Research on Green Efficiency Estimation of Power Plants of National Key Monitoring Enterprises

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Abstract. This paper mainly estimates the green technology efficiency of thermal power plants of national key monitoring power generation enterprises. By taking the use of "Database of China's Industrial Enterprises" and "Compilation of Statistics of China's Power Industry", we sort out the input, output and emission data of national key monitoring enterprises. With the help of directional distance function and the panel stochastic frontier analysis (SFA), we can define and estimate a new indicator for the emission efficiency of power generation plants. The main contribution is the method of efficiency calculation, which can be broadly used for testing the level of emission technology of power generation plants.

1. Introduction

In the process of environmental governance, thermal power companies have always played an important role of emission reduction. Chinese thermal power generation accounts for a high proportion of electricity generation. Since the electricity market reformed in 2002, the installed capacity of thermal power has maintained a high proportion of power generation. Recently, The proportion of thermal power generation has declined due to environmental issues and highly development of renewable energy technology, though thermal power generation is still the main type of generation modes. The coal-based and gas-based power generation technology makes thermal power companies gradually become the main source of pollutants such as sulfur dioxide, nitrogen oxides and soot. The rapid development of thermal power generation has induced serious environmental problems. Therefore, thermal power companies must consider the impact on the environment while pursuing economic benefits. When China is dealing with environmental problems, thermal power, iron and steel, and mining are key target industries for gaseous pollutants. From the perspective of emission reduction technologies, shutting down high-polluting thermal power units and promoting the emission reduction technology of thermal power units are two different paths, which all have been implemented to reduce thermal power emissions.

Before the "Eleventh Five-Years Plan", China's environmental regulations adopted the central-level Ministry of Environmental Protection to formulate policies to stipulate the total emissions, which were implemented by the local environmental administrative departments, but the effect of the implementation process was not satisfactory. After the "Eleventh Five-Year Plan", China issued a list of national key monitoring companies. Based on corporate pollution information, it focused on monitoring industrial companies with large emissions (Zhang et al., 2018)[6]. During the "Thirteenth Five-Year Plan", they achieved greater results. This policy has achieved remarkable results in environmental regulation under the supervision of the central government. Therefore, this article conducts green technology efficiency calculations for the companies on the list of national key monitoring companies, and tries to find the root cause of thermal power companies’ emission
reductions, whether through the improvement of thermal power companies’ green technology efficiency, or by shutting down backward units to achieve emission reduction under national supervision aims.

2. Data
The data in this article comes from the "Database of China's Industrial Enterprises" and "Compilation of Statistics of China's Power Industry" from 2009 to 2012. The combined data includes unbalanced panel data of Chinese coal power generation companies above a certain scale. The "Database of China's Industrial Enterprises" includes information such as company organization code, company ownership, company location, fixed capital stock and average number of employees. In the "Statistical Data Collection of China's Electric Power Industry", variables such as coal-fired power plant power generation and physical energy input, standard coal consumption for power generation, power generation hours, and installed capacity are selected. The list of key state-monitored enterprises comes from documents published by the Ministry of Ecology and Environment of the People's Republic of China. The list includes enterprise area codes, legal person codes and company names.

Since the article calculates the technical efficiency of enterprises considering pollutant emissions, the key national monitoring enterprises mainly regulate sulfur dioxide, nitrogen oxides and exhaust gas. This article uses environmental emission coefficients to estimate the sulfur dioxide emissions of thermal power enterprises. For the emission coefficient, refer to the "Manual of Pollutant General Survey Production and Emission Coefficients", first look up the required industry code, secondly determine the emission coefficient according to the relevant product name, raw material name, production process, and production scale, and finally determine the emission coefficient according to the end treatment technology.

The sorted data is described in Table 1. k is the capital investment of coal-fired power plants, which is converted according to the fixed investment price index of each province, l is the annual average number of employees employed, and e is the coal consumption of the enterprise, converted according to the standard published by the Statistics Bureau For standard coal, y is the company’s power generation and b is the sulfur dioxide emissions. All data are processed by logarithm. This paper deletes the enterprises whose capital input, the number of employees is too small, coal consumption, power generation, and pollution emissions are zero, and the extreme values outside 0.5% and 99.5% are removed. The final observation value is 1693.

|       | mean    | std     | median  | min     | max     |
|-------|---------|---------|---------|---------|---------|
| k/thousand Yuan | 14514.54 | 19186.46 | 7239.56 | 24.60   | 193154.30 |
| l/person       | 724.50  | 0.99    | 6.09    | 3.30    | 8.40    |
| e/thousand ton | 1541.88 | 1781.07 | 992.50  | 0.06    | 15700.00 |
| y/MWh          | 27.27   | 4.09    | 28.56   | 9.01    | 34.29   |
| b/ton          | 25563.46| 29815.60| 16400.00| 0.63    | 265000.00|

3. Method
This paper chooses to consider sulfur dioxide as a directional distance function of undesirable output to measure the efficiency of green technology. First, we need to explain the directional distance function. Fare et al. (1989)[1] introduced undesirable output into the directional distance function, and used non-parametric methods to estimate the technical efficiency of undesirable output. Fare et al. (2005)[2] extended the application of the direction distance function and introduced a method of parameter estimation to the direction distance function. Next, according to Fare et al. (2005)[2] and Wei et al. (2013)[3], the method of using the direction distance function to estimate the efficiency of green technology is introduced.
For the input factor \( x \in \mathbb{R}^N_+ \), it means that there are \( N \) kinds of non-negative inputs, and the output is divided into desirable output and undesirable output. When studying coal-fired power plants, it refers to power generation and sulfur dioxide emissions are represented by \( y \in \mathbb{R}^M_+ \) and \( b \in \mathbb{R}^L_+ \), and the production function of the enterprise can be expressed as equation (1).

\[
P(x) = \{(y, b) : x \in \mathbb{R}^N_+ \text{ can produce } (y, b) \in \mathbb{R}^M_+ \times \mathbb{R}^L_+ \}
\]  

(1)

After the production function is determined, the direction distance function of the desired output and the undesirable output is shown in Figure 1. Assuming that point A represents the actual production situation of the company, the vertical axis is the desired output \( y \), here refers to the power generation, and the horizontal axis is the undesirable output \( b \), here refers to the sulfur dioxide emissions, and the company can extend to the production possibility boundary point B in the direction of the \( g \) vector on. The distance between point A and point B represents the distance from point A to point B of a possible efficient production company. Then the distance can be considered as the green technology inefficiency value of point A. The distance is expressed as equation (2).

\[
D_0(x, y, b; g_y, g_b) = \max \{B : (y + \beta g_y, b - \beta g_b) \in P(x)\}
\]  

(2)

The distance can be expressed by the maximized \( \beta^* \), \( \beta^* = D_0(x, y, b; g_y, -g_b) \), so \( \beta^* \) describes the company’s green technology inefficiency value, and the estimation of green technology efficiency is based on the above theoretical basis.

Figure 1. direction distance function.

Using parameters to estimate the direction distance function requires the use of the conversion properties of the function. The nature of this conversion means that the company produces more normal products of \( \alpha g_y \) and less abnormal products of \( \alpha g_b \). After extending the distance of \( \alpha \) in the direction of \( (g_y, -g_b) \), the company’s green technology has no The efficiency corresponds to a decrease in \( \alpha \) as equation (3).

\[
D_0(x, y + \alpha g_y, b - \alpha g_b; g_y, -g_b) = D_0(x, y, b; g_y, -g_b) - \alpha
\]  

(3)

According to the previous description, the directional distance \( D_0(x, y, b; g_y, -g_b) \) represents the inefficiency of green technology, so according to the SFA’s treatment of technical inefficiency, the following formula can be obtained. \( D_0(x, y, b; g_y, -g_b) + \varepsilon = 0 \), among them, \( \varepsilon = v - \mu \) represents the sum of technical inefficiency terms and random errors. Usually, \( g = (1, -1) \) of the distance function in the given direction is substituted into the previous conversion properties. Finally available \( \alpha = D_0(x, y + \alpha, b - \alpha; 1, -1) + v - \mu \). Let \( \alpha = b \), there are \( -b = D_0(x, y - b, 0; 1, -1) + v - \mu \) . Suppose there are \( k = 1, 2, ..., K \) enterprises, in \( t = 1, 2, ..., T \) periods, we use capital, labor and energy three inputs \( x_i \), \( i = 1, 2, 3 \), electricity generation \( y \) and sulfur dioxide \( b \) two desirable and undesirable output, the direction distance function can be assumed to be a quadratic form, and the estimation equation is as equation (4).

\[
-b_{kt} = a_0 + \sum_{n=1}^{3} \alpha_n x_{nkt} + \beta_1 y_{kt} + \beta_2 b_{kt} + \frac{1}{2} \sum_{n=1}^{3} \sum_{n'=1}^{3} \alpha_{nn'}x_{nkt}x_{n'kt} + \frac{1}{2} \beta_3 y_{kt}^2 + \frac{1}{2} \beta_4 b_{kt}^2 +
\]
\[ \sum_{t=1}^{n} y_t x_{nkt} y_{kt} + \sum_{m=1}^{3} \theta_n x_{nkt} b_{kt} + \theta y_k b_{kt} + v_{it} - \mu_t \]  

For the estimation of the direction distance function, most of the current papers are mainly stochastic frontier analysis and data envelopment analysis. In the choice of the two methods, most papers choose data envelopment analysis (DEA). In addition to DEA, stochastic frontier analysis (SFA) is gradually being used in environmental assessment. Aigner et al. (1977)[4] and Meeusen and Broeck (1977)[5] jointly proposed the SFA method, which uses parameters to estimate the production function or the frontier of the cost function, and decomposes the error term into technical inefficiency terms and random variables. After basic SFA model, more sophisticated model, the panel SFA (Cornwell, 1990)[8] and directional distance functional SFA (Atkinson and Tsionas, 2016)[9] are proposed and applied. The efficiency term is always negative, and the technical inefficiency term in the cost function estimation is always positive. Compared with DEA, SFA uses parameter estimation. The disadvantage is that the technical inefficiency items need to choose distributions, such as semi-normal distribution, exponential distribution, censored normal distribution, and Gamma distribution. However, Meesters (2014)[10] also pointed out that the semi-normal distribution, The inefficiencies estimated by the exponential distribution and the censored normal distribution will be covered by the results of the censored normal distribution. In terms of application, Wei et al. (2013)[3] applied the SFA estimation method to the directional distance function considering emissions to calculate the shadow price of carbon emissions of Chinese thermal power companies. The SFA model considers the influence of random errors, and the use of parameter estimation can be used for testing. In this paper, based on the extreme value of the micro data itself, the panel stochastic frontier model is selected to measure the efficiency of green technology.

4. results and discussion

This paper mainly measures the green technology efficiency of thermal power companies. Thermal power companies cannot ignore the individual heterogeneity. Therefore, this paper adopts the panel SFA model of inefficiency over time for analysis, comprehensively considering environmental emissions, referring to Wei et al. (2013)[3] and Deng (2018)[7] on the use of direction distance function in SFA.

\[ b_{it} = \beta_i + \beta_k k_{it} + \beta_l l_{it} + \beta e e_{it} + \beta y (y_{it} + b_{it}) + \beta_{kl} k_{it} l_{it} + \beta_{ke} k_{it} e_{it} + \frac{1}{2} \beta_{kl} l_{it}^2 + \beta_{ky} k_{it} (y_{it} + b_{it}) + \beta_{le} l_{it} e_{it} + \beta_{ly} l_{it} (y_{it} + b_{it}) + \beta_{ey} e_{it} (y_{it} + b_{it}) + \frac{1}{2} \beta_{kl} k_{it}^2 + \frac{1}{2} \beta_{le} e_{it}^2 + \frac{1}{2} \beta_{ly} y_{it} + b_{it})^2 + v_{it} - \mu_t \]  

In equation (5), \( b_{it} \) is the pollutant emissions of thermal power companies. Here, sulfur dioxide emissions are used, and the quadratic production function is used to estimate the inefficiency of individual companies over time. The inputs used include capital input \( k_{it} \), the annual average number of employees \( l_{it} \), coal consumption \( e_{it} \), and the output includes positive output power generation \( y_{it} \) and undesirable output sulfur dioxide emissions \( b_{it} \), the variables here are all processed by logarithm.

This paper adopts the method of panel SFA in which the inefficiency item changes over time, and also uses the hybrid SFA estimation for comparison. The results are shown in Table 2.

According to the SFA regression results, both models are acceptable. First observe the log-likelihood value. The log-likelihood value of the panel SFA model is 1950.019, which is better than the mixed SFA model's 1699.674. From the goodness of fit of maximum likelihood estimation, it should be rejected Hybrid panel random frontier model, and through the likelihood ratio test, significantly reject the use of mixed panel random frontier model. Secondly, observe the regression of the variable coefficients. Because the data values are large, the coefficients obtained by the regression are all small. The coefficients obtained by the panel SFA model are more significant than the coefficients of the mixed SFA model, and the coefficients are larger. The panel SFA model estimates the results are more credible.
Table 2. Parameter estimation results of panel SFA and hybrid SFA.

|                      | panel SFA   | hybrid SFA  |
|----------------------|-------------|-------------|
| Ln(k)                | -0.000      | -0.096***   |
|                      | (0.001)     | (0.019)     |
| Ln(l)                | 0.182***    | -0.103***   |
|                      | (0.018)     | (0.022)     |
| Ln(e)                | 0.168***    | -0.763***   |
|                      | (0.021)     | (0.204)     |
| Ln(y)+Ln(b)          | 1.27***     | -0.048***   |
|                      | (0.037)     | (0.020)     |
| Ln(k)*Ln(l)          | -0.317***   | -0.001      |
|                      | (0.019)     | (0.003)     |
| Ln(k)*Ln(e)          | 0.015***    | -0.028***   |
|                      | (0.002)     | (0.006)     |
| Ln(k)*(Ln(y)+Ln(b))  | -0.008***   | 0.018***    |
|                      | (0.001)     | (0.003)     |
| Ln(l)*Ln(e)          | -0.056***   | -0.008      |
|                      | (0.006)     | (0.006)     |
| Ln(l)* (Ln(y)+Ln(b)) | 0.024***    | 0.008**     |
|                      | (0.003)     | (0.003)     |
| Ln(e)* (Ln(y)+Ln(b)) | 0.053***    | 0.053***    |
|                      | (0.003)     | (0.004)     |
| 1/2*Ln(k)*Ln(k)      | -0.020***   | -0.001      |
|                      | (0.003)     | (0.002)     |
| 1/2*Ln(l)*Ln(l)      | 0.001       | -0.003*     |
|                      | (0.001)     | (0.002)     |
| 1/2*Ln(e)*Ln(e)      | -0.090***   | -0.051***   |
|                      | (0.006)     | (0.005)     |
| 1/2*Ln(y)*Ln(y)      | 0.002*      | -0.014***   |
|                      | (0.001)     | (0.001)     |
| σ_u                  | 0.067       | 0.124       |
| σ_v                  | 0.044       | 0.054       |
| Log-likelihood       | 1950.019    | 1679.674    |

Note: Standard errors are in parentheses, and ***, **, and * indicate the significance levels of 1%, 5%, and 10%, respectively.
Figure 2. Box diagram of green technology efficiency value of thermal power enterprises.

Figure 2 is a calculated box diagram of two green technical efficiency. The range of green technical efficiency is from 0 to 1. The closer to 0, it means that using the same capital, labor and energy, it emits less pollutants and generates more power. Big, that is, the higher the efficiency of green technology. SFA models adopt exponential distribution assumptions, so it can be seen that the two models basically conform to the exponential distribution. The green technology efficiency values of most companies in the panel SFA and hybrid SFA models are concentrated below 0.3, and the green technology efficiency estimated by the panel SFA model shows that there is For more efficient companies, the distribution of green technology efficiency is relatively loose.

5. Conclusion

Through the panel SFA method, we measure the green technology efficiency of thermal power plants, then analyze the emission reduction methods of thermal power companies. The improvement of the green technology efficiency of enterprises should be achieved by the application of advanced emission reduction technologies. The government can use emission reduction subsidies to encourage power generation enterprises to invest in emission reduction technologies and improve the efficiency of generation technologies. Since pollutants have a positive correlation with normal output, firms can reach emission reduction targets of government through reducing production or applying emission reduction technologies. Emission reduction technology has an attribution of a high initial investment. Compared with reducing production or concealing the actual emissions, companies are more likely to choose the latter. The latter one will reduce the level of social welfare whether it is from the perspective of economic development or environmental protection. Therefore, adopting emission reduction technologies and improving the efficiency of green technologies are in line with the long-term development needs of society. The government should help companies invest in emission reduction technologies, provide emission reduction funds to enterprises, and give technical and financial support to firms that develop emission reduction technologies. In summary, measuring the
efficiency of power generation technology in this paper is an advanced and convenient method for government to evaluate the essence of emission reduction.

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