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A Study on Total Factor Energy Efficiency of Coal-fired Power Plants Considering Environmental Protection

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Abstract: In this study, we measure the total-factor energy efficiency under the constraint of environment of 13 coal-fired power plants in Hebei province over the period of 2009 to 2011 using the DEA model which based on the environmental production technology and the directional distance function. The results indicate that the total factor energy efficiency of sample power plants is still at sub-optimal level of around 0.84 and the efficiency is over estimated when without looking at environmental impacts. This indicates that undesirable outputs have a significant influence on energy efficiency of power plants. Poor performance of few power plants is due to their ability to manage the undesirable outputs need to be improved. In order to improve energy efficiency and achieve sustainable development, plants should concentrate on both energy saving and emission reduction at the same time.

Keywords: Coal-fired power plants; DEA model, environmental production technology, the directional distance function, total factor energy efficiency

INTRODUCTION

Electricity is essential for the economic development of a country, but its production is highly energetic and emission intensive. According to the 2009 Report of the International Energy Agency, the distribution of global electricity generation in terms of resource utilization is as follows: petroleum products 5.6%, natural gas 20.9%, coal 41.5%, nuclear power 13.8%, hydraulic power 15.6% and non-hydraulic renewable and other resources at 2.6%. However, in China, coal-fired power plants are the main supplier of electricity, as well as the largest consumer of coal resources. Besides, these power plants discharge a large amount of pollutants and Greenhouse Gases (GHGs). For instance, in 2008, the electricity generated by coal-fired power plants accounted for about 81.2% of the total production of the country; at the same time, approximately 60% coal out of the total consumption in the country were expended by these plants. Moreover, the corresponding SO_2, NOx and CO_2 emissions by these coal-fired power plants reached 45.8, 50 and 48%, respectively, of the total amount discharged in the country (China Electricity Council, 2009). Therefore, the coal-fired power plants carry the heavy responsibility of building a resource-saving and environment-friendly society. In this regard, measuring and improving the energy efficiency with the consideration of environmental constraints is very important for China to reduce energy consumption and mitigate environment pollution.

The efficiency of a power plant is generally defined as the electricity produced per energy input. This ratio takes only the heating value of fuel into account, while neglecting other variables such as installed capacity and electricity used. Thus, as a single criterion, this ratio cannot comprehensively reflect plant's performance in its entirety. Golany *et al*. (1994) suggested an alternative method to measure the efficiency of a power plant using Data Envelopment Analysis (DEA) (Golany *et al*., 1994), a technique originally proposed by Charnes *et al*. (1979) for evaluating the relative efficiency of decision making units (DMUs) (Charnes *et al*., 1979). Recent studies using DEA models to analyze the efficiency of electricity generations include that of Park and Lesourd (2000), who determined the efficiencies of 64 conventional fuel power plants operating in South Korea. Their results showed that the null hypothesis of equality of means between all fuel types could be accepted. In addition, they found that the efficiency for the oldest plants is significantly smaller than the newer ones. A comparison of the plants' efficiencies by geographical area revealed no significant difference (Park and Lesourd, 2000). Lam and Shiu (2001) measured the technical efficiency of China's thermal power generation based on the cross-sectional data for 1995 and 1996. According to their results, municipalities and provinces along the eastern coast of China and those with rich supplies of coal achieved the highest levels of technical efficiency. They also found that fuel efficiency and the capacity factor significantly

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affect the technical efficiency (Lam and Lesourd, 2001). Nemoto and Goto (2003) evaluated productive efficiencies of Japanese electric utilities over 1981-1995. Results indicated that utilities are efficient in their use of variable inputs and that the inefficiency is attributable to a failure in adjusting quasi-fixed inputs to their optimal levels (Nemoto and Goto, 2003). Thakur *et al*. (2006) assessed comparative efficiencies of Indian State Owned Electric Utilities (SOEUS) and the impact of scale on the efficiency scores was also evaluated. Their results indicated that the performance of several SOEUS is sub-optimal, suggesting the potential for significant cost reduction. It was also found that bigger utilities display greater inefficiencies and have distinct scale inefficiencies (Thakur *et al*., 2006). Vaninsky (2006) estimated the efficiency of electric power generation in the United States for the period of 1991 through 2004 using DEA. His results point to a relative stability in efficiency from 1994 through 2000 at levels of 99-100% with a sharp decline to 94-95% levels in the years following (Vaninsky, 2006). Barros and Peypoch (2007) analyzed the technical efficiency of hydroelectric generating plants in Portugal between 1994 and 2004. They concluded that the hydroelectric generating plants are very distinct and therefore any energy policy should take into account this heterogeneity. It is also concluded that competition, rather than regulation, plays the key role in increasing hydroelectric plant efficiency (Barros and Peypoch, 2007). Sarica and Or (2007) analyzed and compared the performance of electricity generation plants in Turkey and they showed that coal-fired plants have lower efficiency values than natural gas-fired ones. Operational performance efficiency of the public thermal plants was significantly lower than their private counterparts (Sarica and Or, 2007). Wang *et al*. (2007) analyzed the efficiency of Hong Kong's electricity supply industry and its effects on prices under the price-cap performance-based regulation (PBR) model. A DEA method was employed to compute the total factor productivity with the Malmquist productivity index. Results support the use of the approach to account for the relation of the X-factor and the PBR model (Wang *et al*., 2007). Barros and Peypoch (2008) analyzed the technical efficiency of Portuguese thermoelectric power generating plants with a two-stage procedure. In the first stage, the plants' relative technical efficiency was estimated with DEA. In a second stage, the efficiency drivers were estimated by regression analysis. Their results show that the majority of the thermoelectric energy plants were not operating within the efficient frontier (Barros and Peypoch, 2008). Barros (2008) studied the efficiency of hydroelectric generating plants with a two-step procedure. In the first step, a Malmquist DEA model is used to identify the efficient scores of each unit. In the second stage, the efficient scores are regressed in contextual variables to identify the drivers of efficiency. His results showed that the hydroelectric plants exhibit on average improvements in technical efficiency as well as technological change. The increase in technological change was higher than the increase in technical efficiency (Barros, 2008). Nakano and Managi (2008) measured productivity in Japan's steam power-generation sector and examined the effect of reforms on the productivity of this industry over the period 1978-2003. Results showed that the regulatory reforms have contributed to the productivity growth in the steam power-generation sector in Japan (Nakano and Managi, 2008).

A common feature of the above mentioned studies is that the energy efficiency does not consider any undesirable outputs. However, this may not be reasonable in real production settings, for any energy consumption will result in the generation of some undesirable output (e.g., CO_2, SO_2 emissions). The measurement of energy efficiency without considering undesirable outputs does not seem to provide an equitable score for energy efficiency comparisons. It would be appropriate to evaluate the economic-wide energy efficiency within a joint production framework where both desirable and undesirable outputs are considered simultaneously. Therefore, the total-factor energy efficiency under the constraint of environment of 13 large-scale coal-fired power plants in Hebei province over the period of 2009 to 2011 has been measured using the DEA model which based on the environmental production technology and the directional distance function.

In this study, we measure the total-factor energy efficiency under the constraint of environment of 13 coal-fired power plants in Hebei province over the period of 2009 to 2011 using the DEA model which based on the environmental production technology and the directional distance function. The results indicate that the total factor energy efficiency of sample power plants is still at sub-optimal level of around 0.84 and the efficiency is over estimated when without looking at environmental impacts. This indicates that undesirable outputs have a significant influence on energy efficiency of power plants. Poor performance of few power plants is due to their ability to manage the undesirable outputs need to be improved. In order to improve energy efficiency and achieve sustainable development, plants should concentrate on both energy saving and emission reduction at the same time.

ENERGY EFFICIENCY MODEL OF COAL-FIRED POWER PLANTS BASED ON ENVIRONMENTAL CONSTRAINTS

In order to put environmental factors into the analytical framework of total factor energy efficiency of coal-fired power plants, we first construct a production possibility set which contains both "desirable" output and "undesirable" output, namely environmental DEA

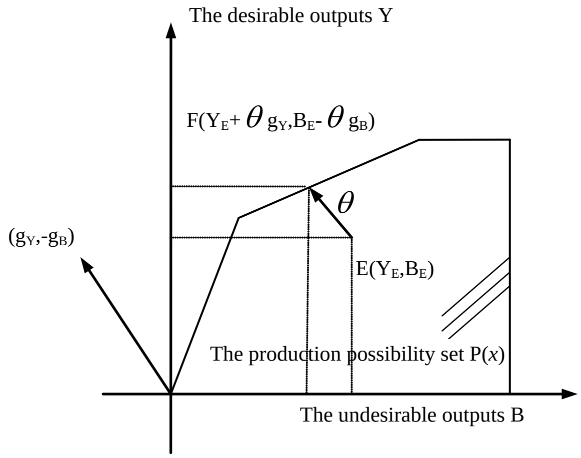

Fig. 1: Directional distance function diagram

technology. Consider an industry producing a vector of desirable outputs Y and a vector of undesirable outputs B from a vector of N inputs $X = (X_1, X_2, \dots, X_N) \in R^N_+$ where $Y = (Y_1, Y_2, \dots, Y_M) \in R^M_+$ and $B = (B_1, B_2, \dots, B_I) \in R^I_+$. Then the environmental DEA technology output set can be completely characterized by the production possibility set P (x) = {(X, Y, B); (Y, B) can be produced from X}, based on a few regularity assumptions of feasibility of all observed input–output combinations, free disposability with respect to inputs and outputs and convexity. One is that the desirable output (Y) and undesirable output (B) have certain relevance. The other thinking of undesirable outputs is weak and can be disposed. That is in a given input level, to reduce the “undesirable” output, it must be will consume part of resource originally used in the "desirable” output, which leads to the reduction of "undesirable" output.

The structure of environmental technology is the basis to calculate the energy efficiency of coal-fired power plants. In order to avoid the environmental technology set only pursuit the maximum increase in desirable output, but did not consider the reduce of undesirable output, we further introduce directional distance function:

$$\vec{D}_0(L,K,E,Y,B;g_Y,-g_B) = \sup\{\theta : (Y+\theta g_Y, B-\theta g_B) \in P(L,K,E,Y,B)\} \quad (1)$$

Figure 1 visually describes the directional distance function. Area of production frontier envelope is the production possibility set P(x), which expresses all possible sets that are able to produce the desirable output Y and the undesirable outputs B in the predetermined input (K, L, E). In the figure, longitudinal and transverse axis respectively representing the desirable output Y and the undesirable outputs B where E expresses the input-output of a coal-fired power plants and $(g_Y, -g_B)$ expresses the direction vector desirable output increase and undesirable output reduction. The θ expresses the distance between the actual output value of E and the projection points F in the production frontier which also the maximum likelihood proportion of the desired output increased with undesirable outputs reducing. The higher the value ofθ, the lower the value of energy efficiency, the greater space of economic growth and sulfur dioxide (SO_2) emissions reduction.

Usually the direction vector is set objectively. For the purpose of this study, we set the following two conditions for the direction vector value:

- Hypothesis g = (Y, 0), it is not considering undesirable outputs, using the following mathematical representation:

$$\begin{aligned} &\vec{D}_0^t(K_i^t, L_i^t, E_i^t, Y_i^t, 0; Y_i^t, 0) = Max\theta \\ &\quad \sum_{i=1}^{N} \lambda_i^t K_i^t \le K_i^t; \sum_{i=1}^{N} \lambda_i^t L_i^t \le L_i^t; \sum_{i=1}^{N} \lambda_i^t E_i^t \le E_i^t \\ &s.t.\ \sum_{i=1}^{N} \lambda_i^t Y_i^t \ge (1+\theta) Y_i^t \\ &\quad \lambda_i^t \ge 0 (i = 1, 2, \dots, N) \end{aligned} \quad (2)$$

- Hypothesis g = (Y, -B). It is to increase output as well as reduce the environmental pollution. It can be expressed by the following mathematical programming:

$$\begin{aligned} &\vec{D}_0^t(K_i^t, L_i^t, E_i^t, Y_i^t, B_i^t; Y_i^t, -B_i^t) = Max\theta \\ &\quad \sum_{i=1}^{N} \lambda_i^t K_i^t \le K_i^t; \sum_{i=1}^{N} \lambda_i^t L_i^t \le L_i^t; \sum_{i=1}^{N} \lambda_i^t E_i^t \le E_i^t \\ &s.t. \sum_{i=1}^{N} \lambda_i^t Y_i^t \ge (1+\theta) Y_i^t \\ &\quad \sum_{i=1}^{N} \lambda_i^t B_i^t = (1-\theta) B_i^t \\ &\quad \lambda_i^t \ge 0 (i = 1, 2, \dots, N) \end{aligned} \quad (3)$$

In the linear programming of formula (3), the inequality of input elements (K, L, E) and the desirable output (Y) says that they are freely disposed and undesirable output (B) equation indicates that the undesirable output (B) is weakly disposition.

VARIABLES AND DATA DESCRIPTION

The economic activity of each power plant is characterized by three inputs producing a single desirable output and undesirable output. Electricity generation is the quantity of electricity produced by a power plant (in 10^8KWH) in a year. It provides a good quantitative measure of the primary output of a power plant. Thus this study uses annual electricity generation of the power plants as the desirable output variable (Y). The undesirable output (B) is measured by the total

Table 1: Descriptive statistics of power plant samples in Hebei Province (2009-2011)

	Mean	S.D.	Max.	Min.
Electricity generation (10^8KWH)	86.415	41.71	163.21	7.98
SO2 emissions (10^4 tons)	5106.67	3802.49	16319	321.5
generation coal consumption (10^4 tons)	402.53	187.25	748	48
Installed capacity (MW)	1362.46	750.73	2500	252
Number of employees (person)	1125.36	743.58	2458	198

According to the survey data collated by SPSS software

Table 2: Total factor energy efficiency of the coal-fired power plants in Hebei Province in 2009-2011

	Results of case I				Results of case II			
Plants	2009	2010	2011	Average	2009	2010	2011	Average
CD	1	1	1	1	1	1	1	1
MT	1	1	1	1	1	1	1	1
WT	1	1	1	1	1	1	1	1
DZH	1	1	1	1	1	1	1	1
LSH	0.831	0.837	0.791	0.82	0.817	0.86	0.772	0.82
HSH	0.926	0.879	0.771	0.86	0.941	0.907	0.718	0.86
SHA	0.912	0.872	0.836	0.87	1	1	1	1
HF	0.841	0.834	0.824	0.83	0.836	1	1	0.95
XT	0.894	0.822	0.789	0.84	0.93	0.857	0.856	0.88
XBP	0.941	0.85	0.827	0.87	1	0.833	0.836	0.89
FR	0.655	0.739	0.65	0.68	0.53	0.651	0.566	0.58
ZJK	0.824	0.72	0.727	0.76	0.787	0.668	0.685	0.71
SJZ	0.521	0.525	0.504	0.52	0.19	0.271	0.258	0.24
Average	0.873	0.852	0.825	0.85	0.849	0.85	0.822	0.84

Case I and case II represent the situation of without and with considering undesirable outputs, respectively

amount of SO_2 released for each year in tons. The three inputs are measured by energy consumption (E), capital (K) and labor (L). This study uses the quantity of coal consumed in a power plant for production of electricity in one year (in million tons), the number of employees at each power plant and the annual installed capacity of each power plant in MW to describe them.

The main operational data for years 2009-2011 were obtained by on-the-spot investigation. The descriptive statistical characteristics are shown in Table1:

EMPIRICAL RESULTS AND ANALYSIS

Comparison of the efficiency of with and without considering environment effect: The essential difference between the energy efficiency of power plans of case I and II is whether to incorporate the environmental impacts. The total-factor energy efficiency of case II is based on the viewpoint of sustainability and considers not only the good outputs, but also the bad outputs. Compared to traditional total-factor energy efficiency, it evaluates energy efficiency much more accurately. Table 2 shows the results of case I and II.

It can be seen from Table 2 that the overall efficiency of power plants considering the environmental constraints is at sub-optimal level of 84%, which needs to be further improved. Without incorporating environmental impacts, the energy efficiency of power plants can be overestimated. As Table 2 shows, the average efficiency of case I is always lower than the average value of case I. From 2009 to 2011, the average efficiency of case I is 0.873, 0.852 and 0.825, while the average efficiency of case II is 0.849, 0.850 and 0.822, respectively. The Mann-Whitney U rank test proves that the difference between cas I and case II presents a statistical significance with a p-value less than 0.001. The comparative result means that the consideration of undesirable outputs has a significant influence on energy efficiency of power plants.

The energy efficiency is higher with only one dimension of energy savings and becomes lower with the added dimension of emission reduction. Under the consideration of environmental impacts, most plants are landing more below the efficient frontier due to poor performance on pollution emission. This indicates that plants have achieved much more improvement in energy savings than that of emission reduction. In order to improve energy efficiency and achieve sustainable development, plants should concentrate on both energy saving and emission reduction at the same time.

According to the comparison, the 13 plants are divided into four groups. The first group includes CD, WT, MT and DZH. There are no gaps between cases of I and II for these four plants, because they always stand on the efficient frontier for both with and without considering environment impacts for each year. The only thing for this group to do is to keep advancing continually in all the plants. The second group consists of XBP, FR and SJZ. Their gaps between cases of I and II are becoming narrower, indicating that their ability to manage the undesirable outputs is enhanced. The third group contains HSH, SHA, HF and XT, whose gaps between cases of I and II are becoming larger. These plants have paid more attention to energy savings, with less attention towards emission reduction. They should vigorously promote energy savings and emission reduction at the same time. The fourth group includes LSH and ZJK showing no regular fluctuations

The energy efficiency of coal-fired power plants under the environmental constraints: First, the overall energy efficiency of 13 large coal-fired power plants in Hebei province during 2009-2011 shows a declining trend. The average efficiency value decreased from 0.849 in 2009 to 0.822 in 2011. Secondly, the gap of energy efficiency values between efficient plants and non-effective plants is increase. By observing the annually efficiency values in Table 2 between DEA efficient plants and non-efficient plants in each samples plants, we can see that the distance of the DEA non-effective plants and the frontier is growing. Again, the individual power plants efficiency value changes more obvious. As a result of DEA model is the relative efficiency of a group of decision-making unit, ranking of the level of plants efficiency values reflects the relative efficiency of the level of enterprises in the sample enterprises. CD, SHA, WT, DZH and MT have the highest energy efficiency, whose energy efficiency scores are all l during the period 2009-2011. The five plants actually constitute the efficiency frontier among all other power plants in Hebei province. The other plants in Hebei which are not yet at the frontier can adjust their technology level and production processes accordingly. The energy efficiency of SJZ and FR is the lowest which ranked in the last two for three years. The energy efficiency of HF compared to other plant progress significantly which has been improved stably and reached the efficient frontier in 2010. The energy efficiency of FR and SJZ with low energy efficiency also has a certain promotion. And for most of the other power plant energy efficiency shows a downward trend, indicating that their energy efficiency in the sample plants has regressed, or after the efficient frontier of speed to drop somewhat, or the pace to catch up with the efficient frontier has declined, such as XBP and HSH. Finally, influence of environmental constraints on energy efficiency for different coal-fired power plants has larger difference. In addition to the DEA efficient plants, the value of the energy efficiency of LSH, of XBP and HSH in Case 1 and Case 2 is basically the same. The value of the energy efficiency of SHA, of XT and HF in Case 2 is much higher than the value of the energy efficiency of in Case 1 indicating that its production process take more attention to environmental protection and has a relatively higher environmental benefits. While the value of the energy efficiency of FR, of ZJK and SJZ in Case 2 is lower than the value of the energy efficiency of in Case 1 indicating that its environmental benefits are relatively low.

CONCLUSION AND ENLIGHTENMENTS

The DEA method considering undesirable outputs on the total factor energy efficiency is a relatively better index and a new idea to analyze and evaluate the energy efficiency. It is more scientific, more in line with the actual of economic development. In this study, we get panel data of 13 large coal-fired power plants during 2009-2011 in Hebei Province through research. Then calculate the total factor energy efficiency of them using the DEA model based on environmental production technology and the directional distance function.

Through the study we found that, on the whole, the total factor energy efficiency of 13 large-scale thermal power plants of Hebei province was showing a fluctuating and slowly downward trend during 2009-2011. But the efficiency difference between plants is gradually increased and the environmental benefit between plants has a great difference.

Based on the above empirical results, combined with the development status of coal-fired power enterprises in Hebei province, we can get the following two points of enlightenment:

- Firstly, accelerate the progress of coal-fired power generation technology, to further strengthen the leading role of technology progress on the total factor energy efficiency. Strengthen the development of high parameters and large-capacity thermal power units such as ultra-supercritical units and supercritical Pressure Generating units, instead of small units with large coal-fired generating units and eliminate the backward production capacity; Strengthen management and promoting the innovation and application of science and technology. Thermal power plants not only need to increase R & D investment, but also to focus on the transformation of scientific and technological achievements. At the same time of in the introduction of new technologies, full attention should be paid to tap the full potential of existing and to improve their efficiency, at the same time reached the technical efficiency and technical progress of improvement.
- Secondly, strengthen the exchanges between enterprises. Through the above empirical research, energy-saving potential is different between thermal power plants whose catch-up effect is not obvious. Therefore, at the same time of the introduction of advanced technology and speed up the elimination of backward production capacity, it is necessary to strengthen exchanges and promotion of energy-saving technologies between enterprises, further improve the energy efficiency of plants with larger energy-saving potential.

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