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## Original article

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# 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 the energy conservation, emissions reduction, and green development of the country's whole power industry.

**Methods:** Considering regional differences and multiple effective decision-making units, this research uses the Meta-SE-SBM undesirable model to comprehensively evaluate the efficiencies of hydropower and thermal power generation in China, taking CO<sub>2</sub> emissions of thermal power generation as the undesirable output.

**Results:** The average group efficiency of thermal power generation in the central region has greatly improved, the eastern and western regions also show an upward trend, but there is a slight downward trend for hydropower in the three regions. The hydropower technological gaps in the three regions have slightly expanded, but their thermal power technology gaps have gradually narrowed. From the perspective of input-output non-efficiency level, the undesirable output CO<sub>2</sub> of thermal power energy efficiency in the eastern, central, and western regions is in a surplus, 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 eastern region the redundancy of equipment utilization hours, number of employees, and installed capacity are all high, but the generation of hydropower in the eastern and central regions is insufficient, leading to relatively low hydropower efficiency in these two regions.

**Conclusions:** When formulating policies to promote China's power efficiency improvement and green development, the government and power industry managers should fully consider regional differences in the efficiencies of hydropower and thermal power. The thermal power industry is relatively mature, but its CO<sub>2</sub> emissions should be reduced and the scale of thermal power cannot be blindly expanded. The hydropower industry needs further policy support to increase market share and to enhance the local power industry's competitiveness under the condition of its resource endowments.

**Key words:** Energy Efficiency; Hydropower; Thermal Power; CO<sub>2</sub>; Super-Efficiency Slack-Based Measure Model; Meta-frontier

## 1 Introduction

According to the "BP Statistical Review of World Energy 2019" report [1], the global power industry in 2018 overall contributed about half of the primary energy growth and carbon emissions.

This is concrete evidence that the power industry plays an important role in both energy consumption and carbon emissions. In 2018, China's power generation increased 7.7% from 2017, accounting for 26.7% of the world's total amount of power generation. China's electricity production clearly occupies an important share of global electricity production.

Thermal power is currently a major part of China's electricity generation, and coal-fired power generation accounts for most of the nation's thermal power generation. Because of the large amount of carbon dioxide produced by coal burning, it is putting huge pressure on the environment in a negative manner. With the greater urbanization and industrialization of China, the demand for electricity is increasing, leading to even more severe pressure on the ecological environment. With the continuous increase in energy consumption and carbon emissions, the country's energy efficiency and structure need to be optimized and adjusted. The positive role of renewable energy such as hydropower cannot be ignored when targeting the green development of the power industry.

China's energy conservation and carbon emissions reduction are a clear focus of the government and its citizens. One of the most important issues throughout the world in the next two decades is how to reduce carbon emissions of the power industry while meeting rapidly growing power demand, especially in developing countries like China. The report of the 19<sup>th</sup> National Congress of the Communist Party of China highlighted the development of the production and consumption of electricity energy in order to promote green development. The key point is how to encourage high-quality and efficient power production that helps reduce carbon emissions.

In order to promote the construction of ecological civilization and realize green development, the China government formulated the 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-kilowatt Hour (KWH), of which thermal power generation and hydropower generation accounted for 70.99% and 18.59%, respectively. In 2017, China's installed power generation capacity hit 1777.08 million kilowatts (kW), an increase of 7.67% over the previous year, whereas 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.

Compared to thermal power development, for hydropower development, two questions arise: Is it competitive enough to grow and mature? What is the difference in hydropower efficiency among the various regions of China? Efficiency evaluation is the basis for understand the pathway towards improvement, and whether it is thermal power or hydropower, enhancing generation efficiency can promote the green development of the whole power industry. This research thus conducts an in-depth analysis and comparison of hydropower and thermal power in the three major regions of China from the perspective of technical efficiency in order to provide a reference for improving power generation efficiency and promoting the green development of the country's power industry. As research evaluation and regional comparative analysis on China's thermal power and hydropower energy are of great theoretical value and practical significance, the clean characteristics of hydropower present a good promotion effect on energy conservation and emissions reduction, thus providing a way to improve the energy structure. Scientific and reasonable efficiency evaluation also helps to accurately grasp the current situation of thermal power and

hydropower generation.

Regarding the study of energy efficiency, first, most studies use the concept of total energy to perform efficiency calculations. More specifically, it is necessary to examine the industry efficiency issues of thermal power generation and hydropower generation. Some scholars have investigated the efficiency of thermal power generation as a research topic, 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 such as hydropower. Second, in the literature on 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 that consider regional differences. Moreover, the analyses do not solve the problem of distinguishing the effective decision-making unit (DMU). It is thus necessary to incorporate 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 as well as to better compare and observe the efficiency differences between hydropower and thermal power.

The efficiency calculated by considering environmental factors gives a more reasonable understanding of the power industry's operations and offers a measurement for the competitiveness and development of each province's or region's power industry. Further in-depth analyses on efficiency and differences of thermal power and hydropower generation in China's eastern, central, and western regions are of great significance for local governments and power industry managers by providing improvement directions on the input and output of electricity production that can help achieve higher power industry efficiency and less emissions. These three regions face different situations both economically and politically, and so policies to improve the efficiency and the structure of their power industries should not be a "one size fits all". For practical applications, data envelopment analysis (DEA) is increasingly recognized as an effective evaluation tool for policy formulation to promote regional development. The Meta-SE-SBM undesirable model we employ in this paper distinguishes the efficient provinces, includes an undesirable output indicator, and considers regional differences in order to measure the efficiencies of thermal power and hydropower in China's three main regions more accurately and to formulate more beneficial policy recommendations.

## **2 Literature Review**

With the rapid development of China's economy, the demand for energy continues to increase, and as such green energy development has become an important trend domestically. In recent years, China's clean energy industry, including hydropower, wind power, solar energy, biomass energy, and nuclear energy, has developed quickly and achieved large-scale expansion. In addition, the proportion of clean energy consumption in total energy consumption is still positively rising. This has prompted many scholars to pay greater attention to the country's clean energy and its efficiency.

The energy efficiency literature is mainly divided into efficiency influencing factors research and efficiency measurement evaluation research. Scholars have applied a variety of research methods to study various industries, including different types of energy use and impact issues. The literature on energy efficiency impact factors, on the one hand, often takes the LMDI method to decompose and evaluate the influencing factors of energy or carbon emissions, such as Liu et al. [2] and Wang and Zhou [3]. On the other hand, econometric models have been also adopted to analyze

influencing factors, such as Meng et al. [4], who utilized polynomial functions and Partial Least Squares (PLS) algorithms to evaluate the effect of market reforms in China's thermal power industry in 2003. Their 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 during the period 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. [5] combined the multiple regression model with the generalized autoregressive conditional heteroscedasticity (GARCH) model to analyze the energy efficiency of thermal power plants in China. The results show that the rate of electricity consumption of power plants has a positive impact on the volatility of energy efficiency. The higher overall energy efficiency index will lead the lower rate of electricity consumption of power plants.

For the literature on efficiency measurement evaluation, the most commonly used methods overall include data envelopment analysis (DEA) and stochastic frontier analysis (SFA). For example, Ghosh and Kathuria [6] employed SFA to investigate the effect of regulatory governance on thermal power generation efficiency in India. The mean technical efficiency of 76.7% indicates there is wide scope for efficiency improvement in the sector, and state-level regulators have positively impacted plant performance. The SFA method requires arbitrary assumptions regarding the functional form or the distributional form of the error terms. However, as a non-parametric method, the DEA model is often used to evaluate the efficiency of power generation, because it does not require any specification of the functional form of the production relationship and has the advantages of avoiding subjective factors and reducing errors. In recent years, the DEA method has been widely applied in various fields to conduct effectiveness analysis. For example, scholars have used DEA to analyze and evaluate energy and environmental efficiency, such as DEA and the Malmquist index by Dyckhoff et al. [7] and Perez et al. [8], SBM-DEA by Choi et al. [9], and meta-frontier by Battese et al. [10] and Beltrón-Esteve et al. [11].

The DEA model was originally proposed by Charnes, Cooper and Rhodes in 1978 [12] and has been used by scholars to evaluate energy and environmental efficiencies. However, CCR [12] and BCC [13] set up radial and oriented models to calculate efficiency, but the input (output) model only measures the degree of inefficiency from one aspect of input (output), and the efficiency measurement of the radial model does not consider an input (output) slack variable, which can overestimate a DMU's efficiency. To solve this problem, Tone then proposed the SBM model [14], which is a DEA model that considers input and output slack and an efficiency evaluation method that takes on undesirable output indicators. However, the SBM model also has some limitations. First, it is impossible to effectively identify the efficiency of the decision-making units, and a quantitative comparison and quantitative analysis on this basis may not be accurate. Second, the SBM model assumes that each DMU faces the same technological frontier. However, practically, DMUs are often in different geographical locations or operate under different national policies or socio-economic conditions. The technological frontiers of these DMUs are not the same - that is, there are heterogeneous technologies. If the homogeneity assumption is adopted without considering the difference in their technological frontiers, then the efficiency measurement results may be biased.

For the energy efficiency literature based on DEA methods, the research objects can be divided into regional-/macro-level and company-/micro-level studies. At the company-/micro-level aspect, Shrivastava et al. [15] estimated the efficiency of thermal power plants in India using the DEA

method. Their results suggest that 31.67% of power plants are good performers, 35% are moderate performers, and 23.33% are laggards, whereas 10% are poor performers based on a ranking of their variable returns to scale (VRS). Moon et al. [16] used a two-stage DEA model to analyze the efficiency of energy-intensive manufacturing companies in South Korea. Their findings are that pure-energy efficiency is more important to improve overall energy efficiency, and each industry has different possibilities to improve energy efficiency, so governments or policy-makers must be informed of the differences and provide support in realistic ways for each industry. Empirical research on the power industry's efficiency is mainly carried out from the level of power plants and power companies by using DEA methods. Previous research do evaluate the efficiency of power companies, but it is not enough to assist our study in understanding the variations in the efficiency of power generation among different regions.

For regional-/macro-level energy efficiency, Lam and Shiu [17] applied the DEA approach to measure the technical efficiency of China's thermal power. Their results show that municipalities and provinces along the eastern coast and those with rich supplies of coal have the highest levels of technical efficiency, and that the presence of labor slack in many regions indicates that labor redundancy is a serious problem. Mei et al. [18] 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. Their results show 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. [19] utilized a slack-based measure approach to study the impact of environmental regulations on the energy efficiency of thermal power generation in China, finding that energy efficiency and environmental efficiency are relatively low and have distinct regional characteristics. Song et al. [20] employed the slack-based endogenous directional distance function (SBEDDF) model to evaluate the environmental impact of China's power generation industry, providing results 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%, and the best solution to reduce emissions is unique to each region.

When using the directional distance function (DDF) to measure energy efficiency, although the undesirable output of environmental pollution is included, it is assumed that the both undesirable output and the desirable output increase or decrease in the same proportion. Thus, the DDF method has the following shortcomings. First, if the input is slack, then the estimated energy efficiency will be biased [20]. Second, the efficiency of a single input element cannot be measured [22]. Li and Shi [23] thus proposed an improved Super-SBM model with bad output that can reasonably distinguish multiple effective DMUs, make the efficiency ranking more capable, 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 beneficial calculations need to be considered, and attention should focus on the regional differences and rankings of effective DMUs.

With the development of new energy, more attention has been paid to the energy efficiency of hydropower. For example, Barros [24] applied DEA to measure and decompose the efficiency of EDP (Portugal Electricity Company) and its hydroelectric energy generating plants, showing that hydropower stations have improved in terms of technical efficiency and technological progress. Barros et al. [25] employed the Virtual Frontier Dynamic Range Adjusted Model (VDRAM) DEA to evaluate the efficiency of 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.

Utilizing undesired output when assessing energy efficiency can reflect the requirements for green development of energy and make efficiency measurement more real and effective. Scholars have taken diversified input-output indicators into their energy efficiency calculations, but they have common points, such as [4], [9], [19], [20], [26]. The input indicators mostly are labor and capital, but special input indicators of raw materials and equipment are also counted. In addition, output indicators are typically production volume, GDP, etc. and include an undesirable output that is unfavorable to the environment. Most studies have selected CO<sub>2</sub> emissions, such as [27]-[31].

From the literature review we find scant studies on the calculation of China's hydropower efficiency, yet relatively more research on the efficiency of China's thermal power sector. Research at the micro-level (firms or plants) is more abundant, and thus research at the regional level still needs further exploration. Moreover, there are fewer comparative studies on the energy efficiency of China's hydropower and thermal power industries. Wang et al. [32] believed that although hydropower and thermal power constitute the two pillars of China's electricity supply, the relationship between the two needs more analysis. They aimed to reveal the relationship between the two under the framework of the autoregressive distributed lag (ARDL) model, which provides useful enlightenment to accurately measure regional hydropower and thermal power efficiencies and to 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 our present 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 efficiency values will not be overestimated. (2) A more realistic and effective efficiency measurement of thermal power and hydropower generation methods is needed, and multiple effective DMUs should be ranked. Comparative studies are relatively lacking, and more comprehensive input-output indicators are required.

The academic contributions of this paper are as follows. First, most scholars typically have studied thermal power or hydropower generation efficiency at the company or plant level. Scant studies have conducted a sub-regional analysis of thermal power or hydropower generation industry efficiency, and even fewer studies have comparatively analyzed the generation efficiencies of thermal power and hydropower from a sub-regional basis. It is thus beneficial to carry out a comparative study on China's thermal power and hydropower generation efficiencies in the eastern, central, and western regions to examine efficiency differences and changing trends in these three regions in order to propose specific power industry development initiatives for regional government and power industry managers.

Second, when investigating power efficiency, some scholars have adopted the stochastic frontier model, BCC, CCR, SBM, and other methods. The defect of these models is that they fail to consider the differences in social culture, economic environment, and production structure of various regions, by assuming that all provinces (in China) have the same technical level. They are

unable to distinguish multiple efficient provinces, which leads to a large deviation in the evaluation results of power efficiency. The Meta-SE-SBM undesirable model used in this paper considers envelope curves that contain all group production frontiers, enabling different groups to measure efficiency under the same common benchmark, which is more accurate for evaluating the efficiency value. This model also sorts multiple effective provinces in the measurement results of thermal and hydropower energy efficiencies and incorporates undesirable outputs into the measurement system, which can more realistically and comprehensively reflect regional power efficiency.

Third, China's power generation production is maintaining an upward trend and occupies a large share in global power generation, and hence information on the segmentation and effectiveness of the country's power generation is urgently needed. Our study's findings on China's thermal power and hydropower generation efficiencies in the eastern, central, and western regions can help evaluate the current situation of the thermal power and hydropower generation industries and propose relevant countermeasures to promote their efficient operations, providing a reference for local governments and power industry managers to achieve green development. On such a basis, local governments and power industry managers can formulate appropriate policies according to local conditions to adjust the development scale, input elements, and structural proportions of thermal power and hydropower generation to achieve synergy between economic and environmental benefits. The findings also provide useful inspiration for the comparison and improvement of thermal power and hydropower efficiencies in other countries or regions.

### **3 Methods**

#### **3.1. SE-SBM model**

As a non-parametric research method, DEA evaluates the relative effectiveness of DMUs from the perspective of input and output. The DEA model is often used by scholars to evaluate energy efficiency, because it has no specification for the functional form of the production relationship and has the advantages of avoiding subjective factors and reducing errors. Traditional DEA models include the CCR and BCC models. The use of the CCR model requires that all DMUs are produced at the optimal scale, and so the return to scale of DMUs remains unchanged. When this condition is not met, the efficiency evaluation results by using the CCR model will be biased. In 1984, Banker, Charles and Cooper improved the CCR model and proposed a BCC model with variable returns to scale.

Traditional DEA models only measure the degree of inefficiency from one aspect of input (output), and the efficiency measurement of the radial model does not consider an input (output) slack variable, which will overestimate the efficiency of DMUs. To solve this problem, the SBM model was proposed by Tone [14] and is a DEA approach that considers slack improvement. It is able to solve the problem that the radial model does not include slack variables in non-efficiency measurements. However, the SBM model has the limitation that it is impossible to effectively identify and compare the efficiency of efficient decision-making units, and the quantitative comparison and quantitative analysis on this basis may not be accurate.

The Super-Efficiency SBM model (SE-SBM) solves the problem of differentiating the

efficiency of DMUs and at the same time incorporates undesirable outputs into the measurement system [33], thus more realistically and comprehensively reflecting regional energy efficiency. It can accurately assess the efficiencies of thermal power and hydropower of different provinces in the three regions, identify effective provinces, compare the efficiency differences between the two forms of electricity, and provide more scientific and reasonable improvement measures to improve the efficiency and green development of the power industry.

$$\begin{aligned} \min \rho &= \frac{1 + \frac{1}{m} \sum_{i=1}^m \frac{s_i^-}{x_{ik}}}{1 - \frac{1}{q_1 + q_2} \left( \sum_{r=1}^{q_1} \frac{s_r^g}{y_{rk}^g} + \sum_{r=1}^{q_2} \frac{s_r^b}{y_{rk}^b} \right)} \quad (1) \\ \text{s.t. } &\sum_{j=1, j \neq k}^n x_{ij} \lambda_j - s_i^- \leq x_{ik}, \quad \sum_{j=1, j \neq k}^n y_{rj} \lambda_j + s_r^{g^+} \geq y_{rk}^g, \quad \sum_{j=1, j \neq k}^n y_{rj}^b - s_r^{b^-} \leq y_{rk}^b \\ &1 - \frac{1}{q_1 + q_2} \left( \sum_{r=1}^{q_1} \frac{s_r^g}{y_{rk}^g} + \sum_{r=1}^{q_2} \frac{s_r^b}{y_{rk}^b} \right) > 0, \quad s^- > 0, \quad s^b > 0, \quad s^g > 0, \quad \lambda > 0 \\ &i = 1, 2, \dots, m; \quad r = 1, 2, \dots, q; \quad j = 1, 2, \dots, n (j \neq k) \end{aligned}$$

The SE-SBM model (Eq. (1)) assumes 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  $Y^b$  as  $X = [x_1, x_2, \dots, x_n]$ ,  $Y^g = [y_1^g, y_2^g, \dots, y_n^g]$ , and  $Y^b = [y_1^b, y_2^b, \dots, y_n^b]$ . In addition,  $s$  is the amount of slack in the input and output,  $\lambda$  is the weight vector, and the objective function is  $\rho$ , whose value is between 0 and 1. Here,  $x_{ij}$  is the  $i^{\text{th}}$  input of the  $j^{\text{th}}$  DMU, and  $y_{rj}$  is the  $r^{\text{th}}$  output of the  $j^{\text{th}}$  DMU.

### 3.2. Meta-frontier and technology gap ratio

Traditional DEA generally assumes that all producers have the same level of technology, but the assessed DMUs are often in different geographical locations or under different national policies or socio-economic conditions. The technological frontiers of these DMUs are not the same - that is, there are heterogeneous technologies. If the homogeneity assumption is adopted without considering the difference in the technological frontiers, then the efficiency measurement results may be biased. Battese et al. [34] proposed a Meta-frontier Production Function, while O'Donnell et al. [35] further established a meta-frontier framework based on DEA that can accurately calculate the group and meta-frontier technical efficiencies.

Suppose that all DMUs are divided into  $H$  groups. DMUs are grouped according to the division of China's eastern, central, and western regions. Group-frontier efficiency is calculated by using the SE-SBM model to measure the efficiency of DMUs in the same group under the group boundary. Meta-frontier efficiency is calculated by using the SE-SBM model to measure the efficiency of DMUs in the total group under the same boundary. Since the meta-frontier contains the group frontier of  $H$  groups, the technical efficiency of the meta-frontier (MFE) is less than the technical efficiency of the group frontier (GFE). The calculated value is called the technical efficiency gap ratio (or technology gap ratio, TGR). The formula is:

$$TGR = \frac{\rho^*}{\rho_0^H} = \frac{MFE}{GFE} \quad (2)$$

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

### 3.3. Meta-SE-SBM undesirable model

We refer to the Super-Efficiency SBM model proposed by Huang [36], 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. In this paper, the three  $H$  groups are China's eastern, central, and western regions. Define the number of DMUs in the  $H$  groups as  $N_h$ , and then  $\sum_{h=1}^H N_h = N$ . Assume that each DMU has three types of input and output variables: inputs, desirable outputs, and undesirable outputs, which are expressed as:  $x = [x_1, x_2, \dots, x_M] \in \mathbb{R}_+^M$ ,  $y = [y_1, y_2, \dots, y_R] \in \mathbb{R}_+^R$ ,  $b = [b_1, b_2, \dots, b_J] \in \mathbb{R}_+^J$ , 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  $k^{\text{th}}$  group of the  $o^{\text{th}}$  DMU ( $o = 1, 2, \dots, N_k$ ;  $k = 1, 2, \dots, H$ ) for the non-directed and non-radial SBM of the meta-frontier formed by all groups can be obtained by solving the following:

$$\begin{aligned} \rho_{ko}^{Meta*} = \min & \frac{1 + \frac{1}{M} \sum_{m=1}^M \frac{s_{mko}^x}{x_{mko}}}{1 - \frac{1}{R+J} \left( \sum_{r=1}^R \frac{s_{rko}^y}{y_{rko}} + \sum_{j=1}^J \frac{s_{jko}^b}{b_{jko}} \right)} \quad (3) \\ \text{s. t. } & x_{mko} - \sum_{h=1}^H \sum_{n=1, n \neq o \text{ if } h=k}^{N_h} \xi_n^h x_{mhn} + s_{mko}^x \geq 0 \\ & \sum_{h=1}^H \sum_{n=1, n \neq o \text{ if } h=k}^{N_h} \xi_n^h y_{rhn} - y_{rko} + s_{rko}^y \geq 0 \\ & b_{jko} - \sum_{h=1}^H \sum_{n=1, n \neq o \text{ if } h=k}^{N_h} \xi_n^h b_{jhn} + s_{jko}^b \geq 0 \\ & 1 - \frac{1}{R+J} \left( \sum_{r=1}^R \frac{s_{rko}^y}{y_{rko}} + \sum_{j=1}^J \frac{s_{jko}^b}{b_{jko}} \right) \geq \varepsilon \\ & \xi_n^h, s^x, s^y, s^b \geq 0 \\ & m = 1, 2, \dots, M; r = 1, 2, \dots, R; j = 1, 2, \dots, J \end{aligned}$$

In Equation (3),  $\xi$  is a non-negative weight vector,  $\varepsilon$  is non-Archimedean and 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  $1 - \frac{1}{R+J} \left( \sum_{r=1}^R \frac{s_{rko}^y}{y_{rko}} + \sum_{j=1}^J \frac{s_{jko}^b}{b_{jko}} \right) \geq \varepsilon$  is added 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  $\sum_{h=1}^H \sum_{n=1, n \neq o \text{ if } h=k}^{N_h} \xi_n^h = 1$  here.

### 3.4. Data sources and description

Due to a lack of statistical data, this study does not consider Hong Kong, Macau, Taiwan, and Tibet as DMUs. In order to consider regional differences, following Liu et al. [27] 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 for 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 been 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 [37], China Energy Statistical Yearbook [38], and China Electric Power Statistical Yearbook [39], and relevant data for 2013 and 2017 are collected.

The input and output variables are selected based on the comprehensive consideration of previous research experience and data availability. Following Zhou et al. **Error! Reference source not found.** and Qu et al. **Error! Reference source not found.**, labor, installed capacity, and energy consumption are all selected as input indicators, and power generation is taken as the output indicator to measure power efficiency. In addition, Qu et al. **Error! Reference source not found.** also chose undesirable output CO<sub>2</sub> emissions, because they were mainly from coal-fired thermal power generation. Bi et al. [19] and Saglam [42] also considered installed capacity as one of the most important input indicators, because of the strong correlation between installed capacity and generated electricity. Zhou and Ang [43] and Bi et al. [19] separated inputs into energy inputs and non-energy inputs, where the former are types of fossil fuel and the latter include capital and labor force. Capital is measured in terms of installed thermal generating capacity.

Input indicators: ① Urban employees in the production and supply industry 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. ② Installed capacity refers to the sum of the rated active power of generator sets actually installed in the power system. It is used to measure the investment scale in thermal power or hydropower generation equipment in each province; the unit is 10,000 kilowatts (kW). ③ Hours are used to indicate the effective utilization rate of the equipment, which clearly reflect the situation of installed power generation capacity and whether there is any excess; the unit is h. ④ Energy is an important input for the operation of thermal power generation. The energy related input of thermal power generation mainly includes coal, oil, and natural gas. The data of thermal power input are from the fossil fuel data of the thermal power industry provided by China Energy Statistics Yearbook [38], 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 [39]; its unit is also 10,000 tons of standard coal.

Desirable output indicator: Power generation directly reflects the actual production performance level of the power industry. 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 (KW H).

Undesirable output indicator: Due to the characteristics of clean energy, hydropower does not consider undesirable output. China's thermal power generation industry is an important sector of energy consumption and carbon emissions. The undesired output brought by thermal power must therefore be fully considered. In the calculation of thermal power efficiency, CO<sub>2</sub> emissions from thermal power generation are selected as the undesirable output, and the unit is 10,000 tons. According to Liu et al. [44] and Qin et al. [31] and based on fossil fuel energy consumption data of the thermal power industry at the provincial level, we estimate the carbon dioxide emissions of thermal power generation in China's provinces in 2013 and 2017. The formula is:

$$C_{it} = \sum E_{ijt} \times CEF_j \times COR_j \times \frac{44}{12} \quad (4)$$

Among the variables above,  $C_{it}$  is 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 latter two are from the research of Liu et al. [44] and Qin et al. [31].

To further verify the acceptability of input-output indicators, we add relevant tests on the factor analysis of the indicator selection. The results of principal component analysis using IBM SPSS Statistics 20.0 appear in Table 1 and Table 2.

**Table 1. Kaiser-Meyer-Olkin (KMO) and Bartlett's test**

Thermal power		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.731
Bartlett's Test of Sphericity	Approx. Chi-Square	681.952
	df	15
	Sig.	0.000
Hydropower		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.777
Bartlett's Test of Sphericity	Approx. Chi-Square	535.515
	df	10
	Sig.	0.000

**Note: The data are from the authors' collection.**

The Kaiser-Meyer-Olkin (KMO) of principal component analysis of input and output indicators of thermal power generation efficiency is 0.731, and the approximate chi-square of Bartlett's sphericity test is large ( $>0.5$ ) and significant ( $p\text{-value} < 0.01$ ), indicating that there is a significant correlation between the selected indicators. The KMO of principal component analysis of input and output indicators of hydropower generation efficiency is 0.777, and the approximate chi-square of Bartlett's sphericity test is large ( $>0.5$ ) and significant ( $p\text{-value} < 0.01$ ), indicating that there is a significant correlation between the selected indicators.

**Table 2. Communalities of thermal power and hydropower**

Variable	Initial	Extraction
Thermal power		
generation	1.000	0.729
CO <sub>2</sub>	1.000	0.945
hour	1.000	0.870
labor	1.000	0.708
energy	1.000	0.947
installed capacity	1.000	0.939
Hydropower		
generation	1.000	0.980
hour	1.000	0.739
labor	1.000	0.879
energy	1.000	0.976
install capacity	1.000	0.983

**Note: The data are from the authors' collection.**

According to the results of principal component analysis of input and output indicators of thermal power generation efficiency, the extraction of the seven variables is greater than 0.70. Thus, these variables are suitable for evaluating the generation efficiency of China's thermal power industry. According to the results of principal component analysis of input and output indicators of hydropower generation efficiency, the extraction of the seven variables is greater than 0.70. Thus, these variables are suitable for evaluating the generation efficiency of China's hydropower industry.

## 4 Results and Discussion

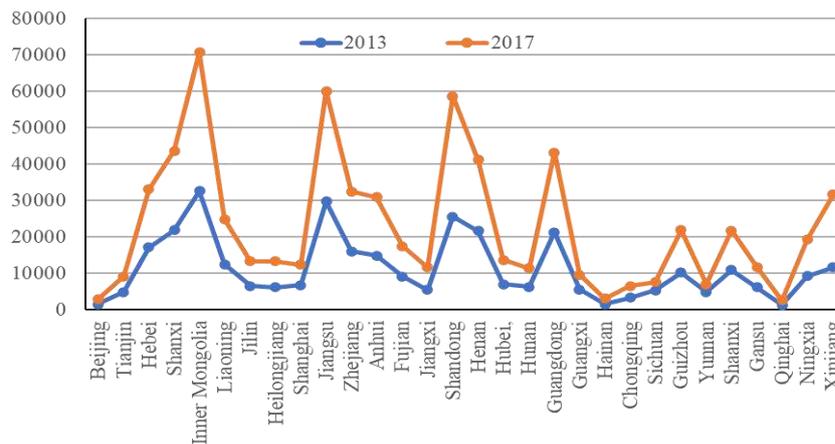
#### 4.1. Input-output indicator statistics

Table 3 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 3. Statistical presentation of input-output variables of thermal power**

Variable	Mean	Std. dev.	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 <sub>2</sub>	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

Figure 1 illustrates the trend of CO<sub>2</sub> emissions from thermal power generation in China's provinces in 2013 and 2017. We see that CO<sub>2</sub> emissions are on the rise, and thus the issue of CO<sub>2</sub> from thermal power generation requires improvement. The energy efficiency calculation of thermal power generation must also consider CO<sub>2</sub> emissions in order to be more realistic.



**Figure 1. Regional CO<sub>2</sub> 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

This study uses MaxDEA Pro 7.0 software to measure the energy efficiency of thermal power and hydropower in China's provinces and cities in 2013 and 2017 and selects output-oriented and non-radial types 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<sub>2</sub> emissions and thermal power generation are placed in the same position.

Table 4 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 4. Meta-efficiency scores and thermal power and hydropower ranks 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
<b>Eastern group average</b>	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
<b>Central group average</b>	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
<b>Western group average</b>	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-efficiencies of Tianjin, Shanghai, Jiangsu, Zhejiang, and Shandong present relatively stable rankings, and Beijing and Hebei have greatly increased their rankings. Compared to 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 has shown 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 to 2013, the meta-efficiency of Jiangsu's hydropower rose 21 places in 2017, as its efficiency value went from 0.9368 to 1.3506. Jiangsu's hydropower generation efficiency is relatively high, which is similar to Tian et al. [45]. However, they focused on hydropower efficiency in the Yangtze River Economic Belt and adopted the traditional CCR model. Therefore, our study on the hydropower efficiency evaluation of different regions in China is warranted. The hydropower meta-efficiencies of Zhejiang, Guangdong, and Fujian have declined significantly. Conversely, Shandong's thermal power and hydropower meta-efficiency rankings are stable.

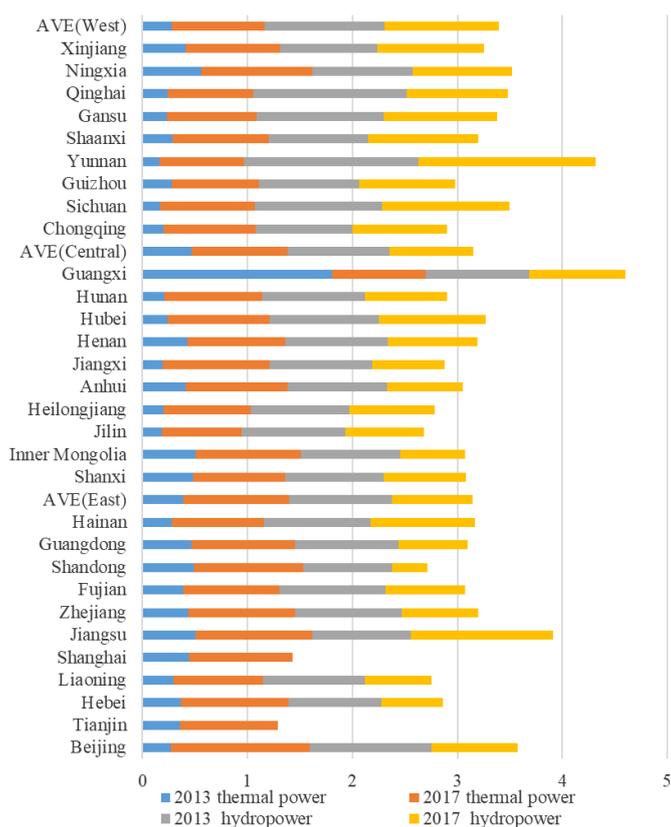
Regarding the central region provinces, Jilin, Heilongjiang, and Anhui have maintained relatively stable rankings in terms of thermal power generation meta-efficiency. Compared to 2013, Jiangxi's thermal power meta-efficiency ranking in 2017 increased by 21 places, as its meta-efficiency value rose from 0.1917 to 1.0219. By contrast, Guangxi and Shanxi declined significantly. Anhui, Henan, Hubei, Hunan, and Guangxi have maintained relatively stable hydropower generation meta-efficiency rankings, 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 to 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 to 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 show a significant upward trend, which is similar to Zhou et al. [40], but they adopted a DEA model that

uses pollutant gas emissions due to thermal power generation as an input variable. This is inconsistent with the actual situation and cannot accurately measure the generation efficiency of thermal power. Different from them, we incorporate CO<sub>2</sub> emissions from thermal power generation as an undesirable output and consider heterogeneity between regions when measuring the efficiency based on the Meta-SE-SBM undesirable model, which is relatively more accurate.

In 2017 the average thermal power generation meta-efficiency ranking was Eastern > Central > Western. The average meta-efficiency values of hydropower generation in the eastern and central regions show a significant downward trend, while the western region has 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. In particular, the western region presents large geographical differences, a large river drop, and relatively rich hydropower resources, which make western provinces' hydropower energy efficiency relatively high. Conversely, there is relatively large room for improving hydropower energy efficiency in the eastern and central provinces. 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 two power industries in each province.

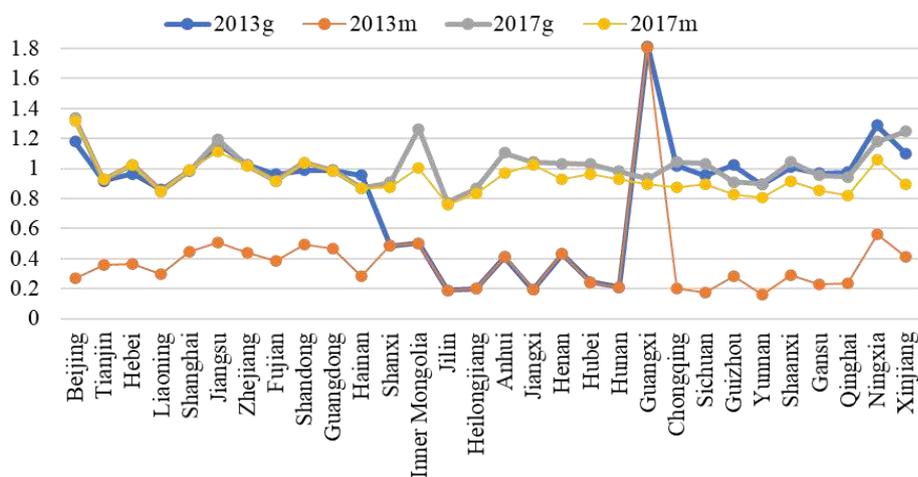


**Figure 2. Thermal power and hydropower meta-efficiency scores in eastern, central, and western regions**

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

Figure 3 exhibits a comparison of the group score and the meta-score of thermal power generation in China's provinces in 2013 and 2017. Group efficiency reflects the relative efficiency

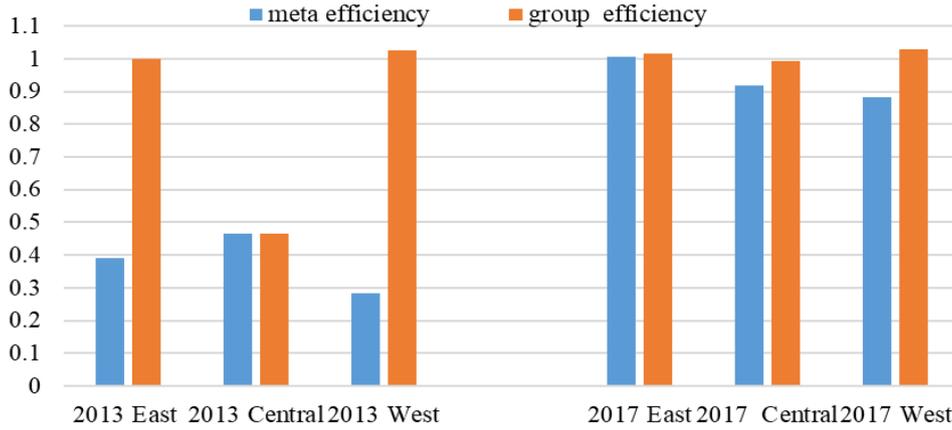
of each province in its group, excluding variations caused by group differences. The specific analysis runs as follows. The group efficiencies of Beijing, Jiangsu, and Zhejiang in the eastern region are greater than 1, and the group efficiencies of Chongqing, Shaanxi, Ningxia, and Xinjiang in the western region are also 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 power in 2013 and 2017**

**Note:** The data source comes from the authors’ collection.

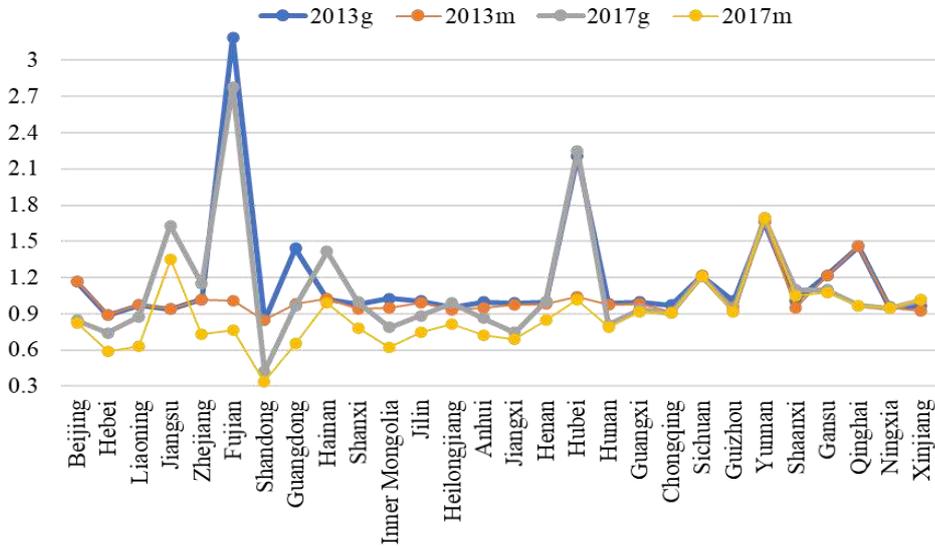
Figure 4 shows the comparison results of thermal power generation group efficiency and meta-efficiency in the eastern, central, and western regions in 2013 and 2017. Specifically, in 2013 the average thermal power generation group efficiency of the three regions was 0.9992, 0.4674, and 1.0253, respectively. Thermal power efficiency is higher in the east and lower in the central and western regions in 2013, which is similar to Wang et al. [46] and Chen and Zhu [47]. The economically developed eastern region has more advanced technology and more mature market mechanisms, which help improve the efficiency of the thermal power generation industry. There are large regional differences in efficiency values, and there is room for improvement in the thermal power generation efficiency of the central region. By 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 western region is able to rely on relatively rich coal resources and national energy policies such as “power transmission from west to east” [46] to improve its efficiency. 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 groups and meta-efficiency scores of thermal power 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 efficiencies of Zhejiang, Fujian, and Hainan in the eastern region are greater than 1, and the group efficiencies of Sichuan, Yunnan, Shaanxi, and Gansu in the western region are greater than 1. Only Hubei's group efficiency in the central region is greater than 1. Lastly, Shandong's hydropower generation group efficiency is the lowest in 2013 and 2017.

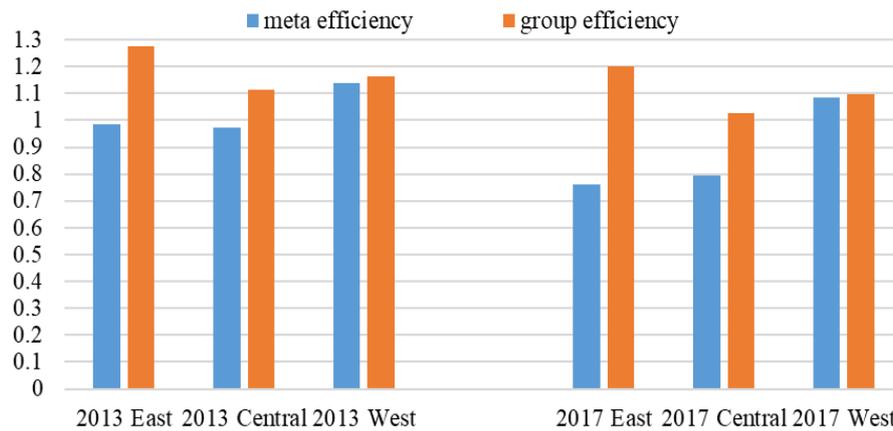


**Figure 5. China's provincial group and meta-efficiency scores of hydropower in 2013 and 2017**

**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, yet 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 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 5 lists the technology gap ratio rankings and technology gap ratio values of the efficiencies 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.

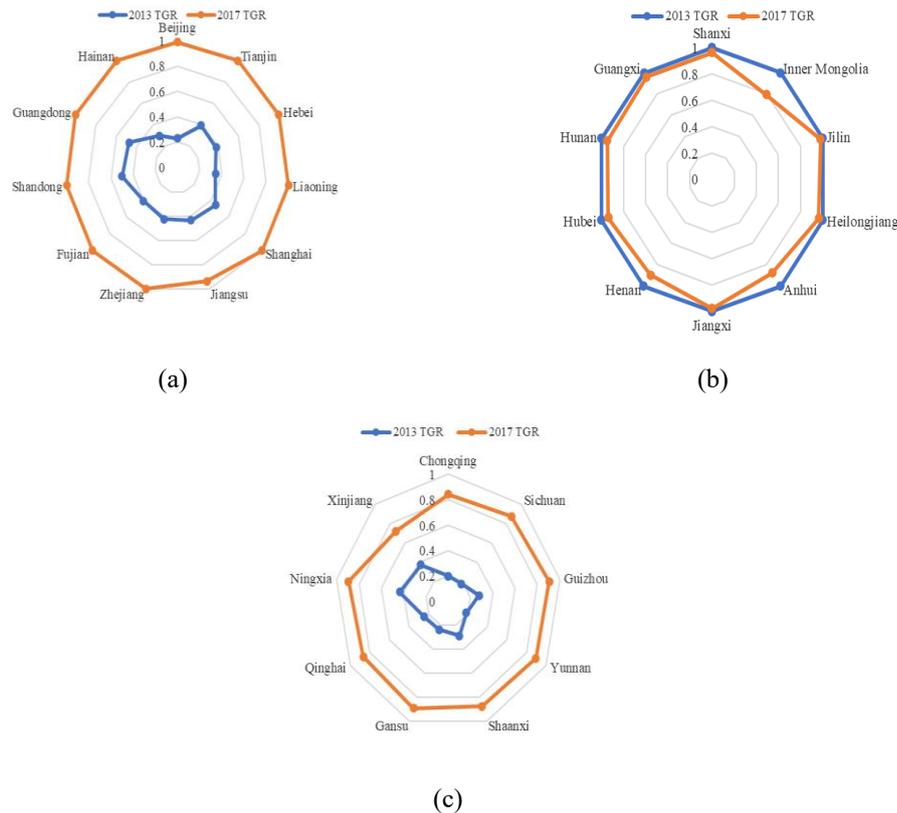
The thermal power efficiency technology gap ratio values and rankings of the eastern provinces in 2017 were significantly better than those of the central and western regions. In 2017, there were 5 provinces in the eastern region tied for first place with a technology gap ratio of 1: Tianjin, Liaoning, Shanghai, Fujian, and Guangdong. Liaoning rose 20 places in 2017, indicating that its thermal power industry's CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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. This 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 5. 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
<b>Eastern mean</b>	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
<b>Central mean</b>	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
<b>Western mean</b>	3	0.2686	3	0.8632	1	0.9771	1	0.9915

Figure 7 shows the TGR values of the thermal power generation efficiencies 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<sub>2</sub> emissions. We see that the gap in thermal power technology in the eastern, central, and western regions has gradually narrowed, indicating that technology in the thermal power industry is becoming more mature and CO<sub>2</sub> emissions control and treatment have made some progress.



**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**

Clustering is a process of classifying and organizing data members that are similar in certain aspects. In order to analyze the characteristics and differences of hydropower's TGR in the three regions, we perform K-means clustering on the TGR values of China's eastern, central and western regions in 2017. Here, we set K to 2, divided into two categories: a group with higher TGR values, and a group with relatively lower TGR values. The clustering results are in Table 6.

From Table 5 and Table 6, according to provincial hydropower efficiency TGR values and rankings in China's three regions, and based on the k-means clustering results of TGR values and ranks of hydropower, we clearly see that the hydropower efficiency TGR values 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, in 2017 Xinjiang and Chongqing increased their

rankings by 19 and 17, respectively, indicating that their hydropower industry development has been greatly promoted, and that the technological level of their hydropower industry has greatly improved. Compared to 2013, the technology gap ratio values and rankings of the eastern provinces in 2017 have 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.

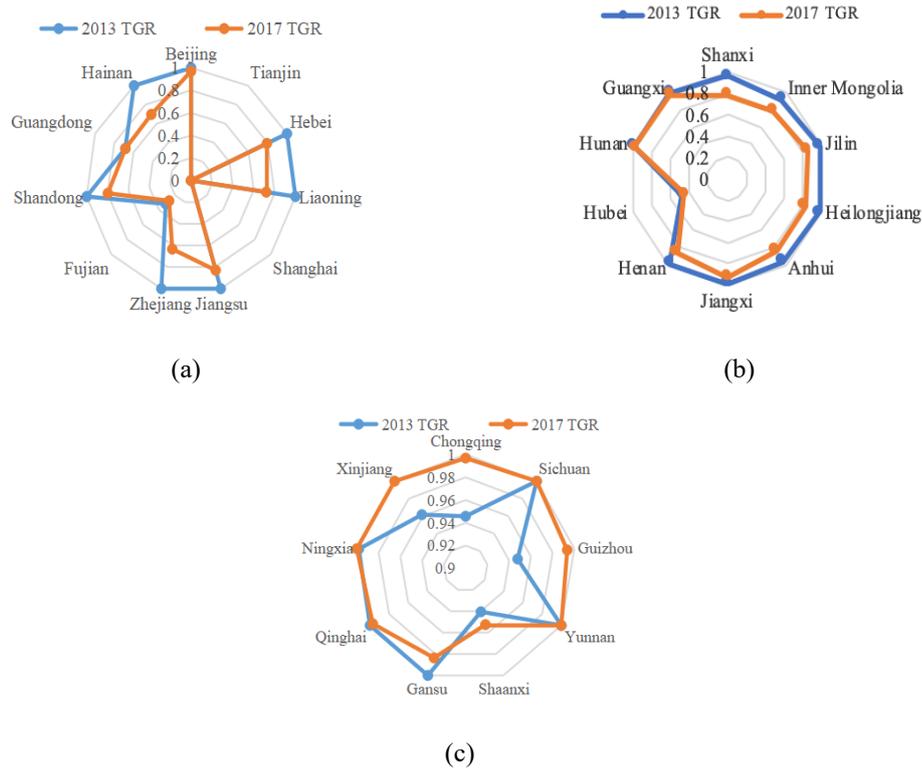
**Table 6. Provincial k-means clustering results of technology gap ratio (TGR) of hydropower in China's three regions**

	DMU	k-means clustering
Eastern region	Beijing	1
	Hebei	1
	Liaoning	1
	Jiangsu	1
	Zhejiang	2
	Fujian	2
	Shandong	1
	Guangdong	1
	Hainan	1
Central region	Shanxi	1
	Inner Mongolia	1
	Jilin	1
	Heilongjiang	1
	Anhui	1
	Jiangxi	1
	Henan	1
	Hubei	2
	Hunan	1
Guangxi	1	
Western region	Chongqing	1
	Sichuan	1
	Guizhou	1
	Yunnan	1
	Shaanxi	1
	Gansu	1
	Qinghai	1
	Ningxia	1
Xinjiang	1	

**Note:** 1 means the group with higher TGR values, and 2 means the group with

**relatively lower TGR values. The data are from the authors' collection**

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.



**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 7 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 [40], reaching more than 20%, and there is a surplus of undesirable output CO<sub>2</sub> at 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<sub>2</sub>, which means that there is a large amount of CO<sub>2</sub> emissions, resulting in relatively low efficiency of thermal power generation in the west.

Excessive resource input not only has failed to increase the expected output power generation, but on the contrary it has greatly increased the undesired output of gas pollution emissions [40]. It shows that there is a lack of effective technical management and blindly thinking that more input means more output, which not only leads to a waste of resources, but also higher pollution control costs.

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<sub>2</sub>, which places 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 is 34% and 28%, respectively. There is a large excess of undesirable output CO<sub>2</sub>, 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 is a serious shortage in thermal power generation output, placing its thermal power generation efficiency at the bottom of its group.

**Table 7. Analysis of the inefficiency level of input-output items of thermal power in 2017 (%)**

DMU	Hour	Labor	Energy	Installed capacity	Generation capacity	CO <sub>2</sub>
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
<b>Eastern mean</b>	-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
<b>Central mean</b>	-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
<b>Western mean</b>	-21	-20	-16	-14	8	-20

Table 8 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 redundancy of the number of employees and installed capacity have reached 34% and 18%, respectively, and the desirable output of hydropower generation is insufficient at 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 its hydropower energy efficiency in last place of its group.

**Table 8. 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
<b>Eastern mean</b>	-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
<b>Central mean</b>	<b>-7</b>	<b>-26</b>	<b>0</b>	<b>-4</b>	<b>28</b>
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
<b>Western mean</b>	<b>-46</b>	<b>-23</b>	<b>-7</b>	<b>-13</b>	<b>-5</b>

## 5 Conclusion and Policy Recommendations

### 5.1 Discussion

Data envelopment analysis (DEA) has been widely applied to evaluate the efficiency of the power industry, yet few studies attempt to compare China's thermal power generation and hydropower generation efficiency by considering regional heterogeneity. This study thus collects 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 generation efficiency of the two industries in the country's three regions, yielding additional insights regarding power generation industry green development and environmental protection. Comparing our results with previous studies, we find some similarities and differences.

Most previous research's objects are thermal power or hydropower plants or companies, and there is little research on China's provincial-level power generation. Taking a specific area as the research object, such as the Yangtze River Economic Belt, is not comprehensive enough. In addition, they did not investigate the difference between the two forms of power generation efficiency. Thus, it is different from a comparative analysis of thermal power and hydropower generation efficiencies in the eastern, central, and western regions in our study.

Scant studies have compared thermal power and hydropower generation efficiencies and presented a sub-regional analysis of the eastern, central, and western regions in China at the same

time. Different from SFA [6], CCR [12], BCC [13], and SBM methods[19], the Meta-SE-SBM undesirable model herein is more accurate for evaluating efficiency values by considering difference variables. Our Meta-SE-SBM undesirable model considers envelope curves that contain all group production frontiers, enabling different groups to measure efficiency under the same common benchmark, which is more accurate for evaluating efficiency values. It can also sort multiple effective decision-making units in the measurement results of thermal and hydropower energy efficiencies and at the same time incorporate undesirable outputs into the measurement system, which can more realistically and comprehensively reflect regional power efficiency.

There are still some future research directions to be carried out. On the one hand, this study has some limitations in grouping China's various provinces according to the geographical attributes of three groups, including the eastern, central, and western region. The grouping method of other economic attributes also needs to be further explored to find out whether this method has any significant influence on efficiency. On the other hand, this study compares the efficiency of thermal power and hydropower generation in China's three regions. With the development of clean energy and data availability, we should be able to compare the efficiencies of more types of electricity such as wind power and solar power.

## **5.2 Conclusion**

First, based on the meta-boundary, the average meta-efficiency values of thermal power generation in China's eastern, central, and western regions in 2017 all showed a significant upward trend, especially provinces along China's eastern coast, which achieved high efficiency. By comparison, the average meta-efficiency values of hydropower generation in eastern, central, and western regions have a downward trend.

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. The thermal power group efficiencies of eastern coastal economically developed provinces (municipalities) such as Beijing, Jiangsu, and Zhejiang are greater than 1. By comparison, the hydropower generation group efficiencies of western inland provinces (municipalities) such as Sichuan, Yunnan, and Xinjiang are greater than 1. This shows that China's thermal power generation industry is currently maturing, but its hydropower generation industry needs further development to improve general hydropower efficiency and narrow the regional gap.

Third, there are regional differences in the technology gap ratio values of the thermal power and hydropower industries in the three major regions. In 2017 the thermal power TGR values and rankings of the eastern region were better than that of the central western regions, whereas the central provinces dropped significantly. While the western region's TGR values and rankings of hydropower were better than the eastern and central regions, the eastern provinces dropped

significantly. The gap in thermal power technology among the three regions has gradually narrowed, indicating that technology in the thermal power industry is maturing and CO<sub>2</sub> emissions control and treatment have made progress. Conversely, the technological gap for hydropower among the three has slightly expanded, indicating that the hydropower generation industry needs further attention and policy support. Regardless of the development of hydropower and thermal power, both need stable regional policy support to promote technical efficiency and narrow their technological gap.

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<sub>2</sub> 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<sub>2</sub> output and a great amount of emissions. This is also the reason for the relatively low efficiency of thermal power generation in the west. 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 why there is relatively low hydropower generation efficiency in the eastern and central regions.

### **5.3 Policy Recommendation**

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, according to the efficiency of the regional thermal power industry, local governments and industry managers should formulate policies that are suitable for the development of local thermal power, reasonably guide and adjust the input factors of the thermal power industry, and do not blindly expand the scale of thermal power. Due to the current dominant position of thermal power in China's power industry, improving the efficiency of thermal power is important for achieving the whole power industry's green development and environmental protection. 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 decrease the undesirable output of carbon dioxide by thermal power emissions. It is especially necessary for coal-fired thermal power generation to improve coal-burning technology to reduce polluting gases. These provinces can improve the technical level of thermal power generation, cut down energy consumption during the process of thermal power generation, and thus reduce carbon dioxide

emissions, thereby improving the quality and efficiency of this industry.

Second, regional governments can formulate policies to encourage the development of the hydropower industry based on their own resource endowment, increase the status of clean energy such as hydropower in the entire power industry, improve hydropower efficiency so as to enhance competitiveness of the hydropower industry, and subsequently reduce carbon dioxide emissions and environmental pollution from the root causes. Policies such as financial subsidies can be adopted to encourage the development of regional hydropower industries, increase hydropower's market share, and continuously expand its competitiveness within the power industry. In the western provinces with their abundant hydropower resources, resource endowment advantages must be fully utilized, so that China's power generation efficiency can be comprehensively improved. 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, cut down on 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 green and efficient management of regional power industries through reforms of the market-based price mechanism, so that the market can play a better role in resource allocation. In addition to attaching importance to the management and policy support of local governments and power industry managers, it is also necessary to give full play to the role of market mechanisms. The efficiency improvement brought about by technological progress must be reflected in electricity prices to achieve the optimal allocation of resources and the overall improvement of power generation efficiency. In addition, innovation of the power industry's management system 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 as well as to strengthen the competitiveness of clean energy such as hydropower, wind power, and solar power according to local conditions. The end result should help promote the green development of the whole power industry.

### **Abbreviations**

BCC: Banker & Charnes & Cooper; CCR: A. Charnes & W. W. Cooper & E. Rhodes; DDF: Directional Distance Function; DEA: Data Envelopment Analysis; DMU: Decision-Making Unit; KMO: Kaiser-Meyer-Olkin; Meta-SE-SBM undesirable model: Meta-frontier Super-Efficiency Slacks-Based Measure undesirable model; SBM: Slacks-Based Measure; SE-SBM: Super-

Efficiency Slacks-Based Measure; SFA: Stochastic Frontier Analysis; TGR: Technology Gap Ratio; VRS: Variable Returns to Scale.

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### **Authors' contributions**

Conceptualization, R.-M.W. and F.-R.R.; methodology, F.-R.R.; software, Z.T.; validation R.-M.W.; formal analysis, R.-M.W.; investigation, R.-M.W. and F.-F.R.; resources, Z.T.; data curation, R.-M.W.; writing - original draft preparation, R.-M.W.; writing - review and editing, Z.T.; visualization, R.-M.W.; supervision, Z.T.; project administration, F.-R.R.; funding acquisition, F.-R.R.

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### **Availability of supporting data**

All data generated or analyzed during this study are included in this published article [and its supplementary information files].

### **Ethics approval and consent to participate**

The submitted paper has not been published previously, is not under consideration for publication elsewhere, its publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out.

### **Consent for publication**

If accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright-holder.

### **Competing interests**

The authors declare that they have no competing interests.

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# Figures

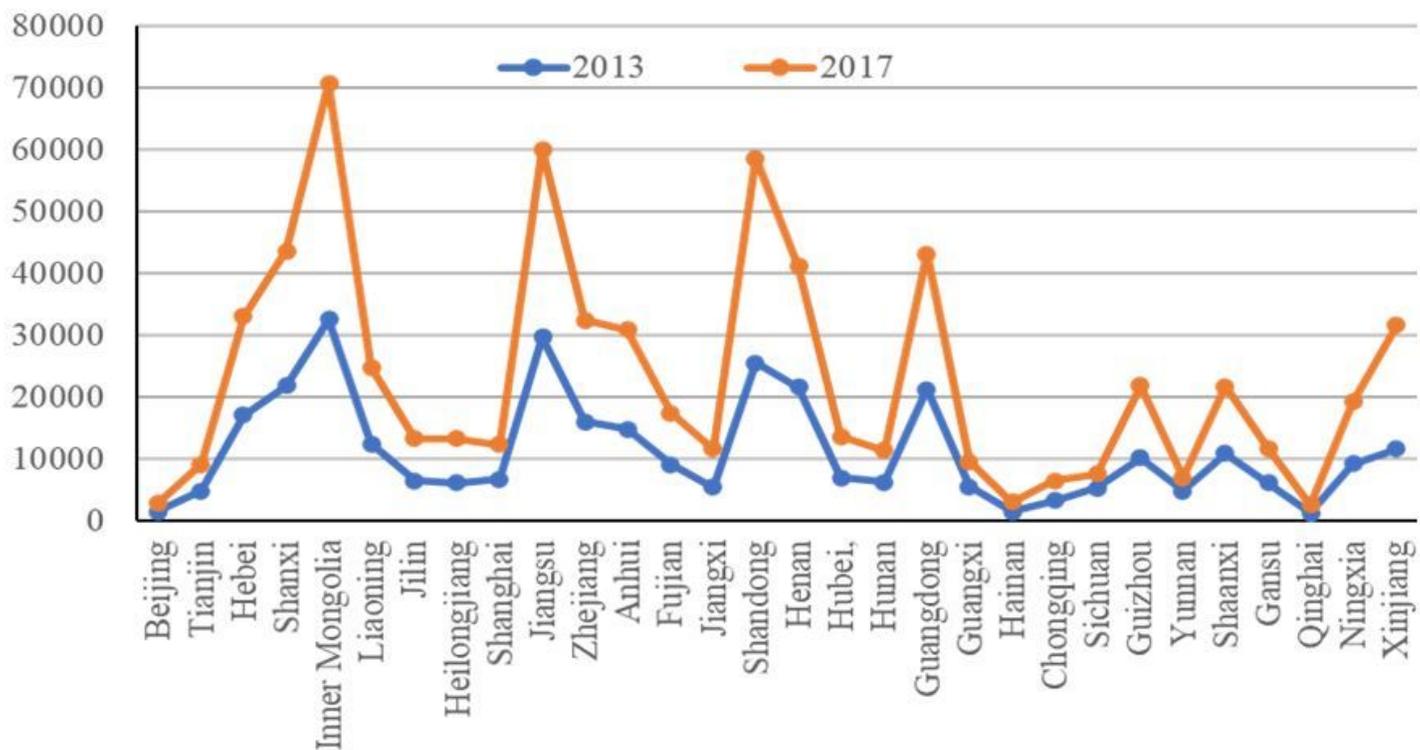
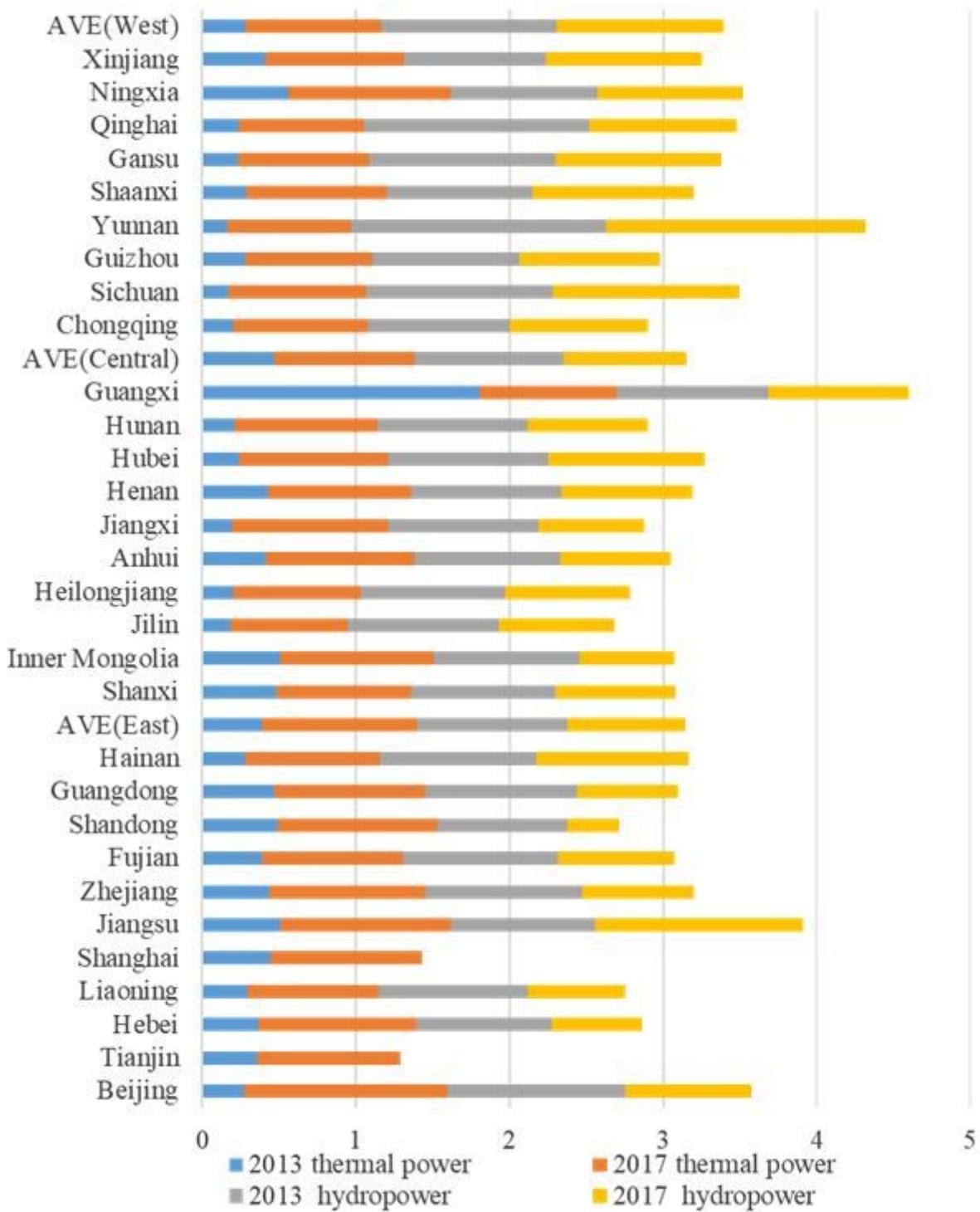


Figure 1

Regional CO2 emissions in China in 2013 and 2017 Note: The data source comes from the authors' collection.



**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.

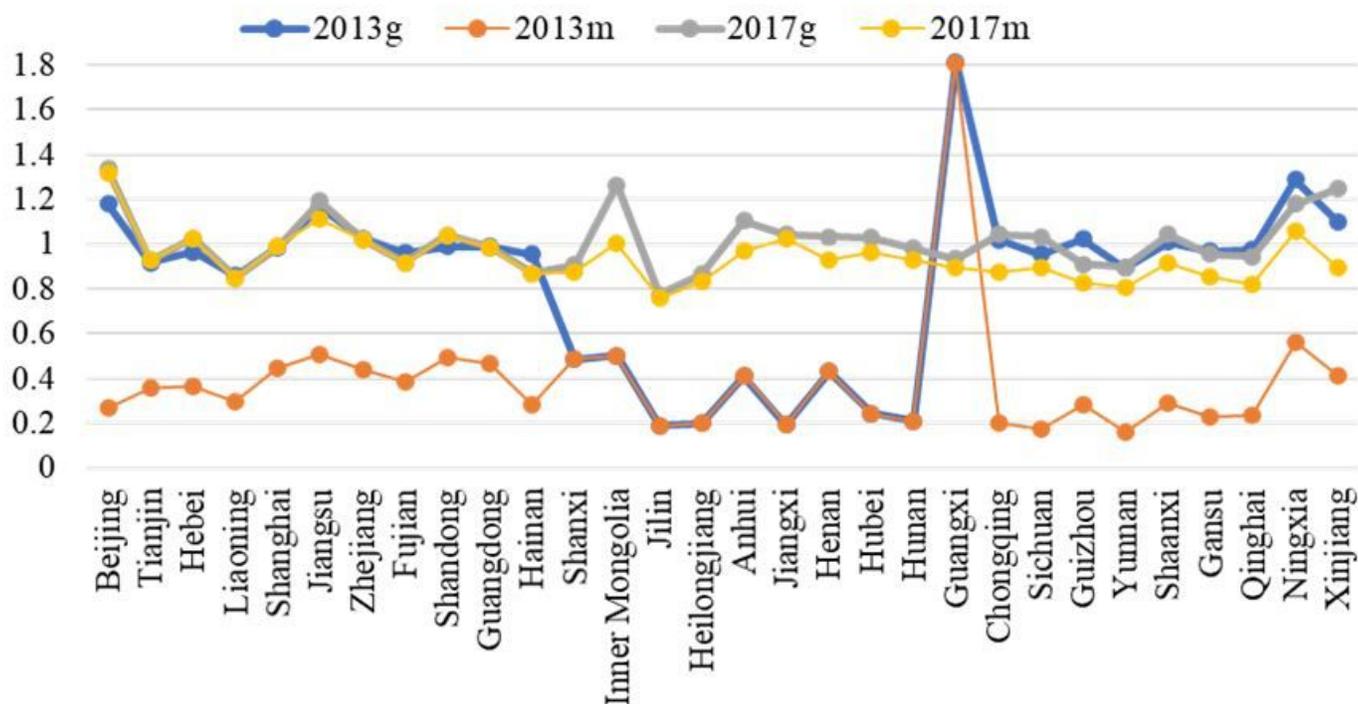


Figure 3

China's provincial group and meta-efficiency scores of thermal powers in 2013 and 2017 Note: The data source comes from the authors' collection.

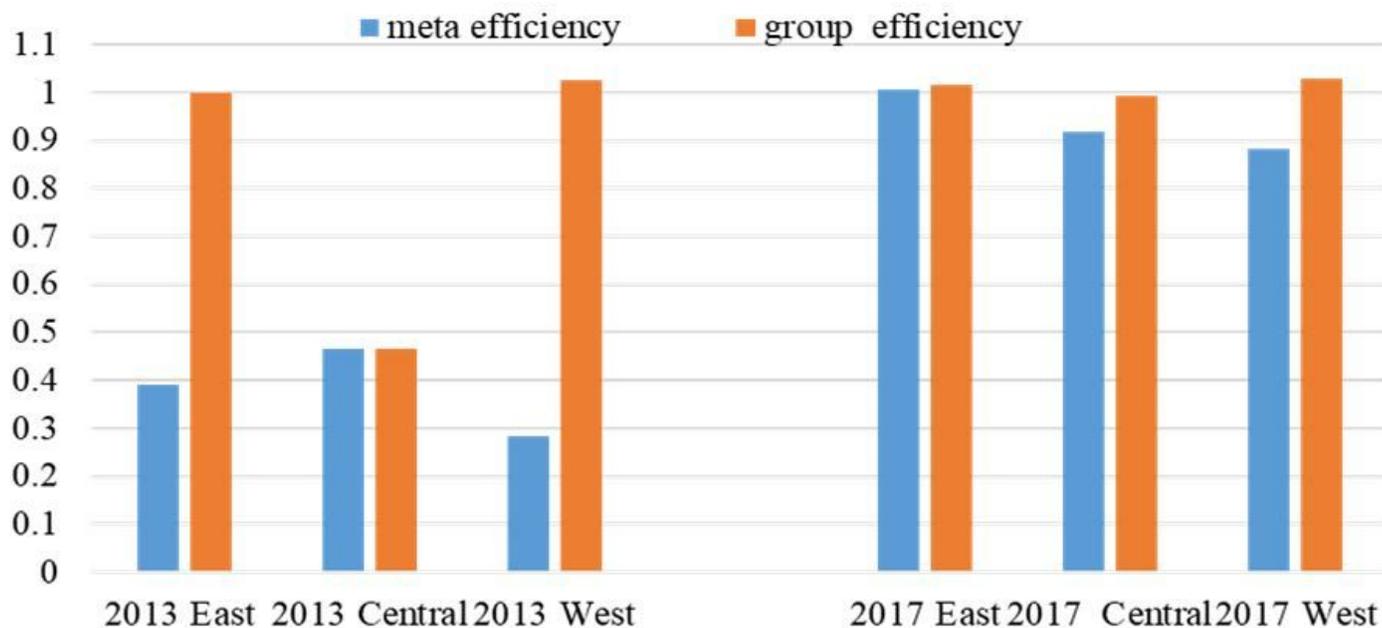


Figure 4

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.

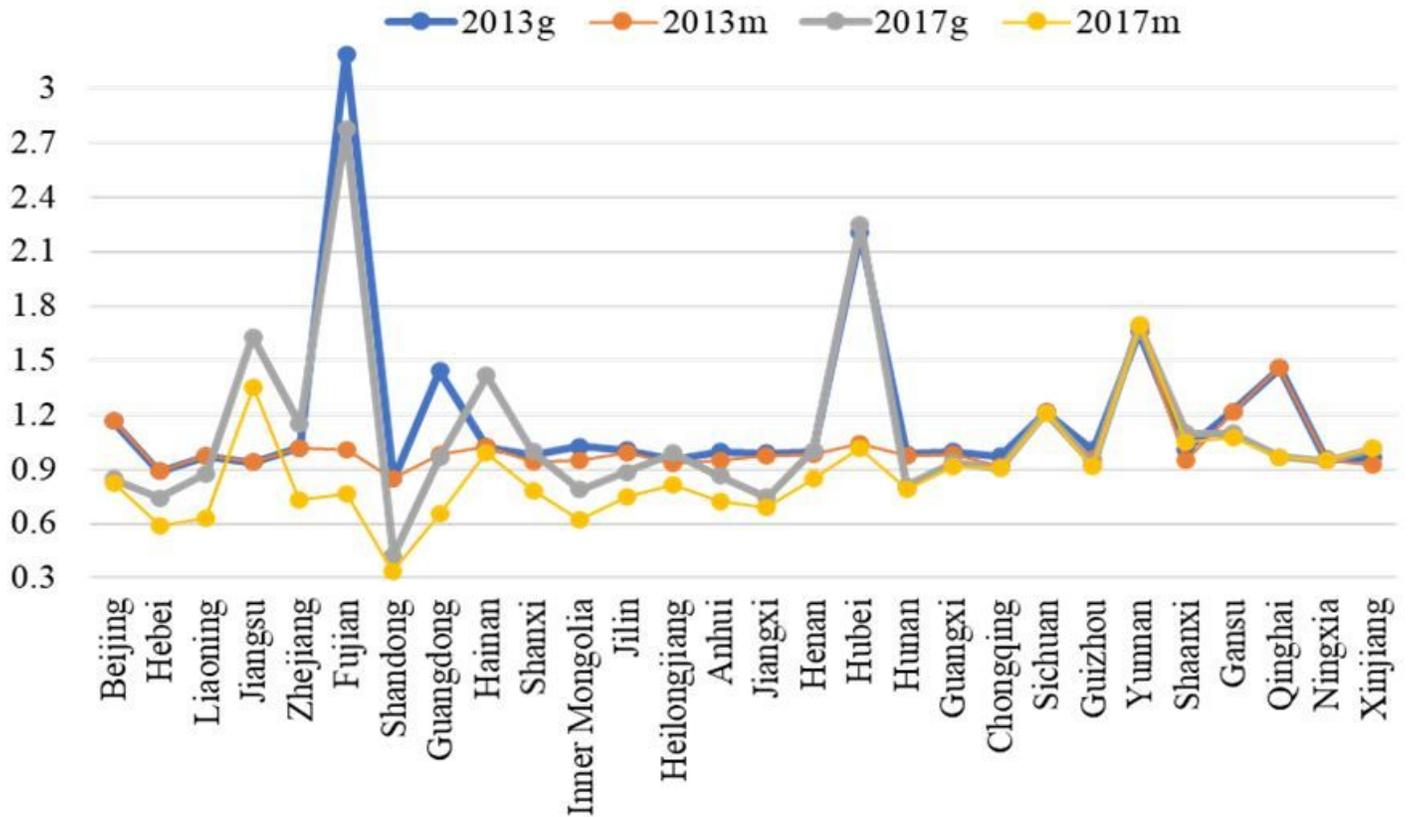


Figure 5

China's provincial group and meta-efficiency scores of hydropower in 2013 and 2017 Note: The data source comes from the authors' collection.

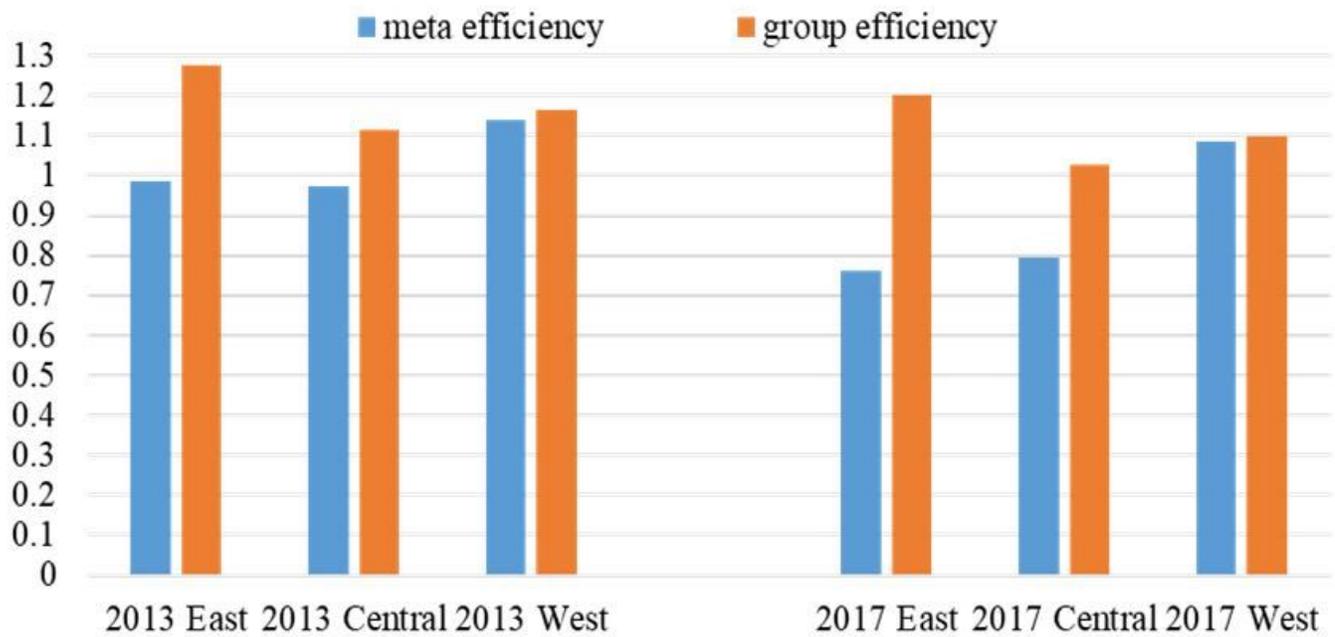
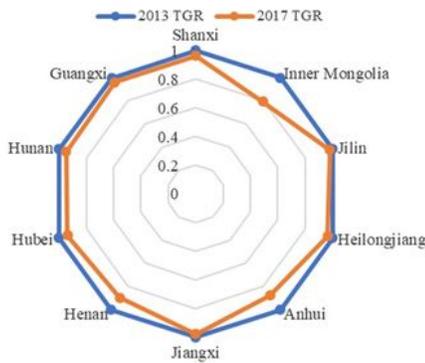


Figure 6

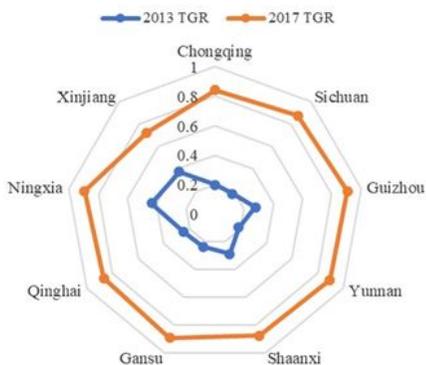
China's east, central, and west regional group, and meta-efficiency scores of hydropower in 2013 and 2017 Note: The data source comes from the authors' collection.



(a)



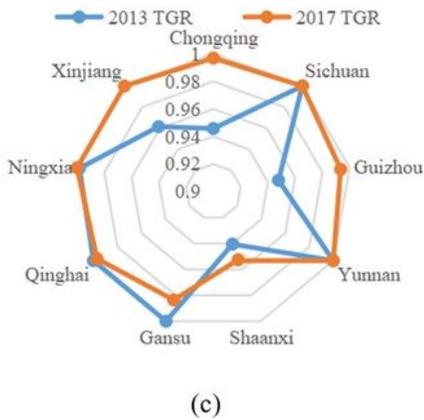
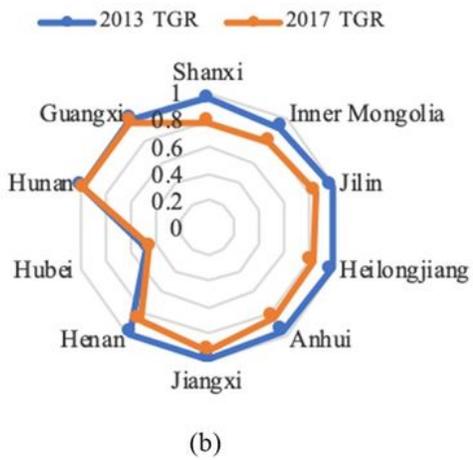
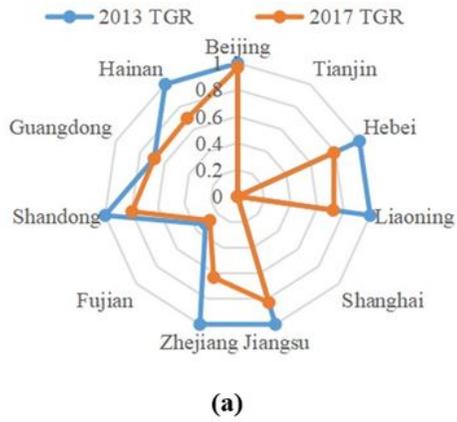
(b)



(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



**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