Aerosol and Air Quality Research, 13: 1815–1823, 2013

ISSN: 1680-8584 print / 2071-1409 online
doi: 10.4209/aaqr.2013.03.0070

Evaluation of NO_x, SO_x and CO_2 Emissions of Taiwan's Thermal Power Plants by Data Envelopment Analysis

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ABSTRACT

An integrated environmental and operational evaluation model is constructed by data envelopment analysis (DEA) to examine seven thermal power plants operating in Taiwan during 2001–2008. Inputs and desirable outputs along with undesirable outputs, including CO_2, SO_x, and NO_x emissions, were simulated. A slack variable analysis was conducted to identify possible ways to improve the inefficient power plants. In addition, three models were compared to identify the actual magnitude of inefficiency. The results indicate that the integrated efficiency and production scale of some plants were inefficient during 2001–2008. Reductions in fuel consumption and CO_2 emissions are identified as the major strategies to improve efficiency. Other options include modifying pre-existing management measures, installing pollution prevention controls and resizing the scale of the power plant. It is anticipated that the findings of this study will help policymakers to achieve better environmental and operational performance with regard to existing thermal power plants.

Keywords: Environmental performance; Utility efficiency of power generation; CO_2 reduction; Extended DEA model.

INTRODUCTION

Electricity is the foundation of a country's national economic development and an essential element of daily modern life. Due to the rapid growth of Taiwan's economy and industrial development, the electricity consumption has increased rapidly. It grew from 134,307 GWh in 1996 to 242,244 GWh in 2011, an average annual increase of 4.01%; while the annual growth rate of domestic energy consumption is only 3.27% (Bureau of Energy, 2012a). This shows that the growth rate of electricity consumption is higher than that of total energy consumption. However, electricity from thermal power generation at its production stage requires other energy input sources such as coal, oil and natural gas. Therefore, electricity consumption results in large emissions of CO_2, NO_x and SO_x, and causes various environmental damages such as greenhouse effects and acid rain. In Taiwan, the CO_2 emission from the electricity sector in 2011 accounted for 65.5% of total CO_2 emissions. Thus, the electricity sector is the most significant source of CO_2 emissions in Taiwan.

Presently, Taiwan is not a member of the UNFCCC, yet the total CO_2 emission in Taiwan contributes 0.89% worldwide, and Taiwan ranks 20rd in the world regarding total CO_2 emission (International Energy Agency, 2012). In order to respond to the post-Kyoto Protocol international trends and challenges and to cope with the increasing electricity consumption as Taiwan moves toward sustainable development, the government issued the "Sustainable Energy Policy Convention", and set up several goals. First, the total emission of CO_2 by 2025 should be set back to the year 2000 level. Second, the energy efficiency should be raised 2% annually for the next eight years. Third, the proportion of low carbon fuel of power generation system should be no less than 55% by 2025. Yet, despite the growing environmental concerns and related policy objectives, few empirical quantitative analyses regarding the performance evaluation of power generation in Taiwan have been conducted. The focus of this study is to construct an integrated performance evaluation model by data envelopment analysis (DEA) (Charnes *et al.*, 1978). This integrated model is aimed to evaluate both technical and environmental efficiencies of Taiwan thermal power plants by considering desirable variables as well as undesirable variables, such as CO_2, SO_x and NO_x. Also, a slack variable analysis is conducted to identify options to improve inefficient power plants. In addition, magnitudes of inefficiency are identified by model comparisons. We

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hope that the results can be valuable for policy making and for improving utility efficiency and environmental concerns of countries with similar thermal power plants.

POWER GENERATION IN TAIWAN

The annual report from the Bureau of Energy (2012a, b) indicated that the gross power generation in Taiwan grew from 141,963 GWh in 1996 to 252,173 GWh in 2011. Taiwan Power Company (TPC) generated 170,067 GWh, accounting for 67.4% of total output, and 42,287 GWh (16.8%) from independent power producers (IPPs) and 39,760 GWh from cogeneration (15.8%) in 2011. It is worth noting that the percentage of electricity produced from thermal power plants increased rapidly from 66.4% in 1996 to 78.6% in 2011 (Bureau of Energy, 2012b). On the other hand, due to the national goal of a "nuclear-free homeland" policy in Taiwan, the percentage of electricity produced from nuclear power plants decreased from 26.6% in 1996 to 16.7% in 2011. In addition, the gross electricity generation of hydro-power systems reduced from 9,044 GWh (6.4%) in 1996 to 6,902 GWh (2.7%) in 2011. Wind power and other green energy supply systems operated on a limited scale and comprised less than 1.9% in 2011. All of this indicates that thermal power generation is currently the dominant source of electricity in Taiwan.

LITERATURE REVIEW

Because DEA is the basic approach of this paper, it is important to review a number of successful studies related to this method. DEA has been widely used to study and compare the efficiency of energy industries, particularly the electricity industry. Recently, DEA has also gained popularity in environmental performance measurement due to its empirical applicability. Yaisawarng and Klein (1994) used DEA to compute a performance analysis for coal-burning plants in the U.S. electric generating industry in the 1980s. Olatubi and Dismukes (2000) used DEA to evaluate the cost efficiency of electric utilities in the United States. Korhonen and Luptacik (2004) used the DEA approach to measure the eco-efficiency of 24 power plants in European countries. Their results indicate DEA can provide an insight into the cause of the eco-inefficiency and the potential for improvement with respect to some particular input and outputs. Vencheh *et al.* (2005) proposed a model for incorporating undesirable factors in DEA. The proposed model evaluates the efficiency level of each DMU by considering undesirable inputs and outputs simultaneously. Zhou *et al.* (2008) have summarized more than 100 DEA applications for environmental protection and energy policy. They found that benchmarking of electricity utilities accounts for the largest number of studies, and the constant returns to scale (CRS) reference technology along with the radial efficiency measures are still the most widely used specifications. Some studies have also been devoted to modeling undesirable factors in DEA, e.g., Zhang *et al.* (2008) conducted an eco-efficiency analysis for regional industrial systems in China by taking various undesirable outputs into account and developing DEA-based models. Results indicated that provinces with higher level GDP per capita had higher eco-efficiency relatively with the exceptions of Hainan and Qinghai. Sueyoshi and Sekitani (2009) discussed nine desirable properties to measure the technical efficiency need to satisfy from the perspective of production economics and optimization. Results showed that all the seven DEA models suffer from a problem of multiple projections and violate the property on aggregation of inputs and outputs. Thus, the seven DEA models do not satisfy all desirable technical efficiency properties. Welch and Barnum (2009) estimated the allocation of coal, gas and oil inputs that minimize carbon emissions and costs in fossil-fuel based electricity generation. Their results indicated that the gap between efficient cost and efficient environmental production was wide, and would require substantial policy intervention, technological change and market adjustment before it could be narrowed. Yang and Pollitt (2009) used different DEA-based efficiency models to examine the impact of uncontrollable variables together with undesirable outputs based on a research sample of the Chinese coal-fired power plants. The results indicated that the impact of uncontrollable variables was relatively significant. This confirms the hypothesis that some power plants with relatively low efficiency scores in the traditional model achieved theirs in part due to their relatively unfavorable operating environments. Fleishman *et al.* (2009) examined the effect of air quality regulations on the efficiency of US power plants based on both economic and environmental outputs. Their results identified several mixed effects of regulations on power plant efficiency when pollution abatement and electricity generation are both included as outputs. Liu *et al.* (2010) surveyed numerous studies, which dealt with the application of DEA to electricity generation. Sueyoshi and Goto (2011) proposed a DEA approach, and applied it to measure the unified efficiency of Japanese fossil fuel power generation for comparison with other previous DEA approaches. Their results indicated that the implementation of the Kyoto Protocol has not been effective on the unified efficiency of Japanese fossil fuel power generation during 2004 to 2008. Chen *et al.* (2012) proposed an integer DEA model with undesirable inputs and outputs. The proposed model is developed based on the additive DEA model, in which input and output slacks are used to compute efficiency scores. Barros (2013) adopted a distance frontier model to rank the plants according to their total productivity for the period 1995–2010. The results display strong evidence that the rankings of technical efficiency with adjustments for pollution differs significantly from the rankings that do not take pollution into account. In this paper, we extended the basic DEA model of Liu *et al.* (2010) to construct a model to include undesirable outputs; therefore, the environmental and operational efficiencies can be integrated and evaluated.

DEA METHODOLOGY

The DEA approach is a non-parametric method for determining a linear efficiency frontier along the most efficient decision making units (DMUs) so as to measure the efficiency relative to the rest of DMUs. Efficiency scores are constructed by measuring how far a utility is from the frontier. DEA also produces detailed information on the efficiency of each utility, not only relative to the efficiency frontier, but also relative to specific efficient utilities that can be identified as role models or comparators (Hawdon, 2003). In addition, DEA allows for efficient measurement of multiple outputs and multiple inputs without pre-assigned weights and without specifying any functional form on the relationships between variables (Thakur, *et al.*, 2006). Therefore, it is not only a non-parametric approach, but also a data-driven frontier analysis technique that floats a linear surface to rest on empirical observations (Cooper, *et al.*, 2006).

Two DEA models are considered in this study to complete the performance analysis. The first model is the CCR (Charnes, Cooper and Rhodes) model which was conducted by Charnes *et al.* (1978). It is built on the assumption of constant returns to scale (CRS) of activities. In other words, if variables (x, y) are feasible, then for every positive scalar k, the variables (kx, ky) are also feasible. The second model, the BCC (Banker, Charnes and Cooper) model, was developed by Banker *et al.* (1984). It is built on the assumption of variable returns to scale (VRS) of activities, and has its production frontiers spanned by the convex hull of the existing DMUs. The frontiers have piecewise linear and concave characteristics, which lead to variable returns to scale characteristics. Details of the basic CCR and BCC models can be found in our previous paper (Liu *et al.*, 2010) in which we evaluated the power-generation efficiency of major thermal power plants in Taiwan by the DEA approach, and a stability test was conducted to verify the stability of the DEA model. In general, the reasons that a DMU is inefficient may result from inappropriate operation of the DMU itself or from inadequate scale of the DMU's operation. The scale efficiency can be presented by the ratio of efficiency scores of CCR and BCC models (Sarica and Or, 2007).

In addition, there are two DEA techniques for each of the CCR and BCC models. The first technique is input-oriented, which aims to minimize inputs while satisfying at least the given output levels. The other technique is output-oriented, which attempts to maximize the output without requiring more of any of the observed input values (Cooper *et al.*, 2000). In this study, we use the input-oriented rather than output-oriented DEA technique to evaluate the performance of Taiwan's power plants because these plants do not take competitive positions in the electric market. The amount of overall electricity generated is mostly based on policies and distribution regulations from the relevant authorities.

In this study, we treat the undesirable outputs as inputs in our extended DEA model for environmental efficiency analysis. Treating the undesirable outputs like classic inputs to be minimized in the DEA model was already valued as a quite intuitive approach (Dyckhoof and Allen, 2001). Assume there are n DMUs, each consuming m inputs and producing s outputs. The outputs corresponding to indices 1, 2,…, t are desirable and the outputs corresponding to indices t + 1, t + 2,…, s are undesirable outputs. We would like to produce as many desirable outputs as possible and not produce undesirable outputs. Let $x \in R_+^{m\times n}$ and $Y \in R_+^{s\times n}$ be the matrices with non-negative elements, and contain the observed input and output for the DMUs. We decompose matrix Y into two parts:

$$Y = \begin{pmatrix} Y^g \\ Y^b \end{pmatrix} \tag{1}$$

where a t × n matrix Y^g represents desirable ("good") outputs and a (s – t) × n matrix Y^b represents undesirable ("bad") outputs (Dyckhoof, 1994). In addition, we denote X_{ij} the quantity of input i consumed by DMU_j, and Y_{rj} the quantity of output r generated from DMU_j. We decompose the vector Y_{rj} into two parts:

$$Y_{rj} = \begin{pmatrix} Y_{rj}^g \\ Y_{rj}^b \end{pmatrix} \tag{2}$$

where the vectors ${Y_{rj}}^g$ and ${Y_{rj}}^b$ stand for the desirable and undesirable output-values of unit j. We will perform the calculations with a CCR model but the results can be generalized to other DEA models as well. Treating the undesirable outputs as inputs, the ratio form of the CCR model is given as follows:

$$\max \ h_k = \frac{\sum_{r=1}^{t} u_r y_{rk}}{\sum_{i=1}^{m} v_i x_{ik} + \sum_{r=t+1}^{s} u_r y_{rk}} \tag{3}$$

Subject to

$$\frac{\sum_{r=1}^{t} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij} + \sum_{r=t+1}^{s} u_r y_{rj}} \le 1 \ ; \quad j = 1,...,n \tag{4}$$
$$u_r, v_i \ge 0, \quad r = 1,...,s \quad i = 1,...,m$$

The above model is difficult to solve because of its fractional objective function. In order to make the linear problem easier to solve and reduce the number of constraints, a standard technique (Charnes *et al.*, 1978; Charnes *et al.*, 1979) to transform the above fractional model into a linear mode is used, and the dual of CCR model is obtained. It can be presented as follows:

$$\min \ \theta_k - \varepsilon\left(\sum_{i=1}^{m} s_{ik}^- + \sum_{r=1}^{t} s_{rk}^g + \sum_{r=t+1}^{s} s_{rk}^b\right) \tag{5}$$

Subject to

$$\theta_k X_{ik} - \sum_{j=1}^{n} \lambda_j X_{ij} - s_{ik}^- = 0 \ ; \quad i = 1,...,m$$
$$Y_{rk}^g - \sum_{j=1}^{n} \lambda_j Y_{rj}^g + s_{rk}^g = 0 \ ; \quad r = 1,...,t \qquad (6)$$
$$\theta_k Y_{rk}^b - \sum_{j=1}^{n} \lambda_j Y_{rj}^b - s_{rk}^b = 0 \ ; \quad r = t+1,...,s$$
$$\lambda_j,\ s_{ik}^-,\ s_{rk}^g,\ s_{rk}^b \ \geq 0 \ ; \quad j = 1,...,n$$

The corresponding BCC model is listed below:

$$\min \ \theta_k - \varepsilon \left(\sum_{i=1}^{m} s_{ik}^- + \sum_{r=1}^{t} s_{rk}^g + \sum_{r=t+1}^{s} s_{rk}^b \right) \qquad (7)$$

Subject to

$$\theta_k X_{ik} - \sum_{j=1}^{n} \lambda_j X_{ij} - s_{ik}^- = 0 \ ; \quad i = 1,...,m$$
$$Y_{rk}^g - \sum_{j=1}^{n} \lambda_j Y_{rj}^g + s_{rk}^g = 0 \ ; \quad r = 1,...,t$$
$$\theta_k Y_{rk}^b - \sum_{j=1}^{n} \lambda_j Y_{rj}^b - s_{rk}^b = 0 \ ; \quad r = t+1,...,s \qquad (8)$$
$$\sum_{j=1}^{n} \lambda_j = 1$$
$$\lambda_j,\ s_{ik}^-,\ s_{rk}^g,\ s_{rk}^b \ \geq 0 \ ; \quad j = 1,...,n$$

The above model integrates the undesirable outputs into consideration, and the DMU can reduce simultaneously the inputs and undesirable outputs to increase environmental efficiency (Dyckhoof and Allen, 2001).

DATA CONSOLIDATION

In Taiwan, there are more than 20 state-run and a few private thermal power plants. Among these plants, the utilities belonging to Taiwan Power Company (TPC) with complete operational statistics were selected for evaluation so as to maintain high level data quality. After screening, only 7 thermal power plants were included in this study. The basic parameters (year of operation, fuel type) of thermal power plants are presented in Table 1. The influence of fuel type is not considered in this study due to the structure setting of the performance evaluation. The main operational data for years 2001–2008 were obtained from the Annual Operation Statistics (2001–2008) (Taiwan Power Company, 2009). The data used in the DEA estimation comprised information for 7 DMUs during 8 years for a total of 56 observations.

In estimating efficiency measures of the thermal power plants in Taiwan, our study adopts six variables as inputs and outputs. Inputs include installed capacity and heating value of total fuels, while the outputs contain one desirable output (net electricity produced) and three undesirable outputs (CO_2, NO_x, SO_x). The data of inputs and desirable output are obtained from publicly available information of TPC. In addition, the data of undesirable output is gathered through TPC annual sustainability reporting (Taiwan Power Company, 2010) and questionnaires from power plants. The variables are described in Table 2. The combination of the measured indicators ensures adherence to the DEA convention that the minimum number of DMU observations should be greater than or equal to three times the number of inputs plus outputs (Raab and Lichty, 2002). In our study, 56 observations are greater than three times the sum of input and output variables [$56 \geq 3(2 + 4)$]. Moreover, by calculating the correlation coefficients between inputs and outputs, a significant correlation was found. The isotonicity that the DEA model required is fulfilled and thus the input and output variables can be used for this research to measure the combined operational and environmental efficiencies (Liu *et al.*, 2010).

Table 1. Basic parameters of seven thermal power plants in Taiwan.

Power plant	Year of operation	Fuel type
Hsiehho	1977	oil
Linkou	1968	coal
Taichung	1991	coal
Talin	1969	coal/oil/ natural gas
Hsinta	1982	natural gas
Tunghsiao	1980	natural gas
Nanpu	1993	natural gas

Table 2. Input/output variables.

	Variable	Unit	Description
Input	Heating value of total fuels	10^9 calories	Sum of the heat value of fossil fuels that used by power plant's operation
	Installed capacity	MW	Maximum design load of generated electricity per month
Desirable output	Net electricity produced	MWh	Sum of generated electricity without electric energy consumed by power plant
Undesirable output	CO_2	tonnes	Carbon dioxide emissions from power plant's operation
	NO_x	tonnes	Nitrogen oxides including various nitrogen compounds such as NO and NO_2 emissions from power plant's operation
	SO_x	tonnes	Sulfur oxides such as SO_2 emissions from power plant's operation

RESULTS AND DISCUSSION

In this study, two inputs with one desirable output and three undesirable outputs are used to estimate the efficiency of thermal power plants in Taiwan. The estimated efficiency considers not only the technical performance but also the air pollution control. Results of the average efficiency scores in 2001–2008 are listed in Table 3. The range of CCR efficiency scores among all thermal power plants are from 0.745 to 0.990, and the range of BBC efficiency scores are from 0.760 to 0.999. It is noticed that Nanpu power plant has the best performance relative to other utilities, and Talin power plant is the worst utility in both CCR and BCC efficiency evaluation. On the other hand, scale efficiency scores range from 0.807 (Linkou) to 0.994 (Hsiehho) (Table 3). This indicates that Hsiehho power plant is operating on the best production scale for utilities; while the Linkou power plant could be replaced or add generators with larger capacity to increase electricity supply and expand its scale. In fact, the expansion plan of Linkou power plant has been supported by the Executive Yuan in 2005 and passed the environmental impact assessment by Environmental Protection Administration (EPA) in 2008. By replacing the 30 year-old thermal generators with three 800 MW new supercritical coal-fired generators, the performance of Linkou power plant is expected to improve significantly by 2015.

The results in Table 3 show that the average CCR, BCC and scale efficiency scores are 0.887, 0.926 and 0.958, respectively. It means that, considering the unified efficiency and the production scale, some plants such as Hsiehho, Linkou and Talin are inefficient in 2001–2008. Power plants in this study can be divided into four groups according to type of power generator. First, the Nanpu and Tunghsiao power plants are gas-fired combined-cycle power plants, and their net heat efficiency was 39–43% during 2001 to 2008. Second, Hsiehho and Talin power plants are coal-fired steam turbine power plants, and their net heat efficiency was 33–35% in 2001–2008. Third, Linkou and Taichung power plants have not only steam turbine generators but also gas turbine generators. Both of them are coal-fired power plants; the net heat efficiency of steam turbine generators was 31–36%, and the net heat efficiency of gas turbine generators was 26–28%. Finally, Hsinta power plant has coal-fired steam turbine generators and gas-fired combined-cycle generators, and the range of its net heat efficiency is 35–44%. Table 3 shows that combined cycle power plants (Nanpu and Tunghsiao) are clearly more efficient than steam turbine power plants (Hsiehho and Talin). Based on the BCC efficiency scores in Table 3, the Talin power plant is the most technically inefficient utility during 2001–2008. This may result from more than 30 years of old generators and the absence of available space to set up the flue gas desulfurization (FGD) and selective catalytic reduction (SCR) units to further reduce the concentration of SO_x and NO_x emissions. If we compare the Linkou and Taichung power plants, the CCR efficiency of the former (0.755) is found to be more inefficient than the latter (0.977), even though they have similar kinds of generation facilities but the operation period of the Linkou power plant is 20 years longer than that of the Taichung power plant. Also, another reason for the difference in performance can be related to different production scales. The scale efficiency of the Linkou power plant is only 0.807, while the Taichung power plant’s scale efficiency score is up to 0.985.

The unified performance of evaluated power plants can be divided into three groups. First, the CCR, BCC and scale efficiency scores of the Tunghsiao and Nanpu power plants have progressed year by year. In 2006–2008, their efficiency scores all reached 1.0. It means that they are at the optimal production level and have steady performance. This is because that they have novel equipment with high operational quality, and they use natural gas which is more environmental friendly than coal and oil as the fuel. Secondly, the Hsiehho and Talin power plants have lower BCC efficiency while their scale efficiency scores are close to 1.0. This indicates that they are technically inefficient, although they are already on the optimal production scale. The over use of electricity and excess pollutant emissions are the main reasons causing the low BCC efficiency of the Talin power plant. Thirdly, the Linkou and Hsinta power plants have higher BCC efficiency than their scale efficiency during 2001–2008, indicating that their operational processes and environmental management are quite appropriate. The scale efficiency of the Hsinta plant has been improved over the period, resulting in a more competitive condition of the plant. On the contrary, the Linkou power plant currently needs more improvement directed toward increasing the production scale.

In addition, a slack variable analysis is conducted to identify options to improve the performance of inefficient

Table 3. Efficiencies of thermal power plants in 2001–2008.

Power plant	CCR efficiency[a]	BCC efficiency[b]	Scale efficiency
Hsiehho	0.832	0.836	0.994
Linkou	0.755	0.937	0.807
Taichung	0.977	0.992	0.985
Talin	0.745	0.760	0.981
Hsinta	0.949	0.989	0.959
Tunghsiao	0.958	0.970	0.987
Nanpu	0.990	0.999	0.991
Average	**0.887**	**0.926**	**0.958**

[a] CCR efficiency stands for overall efficiency. By (1), CCR efficiency = BCC efficiency × Scale efficiency.
[b] BCC efficiency represents pure technical efficiency.

utilities. Considering two input variables (Table 4), the results show that 3 DMUs have inappropriate installed capacity and 8 DMUs use too much fossil fuel. In brief, reduction in fuel consumption is the most effective improvement for major inefficient utilities. Considering three undesirable output variables, we find that more than 40 DMUs have excess NO_x, SO_x and CO_2 emissions. Among them, although the number of DMUs with excess SO_x is higher than that with the other two emissions, it is worth noting that the excess CO_2 emission significantly dominates that of NO_x and SO_x. For this reason, CO_2 emission reduction should be the first priority to lower the environmental impacts to maintain sustainable development for overall better performance of thermal power plants in Taiwan.

Results in Table 4 show that most power plants have no excess installed capacity and heating value of total fuels in 2001–2008. It indicates that the design capacity can meet the electricity demand requirement, and the fuel consumption and allocation is under suitable control. In addition, most power plants except for the Tunghsiao and Nanpu plants have excess air emissions, especially large amount of CO_2 emissions. This situation could be improved by the adjustment of fuel structure, promotion of generator heat rate and adoption of low sulfur fuels in the future.

The efficiency scores from the DEA calculations can be changed by the number of DMU and input/output variables. Due to the nature of the DEA approach, adding more variables not only enlarges DEA efficiency scores, but it also potentially hides the actual magnitude of inefficiency. For this reason, we constructed the original model (Model 1), and two other models (Models 2 and 3) to find the sensitivity of the efficiency magnitude by altering some inputs. Both Models 2 and 3 are developed with one input, one desirable output and three undesirable outputs (Table 5), and the results from the model comparison are shown in Table 6. In addition, the Spearman rank correlation test was also used, and the correlation coefficients between Model 1 and the other two models are 0.857 and 0.964. These correlation coefficients signify that the results are positively related and stable across model specifications.

Based on Model 1 and Model 2, the most efficient plant is the Nanpu plant; however, the least efficient plant from Model 1 is the Tailin plant and the Linkou plant in Model 2. The average score reduces from 0.891 in Model 1 to 0.809 in Model 2. For most power plants, the variations of efficiency scores between Model 1 and Model 2 are less than 0.2, with the exception of the Taichung plant. The Taichung plant appears to be more efficient than most plants in Model 1, because it has the largest installed capacity in Taiwan, therefore it can produce more electricity than other plants. In Model 2, the relative efficiency of the Taichung plant is smaller, because this model was conducted without input of the installed capacity, and only considered heating value of total fuels. The Hsinta plant, which has the second largest installed capacity, also has similar change in results between Model 1 and Model 2. Improvements to the Taichung and Hsinta plants should be oriented to better choice of fuel use, enhancement of pollution control and operation standards to improve the efficiency of electricity generation.

Comparing results of Model 1 and Model 3, the most efficient plant is the Nanpu plant, and the least efficient plant is the Tailin plant. The average score reduces lightly from 0.891 in Model 1 to 0.846 in Model 3 due to Model 3 lacking one input. The difference of efficiency scores of all power plants between Model 1 and Model 3 are less than 0.1. It shows that the gap between Model 1 and Model 3 is smaller than that between Model 1 and Model 2, and the results of Model 3 is more consistent with Model 1. Considering the results of Model 2 and Model 3, the most efficient plant is the Nanpu plant, and the least efficient plant in Model 2 is the Linkou plant, yet in Model 3 it is the Tailin plant. The Taichung and Hsinta plants have some differences in efficiency scores in Model 2 and Model 3. In summary, the above results indicate that Model 1 and Model 3 are more consistent in results due to the domination by the input "installed capacity".

CONCLUSIONS

In this study, three undesirable outputs are integrated with one desirable output and two inputs to evaluate the unified efficiency of Taiwan's thermal power plants by the DEA method. The preceding analysis shows that some power plants such as Hsiehho, Linkou and Talin were inefficient in 2001–2008. This situation could be improved by the adjustment of fuel structure, promotion of generator heat rate and adoption of low sulfur fuels in the future. In addition, by replacing the 30 year-old thermal generators with three 800 MW new supercritical coal-fired generators, the performance of Linkou power plant is expected to improve significantly by 2015. The results of this study demonstrate that combined cycle power plants are more efficient than steam turbine power plants. In addition, combined cycle power plants (Tunghsiao and Nanpu) made continual progress in overall performance during 2001–2008. It is suggested when a new power plant is proposed, an integrated gasification combined cycle (IGCC) and combined heat and power (CHP) power plant with the best available technologies (BAT) should be considered for the future.

Results from comparing three models indicate that the original model (Model 1 with two inputs, one desirable output, and three undesirable outputs) can hide the actual magnitude of inefficiency of the Taichung power plant, because of its large installed capacity, and operators of the Taichung plant have the advantage of measuring the marginal cost and the marginal pollutant emissions from electricity generation to evaluate efficiency scores. Also, results of Model 1 and Model 3 are more consistent due to the domination of the input parameter "installed capacity".

According to the slack variable analysis, reduction in fuel consumption and CO_2 emissions are the most effective methods to improve the efficiency of thermal power plants. Findings of this study can be beneficial for enhancing the environmental performance and power generating efficiency policies of thermal power plants. Also, the method used in

Table 4. Slack variable analysis of thermal power plants in Taiwan (2001–2008).

Power Plant	Year	Excess installed Capacity (MW)	Excess heating value of total fuels (109 cal)	Excess NO_x (tonnes)	Excess SO_x (tonnes)	Excess CO_2 (tonnes)
Hsiehho	2001	0	0	0	11,408	219,949
	2002	0	0	36	10,242	517,503
	2003	0	0	0	9,377	792,331
	2004	0	0	1,120	7,106	1,116,413
	2005	0	0	1,311	6,140	1,038,944
	2006	0	0	639	10,995	518,758
	2007	0	0	644	9,762	933,945
	2008	0	0	363	8,978	1,091,437
Linkou	2001	0	0	1,567	1,019	888,848
	2002	0	0	1,757	978	838,778
	2003	0	0	1,027	815	838,085
	2004	0	0	762	621	792,860
	2005	0	0	921	556	808,132
	2006	0	0	841	603	692,539
	2007	0	0	741	526	729,570
	2008	0	0	954	549	751,750
Taichung	2001	0	0	10,054	2,261	1,520,665
	2002	0	0	8,801	2,708	1,545,053
	2003	0	0	3,865	1,522	849,129
	2004	0	0	1,156	1,326	875,738
	2005	0	0	0	0	0
	2006	0	962,670	0	0	1,041,639
	2007	0	0	0	313	688,189
	2008	0	1,657,220	0	706	1,017,781
Talin	2001	0	0	392	8,805	1,236,595
	2002	0	0	930	8,562	1,438,271
	2003	0	0	2,041	7,122	1,565,416
	2004	44,771	0	2,073	6,833	1,408,608
	2005	0	0	627	7,408	1,744,882
	2006	0	0	2,318	7,129	1,516,783
	2007	0	0	1,479	7,067	1,660,677
	2008	0	0	2,154	6,774	1,481,177
Hsinta	2001	0	0	1,173	11,695	1,381,580
	2002	0	0	260	1,741	1,588,045
	2003	0	0	3,096	2,355	1,489,140
	2004	0	0	2,064	1,827	601,259
	2005	0	0	118	1,673	575,158
	2006	0	0	831	3,113	979,204
	2007	0	0	591	3,111	697,277
	2008	0	42,726	198	3,534	0
Tunghsiao	2001	0	0	8,689	12,980	553,540
	2002	0	0	4,294	4,171	277,086
	2003	0	91,424	2,211	3,957	0
	2004	0	0	2,988	3,172	205,056
	2005	0	0	1,293	163	12,482
	2006	0	0	0	0	0
	2007	0	58,980	741	15	0
	2008	0	194,600	1,081	0	43,946
Nanpu	2001	0	164,869	0	102	0
	2002	0	4,693	79	79	0
	2003	0	0	155	81	0
	2004	58,114	0	174	70	0
	2005	84,683	0	123	40	0
	2006	0	0	0	0	0

Table 4. *(continued).*

Power Plant	Year	Excess installed Capacity (MW)	Excess heating value of total fuels (109 cal)	Excess NO_x (tonnes)	Excess SO_x (tonnes)	Excess CO_2 (tonnes)
	2007	0	0	0	0	0
	2008	0	0	5	0	0

Table 5. Input/Output used in three models

Variable	Model 1	Model 2	Model 3
Input	• Installed capacity • Heating value of total fuels	• Heating value of total fuels	• Installed capacity
Desirable Output	• Net electricity produced	• Net electricity produced	• Net electricity produced
Undesirable Output	• CO_2 • SO_x • NO_x	• CO_2 • SO_x • NO_x	• CO_2 • SO_x • NO_x

Table 6. Average efficiency scores of the different models.

Power plants	Model 1	Model 2	Model 3
Hsiehho	0.834	0.769	0.782
Linkou	0.755	0.688	0.667
Taichung	0.980	0.754	0.966
Talin	0.745	0.729	0.648
Hsinta	0.949	0.808	0.928
Tunghsiao	0.982	0.931	0.941
Nanpu	0.991	0.984	0.990
Average	**0.891**	**0.809**	**0.846**

this research can be applied to countries with similar power plant structures for evaluation of environmental and operational efficiencies and means for improvement. Future research could be extended to include thermal power plants with different categories according to fuel type for further assessment of the relative efficiencies by DEA.

ACKNOWLEDGEMENTS

We wish to thank Taiwan's National Science Council (Project NSC 97-2221-E-006-041-MY3) for financial support. Also, we appreciate the valuable comments and suggestions from the reviewers and the editors of our manuscript.

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Received for review, March 7, 2013
Accepted, September 11, 2013