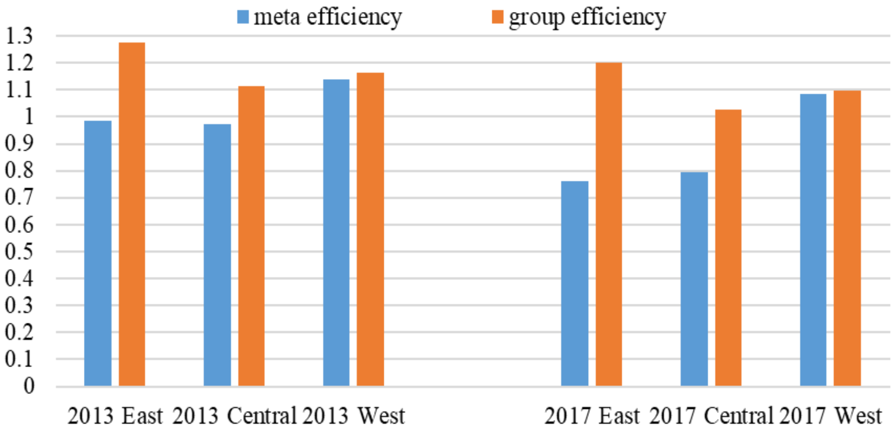


Figure 6. China's east, central, and west regional group, and meta-efficiency scores of hydropower in 2013 and 2017

Note: The data source comes from the authors' collection.

4.3. Technology gap ratio (TGR) scores and ranks of thermal power and hydropower

Table 3 lists the technology gap ratio rankings and technology gap ratio values of the efficiency of thermal power and hydropower generation in the meta- and group boundaries of China's provinces in 2013 and 2017, respectively. The specific analysis goes as follows.

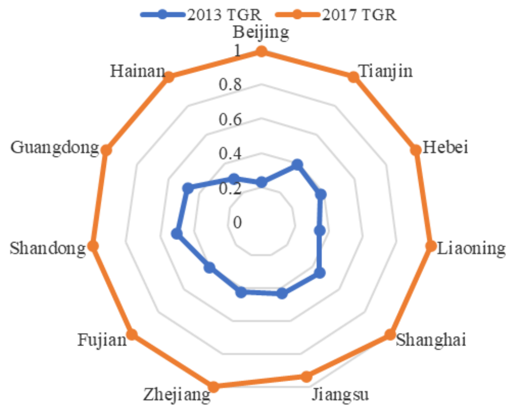
The thermal power efficiency technology gap ratio values and rankings of the eastern provinces in 2017 were significantly better than those of the central and western regions. In 2017, there were 5 provinces in the eastern region tied for first place with a technology gap ratio of 1: Tianjin, Liaoning, Shanghai, Fujian, and Guangdong. Liaoning rose 20 places in 2017, indicating that its thermal power industry's CO_2 emissions have been effectively controlled and reduced. Compared to 2013, the technology gap ratio values and ranking of the provinces in the central region in 2017 decreased significantly. Among them, Inner Mongolia, Anhui, and Henan dropped by 28, 23, and 19 places, respectively, and thus CO_2 emissions from thermal power generation must be reduced. Compared with 2013, the ranking of Xinjiang in the western region in 2017 dropped by 10 places, and its CO_2 emissions of the thermal power industry also need to be controlled. On the contrary, Yunnan rose by 7 places, indicating that its thermal power industry's CO_2 emissions have improved, while the remaining western provinces have relatively stable ranking changes. In general, the ranking of the western provinces is relatively stable, indicating that there has been no major adjustment in policies on carbon dioxide emissions and treatment in the thermal power industry. Moreover, the rankings of the eastern provinces have risen significantly, while the rankings of the central provinces have fallen significantly. It shows that the technological level of the thermal power generation industry in the eastern provinces has improved. These provinces not only target the economic output of thermal power generation, but also attach importance to energy conservation and emissions reduction in the thermal power industry. The central provinces need to strengthen their technology, energy savings, and emissions reduction of the thermal power industry.

Table 3. Technology gap ratio (TGR) and ranks of thermal power and hydropower in 2017

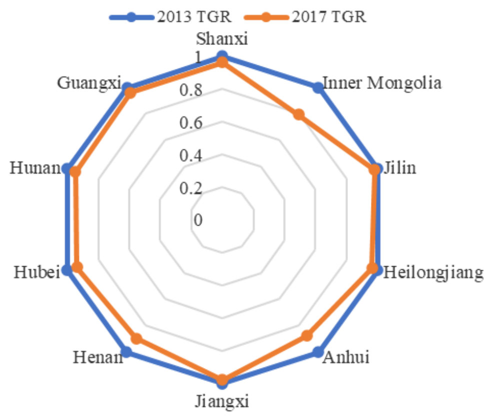
DMU	Thermal power	Hydropower

	2013		2017		2013		2017	
	Rank	TGR	Rank	TGR	Rank	TGR	Rank	TGR
Beijing	27	0.2300	10	0.9868	1	1	11	0.9693
Tianjin	18	0.3924	1	1	-	-	-	-
Hebei	19	0.3785	9	0.9953	1	1	20	0.7903
Liaoning	21	0.3434	1	1	1	1	23	0.7206
Shanghai	13	0.4513	1	1	-	-	-	-
Jiangsu	15	0.4346	18	0.9346	1	1	17	0.8294
Zhejiang	16	0.4256	7	0.9988	1	1	26	0.6332
Fujian	17	0.4012	1	1	28	0.3171	28	0.2749
Shandong	11	0.4984	8	0.9975	1	1	19	0.7970
Guangdong	12	0.4732	1	1	26	0.6851	25	0.6834
Hainan	22	0.2960	6	0.9999	1	1	24	0.6968
Eastern mean	2	0.3931	1	0.9921	3	0.8891	3	0.7105
Shanxi	1	1	14	0.9621	19	0.9639	22	0.7844
Inner Mongolia	1	1	29	0.7951	25	0.9248	21	0.7852
Jilin	1	1	11	0.9807	18	0.9809	15	0.8479
Heilongjiang	1	1	13	0.9644	17	0.9819	18	0.8262
Anhui	1	1	24	0.8787	21	0.9529	16	0.8346
Jiangxi	1	1	12	0.9784	15	0.9859	13	0.9210
Henan	1	1	20	0.8973	16	0.9858	14	0.8505
Hubei	1	1	17	0.9386	27	0.4717	27	0.4521
Hunan	1	1	16	0.9472	13	0.9908	9	0.9752
Guangxi	10	0.9951	15	0.9586	14	0.9904	10	0.9732
Central mean	1	0.9995	2	0.9301	2	0.9229	2	0.8250
Chongqing	28	0.1988	28	0.8415	23	0.9458	6	0.9969
Sichuan	30	0.1805	26	0.8702	1	1	1	1
Guizhou	24	0.2760	19	0.9073	22	0.9478	7	0.9934
Yunnan	29	0.1834	22	0.8953	1	1	1	1
Shaanxi	23	0.2871	25	0.8775	24	0.9405	12	0.9525
Gansu	26	0.2371	23	0.8943	1	1	8	0.9836
Qinghai	25	0.2432	27	0.8678	1	1	5	0.9971
Ningxia	14	0.4346	21	0.8963	12	0.9982	1	1
Xinjiang	20	0.3764	30	0.7187	20	0.9616	1	1
Western mean	3	0.2686	3	0.8632	1	0.9771	1	0.9915

Figure 7 shows the TGR values of the thermal power generation efficiency of the eastern, central, and western regions in 2013 and 2017. In 2017 the thermal power efficiency technology gap ratio values of the eastern provinces were better than that of the central and western provinces. The TGR values of the eastern and western provinces have a rising trend, while the central provinces have declined. China's central region needs to improve the efficiency level of thermal power generation as well as control and reduce CO_2 emissions. We see that the gap in thermal power technology in the eastern, central, and western regions has gradually narrowed, indicating that the technology in the thermal power industry is becoming more mature and CO_2 emissions control and treatment have made some progress.



(a)



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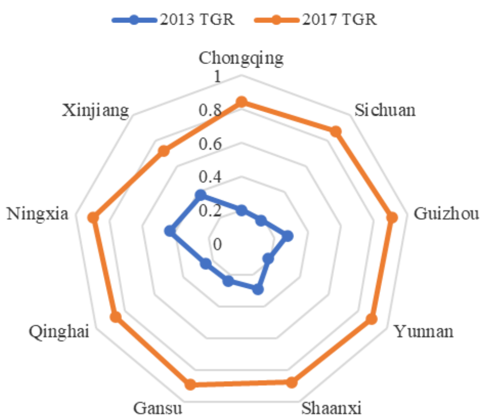


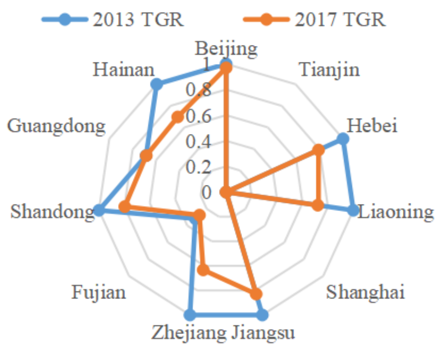
(c)

Figure 7. In 2013 and 2017, (a) China's east regional TGR of thermal power; (b) central regional TGR of thermal power; and (C)west regional TGR of thermal power.

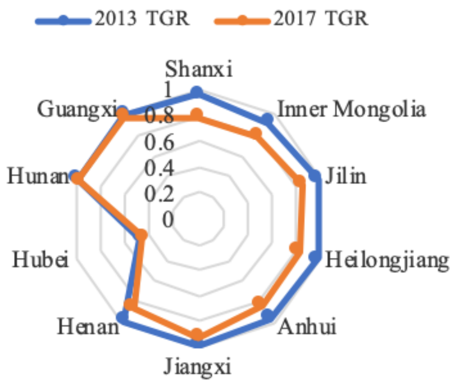
Note: The data are from the authors' collection

From Table 3 we see the hydropower efficiency technology gap ratio values and ranking of the western provinces in 2017 were significantly better than those of the eastern and central regions. In 2017, four provinces in the western region tied for first place with a technology gap ratio of 1: Sichuan, Yunnan, Ningxia, and Xinjiang. Moreover, Xinjiang and Chongqing increased their rankings by 19 and 17, respectively, in 2017, indicating that their hydropower industry development has been greatly promoted, and that the technological level of their hydropower industry has greatly improved. Compared with 2013, the technology gap ratio values and rankings of the eastern provinces in 2017 decreased significantly. Among them, Hebei, Liaoning, Jiangsu, Zhejiang, and Hainan dropped 19, 22, 16, 25, and 23 places, respectively, and efforts must thus be made to improve their efficiency and technology of hydropower generation. Compared with 2013, the rankings of provinces in the central region in 2017 are relatively stable, and the rankings of provinces in the western region have risen relatively. However, the rankings of the provinces in the eastern region have declined significantly, indicating that this region's incentive support policies for hydropower generation are not stable enough.

Figure 8 shows the TGR values of hydropower energy efficiency in the east, central, and west regions for 2013 and 2017. In 2017 the hydropower efficiency technology gap ratio values in the western provinces were better than that in the central and eastern provinces. The TGR values in the western provinces continued to increase, while the central and eastern provinces declined. The central and eastern regions need to improve their technical level of hydropower generation. Moreover, the technological gap among the western, central, and eastern regions has slightly expanded, and the hydropower industry needs further development and attention.



(a)



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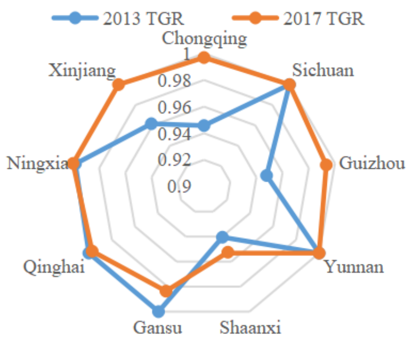

(c)

Figure 8. In 2013 and 2017, (a) China's east regional TGR of hydropower; (b) central regional TGR of hydropower; and (C) west regional TGR of hydropower.

Note: The data are from the authors' collection

4.4. Improvement analysis of input-output items of thermal power and hydropower

Table 4 shows the input-output non-efficiency levels of thermal power generation in China's provinces in 2017 and the average input-output non-efficiency levels of thermal power generation in its three major regions. By calculating the input-output redundancy of thermal power generation in China's provinces in 2017, the average non-efficiency levels of the input and output terms of the three regions can be measured. From the perspective of each group, the redundancy of the labor output in each region is relatively high, reaching more than 20%, and there is a surplus of undesirable output CO_2, with 8%, 11%, and 20% in the eastern, central, and western regions, respectively. The equipment utilization hours, energy input, and installed capacity of the western region are relatively high, and there is a shortage of thermal power generation output there. In addition, there is a large excess of undesirable output CO_2, which means that there is a large amount of CO_2 emissions, resulting in relatively low efficiency of thermal power generation in the west.

In the eastern region, there is a lot of redundancy in Liaoning's number of employees and energy input, and there is a large excess of undesirable output CO_2, which makes this province's thermal power energy efficiency the last in the group. In the central region, Jilin also has a large amount of redundant inputs, and its input redundancy in the number of employees and energy has reached 34% and 28% respectively. There is a large excess of undesirable output CO_2, and its desirable output is insufficient. This puts Jilin's thermal power efficiency at the bottom of its group. In the western region, Yunnan has a severe surplus of employees and installed capacity, with a redundancy of 68% and 47%, respectively. Moreover, there are serious shortages in thermal power generation output. This puts Yunnan's thermal power generation efficiency at the bottom of its group.

Table 4. Analysis of the inefficiency level of input-output items of thermal power in 2017 (%)

DMU	Hour	Labor	Energy	Installed capacity	Generation capacity	CO_2
Beijing	-83	-69	-34	-53	-48	0
Tianjin	-57	0	-15	0	0	-16
Hebei	0	-45	-5	0	-4	0

Liaoning	0	-27	-24	0	5	-30
Shanghai	-62	0	-4	-10	0	-2
Jiangsu	0	0	-3	-15	-21	0
Zhejiang	0	0	0	-14	-4	0
Fujian	-13	0	-6	0	10	-8
Shandong	0	-45	0	-12	-7	0
Guangdong	0	-59	-3	-10	0	-3
Hainan	-77	0	-21	0	0	-30
Eastern mean	-27	-22	-10	-10	-6	-8
Shanxi	-6	0	-7	0	19	-10
Inner Mongolia	0	0	-32	-4	-1	0
Jilin	0	-34	-28	0	28	-36
Heilongjiang	0	-47	-15	0	16	-24
Anhui	-19	0	-2	0	0	-6
Jiangxi	-47	-4	0	0	-4	0
Henan	0	-55	0	-2	13	-3
Hubei	0	-39	-1	-3	0	-7
Hunan	0	-47	-6	-12	0	-15
Guangxi	0	-46	0	-25	15	-8
Central mean	-7	-27	-9	-5	9	-11
Chongqing	-5	0	-17	-21	0	-28
Sichuan	0	-78	-12	-44	0	-23
Guizhou	-5	0	-19	0	18	-24
Yunnan	0	-68	0	-47	40	-9
Shaanxi	0	0	-13	0	0	-19
Gansu	0	-34	-11	0	15	-19
Qinghai	-75	0	-28	0	3	-41
Ningxia	-77	0	-28	-16	-11	0
Xinjiang	-24	0	-15	0	4	-19
Western mean	-21	-20	-16	-14	8	-20

Table 5 shows the input-output inefficiency levels of hydropower in China's provinces in 2017 and the average input-output non-efficiency levels of hydropower in its three major regions. By calculating the input-output redundancy of hydropower in China's provinces in 2017, the average non-efficiency levels of the input and output of the three regions can be measured. From the perspective of each group, the labor force in the three major regions also has redundancy problems, all of which reach more than 20%. Equipment utilization hours, number of employees, and installed capacity in the east are severely redundant, and output of hydropower generation in the east and central regions is insufficient, reaching 49% and 28%, respectively. These are also the reasons for the relatively low hydropower efficiency in the eastern and central regions.

In the eastern region, Shandong has a large number of employees, with a redundancy of 80%, and the desirable output of hydropower generation is insufficient, reaching 197%, which is the reason why Shandong's hydropower energy efficiency is at the bottom of the group. In the central region, Inner Mongolia also has a large amount of redundancy. The number of employees and installed capacity have reached 34% and 18%, respectively, and the desirable output of hydropower generation is insufficient, reaching 61%. These have led to Inner Mongolia's hydropower energy efficiency being at the bottom of the group. In the western region, Chongqing's equipment utilization hours and installed capacity are excessive, with redundancy reaching 44% and 9%, respectively, and there is insufficient hydropower output, which puts Chongqing hydropower energy efficiency in last place of the group.

Table 5. Analysis of the inefficiency level of input-output items of hydropower in 2017 (%)

DMU	Hour	Labor	Energy	Installed capacity	Generation capacity
Beijing	-52	-42	0	0	22
Hebei	0	-53	0	0	71
Liaoning	0	-17	0	0	58
Jiangsu	-45	-80	0	-72	-26
Zhejiang	0	-53	0	-40	37
Fujian	-22	0	-19	0	31
Shandong	0	-80	0	0	197
Guangdong	0	-69	0	-26	52
Hainan	-78	0	0	-29	1
Eastern mean	-22	-44	-2	-19	49
Shanxi	0	-16	0	0	28
Inner Mongolia	0	-34	0	-18	61
Jilin	0	0	0	0	34
Heilongjiang	-61	-77	0	0	23
Anhui	0	0	0	-1	39
Jiangxi	0	-23	0	-13	46
Henan	0	-48	0	0	17
Hubei	0	-27	0	-1	-2
Hunan	0	-31	0	-3	27
Guangxi	-6	0	0	-3	9
Central mean	-7	-26	0	-4	28
Chongqing	-44	0	0	-9	11
Sichuan	0	-51	-19	-15	-17
Guizhou	-25	0	0	-8	9
Yunnan	-51	0	-40	-43	-41
Shaanxi	-46	-25	0	0	-5
Gansu	-61	-59	0	0	-7
Qinghai	-74	0	0	-28	4
Ningxia	-93	-74	0	0	6
Xinjiang	-17	0	0	-14	-2
Western mean	-46	-23	-7	-13	-5

5 Conclusions

This study has collected data on thermal power generation in 30 provinces (municipalities) and hydropower generation in 28 provinces (municipalities) of China for the years 2013 and 2017. We then use the Meta-SE-SBM undesirable model to measure and compare the energy efficiency of thermal power and hydropower generation. The results are as follows.

First, based on the meta-boundary, compared with 2013 the average meta-efficiency values of thermal power generation in the eastern, central, and western regions in 2017 all showed a significant upward trend. The average meta-efficiency of thermal power generation is ranked from high to low in the order of East > Central > West. By comparison, the average meta-efficiency values of hydropower generation in eastern, central, and western regions have a downward trend. In 2017, the average meta-efficiency of hydropower ranked West > Central > East. In summary, the difference in the meta-efficiency values of thermal power generation in all provinces is shrinking, and the difference in the meta-efficiency values of hydropower generation is increasing. This shows that the thermal power generation industry in China's provinces is currently maturing. In particular, the western region has large geographical differences, a large river drop, and relatively rich hydropower resources, which make the western provinces' hydropower energy efficiency relatively high. Conversely, there is relatively large room for improving the hydropower energy efficiency in the eastern and central provinces.

Second, based on group boundaries, the energy efficiency of thermal power and hydropower generation in each province is closer to reality than at the meta-frontier. ①The thermal power group efficiency of Beijing, Jiangsu, and Zhejiang in the eastern region and Chongqing, Shaanxi, Ningxia, and Xinjiang in the western region has been greater than 1, indicating that these provinces have been at the frontier of efficiency in their groups. In 2017, the average thermal power group efficiency in the central region greatly improved, and the eastern and western regions also showed an upward trend. This is related to China's rapid economic development, increasing energy demand and dependence on thermal power, and promoting the importance and rapid development of the thermal power industry. Therefore, the technological level of thermal power generation in the three major regions has generally improved, and the technological differences in regional thermal power generation have gradually narrowed. ②the hydropower generation group efficiency of Zhejiang, Fujian, and Hainan in the eastern regions and Sichuan, Yunnan, Shaanxi, and Gansu in the western region o has been greater than 1, while only Hubei's group efficiency in the central region has been greater than 1. In 2017, the average hydropower group efficiency of the three regions showed a downward trend. We see that there is room for further improvement in the hydropower generation efficiency of the east, central, and west regions, and that the level of hydropower generation technology needs to be improved. The development of the hydropower generation industry also needs continuous encouragement and promotion.

Third, in 2017 the thermal power generation efficiency technology gap ratio values and rankings of the eastern provinces were significantly better than that of the central and western provinces, while the western provinces' hydropower generation efficiency technology gap ratio values and rankings were significantly better than the eastern and central provinces. The gap in thermal power technology among the three regions has gradually narrowed, indicating that the technology in the thermal power industry is maturing and CO_2 emissions control and treatment have made progress. The technological gap for hydropower among the three has slightly expanded, indicating that the hydropower generation industry needs further attention and policy support. In 2017, the thermal power technology gap ratio value of Tianjin, Liaoning, Shanghai, Fujian, and Guangdong in the eastern region was 1; the hydropower generation technology gap ratio value of Sichuan, Yunnan, Ningxia, and Xinjiang in the western region was 1. On the one hand, the technology gap ratio rankings between the thermal power generation technology in the eastern and central provinces are unstable, the rankings of the eastern provinces have increased significantly, and the central rankings have dropped significantly, meaning that the eastern provinces attach importance to improving the level of thermal power technology and do not just target the output of thermal power generation. Moreover, energy conservation and emissions reduction are highly valued. On the other hand, the technology gap ratio rankings of hydropower generation in the eastern provinces have dropped significantly, and the rankings of the western provinces have risen relatively, indicating that the eastern provinces' policies on hydropower generation are not stable enough, and the eastern provinces need to continue to implement relevant policies to support the improvement of the provinces in raising the technical level of hydropower generation.

Fourth, based on the calculation of the input-output non-efficiency level and from the perspective of thermal power generation efficiency, the undesirable output of CO_2 in the eastern, central, and western regions is excessive, reaching 8%, 11%, and 20%, respectively. The equipment utilization hours, energy input, and installed capacity of the western region are relatively high, and there is a shortage of thermal power generation output in the western region. Moreover, there is a large excess of undesirable CO_2 output and a large amount of emissions. This is also the reason for the relatively low efficiency of thermal power generation in the west. The excessive employment and installed capacity of Yunnan in the west and the insufficient output of thermal power generation make Yunnan's thermal power generation energy efficiency the last in the group. From the perspective of hydropower generation efficiency, the equipment utilization hours in the east, the number of employees, and the installed capacity are severely redundant, and the desirable output of hydropower generation in the east and central regions is insufficient, reaching 49% and 28%, respectively. This is also the reason for the relatively low hydropower generation efficiency in the eastern and central regions. There is an excessive number of employees in Shandong, and the desirable output of hydropower generation is insufficient, which puts Shandong's hydropower generation efficiency in the bottom of the group.

Considering the energy efficiency, technological gaps, and input-output non-efficiency levels of thermal and hydropower generation in China's provinces, strategies should be adopted that meet their actual conditions. Therefore, we offer some policy suggestions.

First, the China government should continue to promote innovation in the management system of the thermal power generation industry, implement the most stringent energy regulatory system, improve management and organizational standards, increase environmental protection supervision in the thermal power generation industry, and build a carbon emissions trading and regulatory system for thermal power generation enterprises. The eastern provinces of Liaoning and Hainan, the central provinces of Jilin, and Heilongjiang, and the western provinces of Guizhou, Yunnan, and Qinghai all need to pay attention to their level of output efficiency of thermal power generation, reduce the energy input of thermal power, and reduce the undesirable output of carbon dioxide by thermal power emissions. These provinces can improve the technical level of thermal power generation, reduce energy consumption in the process of thermal power generation, and then reduce carbon dioxide emissions, thereby improving the quality and efficiency of thermal power industry.

Second, financial subsidies should be used to encourage the development of clean energy such as hydropower generation. In particular, importance should be attached to technological innovation of new energy sources, and advanced energy-saving power generation technologies should be promoted. At the same time, the market scale of clean energy such as hydropower needs to be expanded to reduce carbon dioxide emissions and environmental pollution from its root causes. Among them, the eastern provinces of Guangdong, Hebei, Liaoning, and Shandong, the central provinces of Jiangxi, and Inner Mongolia, and the western provinces of Qinghai, Ningxia, Guizhou, and Chongqing need to increase their level of hydropower generation output, increase the amount of hydropower generation, reduce the number of hours of equipment utilization and reduce installed capacity investment, decrease the input of employees in the hydropower generation industry, improve the quality of employees in the hydropower industry, and cultivate new energy technology innovation and management innovation talents.

Third, the China government should continue to promote the management of green and efficient use of regional energy and coordinate the development of the thermal power industry and the hydropower industry according to local conditions. It should promote the reform of the market-based price mechanism of "benchmark price + floating up and down" and promote autonomous and voluntary negotiation of floating prices. This should make the power supply and demand changes be reversely transmitted to the power coal supply and demand relationship and help promote the market to play a better role in resource allocation. The efficiency improvement brought by technological progress must be reflected in the electricity price, and then the low-efficiency units can be gradually withdrawn from the market, so as to achieve the optimal allocation of resources and the overall improvement of power generation efficiency, which is more conducive to promoting the sustainable development of the power industry. In addition, the bidding mechanism should be improved for the power market and power generation companies, and the innovation of the management system of the power industry should be steadily promoted. At the same time, relevant policies should be implemented effectively to restrain the environmental pollution generated by the thermal power industry and develop clean energy such as hydropower, wind power, and solar power according to local conditions. Especially in the western provinces with abundant hydropower resources, resource endowment advantages must be fully utilized, so that China’s power generation efficiency can be comprehensively improved.

Declarations：

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