A Case Study to Evaluate the Productivity Changes of the Thermal Power Plants of the Taiwan Power Company

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***Abstract*—This paper developed an approach based on data envelopment analysis and Malmquist productivity index to investigate the performance of power plants and conducted an empirical study with eight thermal power plants in Taiwan. The analysis results show the productivity improvements, and thus, help Taiwan Power Company to monitor and diagnose changes in the productivity of its thermal power plants. Furthermore, this study also provides specific directions for improvements to increase competitiveness in the face of the continuing liberalization of the Taiwanese power generation market.**

***Index Terms*—Data envelopment analysis (DEA), Malmquist productivity index, productivity change, relative efficiency, state-owned power company.**

I. INTRODUCTION

THIS PAPER presents a case study in which we applied data envelopment analysis (DEA) models to measure the relative efficiencies and employed Malmquist productivity index to measure productivity changes for thermal power plants operated by the Taiwan Power Company (TPC). TPC is a state-owned enterprise in Taiwan, and is the only electric utility in charge of power generation, transmission, distribution, and sales. Facing the challenges of power industry liberalization, TPC has devoted itself to establishing a technology–productivity–competitiveness oriented operating strategy to maintain its competitiveness in power industry [1]. Moreover, to increase competition in the power market, the Taiwanese government is adopting the policy of privatizing the TPC and issuing new licenses to Independent Power Providers (IPPs). Consequently, it is crucial for the TPC to increase the productivity of thermal power plants to cope with the negative impacts of liberalization of the electricity market and competition from IPPs [2]. TPC needs effective methods to evaluate and examine changes in the productivity of thermal power plants.

This study was motivated by a real problem, and thus, aimed to fill the gap for evaluating the performance of the thermal power plants operated by TPC. In particular, this study employs nonparametric Malmquist productivity index to study the productivity changes, which can be classified into efficiency and technology aspects, of the plants from 1994 to 1999. In practice, efficiency evaluation, generally, considers multiple input resources and output factors. DEA, first introduced by Charnes *et al.* in 1978 [3], is a linear programming approach that is capable of simultaneously dealing with multiple inputs and multiple outputs, yet which does not require the predetermined weights to the input and output factors. DEA models offer a practicable approach for evaluating the relative efficiency of decision-making units (DMUs) in various contexts. However, the relative efficiency and the productivity changes of power plants have seldom been addressed in existing studies.

The rest of this paper is organized as follows. Section II describes the fundamentals of this study including DEA models and Malmquist productivity index and also reviews the related literature. Section III describes an empirical study on the productivity changes of thermal power plants in Taiwan. Section VI concludes with discussions on the contributions and future research directions.

II. FUNDAMENTAL

A. Distance Functions and DEA Models

Power generation is a process transforming multiple inputs (resources) to various outputs (services). In this section, we, first, generalize and formalize this transformation process in terms of models, and thus, introduce some relevant techniques based on the generalization for performance evaluation.

Considering $x \in \Re_+^m$ as the input vector and $y \in \Re_+^n$ as the output vector, the production technology Γ such as power generation can be defined as follows:

$$\Gamma \equiv \{(x, y) : \, y \, \text{can be produced by} \, x\}. \tag{1}$$

The boundary of the technology is defined as

$$\partial\Gamma \equiv \{(x, y) : (x, \beta y) \notin \Gamma, \beta > 1\}. \tag{2}$$

Shephard [4] defined the output distance function between any specific input–output bundle (x', y') and the boundary $\partial\Gamma$ as follows:

$$D_O(x', y') \equiv \inf\{\alpha : (x', y'/\alpha) \in \Gamma\} \tag{3}$$

where $D_O(x', y')$ can characterize the relative location of (x', y') to Γ. Thus, $(x', y') \in \Gamma$ if and only if $D_O(x', y') \leq 1$; $(x', y') \in \partial\Gamma$ if and only if $D_O(x', y') = 1$.

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Although the production technology Γ is unknown, given a set of observations $R = \{(x_1, y_1), (x_2, y_2), \ldots, (x_{|R|}, y_{|R|})\}$, where $x_r \in \Re_+^m$ and $y_r \in \Re_+^n$ for $r \in R$, it can be derived based on the conditions of convexity, free disposal, inclusion of observations, and minimum extrapolation [5]. The empirical production technology $\hat{\Gamma}$ derived from the observation set can, then, be expressed as a set of linear inequalities in nonnegative variables as follows:

$$\hat{\Gamma} \equiv \left\{ (x, y) : \sum_{r \in R} x_r \lambda_r \leq x, \sum_{r \in R} y_r \lambda_r \geq y \right. \\ \left. \sum_{r \in R} \lambda_r = 1, \lambda_r \geq 0, r \in R. \right\} \quad (4)$$

Therefore, the output distance function $D_O(x', y')$ for any (x', y') corresponding to $\hat{\Gamma}$ can be estimated as follows:

$$\begin{aligned} [D_O(x', y')]^{-1} = \max \alpha & \\ \text{s.t.} \sum_{r \in R} x_{ir} \lambda_r &\leq x'_i, \quad i = 1, \ldots, n \\ \sum_{r \in R} y_{jr} \lambda_r &\geq \alpha y'_j, \quad j = 1, \ldots, m \\ \sum_{r \in R} \lambda_r &= 1 \\ \lambda_r &\geq 0, \quad r \in R. \end{aligned} \quad (5)$$

If $(x', y') \in R$, i.e., $(x', y') \in \Gamma$, the output distance functions can also be interpreted as the output-based Debreu–Farrell technical efficiency (TE) measures [6], [7], the relative efficiency compared against the peer group R. Combining the concepts of TE and empirical production technology leads to one of the well-known DEA models, i.e., the Banker–Charnes–Cooper (BCC) model [5] as follows:

$$\begin{aligned} &\max \theta \\ &s.t. \sum_{r \in R} x_{ir} \lambda_r \leq x'_i, \quad i = 1, \ldots, n \\ &\sum_{r \in R} y_{jr} \lambda_r \geq \theta y'_j, \quad j = 1, \ldots, m \\ &\sum_{r \in R} \lambda_r = 1 \\ &\lambda_r \geq 0, \quad r \in R. \end{aligned} \quad (6)$$

The optimal value of (6), θ^*, is related to the output-oriented TE for DMU $(x', y') \in R$. For example, if $\theta^* = 1.2$, it means that, compared to the given peer group, this specific DMU (x', y') can increase all its outputs to 120% while maintaining same input usage since a feasible production plan that uses no more than x' to produce no less than $1.2y'$ can be derived from the observed DMUs.

Assuming constant returns to scale (CRS), (6) can be rewritten as another popular DEA model, i.e., the Charnes–Cooper–Rhodes (CCR) model [3] as follows:

$$\begin{aligned} &\max \phi \\ &\text{s.t.} \sum_{r \in R} x_{ir} \lambda_r \leq x'_i, \quad i = 1, \ldots, n \\ &\sum_{r \in R} y_{jr} \lambda_r \geq \phi y'_j, \quad j = 1, \ldots, m \\ &\lambda_r \geq 0, \quad r \in R. \end{aligned} \quad (7)$$

Other DEA variants and more comprehensive reviews can be found, for example, in [8]–[11].

Banker *et al.* [5] referred to $1/\phi^*$ as the overall efficiency, $1/\theta^*$ as the pure TE, and the ratio θ^*/ϕ^* as the scale efficiency (SE). TE determines the operational efficiency. Moreover, a DMU with TE less than one, i.e., $\theta^* > 1$, indicates that the current operation is inefficient and output should be able to be increased while maintaining the same input level. SE measures the difference from the optimum production scale, i.e., the most productive scale size (MPSS). The smaller the SE, the worse the production scale or further difference from MPSS.

The optimal solutions of (7) also guide the direction of improvements in relation to scale. $\sum_{r \in R} \lambda_r^* < 1$ indicates that the DMU operates at increasing returns to scale (IRS) region, i.e., a proportional increase of all input levels would produce a more than proportional increase in output levels. A DMU with $\sum_{r \in R} \lambda_r^* > 1$ operates at decreasing returns to scale (DRS) region, in which a proportional increase of all input levels produces a less than proportional increase in output levels. If a DMU is operating at the MPSS, it is scale efficient, and thus, presents CRS. That is, $\sum_{r \in R} \lambda_r^* = 1$.

Alternatively, a scale-inefficient DMU presents DRS as it exceeds the MPSS and presents IRS as it is lesser than the most productive size. This implies that resources may be transferred from DMUs operating at DRS to those at IRS to increase productivity at both sets of DMUs. That is, using DEA models can specify the directions of resource reallocations to improve SE as well as overall efficiency.

B. Malmquist Productivity Index

Malmquist index is used for bilateral comparisons of the productivity change over time or the productivity difference for any different predefined peer groups [12]. Fare *et al.* proposed a DEA-like nonparametric Malmquist index that can be decomposed into technical change and efficiency change [13], [14].

Let Γ^b and Γ^t represent the production technologies during the base period b and another period t, respectively. Hereafter, the superscripts represent the production technology and/or data from the corresponding periods b or t. Considering $(x^b, y^b) \in \Gamma^b$ and $(x^t, y^t) \in \Gamma^t$, two output distance functions can be defined as follows:

$$D_O^b(x^b, y^b) \equiv \inf\{\alpha : (x^b, y^b/\alpha) \in \Gamma^b\} \quad (8)$$

$$D_O^t(x^t, y^t) \equiv \inf\{\alpha : (x^t, y^t/\alpha) \in \Gamma^t\} \quad (9)$$

where $D_O^b(x^b, y^b)$ and $D_O^t(x^t, y^t)$ measure the distance from (x^b, y^b) and (x^t, y^t) to the corresponding technology boundary $\partial\Gamma^b$ and $\partial\Gamma^t$. It is clear that $D^b_O(x^b, y^b) \leq 1$ and $D^t_O(x^t, y^t) \leq 1$. The projected points are obtained as follows:

$$(\tilde{x}^b, \tilde{y}^b) \equiv \left(x^b, \frac{y^b}{D^b_O(x^b, y^b)}\right) \in \partial\Gamma^b$$

and

$$(\tilde{x}^t, \tilde{y}^t) \equiv \left(x^t, \frac{y^t}{D^t_O(x^t, y^t)}\right) \in \partial\Gamma^t.$$

They are on the technology boundaries, and so, both are technically efficient. The distance function from $(\tilde{x}^b, \tilde{y}^b)$ to the boundary of Γ^t is, thus, the boundary shift measure from $\partial\Gamma^b$ to $\partial\Gamma^t$ with regard to (x^b, y^b), where the input/output mix remains unchanged, and can be expressed as follows:

$$D^t_O(\tilde{x}^b, \tilde{y}^b) \equiv \inf\{\alpha : (\tilde{x}^b, \tilde{y}^b/\alpha) \in \Gamma^t\}. \tag{10}$$

Similarly, the backward distance from $(\tilde{x}^t, \tilde{y}^t)$ to $\partial\Gamma^b$, i.e., the boundary shift from $\partial\Gamma^t$ to $\partial\Gamma^b$, is defined as follows:

$$D^b_O(\tilde{x}^t, \tilde{y}^t) \equiv \inf\{\alpha : (\tilde{x}^t, \tilde{y}^t/\alpha) \in \Gamma^b\}. \tag{11}$$

It should be noted that $D^t_O(\tilde{x}^b, \tilde{y}^b)$ and $D^b_O(\tilde{x}^t, \tilde{y}^t)$ do not necessarily need to be equal to or less than one. The values being greater than one indicates that the base boundary is outside the reference technology, and thus, the base technology outperforms the reference technology. In particular, $D^b_O(\tilde{x}^t, \tilde{y}^t) > 1$ indicates that $(\tilde{x}^t, \tilde{y}^t) \notin \Gamma^b$. If technological improvement occurs from b to t, $D^t_O(\tilde{x}^b, \tilde{y}^b) < 1$, yet $D^b_O(\tilde{x}^t, \tilde{y}^t) > 1$. Moreover, (5) can be used as a practical computation procedure for all distance functions discussed here with some minor changes for the peer group R and the reference basis (x', y').

The geometric mean of $D^t_O(\tilde{x}^b, \tilde{y}^b)$ and $D^b_O(\tilde{x}^t, \tilde{y}^t)^{-1}$ is the technical change that measures the shift in frontier technology (SIT) between the two time periods b and t [13]. The technical change can, thus, be written as follows:

$$\begin{aligned}\text{Technical change} &= \sqrt{D^b_O(\tilde{x}^t, \tilde{y}^t) D^t_O(\tilde{x}^b, \tilde{y}^b)^{-1}}\\ &= \sqrt{\frac{D^b_O(x^t, y^t)}{D^t_O(y^t, y^t)} \frac{D^b_O(x^b, y^b)}{D^t_O(x^b, y^b)}}.\end{aligned} \tag{12}$$

If technical change exceeds one, it indicates that the production technology or capability progresses from period b to t. Meanwhile, if the SIT score is lesser than one, it indicates that the production technology is depressive between the two time periods.

Fare *et al.* [13] defined the efficiency change between b and t as follows:

$$\text{Efficiency change} = \frac{D^t_O(x^t, y^t)}{D^b_O(x^b, y^b)}. \tag{13}$$

Efficiency change measures the degree of catching-up in efficiency (CIE) from period b to t. A CIE score exceeding one indicates an improvement in efficiency, while a CIE score below one implies a decrease in efficiency during these two time periods.

The product of technical change (or SIT) and efficiency change (or CIE) is the overall productivity change between b and t, which is conceptually consistent with the Malmquist index [12]. A score of Malmquist index exceeding one indicates overall productivity improvement during these two time periods.

Both the SIT and CIE scores can be evaluated for understanding the productivity change of the DMU during a specific time period. For example, Chang *et al.* [15] applied the DEA model and the Malmquist productivity approach to evaluate the relative changes of 23 Taiwan administrative regions between 1983 and 1990. Moreover, Chen and Yeh [16] evaluated the relative efficiency of 34 commercial banks and used the Malmquist productivity index to investigate changes in their productivity between 1995 and 1996.

C. DEA Studies

There are a number of DEA studies on power systems and power industry, while DEA has been successfully applied in different domains. Extensive reviews and additional applications can be found in [10] and [11].

For studies on power industry, Fare *et al.* [17] applied DEA to evaluate the relative efficiency of electric utilities regulated by Illinois Commerce Commission, in which an output (net generation) and three inputs (fuel, labor, and capital) were considered. Charnes *et al.* [18] applied the DEA model to evaluate the management efficiency of regulated electricity cooperatives in Texas, in which three outputs (net margin, total kilowatthour sales, and total revenue from sales of electricity) and 11 inputs (operations expenses, maintenance expenses, consumer accounts expenses, administrative and general expenses, miles per consumer, line loss, average outage hours per customer, percentage system unload, total plant, salaries, and inventory) were considered. Miliotis [19] measured the efficiency of 45 electricity distribution districts of the Greek Public Power Corporation in different settings and used four different sets of input and output factors including the number of customers served, network length, capacity of installed transformation points, general expenses, administrative labor hours, technical labor hours, supplied energy, and served area for different analyses. In addition, the authors applied DEA models to evaluate the relative operating efficiency of 22 electricity distribution districts of TPC in Taiwan, and identified specific improvement directions for the inefficient districts [20], in which two outputs (total number of customers and energy supplied) and five inputs (employment expenditure, general expenditure, total assets, distribution network, and transformer capacity) were considered. In addition, we also investigated the reorganization of the districts and proposed organizational changes for improving their operating efficiency. Therefore, we conducted further study to improve the operational efficiency of the poorest district [21] based on DEA analysis. Also, we developed effective data mining methodologies to help TPC for fault location on power distribution feeder to reduce the impact of electricity shortage, and thus, improve operational efficiency [22]–[24]. Pahwa *et al.* [25] conducted a similar study for evaluating the relative efficiency of 50 electricity distribution centers in the United States.

For studies on power plants, Athanassopoulos *et al.* [26] developed the data envelopment scenario analysis for setting targets to electricity generating plants in the United Kingdom, in which four outputs (electricity produced, plant availability, accidents incurred, and pollution generated) and three inputs (fuel, controllable costs, and capital expenditure) were considered in the DEA models. Sueyoshi [27] explored a marginal cost-based pricing measurement using the cost-based DEA approach to examine the tariff structure of nine electric power companies in Japan, in which the output of 11 electricity sales (residential services, commercial services, and other services) and three inputs (labor price, capital price, and materials price) were considered. Park and Lesourd [28] evaluated the operating efficiency of 64 conventional fuel power plants in South Korea and considered an output (net electrical energy) and three inputs (fuel consumption, installed power, and labor). Sueyoshi and Goto [29] proposed a slack-adjusted DEA model to examine the performance of Japanese electric power generation companies from 1984 to 1993 and considered total generation as the output and used three inputs (capacity, total fuel consumption, and total employees). Raczka [30] evaluated the performance of 41 thermo-electric power plants in Poland, in which a single output (heat production) and three inputs (labor, fuel, and air pollution penalty) were considered. Finally, Cook and Green [31] developed a two-stage hierarchical model to evaluate a set of power plants and the individual power generating units, in which three inputs (forced derating, maintenance expenditure, and occupied hours) and two outputs (full capacity operating hours and number of outages) were considered for the analysis.

Furthermore, an increasing number of studies have addressed the growing concern about environmental issues by including pollutants such as SO_2 emissions in the analysis. In particular, Golany *et al.* [32] evaluated the operating efficiency of power plants in the Israel Electric Corporation, in which four outputs (generated power, operational availability, deviation from operational parameters, and SO_2 emissions) and three inputs (installed capacity, fuel consumption, and manpower) were considered. Lee *et al.* [33] studied the Korean electric power industry using data from 1990 to 1995, in which three inputs (labor, capacity, and fuel), one output (annual power generation), and three undesired outputs (emissions of SO_x, NO_x, and total suspended particulates) were studied. Fare *et al.* [34] compared the TE of 209 electric utilities before (in 1993) and after (in 1997) the implementation of the legislation to control acid rain. Fare *et al.* considered three inputs (labor, capacity, and fuel), one positive output of annual power generation, and one undesired output of SO_2 emissions and proposed a method of measuring shadow prices of SO_2 and the output elasticity of substitution between SO_2 and electricity.

III. EMPIRICAL STUDY

This section details an empirical study investigating the productivity changes of the TPC thermal power plants from 1994 to 1999. Following Golany and Roll [35], this empirical study involves three major tasks including problem structuring, determination of input and output factors for measuring the relative efficiency of the selected DMUs, and discussion of the DEA results.

A. Problem Structuring

TPC has eight thermal power plants, namely HSIEHHO, LINKOU, SHENAO, TAICHUNG, HSINTA, TALIN, TUNGHSIAO, and PENGHU. The total power generation of these eight plants exceeds 70% of the total energy generated in Taiwan [36]. On one hand, the eight considered plants using the same inputs to produce the same output factors belong to a homogeneous group for evaluation. On the other hand, their scales are very different in terms of number of employees, installed power generation capacity, production costs, and energy generation. That is, the power plants utilize the same input resources at various levels to generate various levels of energy output. It is difficult for TPC to predetermine an effective set of weights to consider multiple input and output factors for evaluating their operation efficiencies and productivity changes meaningfully. Therefore, DEA offers an appropriate method of filling in this gap and evaluating the relative efficiencies of TPC power plants.

B. Input and Output Factors

According to the guidelines in the TPC Responsibility Center System [37] and Profitability Center System [38], this study uses total energy generated as the output factor and total installed capacity (MW), total number of employees, and total production cost as input factors in the DEA models. The total energy generated is the major output since the function of the plants is to supply electricity to meet demand. The installed power generation capacity is a fundamental input factor that differentiates plant productivity. Meanwhile, the total number of employees is an important input, and in fact, personnel cost is also a critical input factor in state-owned enterprises. Production cost, which includes operating expenditures, fuel expenditures, and maintenance expenditures, is the input factor that covers the cost of supporting and maintaining plant operations. The value is derived from annual reports and adjusted by the wholesale price index (WPI), similar to the well-recognized producer price index (PPI), to constant dollars.

Table I lists the annual data of eight plants used in this study from 1994 to 1999. Using the annual data can reduce the influence of seasonal effects. Moreover, considering six time periods can effectively evaluate the productivity change of the plants along the time.

C. DEA Results for TPC Power Plants

Table II summaries the DEA results in which the eight plants in the same peer group are compared over a six-year period. It is found that all DMUs except for TAICHUNG and HSINTA (1998 and 1999) are found to be in the IRS region. Notably, small plants like PENGHU perform extremely poorly in terms of SE. For those in the IRS region, increasing their production scale offers one way of improving operational efficiency. For

TABLE I
INPUT AND OUTPUT DATA OF EIGHT THERMAL POWER PLANTS FROM 1994 TO 1999

DMUs (year_Plant)		Inputs			Output
		Total installed capacity	Total employees	Total production cost	Total energy generation
		MW	people	thousand NT dollars	million KWH
1	94HSIEHHO	2,000,000	471	12,426,374	12,844,387
2	94LINKOU	785,000	411	3,740,374	3,134,802
3	94SHENAO	400,000	304	1,797,876	1,627,436
4	94TAICHUNG	2,480,000	601	10,702,695	15,634,561
5	94HSINTA	2,100,000	633	9,454,532	14,292,521
6	94TALIN	2,572,000	616	12,038,804	10,582,045
7	94TUNGHSIAO	1,434,800	502	6,279,922	5,351,084
8	94PENGHU	49,000	133	397,607	177,834
9	95HSIEHHO	2,000,000	463	11,137,805	12,164,582
10	95LINKOU	785,000	401	3,442,390	3,376,350
11	95SHENAO	400,000	300	2,163,748	2,695,445
12	95TAICHUNG	2,480,000	689	8,525,404	15,625,863
13	95HSINTA	2,100,000	628	8,775,653	14,372,381
14	95TALIN	2,572,000	596	15,370,834	13,106,630
15	95TUNGHSIAO	1,415,800	496	5,888,324	5,284,628
16	95PENGHU	49,000	136	384,854	185,272
17	96HSIEHHO	2,000,000	452	11,357,979	11,308,192
18	96LINKOU	785,000	396	4,122,219	3,609,760
19	96SHENAO	400,000	295	2,707,973	2,718,372
20	96TAICHUNG	4,130,000	748	14,562,602	20,989,734
21	96HSINTA	2,100,000	658	10,073,417	14,369,615
22	96TALIN	2,572,000	587	15,322,094	13,482,091
23	96TUNGHSIAO	1,415,800	500	6,842,696	5,820,682
24	96PENGHU	49,000	134	447,771	203,563
25	97HSIEHHO	2,000,000	441	13,176,426	11,366,716
26	97LINKOU	785,000	389	4,133,172	3,591,961
27	97SHENAO	400,000	284	2,604,523	2,433,095
28	97TAICHUNG	4,680,000	763	17,086,873	27,276,122
29	97HSINTA	3,450,000	672	10,765,872	13,933,042
30	97TALIN	2,572,000	571	15,366,966	12,118,518
31	97TUNGHSIAO	1,415,800	489	7,376,071	6,434,761
32	97PENGHU	68,000	127	550,454	215,350
33	98HSIEHHO	2,000,000	430	13,796,449	10,861,879
34	98LINKOU	1,085,000	374	3,739,516	3,353,206
35	98SHENAO	400,000	278	2,714,390	2,495,479
36	98TAICHUNG	4,680,000	773	19,263,112	31,882,084
37	98HSINTA	3,942,000	694	9,673,218	12,807,162
38	98TALIN	2,572,000	557	16,293,807	12,489,778
39	98TUNGHSIAO	1,415,800	487	8,043,396	6,302,397
40	98PENGHU	74,000	128	761,849	229,887
41	99HSIEHHO	2,000,000	416	14,623,243	12,278,147
42	99LINKOU	1,085,000	360	3,736,215	3,124,663
43	99SHENAO	400,000	260	2,903,658	2,707,368
44	99TAICHUNG	4,680,000	782	18,494,116	33,039,905
45	99HSINTA	4,625,950	690	10,066,447	13,719,380
46	99TALIN	2,572,000	546	15,062,788	12,249,144
47	99TUNGHSIAO	1,628,500	478	9,086,701	7,621,805
48	99PENGHU	74,000	124	831,826	248,335

example, HSINTA moved from the IRS region to MPSS after increasing its capacity in 1997 and 1998. The plants indicated as in the optimum production scales, such as TAICHUNG and HSINTA, all have the largest installed capacity. This shows that larger power plants are more advantageous—at least up to the scale of TAICHUNG.

TAICHUNG plant has the largest scale than do other plants, and is classified as MPSS each year. From 1994 to 1999, this plant has increased its resource usages including total installed electricity generating capacity from 2480 kMW to 4680 kMW, while increasing total employees from 601 to 782, and total production costs from around NT$ 10 702 million to NT$ 18 494 million. Furthermore, TAICHUNG plant has also increased the total generation energy from 15 634 561 million kWh in 1994 to 33 039 905 million kWh in 1999.

On the other hand, PENGHU plant is located on a small island off Taiwan, and is smaller than other plants. From 1994 to 1999, PENGHU plant increased only its total installed electricity generating capacity from 49 kMW to 74 kMW. Table II shows that PENGHU, generally, exhibits high TE scores, indicating that it has good operational management. However, the SE scores of PENGHU plant are only around 0.5,

TABLE II
SUMMARY OF EFFICIENCY ANALYSIS

DMU	TE	SE	$1/\phi*$	Returns to Scale
94HSIEHHO	0.914	0.995	0.91	IRS
94HSINTA	0.968	0.9961	0.964	IRS
94LINKOU	0.577	0.981	0.566	IRS
94PENGHU	1	0.514	0.514	IRS
94SHENAO	0.606	0.952	0.576	IRS
94TAICHUNG	0.896	0.997	0.893	IRS
94TALIN	0.584	0.997	0.583	IRS
94TUNGHSIAO	0.533	0.991	0.528	IRS
95HSIEHHO	0.866	0.995	0.862	IRS
95HSINTA	0.974	0.995	0.969	IRS
95LINKOU	0.622	0.979	0.609	IRS
95PENGHU	1	0.536	0.536	IRS
95SHENAO	0.997	0.957	0.954	IRS
95TAICHUNG	1	1	1	MPSS
95TALIN	0.724	0.997	0.722	IRS
95TUNGHSIAO	0.534	0.990	0.529	IRS
96HSIEHHO	0.805	0.9951	0.801	IRS
96HSINTA	0.973	0.996	0.969	IRS
96LINKOU	0.663	0.981	0.651	IRS
96PENGHU	1	0.588	0.588	IRS
96SHENAO	1	0.963	0.963	IRS
96TAICHUNG	0.802	1	0.802	MPSS
96TALIN	0.745	0.997	0.742	IRS
96TUNGHSIAO	0.587	0.992	0.582	IRS
97HSIEHHO	0.809	0.995	0.805	IRS
97HSINTA	0.717	0.997	0.715	IRS
97LINKOU	0.66	0.983	0.648	IRS
97PENGHU	1	0.449	0.449	IRS
97SHENAO	0.896	0.962	0.862	IRS
97TAICHUNG	0.892	1	0.892	MPSS
97TALIN	0.669	0.997	0.667	IRS
97TUNGHSIAO	0.649	0.992	0.644	IRS
98HSIEHHO	0.773	0.995	0.769	IRS
98HSINTA	0.727	1	0.727	MPSS
98LINKOU	0.512	0.956	0.489	IRS
98PENGHU	0.799	0.551	0.44	IRS
98SHENAO	0.919	0.961	0.884	IRS
98TAICHUNG	0.978	0.998	0.976	IRS
98TALIN	0.69	0.997	0.688	IRS
98TUNGHSIAO	0.636	0.992	0.631	IRS
99HSIEHHO	0.875	0.994	0.87	IRS
99HSINTA	0.75	1	0.75	MPSS
99LINKOU	0.478	0.954	0.456	IRS
99PENGHU	1	0.475	0.475	IRS
99SHENAO	0.999	0.960	0.959	IRS
99TAICHUNG	1	1	1	MPSS
99TALIN	0.677	0.997	0.675	IRS
99TUNGHSIAO	0.667	0.993	0.663	IRS

indicating that the production is not in an inappropriate production scale, and this aspect deserves further study.

Notably, production technology might have changed during the six-year time frame. Therefore, this study also applies the Malmquist output-based productivity index to investigate the productivity changes of the eight TPC plants from 1994 to 1999 using the panel data listed in Table I.

D. Productivity Changes of the Power Plants

Table III summarizes the results of the overall productivity changes via Malmquist index, which can be further decomposed into technical changes and efficiency changes as addressed earlier. The calculations are based on (5), (12), and (13), in which $b = 1994$ and $t = 1995–1999$. That is, 1994 is set as the base period to be the reference point for observing the annual changes. As shown in Table III, the overall productivity indices increase from 1994 to 1999, except for HSINTA and LINKUO, for which it decreased slightly. The average overall productivity index was 1.134 in 1999. These indicate the improvements in productivity, and the average productivity in 1999 was around 13.4% better than that in 1994.

Examining the efficiency change (CIE), PENGHU and TAICHUNG remain constant (i.e., CIE score equals one) over the six-year study period. After a significant raise in 1995, the CIE scores of SHENAO remain the same. This trend indicates that PENGHU, TAICHUNG, and SHENAO can maintain the same position relative to others in terms of operational

TABLE III
SUMMARY OF THE PRODUCTIVITY INDEX

Change index	DMU Year	1994	1995	1996	1997	1998	1999
Efficiency Change index (CIE)	HSIEHHO	1	1	1	0.974	0.806	0.878
	HSINTA	1	1	1	0.823	0.828	0.789
	LINKOU	1	10.68	1.135	1.287	1.053	0.926
	PENGHU	1	1	1	1	1	1
	SHENAO	1	1.45	1.45	1.45	1.45	1.45
	TAICHUNG	1	1	1	1	1	1
	TALIN	1	1.364	1.359	1.19	1.06	1
	TUNGHSIAO	1	0.964	1.057	1.349	1.162	1.166
	Average	1	1.093	1.114	1.116	1.029	1.01
Technical Change index (SIT)	HSIEHHO	1	0.975	0.921	0.953	1.118	1.191
	HSINTA	1	1.045	0.973	0.965	1.028	1.096
	LINKOU	1	1.046	0.989	0.885	0.983	1.033
	PENGHU	1	1.053	1.371	1.382	1.522	N/A
	SHENAO	1	1.069	0.987	0.931	0.904	0.95
	TAICHUNG	1	1.054	1.114	1.272	1.479	1.536
	TALIN	1	0.921	0.96	0.982	1.149	1.204
	TUNGHSIAO	1	1.072	0.971	0.886	1.007	1.061
	Average	1	1.028	1.028	1.019	1.13	1.122
Productivity Change index	HSIEHHO	1	0.975	0.921	0.929	0.902	1.046
	HSINTA	1	1.045	0.973	0.794	0.85	0.864
	LINKOU	1	1.117	1.122	1.139	1.035	0.957
	PENGHU	1	1.053	1.371	1.382	1.522	N/A
	SHENAO	1	1.55	1.431	1.35	1.31	1.378
	TAICHUNG	1	1.054	1.114	1.272	1.479	1.536
	TALIN	1	1.256	1.304	1.17	1.218	1.204
	TUNGHSIAO	1	1.034	1.027	1.195	1.17	1.237
	Average	1	1.124	1.144	1.137	1.162	1.134

efficiency. That is, these three plants are able to perform better during all periods. However, the CIE scores of another three plants HSIEHHO, HSINTA, and LINKOU were observed to be continuously decreasing since 1997. This implies that these three plants operate inefficiently compared to the other five during these time periods, i.e., their own performance is deteriorating, while the performance of other plants is improving. Further checking the technical change index (SIT) of HSIEHHO, HSINTA, and LINKOU reveals increased scores that exceeded one. This phenomenon implies that the production technology is, generally, progressive but the operations of these three remain at a similar level. That is, all the subject power plants improved but the pace of improvement at these three stations lagged the rest of the group. Compared to the data in Table I, the power generated by HSIEHHO and HSINTA has changed little since 1997, yet the capacity of HSINTA increased from 3454 kMW in 1997 to 4626 kMW in 1999. This shows that HSINTA has failed to achieve the expected returns on its capacity increase.

Moreover, as illustrated in Table II, HSINTA followed an effective direction that its production scale has been increasing and it was, thus, moved from the IRS region to the MPSS. However, it demonstrates slight gains in terms of technology but significant losses in terms of operating efficiency. Similarly, LINKUO increased its capacity from 785 kMW in 1997 to 1085 kMW in 1998. However, after 1997, its technology continued improving while its efficiency reduced. This phenomenon might indicate that HSINTA and LINKUO do not appropriately adjust their short-term operations to incorporate the increase in capacity. Above observations demonstrate the importance of careful managerial adjustment of operations when the production scale is changed. Short-term operational efficiency is not only the key to successful productivity improvement without long-term structural changes such as scale, but is also the key determinant of the success of any strategic structural change in an organization.

In Taiwan, the power industry has undergone major changes owing to the liberalization of the electricity market and the privatization of TPC. In 1995, the government began to liberalize power generation (mostly thermal power plants). For example, the Mailiao thermal power plant owned by Taiwan's largest private enterprise installed three power generation units that started commercial operations on June 1, 1999, September 9, 1999, and September 23, 2000, respectively [36]. These new IPPs are, generally, considered to be efficient since they apply new technology, in contrast to the mostly old thermal power plants of TPC. Consequently, TPC has also taken actions to maintain and renovate its plants. Facing increasing challenges and decreasing government support, TPC should strive to improve the operating efficiencies of its plants to rise to the challenges from new IPPs in the deregulated power market in Taiwan. The proposed approach can, effectively, assist the decision makers to determine which new proposals should be funded, which existing projects should be continued, and what levels of each resource are needed for the thermal power plants. TPC decision makers should also justify their decisions and communicate those decisions to others, including the union, legislators, and government.

IV. CONCLUSION

Using Malmquist productivity index and its decompositions, this study evaluates productivity changes for eight TPC thermal power plants in Taiwan, from 1994 to 1999. This method can be adopted to monitor and diagnose productivity changes resulting from management decisions and the effectiveness of their implementation.

The overall productivity changes of the eight plants showed a slight progressive development. The analytical results provide decision makers with useful information regarding specific areas to be considered in improving the plant efficiency. This study finds significant effects of economic scale, i.e., larger production scale is better for TPC thermal power plants. However, while increasing the production scale that leads to progressive production technologies, greater attention should be paid to short-term managerial effort and operational adjustments. Without incorporating proper and effective short-term management, relative operational efficiency will decrease, damaging the total productivity improvement even when the long-term strategic direction is correct.

Indeed, most inefficient plants suffered from technical inefficiency rather than scale inefficiency, despite TPC attempting to increase the power generation capacity of its thermal power plants to meet the increasing energy demands in Taiwan. Thus, increased efforts should be made to improve operations and resource utilization. To maintain its competitive advantage in the face of the future liberalization of the electricity market and privatization, TPC needs to pay more attention not only to evaluating the relative efficiency and efficiency changes of thermal power plants but also to accomplishing the three major tasks (i.e., improving generation technology, enhancing productivity, and strengthening competitiveness) in the Competitiveness Enhancement Plan [36]. However, since the IPP plants data are confidential, this study could not directly compare the performance of TPC plants with IPP plants. Future research can be done to compare the efficiency among state-owned and IPP plants. In addition, similar approaches can be applied to analyze the productivity of other components of power systems (e.g., transmission and substation systems).

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