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Operational performance management of the power industry: A distinguishing analysis between effectiveness and efficiency

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Abstract: The trend toward a more competitive electricity market has led to efforts by the electric power industry to develop advanced efficiency evaluation models that adapt to market behavior operations management. The promotion of the operational performance management of the electric power industry plays an important role in China's efforts toward energy conservation, emission control and sustainable development. Traditional efficiency measures are not able to distinguish sales effects from productive efficiency and thus are not sufficient for measuring the operational performance of an electricity generation system for achieving its specific market behavior operations management goals, such as promoting electricity sales. Effectiveness measures are associated with the capacity of an electricity generation system to adjust its input resources that influence its electricity generation and, thus, the capacity to match the electricity demand. Therefore, the effectiveness measures complement the efficiency measures by capturing the sales effect in the operational performance evaluation. This study applies a newly developed data envelopment analysis-based effectiveness measurement to evaluate the operational performance of the electric power industry in China's 30 provincial regions during the 2006-2010 periods. Both the efficiency and effectiveness of the electricity generation system in each region are measured, and the associated electricity sales effects and electricity reallocation effects are captured. Based on the results of the effectiveness measures, the alternative operational performance improvement strategies and potentials in terms of input resources savings and electricity generation adjustments are proposed. The empirical results indicate that the current interregional electricity transmission and reallocation efforts are effective in China overall, and a moderate increase in electricity generation with a view to

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improving the effect on sales is more crucial for improving effectiveness.

Keywords: China; Data envelopment analysis (DEA); Electricity generation system; Electricity reallocation; Electricity sales effect

Nomenclature

AR	After electricity reallocation
BR	Before electricity reallocation
DEA	Data envelopment analysis
DMU	Decision making unit
EE	Efficiency-effectiveness
FG	Frontier gap
FYP	Five Year Plan
GDP	Gross domestic product
PF	Production function
RE	Reallocation effect
SPF	Sales-truncated production function
VRS	Variable returns to scale

1 Introduction

In 2014, the electric power industry provided China with 5650 MWh of electricity. It also consumed more than 1200 million tons of coal, which accounts for approximately 45% of the total primary energy supply in China. In addition, coal-fired electric power generation is responsible for more than 40% of carbon emissions from fuel combustion in China. As one of the world's largest energy consumers and greenhouse gas emitters, China has made constructing a resource-saving and environment-friendly society and pursuing sustainable development one of its primary development strategies at the national level. One specific goal of sustainable development in China is to increase energy efficiency — in other words, to reduce energy intensity (i.e., energy consumption per GDP) by 32% by 2015 compared to the 2005 level (SCC, 2007, 2011). Improving energy efficiency is also a major policy in China's electric power industry in that the net coal consumption rate of electricity generation needs to be reduced from 370 grams of coal equivalent per kilowatt hour (gce/kWh) in 2005 to 325 gce/kWh (SERC, 2011).

The data envelopment analysis (DEA) approach is one of the most widely used methods for evaluating productive efficiency in the electric power industry (e.g., Park and Lesourd, 2000; Lam and Shiu, 2001, 2004; Lo et al., 2001; Vaninsky, 2006; Cook and Zhu, 2007; Fallah et al., 2011; Cook et al., 2015). DEA is a nonparametric linear programming method that helps analysts estimate the production function without assuming the form of the function and identify a productive efficiency frontier by defining efficiency as a ratio of a weighted sum of multiple outputs to a weighted sum of multiple inputs (Cooper et al., 2011; Cook and Zhu, 2014; Zhu, 2015). DEA constructs a piece-wise linear frontier encompassing all observations based on the minimum extrapolation principle (Cherchye and Post, 2003). The production function or efficiency frontier is utilized as the benchmark for efficiency estimation (e.g., Sueyoshi and Goto, 2011, 2012; Wang et al., 2012, 2014; Wang and Wei, 2016) or resource allocation (e.g., Wu et al, 2013; Wang et al., 2013). Take the output-oriented DEA as an example: a decision-making unit (DMU) (i.e., an electric power industry sector or an electricity generation process) is considered efficient if its electricity generation output has leveled with regard to the production function or has reached the maximum attainable electricity generation output on the efficiency frontier, assuming that the current levels of input resources (e.g., capital, labor and fuel) are unchanged.

There have been several studies that use DEA to evaluate the productive efficiency of China's electric power industry or power plant. For example, Bi et al. (2014) estimated the total factor energy efficiency of China's thermal power generation system in each provincial region from 2007 to 2009 with DEA models. Installed capacity, labor, coal and gas consumption were utilized as the inputs, and power generated was utilized as the desirable output in their efficiency estimation. Xie et al. (2012) evaluated the operational efficiency of electricity generation corporations in China's 30 regions during 2002-2009 through a two-stage network DEA model. In the first stage of the model, the author applied capital, equipment, fuel, labor and auxiliary power of the electricity generation system as the input and applied on-grid electricity as the desirable output of the system for efficiency estimation. Yang and Pollitt (2009, 2010) provide two estimations of operational efficiency of China's 221 and 582 coal-fired power plants in 2002 using a traditional DEA model and several uncontrollable variable-adjusting DEA models.

In the last decade, the trend towards a more competitive electricity market both in China and abroad has led to increasing efforts by the electric power industry to develop advanced efficiency evaluation methods that are adapted to market behavior operations performance evaluation and management. However, all of the above studies are considered typical efficiency estimations that do not distinguish between performance in terms of production (when outputs are units produced) and performance in terms of sales (when outputs are units sold)

(Lee and Johnson, 2015). In other words, previous studies do not distinguish the sales effect from productive efficiency. In fact, a firm's profitability is indeed affected by the outputs consumed rather than the outputs generated. As noted by Lee (2015), in practice, a single efficiency estimation is not sufficient to measure the operational performance of an organization or system against specific goals or objectives, such as sales, and this part of the operational performance estimation with respect to realizing the given goals is often defined as effectiveness (Golany et al., 1993; Asmild et al., 2007). Namely, operational performance should be divided into two parts: efficiency (which is measured to promote production behavior operations performance) and effectiveness (which is measured to promote market behavior operations performance, i.e., sales). Some other studies use DEA to address the issue of the effectiveness measure. For example, Fielding et al. (1985) evaluated the performance of the transportation system by distinguishing between the performance of the production process and consumption process. Byrnes and Freeman (1999) evaluated the efficiency and effectiveness in a two-stage health service process. Yu and Lin (2008) evaluated the service and technical effectiveness of a railway system by considering the consumption process. Lee and Johnson (2015) proposed a sales-truncated production function, on which basis the profit effectiveness (with the sales effect taken into account) of 13 US airlines are evaluated. By applying similar DEA models, Lee (2015) further evaluates the operational efficiency and effectiveness of a power plant system in the United States.

Electricity generation is the most commonly used output for the operational performance evaluation of the electric power industry, which should be defined as an effective output (Lee and Johnson, 2014) instead of a normal output because it needs to be consumed as soon as it is generated (or quickly consumed); otherwise, it has to be abandoned and the associated inputs for electricity generation are then considered wasted and thus lead to operational inefficiency. An effectiveness measure rather than an efficiency measure is related to an electricity generation system's capacity to adjust some of its input resources, influencing its electricity generation output when it also attempts to match electricity demand. More specifically, the locations of electricity generation and electricity consumption may be different; that is, electricity transmission plays a critical role in electricity reallocation and demand fulfillment. Therefore, the effectiveness measure could be considered as a complement of the efficiency measure in the electric power industry.

This study provides a DEA-based effectiveness measure of China's regional electric power industry that considers electricity consumption in order to distinguish electricity sales effects from traditional productive efficiency measures. To the best of our knowledge, this study is the first attempt to measure the effectiveness of the operational performance of China's electric power industry, and the associated improvement strategy of the operational performance is provided. The remainder of this paper is organized as follows. Section 2 introduces the models for efficiency and effectiveness measures in the electricity generation system. Section 3 introduces the measurements of the electricity sales effects and the reallocation effects associated effectiveness measure. Section 4 provides an empirical study of the effectiveness measure in China's electric power industry during 2006-2010. Section 5 concludes this paper.

2 Measures of effectiveness and efficiency of electric power production

In this section, we first describe the traditional production function associated with the efficiency measure and the sales-truncated production function associated with the effectiveness measure. Two DEA-based models are then presented to show the efficiency measure and effectiveness measure of electric power production. In the following section, we first provide the nomenclature in Table 1 to define the letters and symbols utilized in the model.

[Insert Table 1 here]

2.1 Production function and DEA-based efficiency measure

Given input resources, a production function (PF) defines the maximum outputs that a production system can produce. Let $\boldsymbol{x}$ and $\boldsymbol{y}$ be a vector of the input variable and output variable of this system, respectively. A traditional production function can be defined as $\boldsymbol{y}^{PF}=f(\boldsymbol{x})$. When considering a multiple input and output electric power production system, let $\boldsymbol{x} \in \mathbb{R}_{+}^{m}$ denote an input vector and $\boldsymbol{y} \in \mathbb{R}_{+}^{s}$ denote an output vector of this system. The production possibility set T can then be defined as $T = \{(\boldsymbol{x}, \boldsymbol{y}): \boldsymbol{x} \text{ can produce } \boldsymbol{y}\}$. We use $i=1,\ldots,m$ as the input index, $r=1,\ldots,s$ as the output index, and $j=1,\ldots,n$ as the observation (i.e., DMU) index. We can then measure the output oriented technical efficiency θ of each DMU by using the distance function $D_y(\boldsymbol{x}, \boldsymbol{y}) = \sup\{\theta \mid (\boldsymbol{x}, (1+\theta)\boldsymbol{y}) \in \bar{T}\}$, and $\bar{T}$ is defined as in (1) with the variable returns to scale (VRS) estimation.

$$\bar{T}=\left\{(x,y)\middle|\sum_j \lambda_j x_{ij}\le x_i,\forall i;\sum_j \lambda_j y_{rj}\ge y_r,\forall r;\sum_j \lambda_j=1;\lambda_j\ge 0,\forall j\right\} \qquad (1)$$

where λ_j is the intensity variable for the convex combination for the jth region. Let $\theta^*= D_y(\boldsymbol{x}, \boldsymbol{y})$. If $\theta^*=0$, the firm is efficient; if $\theta^*>0$, the firm is inefficient and should drive productivity towards the efficient benchmark calculated by the optimal value of the intensity variable.

2.2 Sales-truncated production function and DEA-based effectiveness measure

Diverging from the definition of production function, Lee and Johnson (2015) defined the effective output $\boldsymbol{y}^E$ as the output product of a production system that is consumed and the sales-truncated production function (SPF) as the maximum sales for a product that can be fulfilled given the input resources. A sales-truncated production function is defined based on the realized sales level instead of the production level. Let $\boldsymbol{d}$ be the realized sales; the effective output $\boldsymbol{y}^{SPF}$ is obtained according to two variables: the frontier production output level $\boldsymbol{y}^{PF}$ and the realized sales $\boldsymbol{d}$, as $\boldsymbol{y}^{SPF}=\min(\boldsymbol{y}^{PF}, \boldsymbol{d}) = \min(f(\boldsymbol{x}), \boldsymbol{d})$. See Lee and Johnson (2015) and Lee (2015) for the detailed definition and discussion on the SPF. Similarly, let $\boldsymbol{y}^E\in\mathbb{R}_+^s$ denote an effective output vector that is produced and consumed. The sales-truncated production possibility set T^E can be defined as $T^E = \{(\boldsymbol{x}, \boldsymbol{y}^E)$: $\boldsymbol{x}$ can produce $\boldsymbol{y}^E$, which will be consumed in the current period}. We use y_{rj}^E and d_{rj} as the rth output produced by the jth DMU and consumed given the rth specific sales of the jth DMU. We then have $y_{rj}^E=\min(y_{rj},d_{rj})$. $\bar{T}^E$ is defined as in (2) with the VRS estimation.

$$\bar{T}^E=\left\{(x,y^E)\middle|\sum_j \lambda_j x_{ij}\le x_i,\forall i;\sum_j \lambda_j y_{rj}\ge y_r^E,d_r>y_r^E,\forall r;\sum_j \lambda_j=1;\lambda_j\ge 0,\forall j\right\} \qquad (2)$$

We can measure the output oriented technical effectiveness θ^E of each DMU by using the distance function $D_y^E(\boldsymbol{x}, \boldsymbol{y}^P) = \sup\{\theta^E \mid (\boldsymbol{x}, (1+\theta^E)\boldsymbol{y}^P)\in\bar{T}^E\}$, where $\boldsymbol{y}^P$ is the penalized output that quantifies the gap between the electric power producing level and its sales or demand level. We assume that producing less electricity than the demand or sales will lead to lost sales (i.e., electricity generation capacity shortage) and, on the contrary, that producing more electricity than the demand or sales will lead to waste or power-abandonment loss (i.e., electricity generation capacity surplus). According to Lee (2015), the loss associated with the capacity shortage refers to either the electricity shortage cost that a plant or a region purchases from other plants or regions or the blackout cost of the electric power system. Furthermore, the cost associated with the capacity surplus refers to the input resource waste of the electric power system, such as coal burning, capacity investment and hiring labor.

We calculate the penalized electric power output $\boldsymbol{y}^P$ as follows. If $y_{rj} \leq d_{rj}$, then the opportunity to sell more electricity $d_{rj} - y_{rj}$ is lost, and the penalized output is computed as $y_{rj}^P = y_{rj} - \alpha_{rj}(d_{rj} - y_{rj})$. Otherwise, if $y_{rj} > d_{rj}$, then the surplus electricity generation $y_{rj} - d_{rj}$ is abandoned and the penalized output is calculated as $y_{rj}^P = d_{rj} - \beta_{rj}(y_{rj} - d_{rj})$. $\alpha_{rj}(d_{rj} - y_{rj})$ and $\beta_{rj}(y_{rj} - d_{rj})$ are the penalties associated with lost sales and abandonment loss, respectively. $\alpha_{rj} \geq 0$ and $\beta_{rj} \geq 0$ are the penalty parameters used for quantifying the effects of lost sales and abandonment loss, respectively, or in other words, to control the tradeoff of the electricity shortage and resource waste on effectiveness measures.

2.3 Models for efficiency and effectiveness measurements of electric power industry

Suppose that we use three input resources — nameplate capacity (C), labor force (L), and energy consumption (E) — in addition to one output — electricity generation (Y) — to measure efficiency and another output — electricity supply (G), which is associated with electricity generation — to measure the effectiveness of China's electric power industry in each region (DMU). In addition, electricity sales (D) are utilized for SPF estimation and effectiveness measures.

Model (3) computes the efficiency:

$$\begin{aligned}
&\max \theta \\
&s.t. \ \sum\nolimits_{j=1}^{n} \lambda_j C_j \leq C_{j_0}, \\
&\quad \sum\nolimits_{j=1}^{n} \lambda_j L_j \leq L_{j_0}, \\
&\quad \sum\nolimits_{j=1}^{n} \lambda_j E_j \leq E_{j_0}, \qquad\qquad (3) \\
&\quad \sum\nolimits_{j=1}^{n} \lambda_j Y_j \geq Y_{j_0}(1+\theta), \\
&\quad \sum\nolimits_{j=1}^{n} \lambda_j = 1, \\
&\quad \lambda_j \geq 0, \quad j = 1, \ldots, n.
\end{aligned}$$

where the decision variable θ is the efficiency measure for the jth region. The optimized objective value of Model (3) is denoted as the efficiency measure θ^*, and if $\theta^* = 0$, the electric power industry sector of a region is efficient; otherwise, it is inefficient. $Y_{j_0}(1+\theta^*)$ indicates the maximum amount of electricity that an electric power industry sector of the region (denoted by index j_0) can produce given its current input resources, and $Y_{j_0}\theta*$ implies the operational performance improvement potential associated with efficiency measures, which also can be seen as a measure of inefficiency of the electric power industry sector for region j_0.

Models (4) and (5) compute the effectiveness before the interregional electricity reallocation (BR) and after reallocation (AR), respectively:

$$
\begin{aligned}
&\max \theta^{EBR} \\
&s.t.\ \sum_{j=1}^{n} \lambda_j C_j \le C_{j_0}, \\
&\quad \sum_{j=1}^{n} \lambda_j L_j \le L_{j_0}, \\
&\quad \sum_{j=1}^{n} \lambda_j E_j \le E_{j_0}, \\
&\quad \sum_{j=1}^{n} \lambda_j Y_j \ge Y_{j_0}^{P}(1+\theta^{EBR}), \\
&\quad D_{j_0} \ge Y_{j_0}^{P}(1+\theta^{EBR}), \\
&\quad \sum_{j=1}^{n} \lambda_j = 1, \\
&\quad \lambda_j \ge 0, \quad j = 1, \ldots, n.
\end{aligned}
\tag{4}
$$

$$
\begin{aligned}
&\max \theta^{EAR} \\
&s.t.\ \sum_{j=1}^{n} \lambda_j C_j \le C_{j_0}, \\
&\quad \sum_{j=1}^{n} \lambda_j L_j \le L_{j_0}, \\
&\quad \sum_{j=1}^{n} \lambda_j E_j \le E_{j_0}, \\
&\quad \sum_{j=1}^{n} \lambda_j G_j \ge G_{j_0}^{P}(1+\theta^{EAR}), \\
&\quad D_{j_0} \ge G_{j_0}^{P}(1+\theta^{EAR}), \\
&\quad \sum_{j=1}^{n} \lambda_j = 1, \\
&\quad \lambda_j \ge 0, \quad j = 1, \ldots, n.
\end{aligned}
\tag{5}
$$

where decision variables θ^{EBR} and θ^{EAR} represent the effectiveness measures of the electric power industry sector of region j before electricity reallocation and after reallocation, respectively. $Y_{j_0}^{P}$ and $G_{j_0}^{P}$ are penalized outputs associated with electricity production and supply. The difference between electricity generation Y_j and electricity supply G_j of a specific region indicates electricity reallocation in this region and, therefore, the difference between Models (4) and (5) can be used to calculate the effectiveness improvement of the electric power industry sector of each region before and after the electricity reallocation. D_{j_0} denotes the electricity sales of region j_0, and the associated constraints in Models (4) and (5) represent the consumption levels truncating the production function.

The penalized outputs are calculated as in (6) and (7):

$$Y_j^P = \begin{cases} Y_j - \alpha_j (D_j - Y_j), & \text{if} \quad D_j \geq Y_j, \\ D_j - \beta_j (Y_j - D_j), & \text{if} \quad D_j < Y_j. \end{cases} \qquad (6)$$

$$G_j^P = \begin{cases} G_j - \alpha_j (D_j - G_j), & \text{if} \quad D_j \geq G_j, \\ D_j - \beta_j (G_j - D_j), & \text{if} \quad D_j < G_j. \end{cases} \qquad (7)$$

In Models (4) and (5), if the optimized objective values $\theta^{EBR*} = 0$ or $\theta^{EAR*} = 0$, the electric power industry sector of a region is effective; otherwise, it is ineffective. Similarly, $Y_{j_0}^P(1+\theta^{EBR*})$ or $G_{j_0}^P(1+\theta^{EAR*})$ indicate the maximum electricity sales that an electric power industry sector of a region can fulfill given the input resources; and $Y_{j_0}^P\theta^{EBR*}$ or $G_{j_0}^P\theta^{EAR*}$ imply the operational performance improvement potential associated with the effectiveness measure which also can be seen as measures of ineffectiveness of the electric power industry sector of region j_0 before and after electricity interregional reallocation.

The electricity generation weighted means of efficiency measure and effectiveness measure are utilized for dividing low and high efficiency or effectiveness categories. Regions located in a category with both high efficiency and effectiveness measures are referred to as "Laggard" regions, while regions located in a category with both low efficiency and effectiveness measures are referred to as "Leader" regions. Moreover, the category with low efficiency and high effectiveness measures is referred to as having an electricity "Production Focus". In contrast, the category with high efficiency and low effectiveness measures is referred to as having an electricity "Sales Focus".

3 Measurements of sales effect and reallocation effect of electric power production

This section describes the measures of the electricity sales effect characterized as the difference between the efficiency measure and the effectiveness measure, as well as the electricity reallocation effect denoted as the effectiveness change after interregional electricity reallocation.

"Sales effect" measures the operational performance of electricity generation that takes electricity sales into account, and therefore, it identifies the part of the inefficiency attributed to the lack of electricity sales. We first consider the electricity sales effect from the economics perspective that describes the gap between production function (PF) and sales-truncated production function (SPF) (Lee and Johnson, 2015). By using the decomposition of the Malmquist Productivity Index (Caves et al, 1982; Färe et al., 1992, 1994), the sales effect can be defined as the combination of the efficiency-effectiveness (EE) ratio and the frontier gap (FG):

$$\text{Sales effect } = \left[\frac{\bar{D}_y(\boldsymbol{x},\boldsymbol{y})}{\bar{D}_y(\boldsymbol{x},\boldsymbol{y}^P)} \times \frac{\bar{D}_y^E(\boldsymbol{x},\boldsymbol{y})}{\bar{D}_y^E(\boldsymbol{x},\boldsymbol{y}^P)}\right]^{\frac{1}{2}} = \frac{\bar{D}_y(\boldsymbol{x},\boldsymbol{y})}{\bar{D}_y^E(\boldsymbol{x},\boldsymbol{y}^P)} \times \left[\frac{\bar{D}_y^E(\boldsymbol{x},\boldsymbol{y}^P)}{\bar{D}_y(\boldsymbol{x},\boldsymbol{y})} \times \frac{\bar{D}_y^E(\boldsymbol{x},\boldsymbol{y})}{\bar{D}_y(\boldsymbol{x},\boldsymbol{y}^P)}\right]^{\frac{1}{2}} = EE \times FG \qquad (8)$$

where

$\bar{D}_y(\boldsymbol{x},\boldsymbol{y}) = 1/(1 + D_y(\boldsymbol{x},\boldsymbol{y}))$, $\bar{D}_y^E(\boldsymbol{x},\boldsymbol{y}) = 1/(1 + D_y^E(\boldsymbol{x},\boldsymbol{y}))$, $\bar{D}_y(\boldsymbol{x},\boldsymbol{y}^P) = 1/(1 + D_y(\boldsymbol{x},\boldsymbol{y}^P))$, $\bar{D}_y^E(\boldsymbol{x},\boldsymbol{y}^P) = 1/(1 + D_y^E(\boldsymbol{x},\boldsymbol{y}^P))$, and $EE = \frac{(1+\theta^{E*})}{(1+\theta^*)}$.

The EE ratio represents the difference between the efficiency measure and effectiveness measure, while the frontier gap characterizes the change in sales. An EE ratio larger than 1 (i.e., $\theta<\theta^E$) indicates that the electric power industry sector of a region need to increase focus on market development to increase its electricity sales, while an EE ratio less than 1 (i.e., $\theta>\theta^E$) indicates that the electric power industry sector of a region needs to focus on productivity improvement to catch up its operational benchmark regions. FG represents the shift between PF and SPF and is always greater than or equal to 1.

Next, we calculate the reallocation effect (RE) as the ratio of effectiveness before and after reallocation: RE=[1/(1+θ^{EAR})]/[1/(1+θ^{EBR})]=(1+θ^{EBR})/(1+θ^{EAR}). The reallocation effect is a measure that accounts for the effect of interregional electricity reallocation on the operational performance of electricity generation, and thus, it implies the part of the inefficiency that is related to the ineffectiveness of the electricity transmission. RE < 1 or > 1 indicates an effectiveness decline or growth after electricity reallocation, respectively.

4 Empirical study of China's regional electric power industry

In this section, we provide an empirical study of the measurements of the efficiency and effectiveness of China's 30 regional electric power industry sectors during the period 2006-2010, i.e., China's 11th Five Year Plan (FYP) period. As mentioned above, we applied three input variables (i.e., nameplate capacity, labor force, energy consumption), two output variables (i.e., electricity generation and electricity supply), and one demand or sales variable (i.e., retail sale of electricity) for estimation. The efficiency measure is conducted by using the traditional DEA Model (3) associated with the electricity generation output, while the effectiveness measure is conducted through the modified DEA Models (4) or (5) associated with electricity generation output or electricity supply output, respectively. The variable for the electricity sales is introduced to truncate the production function and calculate the penalized electricity generation or penalized electricity supply to identify the electricity sales effect from operational performance. Moreover, the effectiveness measures are conducted both before interregional electricity reallocation and after reallocation, and thus, the effect of the electricity reallocation can be identified. Through a comparative analysis of efficiency and effectiveness measures, a specific improvement strategy of the operational performance is provided for each regional electric power industry sector in China.

4.1 Data and description

A panel data set of the electric power industry sectors in China's 30 provincial-level regions during 2006-2010 was collected for investigation[†]. The nameplate capacity (C) input is measured in megawatts (MW), which covers all electric power sectors, including thermal power, hydro power, wind power, nuclear power, etc. The labor force (L) input is the annual average number of staff in the electric power industry and is measured in thousands of people. The energy consumption (E) input is the annual amount of total energy consumption in the electric power industry covering coal, petroleum, natural gas, and other energy, which are all converted into thousands of tons of coal equivalent (ktce) and are aggregated. The conversion factors from the physical unit to coal equivalent provided in the 2011 China Energy Statistical Yearbook are utilized for this conversion[‡]. The electricity generation (Y) output is the annual amount of electricity generated in each region, while the electricity supply (G) is the annual amount of electricity supplied in each region. They are both measured in megawatt hours (MWh). The retail sale of electricity (D) indicates the electricity consumption in each region and is also measured in MWh. The data on nameplate capacity, electricity supply, and retail sale

[†] The empirical study is conducted at the provincial level instead of the plant level so as to take the interregional transmission of electricity into account and thus the effect of electricity reallocation can be detected and the associated operational performance improvement strategy can be obtained.

[‡] The factors include those for Raw coal, Cleaned coal, Washed coal, Coke, Coke oven gas, Coal gas, Crude oil, Gasoline, Kerosene, Diesel oil, Fuel oil, Liquefied petroleum gas, Refinery gas, Natural gas, and Biomass energy.

of electricity are collected from the China Electric Power Yearbook (2007-2011). The data on labor force are collected from the China Industry Economy Statistical Yearbook (2007-2011). The data on electricity generation and energy consumption are obtained from the Energy Balance Table in the China Energy Statistical Yearbook (2007-2011). Table 2 summarizes the input and output data.

[Insert Table 2 here]

During the study period, China's total electricity generation and electricity supply experienced annually increases of 10.1% and 11.2%, respectively, and China's total electricity sale increased 11.4% annually. In 2010, the national electricity generation, supply and sale reached 4205, 3763 and 3527 MWh, respectively. In addition, to satisfy electricity demand, electricity transmission across Chinese provinces, i.e., electricity interregional reallocation, was 322 MWh in 2010, accounting for 7.7% of generated electricity or 8.6% of supplied electricity. The major electricity net import regions are Guangdong, Beijing, Hebei, Liaoning, Jiangsu and Shanghai, and the major electricity net export regions include Inner Mongolia, Shanxi, Hubei, Guizhou, Yunnan and Anhui. Large amounts of net interregional electricity transmissions imply that the effectiveness measures before and after the electricity reallocation are justified, which may provide new insights into the operational performance of China's electric power industry.

4.2 Efficiency measurements

Table 3 reports the operational performances and related ranks for China's 30 regions in 2006 and 2010 (the beginning and ending years in our study period). The first and second columns list the names and initial codes of these regions. We use θ^* from Model (3) to represent the inefficiency measure. If the number equals 0, the associated region is efficient in electricity generation; the larger the number is, the lower the efficiency in the region is. It can be seen that in 2006, 10 regions (e.g., Shanxi, Shanghai and Hubei) were considered efficient in electricity generation, while Jilin was the most inefficient region in China. In 2010, Shanxi and Ningxia become inefficient, while Tianjin becomes efficient. The other eight regions that were considered efficient in 2006 maintained their high performance and were still considered efficient in 2010. During this period, the most significant relative efficiency increase occurred in Beijing and Chongqing, followed by Tianjin and Anhui, while the most significant relative efficiency decrease occurred in Ningxia, followed by Gansu, Liaoning, Shanxi and Inner Mongolia. The ranks of these regions all changed by more than 10. In 2010, most regions (7 out of 9 regions) with efficient electric power industries were eastern and coastal Chinese regions with advanced economic and social development, while the five regions with the lowest efficiency levels are all in northwestern and northeastern areas of China and are characterized as heavy industry bases with relatively slower economic growth during the 11th FYP period.

[Insert Table 3 here]

4.3 Effectiveness measurements with sales effect

The effectiveness measures in 2006 and 2010 are also presented in Table 3 and are displayed according to their rankings. We assume that the effect of an electricity shortage is one hundred times more serious than an electricity surplus, and thus, we allow α_{rj} = 0.1 and β_{rj} = 0.001 to quantify the effects of shortage loss and the abandonment loss of electricity. Given the definition of the electricity shortage and electricity surplus penalties, the effectiveness measure is suitable for characterizing an electricity production system that takes electricity shortage and abandonment costs into account. The parameters α_{rj} and β_{rj} characterize the relationship between the shortage cost and abandonment cost. According to Lee (2015) and Lee and Johnson (2015), α_{rj} can be defined as a function of β_{rj} (e.g., $\alpha_{rj}=\rho\cdot\beta_{rj}$) to capture the relationship between these two costs by utilizing the ratio (ρ) of the real cost of the lost electricity sales over the real cost of electricity abandonment. In practice, the cost of the lost electricity sales includes i) the direct cost indicated by the electricity purchases of a plant that suffers from an electricity shortage from other plants and ii) the indirect cost represented by the social welfare loss caused by electricity shortages and blackouts. Moreover, the cost of electricity abandonment also includes i) the direct cost denoted by abandoned electricity generation and ii) the indirect cost caused by exceeding coal consumption, unnecessary capacity investment, and redundant employment. Being subject to data availability, some of the above direct and indirect costs are not currently available; thus, for simplification, the "one hundred times" relationship assumption is utilized in this study[§].

[§] There are two additional considerations on this assumption. First, since the beginning of 11th FYP period (2006-2010), the electricity supply and demand has become balanced at the national level because of the rapid increase in installed capacity and the accelerated grid reconstruction during the 10th FYP period, and thus, electricity blackout and brownout has become rare in most regions of China. In such background, we consider that, during our study period, electricity shortage is much more serious than electricity surplus

We first focus on the effectiveness measures before electricity reallocation. Here, θ^{EBR*} from Model (4) is utilized to measure ineffectiveness. Similarly, if the number is 0, the associated region is effective in electricity sales; the larger in number is, the lower in effectiveness the region is. It can be seen from Table 3 that in both 2006 and 2010, Zhejiang is ranked among the top two in the effectiveness measure. Liaoning is ranked first in 2006, but its effectiveness sharply decreases to 28th in 2010. Meanwhile, Tianjin experienced an obvious increase in effectiveness from 27th to the 2nd place. In addition, Jiangsu is measured with relatively high effectiveness in both 2006 and 2010. In 2010, the five regions that ranked the highest in effectiveness are Zhejiang, Tianjin, Jiangsu, Henan and Qinghai, of which Zhejiang, Tianjin, and Jiangsu are located on the eastern coast of China. The above findings imply that the measures of effectiveness are different from efficiency measures and strong performance in electricity generation (i.e., high efficiency) does not lead to strong performance in electricity sales (i.e., high effectiveness).

Next, we calculate the sales effect, represented by the *EE* ratio, of the electric power industry for each region, which helps to identify the inefficiency attributed to the lack of electricity sales in each region. The *EE* ratios of China's 30 regions in 2010 reveal that, first, the ratios of 11 regions (BJ, TJ, HB, SH, JS, ZJ, HuB, GD, HaN, SC, and QH) are larger than 1, indicating that the electric power industry sectors of these 11 regions should focus on increasing electricity sales and increase focus on market development. Second, the five regions with the lowest ratios are Jilin, Inner Mongolia, Heilongjiang, Gansu and Jiangxi, whose ratios are far lower than 1, indicating that these regions should focus on technical efficiency promotion and matching the scores of the benchmark regions (e.g., Shanghai and Zhejiang) that have most advanced electricity generation technologies. A comparison of the *EE* ratios between 2006 and 2010 indicates that the most significant increase and decline in sales effects (i.e., increase and decline in inefficiency measure caused by the lack of electricity sales) occur in Anhui and Guangxi, respectively.

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since the social welfare loss (industry shut down, business break off and residence power cut) caused by electricity shortage is much higher than the loss from electricity abandoning and resources waste, and a priority at the "one hundred" scale is appropriate for characterizing this relationship. Secondly, to justify these parameters, we assessed the utilization of different α_{rj} and β_{rj} which showed similar results, and, in addition, α_{rj} = 0.1 and β_{rj} = 0.001 provide the most significant distinguishing results between effectiveness and efficiency measures.

4.4 Effectiveness measurements with electricity reallocation

The net interregional transmission of electricity** accounts for approximate 8% of the electricity supply in China. According to the data in 2010, Guangdong is the largest net electricity importer, which imported 68.0 MWh electricity in 2010, followed by Beijing (52.9 MWh) and Hebei (51.2 MWh). Inner Mongolia is the largest net electricity exporter and exported 104.9 MWh electricity in 2010, followed by Shanxi (49.6MWh) and Hubei (49.1 MWh). In this section, we further measure the ineffectiveness of these 30 regions after the interregional electricity reallocation through the measure of θ^{EAR*} from Model (5) to take the electricity reallocation effect into account. Table 3 shows that the ranks of 19 and 15 regions out of all 30 regions increase after the electricity reallocation in 2006 and 2010, respectively, which indicate that the effectiveness of the electric power industry in half of China's regions experienced relative increases. In addition, the overall effectiveness of China's electric power industry after the electricity reallocation increases, which validates China's interregional electricity import and export deployment during the 11th FYP period.

The reallocation effect of each region, which is denoted as the ratio of effectiveness before and after reallocation, is further calculated, and the results indicate that no region shows poor effectiveness after electricity reallocation because all 30 regions have the RE ratios larger than 1. This finding again implies that the international electricity reallocation in China is effective overall because it increases the effectiveness measure of the electric power industry in each region in China.

Moreover, the distribution of reallocation effect among China's 30 regions also characterizes the mismatch of the regional resource endowment with regional economic development. As mentioned above, Guangdong, Beijing and Hebei are the three largest net electricity importing regions in China in 2010. Regionally, Guangdong has the largest economy in China, Beijing has the second highest GDP per capita in China, and Hebei has the largest iron and steel industry base of China. These economically well-developed regions have huge electricity demands but are also characterized by the lack of primary energy production. Electricity imports help meet their electricity demand, and at the same time, the interregional electricity transmission also significantly increases the effectiveness of their electric power industry, which is additionally validated by their relative higher average RE ratio (1.117) compared to the national average RE

** Exclude net electricity export from China to neighboring countries and regions (Hong Kong, Macau, Vietnam, Myanmar, Laos and North Korea) which account for less than 1% of China's electricity supply in 2010.

ratio (1.015).

4.5 Efficiency vs. effectiveness and operational performance improvement strategy

To provide an overall comparative analysis of the efficiency and effectiveness measures of China's regional electric power industry, we calculate the five-year average efficiency and effectiveness of all 30 regions. The results of the efficiency and effectiveness measures associated with their ranks and strategic positions are reported in Table 4.

[Insert Table 4 here]

Table 4 shows that during the entire 11th FYP period, six regions are measured as efficient in electricity generation, but among them, only two region (i.e., Jiangsu and Qinghai) are also measured as having high effectiveness in electricity sales before and after the electricity reallocation, respectively. In addition, four other regions are highly ranked in effectiveness after the electricity reallocation: Inner Mongolia, Guizhou, Ningxia and Fujian. The differences in the ranks between the efficiency measure and the two effectiveness measures are further clustered into seven groups illustrated in Figure 1 to provide a better understanding of the operational performance changes from different evaluation perspectives. The leftmost group shown in Figure 1 includes the regions whose ranks decreased by more than 20, while the rightmost group includes the regions whose ranks increased by more than 20. The central group of regions show no rank changes. It can be seen that, first, almost all regions experience rank changes between efficiency and effectiveness measures, which again validates the argument that the effectiveness measure is different from the efficiency measure, and the former can be seen as a complement of the latter. The difference in the efficiency and effectiveness ranks also indicates that high efficiency does not guarantee strong effectiveness and vice versa. Second, Figure 1 shows that 17 regions in China experienced relative effectiveness increases after the electricity reallocation. This finding implies that the electricity transmission and reallocation across regions in China is effective for more than half of China's regions, even from the perspective of relative ranking changes during the 11th FYP period.

[Insert Figure 1 here]

Figures 2 and 3 provide the comparisons between the efficiency and effectiveness measures from another perspective, in which the two-dimensional strategic positions of the electric power industry in each region are illustrated. According to the category shown in Figure 2, it can be seen that before the electricity reallocation, three regions (BJ, LN and CQ) are labeled as Laggard regions, four regions (TJ, HB, SH and GD) are labeled as electricity Production Focus regions, 12 regions (NMG, JL, HLJ, AH, FJ, JX, HN, HuN, GX, YN, ShX and XJ) are labeled as electricity Sales Focus regions, and the remaining 12 regions are labeled as Leader regions. Furthermore, Figure 3 illustrates that the categories for these regions shift after electricity reallocation. There are 8, 6, 7 and 9 regions located in the Laggard, Production Focus, Sales Focus and Leader categories, respectively.

[Insert Figures 2 and 3 here]

Using the categories after the electricity reallocation for analysis, if the electric power industry of one region is labeled as Laggard (e.g., Hunan), the region needs to improve both its technical efficiency in electricity production and its market development in electricity delivery or it will be taken out of market. If the regions are part of the electricity Production Focus category (e.g., Shanxi and Hubei), they are leading the electric power industry in terms of making the best use of capacity, labor and energy inputs as well as the best use of technology, but they may waste some input resources by generating more electricity than the local electricity demand. If the regions are labeled as part of the electricity Sales Focus group (e.g., Inner Mongolia and Yunnan), they are implementing market-oriented policies and focusing on matching electricity generation to electricity sales or expanding their market shares. However, these regions are technically inefficient in the electricity production process. Finally, if the regions are labeled as Leaders (e.g., Tianjin and Shanghai), they are good at matching electricity generation with sales, developing new electricity delivery markets, using input resources efficiently in electricity generation, and innovating technology and management to maintain competitive advantages.

Figure 4 shows the strategic position of the regional electric power industry in China, in which the effectiveness measure is shown after electricity reallocation. It can be seen that the Laggard regions are primarily concentrated in the central-west and northeast areas, while the leader regions are mainly located in the northwest and north coastal areas.

[Insert Figure 4 here]

4.6 Operational performance improvement potential

The evaluation results from Models (3) to (5) do not simply indicate the efficiency and effectiveness levels of the electric power industry in each region but also provide a benchmark (denoted by the optimal values of intensity variables λ_j) on the efficiency or effectiveness frontier for each region, which implies the operational performance improvement potential that each region can achieve. Table 5 reports the improvement potential for input resources (i.e., input savings) and electricity generation or supply (i.e., output expansions).

[Insert Table 5 here]

From the perspective of efficiency measures, at the national level, the input saving ratio shows -0.4% in nameplate capacity, -24.3% in labor force, and -3.2% in energy consumption, while the output expansion rate in electricity generation is 8.2%. Furthermore, from the perspective of the effectiveness measures before (or after) the electricity reallocation, at the national level, the nameplate capacity saving ratio is -20.8% (or -23.2%), the labor force saving ratio is –25.3% (or -19.2%), and the energy consumption saving ratio is -11.0% (or -5.8%), while the electricity generation expansion ratio (from effectiveness measure BR) and the electricity supply expansion ratio (from effectiveness measure AR) are 0.82% and 0.01%, respectively. Compared with the improvement ratios from the efficiency measure, the ratios for the nameplate capacity savings and energy consumption savings from effectiveness measures are much higher. On the contrary, the electricity generation or supply expansion ratios from effectiveness measures are much lower than those of the efficiency measures. This finding implies that a moderate increase in electricity generation by 0.82% (instead of increasing by 8.2%) overall in China during the 11th FYP period is suggested from an effectiveness perspective. Furthermore, considering that China's interregional electricity transmission and reallocation is relatively effective, the above suggested electricity generation increase ratio could be even lower. Therefore, moderate increases in electricity generation and the continued effective reallocation or delivery of electricity across regions should be given more attention rather than an expansion of electricity generation in regions that have already over generated electricity.

5 Conclusion and discussion

The increasing competitiveness in the electricity market is leading to an increasing effort in the electric power industry in developing new approaches for operational performance evaluation that adapts to market behavior operations management. Therefore, the operational performance evaluation should be divided into two components: an efficiency evaluation, which measures the production behavior operations performance, and an effectiveness evaluation, which measures market behavior operations performance. Effectiveness measures complement efficiency measures by capturing sales effects in operational performance management.

The effectiveness measure of the electric power industry is related to the capacity of an electricity generation system to adjust its input resources, influencing its electricity generation output to meet electricity demand or consumption. Therefore, the effectiveness measure helps to evaluate the operational performance of an electricity generation system to achieve its market behavior operations management goals for electricity sales. This study applies a newly developed DEA-based effectiveness measure to evaluate the operational performance of the electric power industry in China's 30 provincial regions during 2006-2010. Both the efficiency (in terms of electricity generation) and the effectiveness (in terms of the electricity distribution/supply and consumption) of each regional electric power industry sector are measured, and both the electricity sales effect (i.e., the ratio between the effectiveness and efficiency measures) and electricity reallocation effect (i.e., the ratio between the effectiveness measures before and after interregional electricity transmission) are estimated. Furthermore, the operational performance improvement strategy and improvement potential of each regional electric power industry sector are proposed to support further decision making.

The estimation results of an empirical study show that i) effectiveness measures are different from efficiency measures, and high performance in electricity generation does not guarantee high performance in electricity sales; ii) according to the efficiency-effectiveness ratio in 2010, the electric power industry sectors of 11 regions should pay more attention to electricity market development to increase electricity sales, and the remaining regions should primarily focus on increasing technical efficiency to meet the benchmark region levels; iii) during 2006-2010, Guangxi and Anhui show the most obvious decreases and increases in operational performance caused by the lack of electricity sales (i.e., electricity sales effect), respectively; iv) interregional electricity transmission and reallocation in China is effective overall because it increases the effectiveness measure of the electric power industry in each region in China during 2006-2010; v) two-dimensional strategic positions (labeled as Leader, electricity Sales Focus, electricity Production Focus, and Laggard) characterized by both the efficiency and effectiveness measures of each region are proposed to provide alternative strategies for enhancing operational performance; and vi) an estimation of the improvement potential of operational performance implies that to further improve effectiveness, it is urgent to moderately increase electricity generation with emphasizing the development of electricity market and to continue effectively reallocating electricity across regions in China.

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References

Asmild, M., Paradi, J. C., Reese, D. N., & Tam, F. (2007). Measuring overall efficiency and effectiveness using DEA. European Journal of Operational Research, 178(1), 305-321.

Bi, G. B., Song, W., Zhou, P., & Liang, L. (2014). Does environmental regulation affect energy efficiency in China's thermal power generation? Empirical evidence from a slacks-based DEA model. Energy Policy, 66, 537-546.

Byrnes, P., & Freeman, M. (1999). Using DEA measures of efficiency and effectiveness in contractor performance fund allocation. Public Productivity & Management Review, 23(2), 210-224.

Caves, D. W., Christensen, L. R., & Diewert, W. E. (1982). The economic theory of index numbers and the measurement of input, output, and productivity. Econometrica, 50(6), 1393–1414.

Cherchye, L., & Post, T. (2003). Methodological advances in DEA: A survey and an application for the Dutch electricity sector. Statistica Neerlandica, 57(4), 410-438.

Cook, W. D., & Zhu, J. (2007). Within-group common weights in DEA: an analysis of power plant efficiency. European Journal of Operational Research, 178(1), 207-216.

Cook, W. D., & Zhu, J. (Eds.). (2014). Data envelopment analysis: A handbook of modeling internal structure and network (Vol. 208). Springer.

Cook, W. D., Du, J., & Zhu, J. (2015). Units invariant DEA when weight restrictions are present: ecological performance of US electricity industry. Annals of Operations Research, doi: 10.1007/s10479-015-1881-x.

Cooper, W. W., Seiford, L. M., & Zhu, J. (2011). Handbook on data envelopment analysis (Vol. 164). Springer Science & Business Media.

Fallahi, A., Ebrahimi, R., & Ghaderi, S. F. (2011). Measuring efficiency and productivity change in power electric generation management companies by using data envelopment analysis: A case study. Energy, 36(11), 6398-6405.

Färe, R., Grosskopf, S., Lindgren, B., & Roos, P. (1992). Productivity changes in Swedish pharmacies 1980–1989: A non-parametric Malmquist approach. Journal of Productivity Analysis, 3(1–2), 85–101.

Färe, R., Grosskopf, S., Norris, M., & Zhang, Z. (1994). Productivity growth technical progress, and efficiency change in industrialized countries. American Economic Review, 84(1), 66–83.

Fielding, G. J., Babitsky, T. T., & Brenner, M. E. (1985). Performance evaluation for bus transit. Transportation Research Part A: General, 19(1), 73-82.

Golany, B., Phillips, F. Y., & Rousseau, J. J. (1993). Models for improved effectiveness based on DEA efficiency results. IIE transactions, 25(6), 2-10.

Lam, P. L., & Shiu, A. (2001). A data envelopment analysis of the efficiency of China's thermal power generation. Utilities Policy, 10(2), 75-83.

Lam, P. L., & Shiu, A. (2004). Efficiency and productivity of China's thermal power generation. Review of Industrial Organization, 24(1), 73-93.

Lee, C.-Y., & Johnson, A. L. (2014). Proactive data envelopment analysis: Effective production and capacity expansion in stochastic environments. European Journal of Operational Research, 232(3), 537–548.

Lee, C.-Y. (2015). Distinguishing Operational Performance in Power Production: A New Measure of Effectiveness by DEA. IEEE Transactions on Power Systems, 30(6), 3160-3167.

Lee, C.-Y., & Johnson, A. L. (2015). Effective production: measuring of the sales effect using data envelopment analysis. Annals of Operations Research, 235(1), 453-486.

Lo, F. Y., Chien, C. F., & Lin, J. T. (2001). A DEA study to evaluate the relative efficiency and investigate the district reorganization of the Taiwan power company. IEEE Transactions on Power Systems, 16(1), 170-178.

Park, S. U., & Lesourd, J. B. (2000). The efficiency of conventional fuel power plants in South Korea: A comparison of parametric and non-parametric approaches. International Journal of Production Economics, 63(1), 59-67.

SCC (2011). State Council of the People's Republic of China: Plan for Energy Conservation and Emissions Reduction in the 12th Five Year Plan Period.

SCC. (2007). State Council of the People's Republic of China: Comprehensive Work Plan for Energy Conservation and Emissions Reduction.

SERC. (2011). State electricity regulatory commission of the People's Republic of China: Energy and emission reduction conditions of the power industry in 2010 and during the 11th Five Year Plan period.

Sueyoshi, T., & Goto, M. (2011). DEA approach for unified efficiency measurement: assessment of Japanese fossil fuel power generation. Energy Economics, 33(2), 292-303.

Sueyoshi, T., & Goto, M. (2012). Efficiency-based rank assessment for electric power industry: a combined use of data envelopment analysis (DEA) and DEA-discriminant analysis (DA). Energy Economics, 34(3), 634-644.

Vaninsky, A. (2006). Efficiency of electric power generation in the United States: analysis and forecast based on data envelopment analysis. Energy Economics, 28(3), 326-338.

Wang, K., Huang, W., Wu, J., & Liu, Y. N. (2014). Efficiency measures of the Chinese commercial banking system using an additive two-stage DEA. Omega, 44, 5-20.

Wang, K., & Wei, Y. M. (2016). Sources of energy productivity change in China during 1997–2012: A decomposition analysis based on the Luenberger productivity indicator. Energy Economics, 54, 50-59.

Wang, K., Wei, Y. M., & Zhang, X. (2012). A comparative analysis of China's regional energy and emission performance: Which is the better way to deal with undesirable outputs?. Energy Policy, 46, 574-584.

Wang, K., Zhang, X., Wei, Y. M., & Yu, S. (2013). Regional allocation of CO 2 emissions allowance over provinces in China by 2020. Energy Policy, 54, 214-229.

Wu, H., Du, S., Liang, L., & Zhou, Y. (2013). A DEA-based approach for fair reduction and reallocation of emission permits. Mathematical and Computer Modelling, 58(5), 1095-1101.

Xie, B. C., Fan, Y., & Qu, Q. Q. (2012). Does generation form influence environmental efficiency performance? An analysis of China's power system. Applied Energy, 96, 261-271.

Yang, H., & Pollitt, M. (2009). Incorporating both undesirable outputs and uncontrollable variables into DEA: The performance of Chinese coal-fired power plants. European Journal of Operational Research, 197(3), 1095-1105.

Yang, H., & Pollitt, M. (2010). The necessity of distinguishing weak and strong disposability among undesirable outputs in DEA: environmental performance of Chinese coal-fired power plants. Energy Policy, 38(8), 4440-4444.

Yu, M. M., & Lin, E. T. J. (2008). Efficiency and effectiveness in railway performance using a multi-activity network DEA model. Omega, 36(6), 1005-1017.

Zhu, J. (Ed.). (2015). Data Envelopment Analysis: A Handbook of Models and Methods (Vol. 221). Springer.

Figures and tables

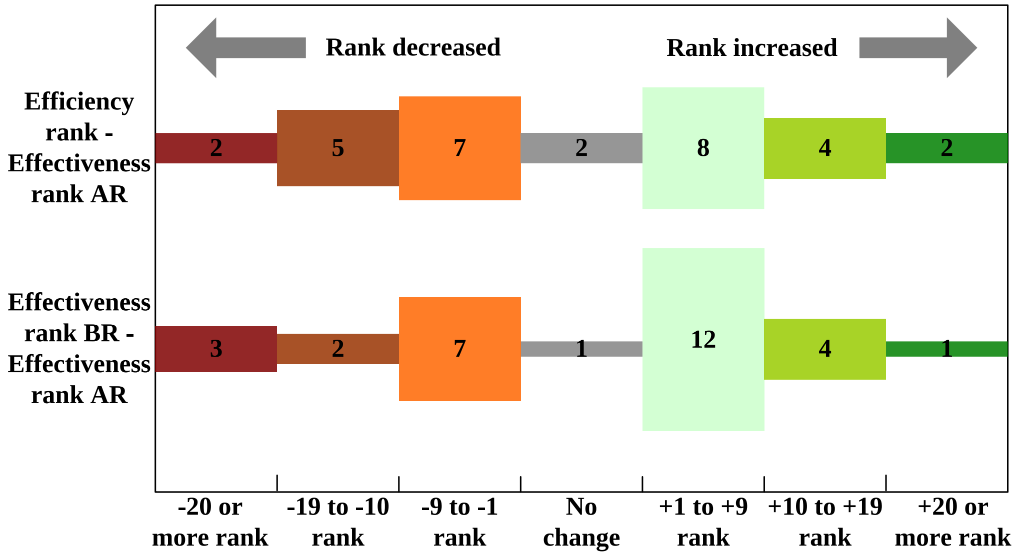


Figure 1 Rank changes on efficiency and effectiveness measures

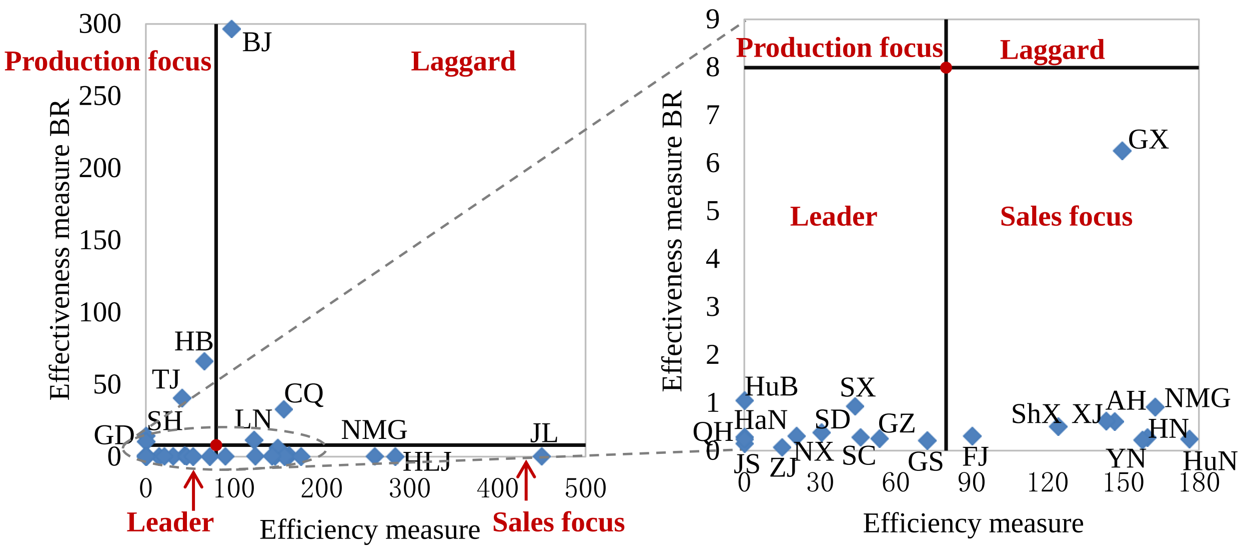


Figure 2 Efficiency vs. effectiveness before electricity reallocation and strategic position

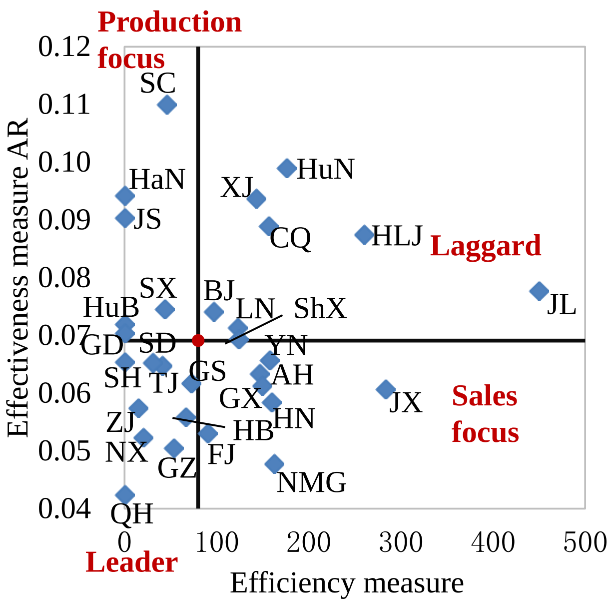
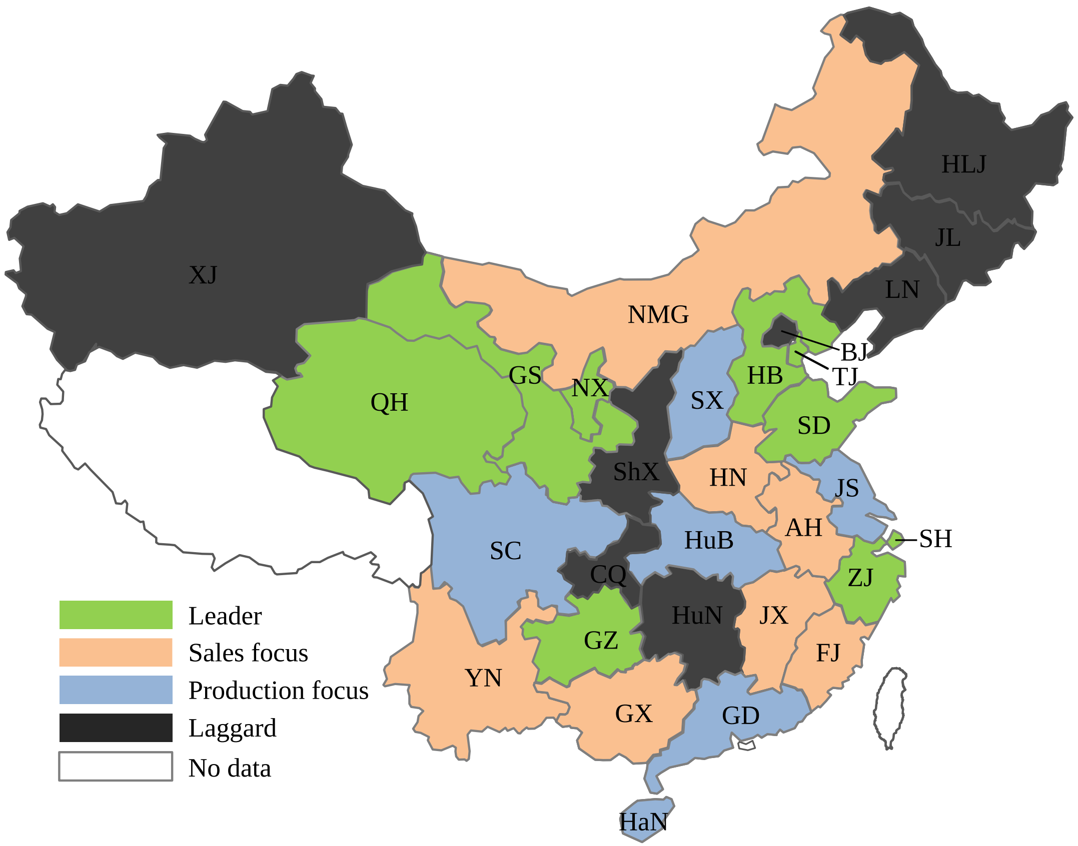


Figure 3 Efficiency vs. effectiveness after electricity reallocation and strategic position



Region	Code
Beijing	BJ
Tianjin	TJ
Hebei	HB
Shanxi	SX
Inner Mongolia	NMG
Liaoning	LN
Jilin	JL
Heilongjiang	HLJ
Shanghai	SH
Jiangsu	JS
Zhejiang	ZJ
Anhui	AH
Fujian	FJ
Jaingxi	JX
Shandong	SD
Henan	HN
Hubei	HuB
Hunan	HuN
Gaungdong	GD
Guangxi	GX
Hainan	HaN
Chongqing	CQ
Sichuan	SC
Guizhou	GZ
Yunnan	YN
Shaanxi	ShX
Gansu	GS
Qinghai	QH
Ningxia	NX
Xinjiang	XJ

Figure 4 Strategic position of regional electric power industry in China

Table 1 Letters and symbols applied in the modelling

Letter and symbol	Definition
$\boldsymbol{x}$	Input vector
$\boldsymbol{y}$	Output vector
$\boldsymbol{y}^{E}$	Effective output vector
$\boldsymbol{y}^{P}$	Penalized output vector
$\boldsymbol{\lambda}$	Intensity variable
$\boldsymbol{\theta}$	Output oriented technical efficiency measure
$\boldsymbol{\theta}^{E}$	Output oriented technical effectiveness measure
$\boldsymbol{T}$	Production possibility set
$\overline{\boldsymbol{T}}$	Production possibility set under variable returns to scale
$\boldsymbol{T}^{E}$	Sales-truncated production possibility set
$\overline{\boldsymbol{T}}^{E}$	Sales-truncated production possibility set under variable returns to scale
$\boldsymbol{y}^{PF}$	Traditional production function
$\boldsymbol{y}^{SPF}$	Effective production function
$\boldsymbol{d}$	Realized sales
$\boldsymbol{\alpha}$	Penalty parameters associated with lost sales
$\boldsymbol{\beta}$	Penalty parameters associated with abandoning loss
$\boldsymbol{D_y(x,y)}$	Distance function for efficiency measure
$\boldsymbol{D_y^E}(\boldsymbol{x},\boldsymbol{y^P})$	Distance function for effectiveness measure

Table 2 Statistics of regional electric power industries in China

Year	Statistics	Nameplate capacity (Million W)	Labor force (Thousand person)	Energy consumption (thousand tonnes)	Electricity generation (Million Wh)	Electricity supply (Million Wh)	Electricity consumption (Million Wh)
2006	Mean	2072	86209	3011	955	820	764
	Std.Dev.	1462	50503	2312	675	617	572
	Max	5403	206200	8747	2536	2802	2599
	Min	266	14300	196	97	82	74
2007	Mean	2376	85526	3334	1093	943	881
	Std.Dev.	1633	50340	2526	760	708	659
	Max	5932	193949	9090	2732	3178	2955
	Min	282	14400	250	115	93	85
2008	Mean	2640	85736	3411	1155	1011	947
	Std.Dev.	1670	48902	2675	780	743	694
	Max	5995	201124	9418	2777	3284	3059
	Min	279	11800	262	118	101	92
2009	Mean	2912	92420	3534	1238	1086	1018
	Std.Dev.	1759	55968	2702	807	780	732
	Max	6508	232400	9705	2928	3393	3203
	Min	389	11800	277	128	111	102
2010	Mean	3205	91696	4066	1402	1254	1176
	Std.Dev.	1898	55397	3095	898	918	861
	Max	7089	220067	11335	3359	3882	3643
	Min	386	12145	347	153	131	121

Table 3 Efficiency and effectiveness measures of China's electric power industries in selected years

Region	Code	2006						2010					
		Efficiency		Effectiveness BR		Effectiveness AR		Efficiency		Effectiveness BR		Effectiveness AR	
		Measure	Rank	Measure	Rank	Measure	Rank	Measure	Rank	Measure	Rank	Measure	Rank
Beijing	BJ	219.2	27	426.46	30	0.076	17	15.7	10	218.69	30	0.073	19
Tianjin	TJ	44.4	13	11.53	27	0.069	15	0.0	1	0.07	2	0.062	13
Hebei	HB	27.1	12	9.80	26	0.058	5	102.4	17	119.03	29	0.055	9
Shanxi	SX	0.0	1	0.94	22	0.077	18	72.8	14	0.97	23	0.069	17
Inner Mongolia	NMG	60.1	17	0.88	21	0.049	2	329.2	29	0.84	22	0.053	8
Liaoning	LN	49.1	14	0.06	1	0.071	16	303.9	28	57.11	28	0.076	23
Jilin	JL	399.0	30	0.39	14	0.084	23	617.8	30	0.34	16	0.073	20
Heilongjiang	HLJ	182.8	24	0.53	19	0.083	22	300.3	27	0.39	18	0.084	25
Shanghai	SH	0.0	1	8.29	25	0.067	13	0.0	1	17.28	27	0.064	15
Jiangsu	JS	0.0	1	0.27	7	0.094	26	0.0	1	0.08	4	0.086	27
Zhejiang	ZJ	0.0	1	0.12	2	0.067	14	0.0	1	0.06	1	0.051	5
Anhui	AH	162.5	22	0.40	16	0.063	8	64.3	11	0.71	20	0.063	14
Fujian	FJ	77.3	18	0.40	15	0.051	4	95.0	15	0.18	9	0.075	22
Jiangxi	JX	229.4	28	0.33	12	0.064	9	234.2	25	0.18	8	0.052	6
Shandong	SD	50.0	15	0.46	17	0.066	12	69.8	13	0.17	6	0.062	12
Henan	HN	134.0	19	0.50	18	0.061	6	200.4	24	0.08	3	0.057	10
Hubei	HuB	0.0	1	0.95	23	0.079	21	0.0	1	1.01	24	0.071	18
Hunan	HuN	183.9	25	0.22	5	0.106	29	130.2	21	0.33	15	0.096	29
Guangdong	GD	0.0	1	5.43	24	0.078	20	0.0	1	12.70	26	0.066	16
Guangxi	GX	150.8	20	30.90	28	0.078	19	104.2	19	0.26	13	0.053	7
Hainan	HaN	0.0	1	0.31	9	0.108	30	0.0	1	0.26	12	0.083	24
Chongqing	CQ	254.6	29	151.99	29	0.091	25	67.3	12	12.47	25	0.090	28
Sichuan	SC	0.0	1	0.24	6	0.103	27	0.0	1	0.38	17	0.119	30
Guizhou	GZ	56.8	16	0.31	10	0.051	3	116.7	20	0.21	10	0.050	4

Yunnan	YN	163.7	23	0.18	3	0.086	24	157.7	23	0.25	11	0.045	3
Shaanxi	ShX	151.8	21	0.32	11	0.065	10	99.8	16	0.66	19	0.073	21
Gansu	GS	9.4	11	0.20	4	0.066	11	269.8	26	0.18	7	0.058	11
Qinghai	QH	0.0	1	0.37	13	0.049	1	0.0	1	0.11	5	0.040	1
Ningxia	NX	0.0	1	0.27	8	0.062	7	102.9	18	0.29	14	0.042	2
Xinjiang	XJ	184.3	26	0.78	20	0.104	28	147.6	22	0.78	21	0.084	26

Note: Values on efficiency and effectiveness measures are multiplied by 10^3 to increase discrimination.

Table 4 Efficiency and effectiveness measures and strategic positions of China's regional electric power industries

Region code	Efficiency		Effectiveness BR		Effectiveness AR		Strategic position BR	Strategic position AR
	Measure	Rank	Measure	Rank	Measure	Rank		
BJ	96.9	17	296.80	30	0.074	21	Lag	Lag
TJ	40.9	10	40.80	28	0.065	13	PF	L
HB	66.2	14	66.25	29	0.056	6	PF	L
SX	43.7	11	0.93	21	0.075	22	L	PF
NMG	162.5	26	0.92	20	0.048	2	SF	SF
LN	122.6	18	11.73	25	0.071	19	Lag	Lag
JL	449.8	30	0.35	14	0.078	23	SF	Lag
HLJ	260.0	28	0.46	16	0.087	24	SF	Lag
SH	0.0	1	14.60	26	0.065	15	PF	L
JS	0.0	1	0.15	2	0.090	26	L	PF
ZJ	14.8	7	0.08	1	0.057	7	L	L
AH	146.5	21	0.61	18	0.063	12	SF	SF
FJ	90.1	16	0.31	12	0.053	5	SF	SF
JX	283.2	29	0.23	5	0.061	9	SF	SF
SD	30.4	9	0.39	15	0.065	14	L	L
HN	159.5	25	0.28	9	0.058	8	SF	SF
HuB	0.0	1	1.05	22	0.072	20	L	PF
HuN	176.1	27	0.25	7	0.099	29	SF	Lag
GD	0.0	1	10.65	24	0.070	18	PF	PF
GX	149.5	22	6.27	23	0.061	10	SF	SF
HaN	0.0	1	0.29	11	0.094	28	L	PF
CQ	156.4	23	32.90	27	0.089	25	Lag	Lag
SC	45.9	12	0.29	10	0.110	30	L	PF
GZ	53.4	13	0.26	8	0.051	3	L	L
YN	157.4	24	0.23	4	0.066	16	SF	SF

ShX	124.1	19	0.51	17	0.069	17	SF	Lag
GS	72.3	15	0.22	3	0.062	11	L	L
QH	0.0	1	0.24	6	0.042	1	L	L
NX	20.6	8	0.31	13	0.052	4	L	L
XJ	143.1	20	0.63	19	0.094	27	SF	Lag

Note: Values on efficiency and effectiveness measures are multiplied by 10^3 to increase discrimination.

Table 5 Improvement potentials on inputs and outputs toward efficient and effective frontier benchmarks

Region code	Efficiency measure based improvement ratios (%)				Effectiveness measure based improvement ratios BR (%)				Effectiveness measure based improvement ratios AR (%)			
	Nameplate capacity	Labor force	Energy consumption	Electricity generation	Nameplate capacity	Labor force	Energy consumption	Electricity generation	Nameplate capacity	Labor force	Energy consumption	Electricity supply
BJ	0.00	-45.09	0.00	9.24	0.00	-45.09	0.00	29.23	-0.06	-6.54	-1.82	0.01
TJ	0.00	-2.94	0.00	3.80	-0.65	-2.91	0.00	3.86	0.00	0.00	-3.87	0.01
HB	0.00	-43.02	-13.93	6.90	0.00	-39.44	-14.85	7.03	0.00	-1.43	-0.30	0.01
SX	0.00	-1.75	-2.76	4.69	-36.49	-25.83	-34.70	0.09	0.00	0.00	0.00	0.01
NMG	-1.32	-2.15	-12.47	17.77	-40.95	-34.28	-41.19	0.09	0.00	0.00	0.00	0.00
LN	0.00	-56.29	-6.20	12.91	-8.15	-46.98	-12.70	1.32	-4.47	-26.95	-2.57	0.01
JL	0.00	-46.21	0.00	45.77	-12.65	-15.81	-1.30	0.04	-9.64	-21.41	-1.30	0.01
HLJ	0.00	-70.02	-2.15	26.26	-9.43	-52.84	-2.88	0.05	-6.30	-56.76	-3.48	0.01
SH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.47	0.00	0.00	0.00	0.01
JS	0.00	0.00	0.00	0.00	-11.84	-9.31	-10.41	0.01	-7.78	0.00	-7.94	0.01
ZJ	-1.86	0.00	0.00	1.34	-20.07	0.00	0.00	0.01	-29.29	-0.37	-4.36	0.01
AH	0.00	-6.02	-0.83	13.39	-20.71	-3.25	-13.08	0.06	-7.45	-1.83	-0.41	0.01
FJ	0.00	-0.66	0.00	9.16	-31.72	-11.29	0.00	0.03	-47.70	-12.71	0.00	0.01
JX	0.00	-33.81	0.00	28.20	-20.36	-18.97	0.00	0.02	-17.94	-22.97	0.00	0.01
SD	-2.17	-38.78	-7.75	3.07	-19.46	-43.00	-14.79	0.04	-38.79	-29.36	-29.63	0.01
HN	0.00	-46.04	-0.39	16.17	-22.31	-27.91	-5.30	0.03	-23.04	-30.55	-6.30	0.01
HuB	0.00	0.00	0.00	0.00	-57.32	-35.33	0.00	0.11	-64.57	-31.98	0.00	0.01
HuN	0.00	-21.52	0.00	17.06	-33.63	-39.60	0.00	0.03	-47.44	-39.11	0.00	0.01
GD	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.08	-6.13	-5.62	0.00	0.01
GX	0.00	-29.08	0.00	14.12	-18.39	-39.78	0.00	0.41	-53.88	-37.36	0.00	0.01
HaN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.01
CQ	0.00	-12.43	0.00	14.26	-6.74	-2.33	-2.43	2.45	-25.50	-1.03	-3.70	0.01
SC	0.00	-20.30	0.00	4.09	-27.62	-41.58	0.00	0.03	-56.18	-43.93	0.00	0.01

GZ	0.00	0.00	0.00	5.47	-24.48	-3.39	0.00	0.03	-38.36	-3.32	-12.34	0.01
YN	0.00	0.00	0.00	15.75	-30.87	-7.72	0.00	0.02	-44.48	-4.95	0.00	0.01
ShX	0.00	-34.68	0.00	12.50	-14.57	-6.90	-1.61	0.05	-11.69	-12.28	-1.61	0.01
GS	0.00	-11.84	0.00	8.29	-21.34	-19.25	0.00	0.02	-34.45	-15.39	0.00	0.01
QH	0.00	0.00	0.00	0.00	-5.22	-0.40	0.00	0.02	-4.88	-0.28	-0.32	0.00
NX	0.00	0.00	0.00	2.54	-15.11	0.00	-24.40	0.03	-13.41	0.00	-25.36	0.01
XJ	0.00	-13.80	0.00	14.14	-31.15	0.00	-30.68	0.06	-37.44	0.00	-39.18	0.01