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# Benchmarking Cleaner Production Performance of Coal-fired Power Plants Using Two-stage Super-efficiency Data Envelopment Analysis

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***Abstract*—**Benchmarking cleaner production performance is an effective way of pollution control and emission reduction in coal-fired power industry. A benchmarking method using two-stage super-efficiency data envelopment analysis for coal-fired power plants is proposed – firstly, to improve the cleaner production performance of DEA-inefficient or weakly DEA-efficient plants, then to select the benchmark from performance-improved power plants. An empirical study is carried out with the survey data of 24 coal-fired power plants. The result shows that in the first stage the performance of 16 plants is DEA-efficient and that of 8 plants is relatively inefficient. The target values for improving DEA-inefficient plants are acquired by projection analysis. The efficient performance of 24 power plants and the benchmarking plant is achieved in the second stage. The two-stage benchmarking method is practical to select the optimal benchmark in the cleaner production of coal-fired power industry and will continuously improve plants' cleaner production performance.

***Keywords*—**benchmarking, cleaner production performance, coal-fired power plant, super-efficiency data envelopment analysis

## I. Introduction

THE coal-fired power industry is an important part of the electric utilities and about 80% electricity generation is from coal-fired power plants at present in China. In 2007, the installed capacity of the thermal power was 554420 MW, accounting for 77.7% of the total; and 82.9% of the electricity production was from thermal power generation, with 76% from coal-fired power plants, which resulted in 34% coal consumption of the total coal output in China [1]. The dominant position of coal in the primary energy structure led to the generating pattern of coal-oriented power industry. The Energy Research Institute of China forecasted that by 2020 Chinese installed capacity of electric power would reach 961000 MW, with 600000 MW from the coal-fired power industry, still accounting for 60% [2]. In 2007, China's sulfur dioxide emissions were over 24.68 million tons, which made China become the largest emitting country of sulfur dioxide and resulted in serious pollution of acid rain in one-third regions of China. Meanwhile, China's carbon dioxide emission was 62000 million tons (13.5% of the world) in 2007 [3], including 27000 million tons (about 43.5%) from the electric power sectors, and it would reach 32000 million tons by 2010 [4]. The carbon emission reduction pressure of China is getting bigger and bigger. With large amounts of carbon dioxide, sulfur dioxide, nitrogen oxides, dust, wastewater and other pollutants discharged in the power generation, the development of the power industry in China is severely restricted by the environment and climate issues.

Cleaner production, a creative idea, applies an integrated and preventative environment strategy to the producing, products and services, so that the eco-efficiency can be increased and the risks to the human and the environment can be reduced. This thinking also highlights the important concepts of overall prevention, eco-efficiency, environmental strategies, full life cycle, etc. and covers the whole procedure of raw materials, production, consumption and pollutant disposal, which has been well recognized for years by all countries in the world.

Implementing cleaner production technology and cleaner production management in coal-fired power industry to continuously improve the cleaner production performance (CPP) of power plants is one of the most effective measures to reduce emissions. In 1980, the US launched the clean coal technology to solve the environmental problems caused by coal-burning and made remarkable achievements. From 1980 to 1998, the coal consumption of coal-fired power plants in the US increased by 60%. Due to the cleaner production action, the emissions of sulfur dioxide and nitrogen oxide had decreased by 23% and 12% respectively. The investment on cleaner technology and management was 5200 million US dollars, while the economic benefits were 100000 million dollars [5]. In the recent years, Chinese government has promoted cleaner production technology and cleaner production benchmarking management in the electric industry. A series of developing plans have been formulated, such as *The Cleaner Production Promotion Law* approved by the National People's Congress of China, *The Cleaner Production Evaluation Index System for Thermal Power Industry* issued by the National Development and Reform Council (NDRC), and *The Cleaner Production Standards – Coal-fired Power Plant* developed by the Ministry of Environmental Protection (MEP). These policies and

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measures provide a basis for implementing cleaner production program in the coal-fired power industry.

## II. Literature review

The benchmarking method of cleaner production is actually based on measuring the CPP. The benchmark is selected from the enterprise with relatively efficient performance and stable and efficiency; and other enterprises will improve their efficiencies in the light of the benchmarks' input-output indicators. Therefore, the key to selecting optimal production benchmark is to establish an evaluation index and a measuring method for the CPP in practice.

At present, the evaluation index for cleaner production varies in different countries. The commonly used and accepted evaluation index mainly includes the following 6 indicators: ecological efficiency, climate change, environmental performance, environmental load, waste generating rate and emission-reduction trade. And in China, it generally includes indicators of raw materials, products, resources and pollutants, among which the index of environmental quality, pollution reduction, raw materials, energy consumption, environmental management, as well as comprehensive utilization of resources are mostly applied [6]–[8]. From the assessing contents of cleaner production, the evaluation of cleaner production degree, CPP assessment and measuring the potential for cleaner production, etc. are involved. The assessment method for cleaner production is mainly based on the Life Cycle Analysis (LCA), which can measure the environmental impact of the research objects [9], [10]. The LCA has been applied to the cleaner production assessment (CPA) of the electrolytic aluminum production, cement enterprises and so on [11], [12]. There are still other methods like the percentage method, the composite index analysis, fuzzy math method, etc. The fuzzy math method is widely used to evaluate the CPA of steel firms, electrolytic aluminum industry, cement enterprises, coal industry, paper industry, eco-industrial parks and so forth [13]–[18]. In addition, the CPA measured with the DEA model is a new method developed in the recent years. DEA is commonly used to assess the relative performance or efficiency of cleaner production so as to select the benchmark and to improve the CPA [19].

The benchmarking methods mainly include the ideal state analysis [17], the relative performance evaluation [20], [21], and production frontier analysis [22]. And major models applied benchmarking are DEA model or extended DEA models, for example, the optimal decision-making model for benchmarking cleaner production with qualitative information [23], benchmarking management of public sectors' performance with DEA [24], super-efficiency DEA model applied in benchmarking management [25], and sensitivity analysis of DEA benchmarking model [26]. In addition, the benchmarking management has been evolved to yardstick competition in enterprise management, that is, enterprises compete with each other to become the benchmark under the incentive regulation mechanism. Such a mechanism has been fully applied in electric power generation and pollution reduction [27]–[29].

For the DEA model involved in the benchmarking management, whether CCR, BCC, G/DEA or SE-DEA has neglected an important issue, namely, the benchmark is acquired from measuring the original data with some DEA model. It is a method of selecting benchmark in the "bad sample", because there are some DEA-inefficient DMUs in the raw data. Thus the benchmarking DMU may not be the best choice. Therefore, it is practical to select benchmark based on DEA-efficient DMUs after improving the DEA-inefficient or weakly DEA-efficient DMUs.

## III. Method and Model

### A. Super-efficiency DEA Model

There are mainly two DEA models – CCR model and BCC model [30], [31]. The CCR model can be used to evaluate the efficiencies of scale and technique simultaneously. In other words, the DEA-efficient decision making unit (DMU) in the CCR model is either appropriate in its scale or efficient in the technical management. The BCC model can only be used to assess the technique efficiency of DMUs. In addition, DEA model can be divided into two types: input-oriented model and output-oriented model. The input orientation means to achieve the efficiency by reducing input under the existing output level, while the output orientation tells what an efficient status is by increasing output under present input.

However, the CCR model can only figure out whether the DMUs are DEA-efficient or DEA-inefficient. It cannot distinguish the efficiencies of the DEA-efficient DMUs. On the basis of CCR model, Andersen and Petersen put forward the super-efficiency data envelopment analysis (SE-DEA) model (1) in 1993 [32]. In this model, the efficiency value will no longer be restricted in the scope of 0-1. That is to say, the efficiency value will probably be bigger than 1. Thereby, the DEA-efficient and DEA-inefficient DMUs can be ranked according to their super-efficiency values and the benchmark can be selected.

$$\begin{cases} \min V_D = \theta - (\varepsilon\varepsilon^- + \hat{\varepsilon}s^+) \\ s.t. \sum_{\substack{j=1 \\ j \neq j_0}}^{n} \lambda_j X_j + s_j^- = \theta X_{j_0}, \ \sum_{\substack{j=1 \\ j \neq j_0}}^{n} \lambda_j Y_j - s_j^+ = Y_{j_0} \\ \lambda_j \geq 0, j = 1,2,\ldots,n; s_j^+ \geq 0, s_j^- \geq 0 \end{cases} \tag{1}$$

Literatures have studied the relationship between the CCR model and SE-DEA model (Fig. 1). When the sample DMUs are measured by the SE-DEA model, the super-efficiency values of the DEA-inefficient DMUs are the same as their DEA efficiencies respectively, still smaller than 1 (e.g. point $B_1$' point $B_2$' and in Fig. 1), and the input redundancies and output deficiencies are consistent with the values from the CCR model;

for the weakly DEA-efficient DMUs, their super-efficiency values are equal to 1 and input-output redundancies will not change (e.g. point $A_1$ and point $A_2$ in Fig. 1); the production frontier of the DEA-efficient DMUs has been changed and their super-efficiency values are greater than 1 (e.g. point $B_1$, point $B_2$, point $C_1$, point $C_2$, and point $D_1$, point $D_2$, in Fig. 1) [25], [33]. Therefore, we can directly evaluate the CPP of coal-fired power plants with the SE-DEA model, instead of using CCR model.

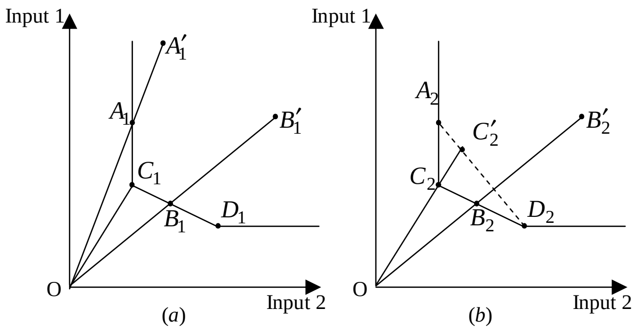


Fig. 1 CCR model (*a*) vs. SE-DEA model (*b*)

*B. Projection Analysis*

The super-efficiency values ($\theta^*$), input redundancies ($s^{-*}$) and output deficiencies ($s^{+*}$) of all DMUs can be acquired with the SE-DEA model in (1), which will be used for the projection analysis of DEA-inefficient and/or weakly DEA-efficient DMUs. And the input-out data of these DMUs may be adjusted according to the projected values (input-output targets) so as to improve the productive efficiency. The projection analysis model can be expressed as (2).

$$\begin{cases} \hat{x}_j = \theta^* \cdot x_0 - s_j^- \\ \hat{y}_j = y_0 + s_j^+ \end{cases} \tag{2}$$

According to the principle of projection analysis, the projected values of DEA-inefficient and weakly DEA-efficient DMUs at the production frontier are DEA-efficient [34]. Thus all DMUs can achieve the DEA-efficient efficiencies.

*C. Sensitivity Analysis*

The benchmarking method requires that the efficiency benchmark be relatively efficient and stable with a wide variation range to maintain DMUs DEA-efficient. The range can be achieved through sensitivity analysis.

Suppose that the input-output data of a single DMU turns into $(1 \pm \gamma)$ times of the original data, namely, $DMU_0$ changes as:

$$\begin{cases} \hat{x}_0 = (1+\gamma)x_0 \\ \hat{y}_0 = (1-\gamma)y_0 \end{cases}, \ 0 \le \gamma < 1 \tag{3}$$

Then, the necessary and sufficient conditions for $DMU_0$ maintaining DEA-efficient are:

$$\theta_0 > 1, \ 0 \le \gamma \le \frac{\theta_0 - 1}{\theta_0 + 1} = 1 - \frac{2}{\theta_0 + 1} \tag{4}$$

If all the DMUs change at the same time, considering the rest $DMU_j$ change in the opposite direction of the change trend of $DMU_0$ (i.e. the most adverse cases), $DMU_0$ still changes based on (3), while the rest $DMU_j$ change according to (5).

$$\begin{cases} \hat{x}_j = \dfrac{1}{1+\gamma} x_j \\ \hat{y}_0 = \dfrac{1}{1-\gamma} y_j \end{cases}, \ j=1,\ldots,n, \ j\neq 0 \tag{5}$$

Then, the necessary and sufficient conditions for $DMU_0$ maintaining DEA-efficient are:

$$\theta_0 > 1, \ 0 \le \gamma \le \frac{\theta_0^{\frac{1}{2}} - 1}{\theta_0^{\frac{1}{2}} + 1} = 1 - \frac{2}{\theta_0^{\frac{1}{2}} + 1} \tag{6}$$

We can see from (4) and (6) that DMUs with high the super-efficiency values are with more stability and wide range maintaining DMUs DEA-efficient, whether a single DMU changes or all DMUs change simultaneously; that is, the DMU with the highest super-efficiency can serve as the benchmark [25], [33].

*D. Benchmarking Process of Coal-fired Power Plant's CPP*

On the basis of cleaner production benchmarking management and CPP evaluation, the benchmarking process of CPP for coal-fired power plants can be divided into two stages (Fig. 2).

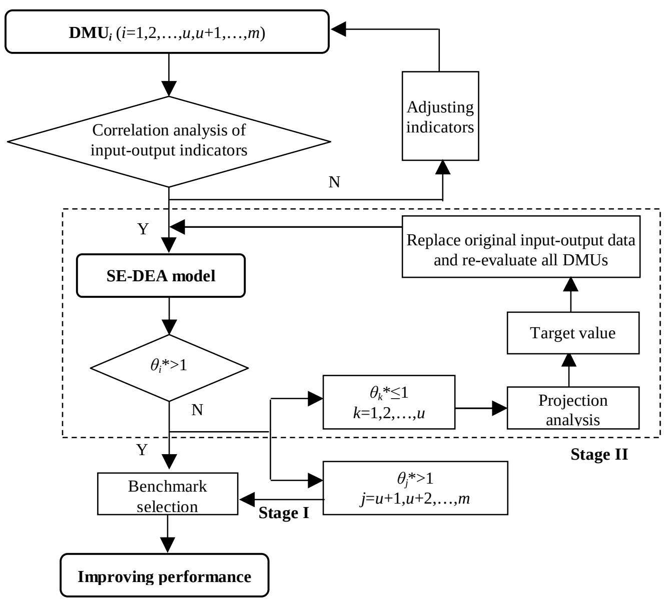


Fig. 2 Benchmarking process of cleaner production performance

Stage I: To carry out the correlation analysis of the original input-output data to test whether the input and output data meet the requirement of isotonicity; then the SE-DEA model in (1) will be used to evaluate the relative performance of all power plants DMU$_i$ ($i$ = 1,2, ..., $u$, $u$+1, ... m); and the super-efficiency value ($\theta_1^*$), input redundancy ($s_1^{-*}$), and output deficiency ($s_1^{+*}$) of each power plant can be figured out; the benchmark $B_1$ and the sensitivity $\gamma_1$ in Stage I can also be achieved. Then the target values of DEA-inefficient and/or weakly DEA-efficient DMUs ($j$=1,2,…,$u$) are calculated by projection analysis in (2).

Stage II: Suppose that the DEA-inefficient and/or weakly DEA-efficient DMUs adjusting their input-output data based on the projection analysis to improve their CPP, the original input-output data of corresponding DMUs may be replaced with the target values achieved in Stage I and this new data set will be evaluated by the SE-DEA model to get the new super-efficiency value ($\theta_2^*$), input redundancy ($s_2^{-*}$), and output deficiency ($s_2^{+*}$). Using the sensitivity analysis by (4) and (6), the final benchmark $B_2$ and the sensitivity $\gamma_2$ of Stage II can be determined.

## IV. Empirical Study

### A. Input-output Indicators

At present, the DEA method has been applied in many fields. As to application to the cleaner production assessment, the key is to introduce the inefficient output of pollutant into the DEA model. In measuring efficiency, the more output is usually the better, but the pollutant emission is just the opposite. Obviously, to treat the pollutant as the output indicator cannot meet the requirements of the model. From the perspective of cleaner production, pollutant emission, as a DMU of output, is an undesired output and it should be minimized. When the cleaner production assessment is carried out based on the output DMU of pollutants, neither CCR model nor SE-DEA model is available. Therefore, only when the pollutant emissions are considered as negative outputs or inputs, the calculation and evaluation can be operated by means of the DEA model [35], [36].

Combined with *The Cleaner Production Evaluation Index System for Thermal Power Industry* and *The Cleaner Production Standards – Coal-fired Power Plant* issued by NDRC and MEP of China, the input-output indicators for measuring the CPP of the coal-fired power plant is set up, considering the requirements of operating the SE-DEA model simultaneously.

Input indicators (per unit power generation): $x_1$, coal consumption; $x_2$, water consumption; $x_3$, energy consumption; $x_4$, flyash output volume; $x_5$, smoke dust emission volume; $x_6$, sulfur dioxide emissions; $x_7$, nitrogen dioxide emissions; $x_8$, wastewater emissions.

Output indicators: $y_1$ utilization rate of flyash; $y_2$, utilization rate of recycled water; $y_3$, total output value per unit power generation.

### B. Sample Data and Isotonicity of Input-output Indicators

Golany & Roll proposed the good rule of thumb for the number of DMUs in applying DEA model, namely, the number of DMUs should be at least twice the number of inputs and

TABLE I
SURVEY DATA OF 24 COAL-FIRED POWER PLANTS

| Power plant | Input indicators [a, b] | | | | | | | | Output indicators [a] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ | $x_6$ | $x_7$ | $x_8$ | $y_1$ | $y_2$ | $y_3$ |
| P01 | 815 | 563 | 0.184 | 3296 | 2.99 | 5.06 | 2.129 | 1550 | 0.886 | 0.849 | 0.823 |
| P02 | 514 | 723 | 0.154 | 6293 | 2.66 | 4.10 | 2.774 | 1830 | 0.643 | 0.745 | 0.734 |
| P03 | 416 | 441 | 0.086 | 2303 | 2.89 | 2.70 | 0.631 | 810 | 0.632 | 0.649 | 0.701 |
| P04 | 440 | 820 | 0.104 | 3527 | 1.95 | 2.94 | 0.611 | 820 | 0.631 | 0.750 | 0.598 |
| P05 | 729 | 850 | 0.172 | 7091 | 3.17 | 2.24 | 1.560 | 1130 | 0.837 | 0.823 | 0.668 |
| P06 | 404 | 800 | 0.108 | 2953 | 2.83 | 3.26 | 0.547 | 1330 | 0.568 | 0.650 | 0.621 |
| P07 | 616 | 912 | 0.199 | 8849 | 3.35 | 4.99 | 1.568 | 1680 | 0.772 | 0.785 | 0.711 |
| P08 | 533 | 494 | 0.135 | 7648 | 2.87 | 4.05 | 1.692 | 1780 | 0.651 | 0.620 | 0.655 |
| P09 | 711 | 776 | 0.178 | 7345 | 1.96 | 2.82 | 0.993 | 1230 | 0.729 | 0.699 | 0.801 |
| P10 | 854 | 903 | 0.184 | 2355 | 2.24 | 3.69 | 2.354 | 1645 | 0.898 | 0.800 | 0.794 |
| P11 | 568 | 874 | 0.099 | 7327 | 2.57 | 3.66 | 0.897 | 999 | 0.821 | 0.802 | 0.886 |
| P12 | 707 | 768 | 0.178 | 6684 | 3.99 | 4.99 | 2.205 | 1456 | 0.698 | 0.900 | 0.900 |
| P13 | 495 | 692 | 0.186 | 6503 | 2.32 | 3.51 | 1.367 | 1698 | 0.768 | 0.733 | 0.653 |
| P14 | 803 | 658 | 0.156 | 4897 | 1.98 | 4.35 | 2.094 | 1765 | 0.649 | 0.853 | 0.780 |
| P15 | 799 | 593 | 0.171 | 5635 | 3.23 | 3.29 | 1.779 | 1811 | 0.850 | 0.784 | 0.787 |
| P16 | 663 | 990 | 0.149 | 8735 | 3.17 | 4.45 | 0.999 | 1258 | 0.900 | 0.800 | 0.706 |
| P17 | 623 | 789 | 0.128 | 6742 | 2.76 | 2.87 | 1.643 | 1603 | 0.822 | 0.865 | 0.863 |
| P18 | 700 | 808 | 0.181 | 4963 | 2.12 | 3.35 | 2.680 | 1633 | 0.651 | 0.830 | 0.741 |
| P19 | 822 | 954 | 0.172 | 5005 | 2.68 | 4.21 | 2.011 | 1599 | 0.729 | 0.739 | 0.805 |
| P20 | 586 | 897 | 0.176 | 6120 | 2.54 | 4.25 | 1.782 | 1135 | 0.588 | 0.825 | 0.871 |
| P21 | 737 | 803 | 0.165 | 6563 | 2.32 | 3.17 | 2.020 | 1369 | 0.773 | 0.758 | 0.820 |
| P22 | 675 | 762 | 0.158 | 5869 | 2.16 | 3.88 | 1.886 | 1238 | 0.726 | 0.865 | 0.795 |
| P23 | 642 | 735 | 0.155 | 4937 | 2.21 | 2.96 | 1.835 | 1457 | 0.689 | 0.830 | 0.785 |
| P24 | 708 | 783 | 0.168 | 6097 | 2.49 | 4.12 | 1.692 | 1326 | 0.805 | 0.741 | 0.856 |

[a] The carbon dioxide emissions from the power generation can be estimated based on the coal consumptions and the thermal efficiency of the boiler. There is the coal consumption indicator ($x_1$) in the resource consumption indicators and both the carbon dioxide emission and coal consumption are treated as the input in the model operation, so it is unnecessary to consider the indicator of carbon dioxide emissions in the waste discharge.

[b] The evaluation in the SE-DEA model is dimensionless, so the unit of each indicator is omitted.

outputs considered [37]. There are 8 input indicators and 3 output indicators in measuring the CPP of the coal-fired power plant. Thus at least 22 DMUs should be involved in running the model. To satisfy this rule, this research investigated the power generation of 24 coal-fired power plants with similar technology and scale. The survey data based on the input-output indicators and the requirements of SE-DEA model is listed in Table I.

DEA model requires that the DMUs be homogeneous with comparability and the input-output indicators meet the requirement of isotonicity, namely, the output will not decrease along with the increase of input [38]. This can be tested by correlation analysis of the input-output data. It should be noted that this paper does not use the indicator of "flyash discharge per unit power generation" because it cannot satisfy the requirement of isotonicity. The correlation analysis result of the input-output indicators of 24 power plants is listed in Table II, from which we can see that the input-output indicators are positive related, indicating that the input-output indicators in this research meets the requirement of isotonicity and reflects the input-output relationship of implementing cleaner production of coal-fired power plants.

### C. Evaluation of the Original Data

The original data in Table I is calculated with EMS software and the result is listed in Table III. The result shows the CPP of 16 plants is DEA-efficient and that of the rest 8 plants is relatively inefficient with input redundancy and output deficiency. The super-efficiencies of the 24 power plants are achieved and P03 is with the biggest super-efficiency and sensitivity.

### D. Projection Analysis

The purpose of benchmarking CPP is to adjust and optimize relevant indicators of inefficient or weakly efficient DMUs so that the performance of coal-fired power plants can be improved. By operating (1) with super-efficiency values (Table III) and input-output slacks (Table IV), the projected values of 8 DEA-inefficient power plants can be figured out by (2), and these 8 power plants may improve the power generation process and input-output data based on the target values (Table V).

### E. Benchmark Selection

According to the benchmarking process in the context, the original input-output data of the 8 DEA-inefficient power plants is replaced by the target values in Table V. The SE-DEA model in (1) is applied again to gain the measuring result of CPP of improved coal-fired power plants (Table VI). It can be seen that the CPP of all power plants are DEA-efficient. In the second stage, the super-efficiency and sensitivity of P10 are bigger than those of any other plant, that is, the final benchmark is no longer plant P03 but P10.

## V. Conclusion

The benchmark selection of CPP for the coal-fired plant can be divided into two stages. In the first stage, the CPP assessment of the original data of all power plants and the projection

TABLE II
CORRELATION COEFFICIENTS OF INPUT-OUTPUT INDICATORS

| | $y_1$ | $y_2$ | $y_3$ |
|---|---|---|---|
| $x_1$ | 0.5802 | 0.5327 | 0.5437 |
| $x_2$ | 0.2203 | 0.3205 | 0.1582 |
| $x_3$ | 0.3401 | 0.3957 | 0.2693 |
| $x_4$ | 0.2463 | 0.1308 | 0.1434 |
| $x_5$ | 0.2399 | 0.1074 | 0.0824 |
| $x_6$ | 0.0988 | 0.2786 | 0.3117 |
| $x_7$ | 0.0994 | 0.4828 | 0.4079 |
| $x_8$ | 0.1450 | 0.1146 | 0.0692 |

TABLE III
EVALUATION RESULT OF CPP OF 24 COAL-FIRED POWER PLANTS (STAGE I)

| Power plant | DEA-efficient | $\gamma_1$ | $\gamma_1$* | SE-DEA efficiency | Rank |
|---|---|---|---|---|---|
| P01 | Y | 0.0826 | 0.0414 | 1.1801 | 6 |
| P02 | N | – | – | 0.9508 | 20 |
| P03 | Y | 0.2381 | 0.1208 | 1.6249 | 1 |
| P04 | Y | 0.1680 | 0.0846 | 1.4039 | 3 |
| P05 | Y | 0.1513 | 0.0761 | 1.3565 | 4 |
| P06 | Y | 0.0351 | 0.0175 | 1.0727 | 13 |
| P07 | N | – | – | 0.8242 | 24 |
| P08 | N | – | – | 0.9135 | 21 |
| P09 | Y | 0.0778 | 0.0390 | 1.1687 | 7 |
| P10 | Y | 0.1718 | 0.0865 | 1.4148 | 2 |
| P11 | Y | 0.1153 | 0.0578 | 1.2606 | 5 |
| P12 | N | – | – | 0.8694 | 22 |
| P13 | Y | 0.0461 | 0.0230 | 1.0966 | 10 |
| P14 | Y | 0.0569 | 0.0285 | 1.1207 | 9 |
| P15 | Y | 0.0418 | 0.0209 | 1.0873 | 11 |
| P16 | N | – | – | 0.9516 | 19 |
| P17 | Y | 0.0622 | 0.0311 | 1.1327 | 8 |
| P18 | Y | 0.0005 | 0.0003 | 1.0011 | 16 |
| P19 | N | – | – | 0.8630 | 23 |
| P20 | Y | 0.0125 | 0.0063 | 1.0254 | 15 |
| P21 | N | – | – | 0.9743 | 18 |
| P22 | Y | 0.0347 | 0.0173 | 1.0718 | 14 |
| P23 | Y | 0.0362 | 0.0181 | 1.0752 | 12 |
| P24 | N | – | – | 0.9961 | 17 |

TABLE VI
EVALUATION RESULT OF CPP OF 24 COAL-FIRED POWER PLANTS (STAGE II)

| Power plant | DEA-efficient | $\gamma_2$ | $\gamma_2$* | SE-DEA efficiency | Rank |
|---|---|---|---|---|---|
| P01 | Y | 0.0653 | 0.0327 | 1.1398 | 6 |
| P02 | Y | 0.0000 | 0.0000 | 1.0001 | 23 |
| P03 | Y | 0.1496 | 0.0752 | 1.3517 | 3 |
| P04 | Y | 0.1314 | 0.0660 | 1.3026 | 4 |
| P05 | Y | 0.1513 | 0.0761 | 1.3565 | 2 |
| P06 | Y | 0.0351 | 0.0175 | 1.0727 | 13 |
| P07 | Y | 0.0018 | 0.0009 | 1.0037 | 16 |
| P08 | Y | 0.0008 | 0.0004 | 1.0017 | 19 |
| P09 | Y | 0.0666 | 0.0333 | 1.1427 | 5 |
| P10 | Y | 0.1718 | 0.0865 | 1.4148 | 1 |
| P11 | Y | 0.0636 | 0.0318 | 1.1359 | 7 |
| P12 | Y | 0.0011 | 0.0006 | 1.0023 | 17 |
| P13 | Y | 0.0412 | 0.0206 | 1.0859 | 11 |
| P14 | Y | 0.0569 | 0.0285 | 1.1207 | 9 |
| P15 | Y | 0.0418 | 0.0209 | 1.0873 | 10 |
| P16 | Y | 0.0009 | 0.0004 | 1.0018 | 18 |
| P17 | Y | 0.0622 | 0.0311 | 1.1327 | 8 |
| P18 | Y | 0.0005 | 0.0003 | 1.0011 | 20 |
| P19 | Y | 0.0003 | 0.0002 | 1.0007 | 21 |
| P20 | Y | 0.0125 | 0.0063 | 1.0254 | 15 |
| P21 | Y | 0.0000 | 0.0000 | 1.0001 | 24 |
| P22 | Y | 0.0341 | 0.0171 | 1.0706 | 14 |
| P23 | Y | 0.0362 | 0.0181 | 1.0752 | 12 |
| P24 | Y | 0.0002 | 0.0001 | 1.0004 | 22 |

TABLE IV
INPUT-OUTPUT REDUNDANCY OF 8 DEA-INEFFICIENT POWER PLANTS

| Power plant | Input redundancy | | | | | | | | Output deficiency | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $s_1^-$ | $s_2^-$ | $s_3^-$ | $s_4^-$ | $s_5^-$ | $s_6^-$ | $s_7^-$ | $s_8^-$ | $s_1^+$ | $s_2^+$ | $s_3^+$ |
| P02 | 0 | 0 | 0.040 | 1822 | 0.00 | 0.75 | 1.830 | 830 | 0.050 | 0.000 | 0.000 |
| P07 | 0 | 63 | 0.020 | 2415 | 0.00 | 0.65 | 0.230 | 41 | 0.000 | 0.000 | 0.030 |
| P08 | 0 | 0 | 0.010 | 4334 | 0.00 | 0.58 | 0.540 | 635 | 0.000 | 0.030 | 0.010 |
| P12 | 0 | 0 | 0.020 | 1732 | 0.00 | 0.51 | 0.710 | 93 | 0.140 | 0.000 | 0.030 |
| P16 | 12 | 0 | 0.020 | 1549 | 0.00 | 0.22 | 0.000 | 80 | 0.000 | 0.120 | 0.250 |
| P19 | 0 | 0 | 0.000 | 0 | 0.00 | 0.05 | 0.000 | 0 | 0.070 | 0.050 | 0.000 |
| P21 | 22 | 0 | 0.000 | 0 | 0.00 | 0.00 | 0.680 | 0 | 0.000 | 0.000 | 0.000 |
| P24 | 0 | 0 | 0.020 | 0 | 0.00 | 0.24 | 0.290 | 0 | 0.000 | 0.070 | 0.000 |

TABLE V
INPUT-OUTPUT TARGET VALUES OF 8 DEA-INEFFICIENT POWER PLANTS

| Power plant | Target input | | | | | | | | Target output | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $x_1$ | $x_2$ | $x_1$ | $x_2$ | $x_1$ | $x_2$ | $x_1$ | $x_2$ | $x_1$ | $x_2$ | $x_1$ |
| P02 | 489 | 687 | 0.106 | 4161 | 2.53 | 3.15 | 0.808 | 910 | 0.693 | 0.745 | 0.734 |
| P07 | 508 | 689 | 0.144 | 4879 | 2.76 | 3.46 | 1.062 | 1344 | 0.772 | 0.785 | 0.741 |
| P08 | 487 | 451 | 0.113 | 2653 | 2.62 | 3.12 | 1.006 | 991 | 0.651 | 0.650 | 0.665 |
| P12 | 615 | 668 | 0.135 | 4079 | 3.47 | 3.83 | 1.207 | 1173 | 0.838 | 0.900 | 0.930 |
| P16 | 619 | 942 | 0.122 | 6764 | 3.02 | 4.01 | 0.951 | 1117 | 0.900 | 0.920 | 0.956 |
| P19 | 709 | 823 | 0.148 | 4319 | 2.31 | 3.58 | 1.735 | 1380 | 0.799 | 0.789 | 0.805 |
| P21 | 696 | 782 | 0.161 | 6394 | 2.26 | 3.09 | 1.288 | 1334 | 0.773 | 0.758 | 0.820 |
| P24 | 705 | 780 | 0.147 | 6073 | 2.48 | 3.86 | 1.395 | 1321 | 0.805 | 0.811 | 0.856 |

analysis for the DEA-inefficient DMUs are conducted to get the target input-output values, and the benchmark $B_1$ in the first stage is achieved simultaneously. The DEA-inefficient plants may adjust their input-output data according to the projected values. In the second stage, the CPP of the DEA-efficient plants and the improved DEA-inefficient DMUs will be evaluated again. All power plants will be DEA-efficient and the benchmark $B_2$ in the second stage (final benchmark) can be acquired. $B_2$ is different from $B_1$ because $B_2$ is obtained under the premise that all DMUs are DEA-efficient. In the first stage, $\text{DMU}_{B1}$ is DEA-efficient and its input-output data does not change during the second stage; in the second stage, both $\text{DMU}_{B1}$ and $\text{DMU}_{B2}$ are DEA-efficient, but the super-efficiency of $B_2$ is bigger than that of $B_1$. In fact, the $B_1$ and $B_2$ can be regarded as “to select the best in the bad or in the good”. The second stage can be considered as a re-benchmarking process. Therefore, $B_2$ is a more appropriate benchmark and we can put the two stages above into practice and improve the CPP of coal-fired power plants.

The above analysis shows that the CPP of coal-fired power plants can be measured, benchmarked, ranked, and improved through the SE-DEA model. An empirical study of 24 coal-fired power plants gives the fact that the efficiency benchmark will probably change. The benchmark $B_1$ achieved in the first stage may be not the best choice and the benchmark $B_2$ got in the second stage is better than $B_1$. To select $B_2$ as a benchmark will be more conducive to improve the CPP.

It should be noted that the benchmarking based on SE-DEA model is a relative measuring method. In the process of implementing cleaner production and in the course of valuing and improving CPP of coal-fired power plants, the national or industrial standard methods should also be used to assess the developing level of cleaner production. Only to combine the relative assessment with the absolute evaluation can continuously improve the CPP in the coal-fired power industry, and can the benchmarking of CPP guide the power generation and the emission reduction.

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