Thermal Power Plant Environmental Performance Evaluation Based on Data Envelopment Analysis

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Abstract. Enterprise environmental performance refers to the results of environmental protection and environmental pollution control in the company's business activities. The evaluation of enterprise environmental performance is one of the core issues of enterprise management. The relationship between the resource consumption of an enterprise and the environmental protection data and environmental performance assessment results is complex and difficult to describe using a linear model. Based on the data envelopment analysis method, the case study of domestic thermal power plant environmental protection information was conducted to build an environmental performance evaluation model, and through an analysis, weak points in the decision-making unit for poor environmental performance were identified. Through sensitivity analysis, the specific influences of various input and output variables in the decision-making unit are obtained, and the work focus for the environmental performance management of different decision-making units is found. The data envelopment analysis method provides a means for evaluating and improving environmental performance of thermal power plant enterprises.

1. Introduction

The rapid economic development has brought a tremendous impact on the environment, and it has threatened the survival and development of mankind seriously. China's energy consumption is dominated by coal, and thermal power is the main power source in China. There are more than 1,300 coal-fired power plants in China. In 2016, the annual power generation amounted to 61,424.90 billion kWh, of which thermal power generation amounted to 447.370 trillion kWh, accounting for 72.2% of the total generation. Coal-fired thermal power, a traditional high-energy-consuming and highly-polluting industry, needs transformation and upgrading in order to ease environmental damage and ensure national energy security. The thermal power unit mainly adopts the methods of cogeneration, ultra-low emission reform, and energy-saving transformation to improve energy efficiency and reduce pollutant emissions. To ensure the sustainable development and development of thermal power companies, implementing environmental performance evaluations on thermal power companies is an important measure to urge them to strengthen environmental protection and perfect their environmental responsibility systems.

Domestic and foreign scholars' research on environmental performance evaluation of coal-fired thermal power companies includes index system establishment and fuzzy matrix assessment[1-5]. However, these research methods will be affected by human factors and therefore lack a certain degree
of objectivity and science. At the same time, with the continuous development of thermal power companies, their evaluation indicators are increasingly complex. Traditional evaluation methods cannot play their role in the case of multiple inputs and multiple outputs and no uniform standards for evaluation indicators. Therefore, scholars began to quote the data envelopment analysis method (DEA) to evaluate the effectiveness of the same type of departments with multi-indicator inputs and multi-indicator outputs. Data Envelopment Analysis also has the advantages of not having to assume a functional relationship between inputs and outputs, not having to determine weights, and not affecting the efficiency value due to different units of measure.

The relationship between resource consumption and emission parameters of thermal power plants and environmental performance assessment results is complex, and difficulty using linear models to describe. This paper is based on the data envelopment analysis and takes the environmental protection information about 11 thermal power companies as an example to discuss the evaluation methods of environmental performance and the ways to improve.

2. Data envelopment analysis method

Data Envelopment Analysis (DEA) is a new area of cross-disciplinary research in operation research, management science, and mathematical economics. It is based on a number of input indicators and a number of output indicators, using linear programming methods, evaluating the relative validity of comparable units of the same type. The DEA method has been widely used in different industries and departments since 1978 by the famous American operations researcher Charnes and Cooper, and it has achieved great results in dealing with multi-input and multi-indicator output. The advantage of this method is that there is no need to estimate the parameters in advance, nor does it need to determine the functional relationship of the input and output factors in advance. Using the projection theorem of the DEA method can put forward improvement methods for the evaluation object.

The DEA method can use mathematical programming models to evaluate the relative efficiency of different decision units (DMU) which have multiple input and output variables, and judge their effectiveness based on the relative efficiency of each decision unit. Suppose there are n departments or units engaged in the same production activity, that is, a decision unit DMU. Each decision unit has m types of inputs (indicating that the DMU resources consumes, similar to production factors) and s types of outputs (refers to the indicator of effectiveness of the DMU after it has consumed resources, such as economic efficiency, product quality, etc.). For the efficient evaluation index of the decision unit DMUj (1≤j≤n):

$$h_j = \frac{U^T Y_j}{V^T X_j} = \frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}}$$

(1)

In the formula: $h_j$ is the efficiency evaluation index of the decision making unit; $X_j$ is the input vector of the $j$th column; $Y_j$ is the output vector of the $j$th column; $x_{ij}$ is the input variable of row $i$ and column $j$; $y_{rj}$ is the output variable of row $r$ and column $j$; $u_r$ is the weight of the output variable $y_{rj}$ in the $r$th row and $j$th column; $v_i$ is the weight of the input variable $x_{ij}$ of row $i$ and column $j$; V is a weight vector of m inputs; U is the weight vector of s outputs.

In formula (1), the molecular represents the sum of the output factors, and the denominator represents the sum of the input factors. The larger $h_j$ indicates that the DMU is able to use relatively less input to get relatively more output, which is higher efficiency. With the goal of maximizing the efficiency evaluation index $h_j$ of the decision unit and constraining the evaluation index of all decision-making units less than 1 to construct C2R Data Envelopment Analysis Model. Using the Charnes-Cooper transformation to transform it into an equivalent linear programming model, while introducing non-Archimedean infinitesimal $\varepsilon$, we get the following equation:

$$V(\varepsilon) = \min[\theta(\varepsilon^T s^* + \varepsilon^T S^*)]$$
In the formula: $x_0, y_0$ is the input and output vector of $a$ to be evaluated DMU $j_0$; $\varepsilon$ is non-Archimedean infinite small quantity, greater than 0 and less than any positive number, generally take $10^{-10}$; $s^-$ and $s^+$ are slack variables for input and output; $\theta$ is the effective value of DMU $j_0$; $e^T_1 = (1, 1, \cdots, 1)_{1 \times n}, e^T_2 = (1, 1, \cdots, 1)_{1 \times n}$.

Equation (2) can be used to determine the validity of a DMU $j_0$: If $\theta = 1$, and $s^- = 0$, $s^+ = 0$, the DMU $j_0$ to be evaluated is valid for the DEA with respect to other decision units. If $\theta = 1$, but at least one slack variable is not 0, the DMU $j_0$ to be evaluated is weakly valid for DEA. If $\theta < 1$, the DMU $j_0$ is non-DEA valid.

3. Thermal Power Enterprise Environmental Performance Data Envelope Analysis Case

In this paper, the environmental performance of some thermal power enterprises is taken as an example. Five indicators, water consumption of per unit power generation (kg/kWh), coal consumption of per unit power generation (kg/kWh), solid waste utilization, power generation of per unit SO2 emission and NOX emission, are used as input parameters for environmental performance evaluation\cite{8,9}. Environmental verification data of 11 coal-fired power enterprises are shown in Table 1.

| Enterprise | Unit water consumption (kg/kWh) | Unit coal consumption (kg/kWh) | Solid waste utilization (%) | Power generation of per unit SO2 emission (kWh/g) | Power generation of per unit NOX emission (kWh/g) |
|------------|--------------------------------|-------------------------------|----------------------------|-----------------------------------------------|-----------------------------------------------|
| Enterprise A | 0.32                           | 0.47                          | 96                         | 1.92                                          | 4.76                                          |
| Enterprise B | 0.21                           | 0.29                          | 95                         | 1.19                                          | 3.12                                          |
| Enterprise C | 0.39                           | 0.40                          | 90                         | 0.53                                          | 1.23                                          |
| Enterprise D | 0.25                           | 0.36                          | 86                         | 1.19                                          | 1.43                                          |
| Enterprise E | 0.29                           | 0.40                          | 46                         | 1.14                                          | 1.41                                          |
| Enterprise F | 0.31                           | 0.39                          | 38                         | 0.78                                          | 1.12                                          |
| Enterprise G | 0.24                           | 0.29                          | 52                         | 2.50                                          | 3.57                                          |
| Enterprise H | 0.28                           | 0.61                          | 63                         | 0.99                                          | 0.94                                          |
| Enterprise I | 0.43                           | 0.39                          | 35                         | 0.39                                          | 0.62                                          |
| Enterprise J | 0.32                           | 0.38                          | 72                         | 0.29                                          | 1.96                                          |
| Enterprise K | 0.26                           | 0.38                          | 92                         | 1.47                                          | 3.22                                          |
3.1. Analysis of Environmental Performance Value

Horizontal evaluation of environmental performance of 11 thermal power enterprises based on data envelopment analysis. We obtained the environmental performance efficiency evaluation index \( h \) of 11 enterprises, as shown in Table 2.

Table 2. Enterprise Environmental Performance Evaluation Index.

| Efficiency | Efficiency | Efficiency |
|------------|------------|------------|
| Enterprise A | 1.0000 | Enterprise E | 0.4813 |
| Enterprise B | 1.0000 | Enterprise F | 0.3530 |
| Enterprise C | 0.6868 | Enterprise G | 1.0000 |
| Enterprise D | 0.7909 | Enterprise H | 0.5458 |

From the above mathematical model, we can see that the efficiency evaluation index of A power plant, B power plant and G power plant is 1, indicating that these enterprises are at least weak valid for DEA. That is, these enterprises operate well in their energy use and exhaust emissions, and their environmental performance levels are basically in an optimal state. Although the K power plant is not at valid state for DEA, its score is close to 1, and its environmental performance is acceptable. Other companies have relatively low environmental performance score, indicating that their energy use efficiency is not high and waste emissions are too large. The number of such enterprises accounted for 64%, more than half\(^{10,11}\).

3.2. Projection Value Analysis

Using the DEA method and using the formula (2) for further analysis, the validity of the weak DMU can be judged. At the same time, the reasons for the non-valid of the other DMUs can be analyzed, and the adjustment methods of each index can be obtained, as shown in Table 3.

Table 3. Program Operation Results.

| \( S_1^- \) | \( S_2^- \) | \( S_1^+ \) | \( S_2^+ \) | \( S_3^+ \) |
|------------|------------|------------|------------|------------|
| Enterprise A | 0.0000 | 0.0408 | 28.0004 | 0.2747 | 0.0000 |
| Enterprise B | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Enterprise C | 0.0689 | 0.0000 | 0.0000 | 0.0000 | 1.7260 |
| Enterprise D | 0.0000 | 0.0142 | 0.0000 | 0.0000 | 1.5139 |
| Enterprise E | 0.0000 | 0.0123 | 0.0000 | 0.0000 | 0.6684 |
| Enterprise F | 0.0048 | 0.0000 | 0.0000 | 0.0000 | 0.4335 |
| Enterprise G | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Enterprise H | 0.0000 | 0.1264 | 0.0000 | 0.0000 | 1.3310 |
| Enterprise I | 0.0404 | 0.0000 | 0.0480 | 0.5302 |
| Enterprise J | 0.0259 | 0.0000 | 0.6116 | 0.4076 |
| Enterprise K | 0.0000 | 0.0252 | 0.0000 | 0.1204 |

According to the calculation results in Table 3, the values of \( s^- \) and \( s^+ \) in both the B and G enterprise are zero. It can be seen that the two decision units together constitute the envelope front of the environmental performance assessment of thermal power plants. Other decision units are relatively inefficient and need further management and reengineering.

Among the enterprises that need to adjust inputs, the C power plant has to control the unit water consumption, and it needs to be reduced by 17.6% on the original basis. The I power plant also needs to reduce the water consumption by 9.4% in this respect. The K power plant needs to reduce the unit coal consumption from 0.61kg/kWh to 0.49kg/kWh. For output aspects, power plant C, power plant D, and power plant H have greater space for improvement in power generation of per unit NO\(_x\) emission, and the power plant C can also make a 200% increase in power generation of per unit SO\(_2\) emission.

3.3. Sensitivity Analysis

The environmental performance data analysis model gives the mapping relationship between unit water consumption, unit coal consumption, solid waste utilization rate, power generation of per unit
SO₂ emission and NOₓ emission, and environmental performance. Using this model can guide companies how to improve environmental protection parameters so that make the company's environmental performance meet the qualified standard.

Sensitivity indicates the effect of an increase or decrease in input or output variables on the evaluation index. The greater the slope of the sensitivity plot, the greater the influence of this parameter on the evaluation index value. Taking power plant I which has poor environmental performance assessment as an example, keeping other production parameters unchanged, the relationship between power generation of per unit SO₂ emission, power generation of per unit NOₓ emission, solid waste utilization and environmental performance is shown in Figure 1. With other parameters unchanged, when the power generation of per unit SO₂ emission is increased from 0.6kWh/g to 2.2kWh/g, the environmental performance level can be increased from 30% to 65%. Similar economic explanations can also be made for the power generation of per unit NOₓ emission and solid waste utilization.

Figure 1. Relationship between environmental protection parameters and environmental performance.

Through the case study, we obtained the environmental performance of the above 11 enterprises: The A, B, and G enterprises have the best environmental performance. The I, F, and E enterprises perform poorly, and the remaining enterprises perform generally. Among them, the C enterprise, I enterprise, and K enterprise should focus on the analysis of resource utilization and increase the efficiency of resource utilization. C enterprise, D enterprise, and H enterprise need to control the current level of pollution and strengthen the regulation of industrial waste discharge.

4. Conclusion

Taking the thermal power enterprise environmental information as a case, this paper comprehensively considers the input of the company's water resources and coal resources, selects a series of input and output indicators, and uses data envelopment analysis methods to quantitatively analyze the environmental performance of the 11 coal companies. Overall efficiency analysis and assessment were conducted.

The article finds weak points in decision-making units with poor environmental performance through projection value analysis. Through sensitivity analysis, the specific influence of various input and output variable factors on the decision-making unit is tapped, and the focus of work for the environmental performance management of different decision-making units is found. Through percentage analysis, find out the key improvement indicators in the relatively ineffective enterprises.

From the analysis results, most of the low-efficiency thermal power companies have the phenomenon that the input amount cannot be effectively converted into output. At the same time, the company's waste emissions are really large, and only a small part of the company's environmental performance level is in an optimal state. In the 21st century when the world changes rapidly, thermal power companies should pay more attention to environmental protection, improve the level of environmental performance, and ensure the prosperity and development of enterprises.

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