Sustainability **2014**, *6*, 779-793; doi:10.3390/su6020779

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Article

Unified Efficiency Measurement of Electric Power Supply Companies in China

Jinchao Li [1,*], Jinying Li [2] and Fengting Zheng [1]

[1] School of Economics and Management, North China Electric Power University, Beinong Road 2, Changping District, Beijing 102206, China; E-Mail: 15811441429@163.com

[2] Department of Economic Management, North China Electric Power University, Baoding 071003, China; E-Mail: jgxljy@163.com

* Author to whom correspondence should be addressed; E-Mail: lijc@ncepu.edu.cn;
Tel.: +86 15901161636.

Received: 16 December 2013; in revised form: 17 January 2014 / Accepted: 28 January 2014 / Published: 10 February 2014

Abstract: This paper measured the economic and unified efficiency of 24 electric power supply companies in China. With the development of a low carbon economy, further requirements for energy-saving and emission-reducing have been put forward for electric power supply companies. In this case, we considered the desirable (good) outputs (e.g., electricity sale amount) and undesirable (bad) outputs (e.g., line loss) in evaluating the performance of power supply companies. We combined the unified efficiency data envelopment analysis (DEA) model and the super-efficiency DEA model to create tge USDEA model, calculating companies' unified efficiency. The unified efficiency DEA model can easily incorporate both desirable and undesirable outputs in a unified analytical structure. The super-efficiency data envelopment analysis model can make a comparison among various efficient decision making units (DMUs). Our results showed that the electric power supply companies of Hebei, Qinghai, Ningxia, Beijing and Shanghai achieved the highest levels of unified efficiency during the observed period (2003–2010), which differed from the economic efficiency results. The results meant that using unified efficiency to evaluate power supply companies will motivate them to care more about social and environmental benefit besides economic benefit.

Keywords: electric power supply company; super data envelopment analysis; unified efficiency.

---

1. Introduction

With rapid growth of the economy and support from foreign countries, China's electric power industry has entered a new stage. China has achieved second in the world in electric power generation capacity and first in transmission line and transformation capacity. At the end of 2011, the national power generation capacity was 1,055.76 gigawatts (GW), the total transformation capacity above 110(66) kilovoltage (kV) was $239,162 \times 10^4$ kVA, the total length of transmission lines above 35 kV was 135×10^4 km. If these amounts of resources could not be used well or oversupplied, lots of labor force, materials and money could be consumed in vain. In order to avoid blind investment, we should pay more attention to the performance of electric power supply companies. However, the economic benefits, such as investment revenue rate and total production value, are usually used as the targets of performance evaluation of Chinese electric power supply companies. In fact, with the voice of "sustainable development" continuing to soar, Chinese electric power supply companies should also consider the environmental benefit and social benefit as well. In order to achieve this, we need to measure the unified performance of electric power supply companies, which is also important for comparing traditional economic performance.

The data envelopment analysis (DEA) method is a common method to measure the efficiency scores. The DEA method was proposed by Charnes *et al.* [1] for evaluating the relative efficiency of the decision making units (DMUs). Now, the DEA method has been used to measure the efficiency of the electric power supply companies around the world, such as Turkey [2], Sweden [3], Australia, New Zealand [4], Philippines [5], UK [6], Taiwan [7], and Scandinavian Electricity Distribution [8]. However, research about Chinese electric power supply companies' unified efficiency is rare.

In this paper, we measured the performance of Chinese electric power supply companies with the consideration of energy saving by a proposed DEA approach, the unified super data envelopment analysis (USDEA) approach, which is a combination of unified efficiency data envelopment analysis (DEA) model and the super-efficiency DEA model. The remaining structure of this study is organized as follows: In section 2, the current structure of the electric power supply industry in China was outlined. Section 3 described previous DEA approaches and introduces a modified DEA approach methodology, which is a combination of unified DEA and super DEA. Section 4 described the efficiency measurement of the electric power supply companies in China. The last section made conclusions and discussed the implications of our empirical results.

2. The Current Structure of the Electric Power Supply Industry in China

In China, 90% of generating companies are owned by the state, and transmission is 100% government-owned. In order to accelerate the development of the electric power industry, the Chinese government implemented reforms in 2002 to dismantle the State Power Corporation into 11 new companies including two electric power supply companies, five electric power generation companies and four other companies, in order to end the power corporation's monopoly. However, until now, the grid corporation is still a central enterprise belonging to state monopoly management. The two electric power supply companies are the State Power Grid (SGCC) and China South Power Grid. The SGCC is the largest electric power supply company including 26 provinces' electric power supply subsidiary companies such as Beijing electric power supply company, Tianjin electric power supply company, and Hebei electric power supply company, which are shown in Figure 1. The length of the transmission lines above 35 kV operated by SGCC was 316,770 km at the end of 1997 and increased to 727,820 km until 2010. The average growth rate is 6.63%. Detailed data are shown in Figure 2. The voltage degrees of the transmission lines are 750 kV, 500 kV, 330 kV, 220 kV, 110 kV, and 35 kV. The percentage of voltage degrees of the transmission lines in 1997 and 2010 are shown respectively in Figure 3. It shows that the proportion of high voltage degree transmission lines has increased, with the proportion of transmission lines above 330kV being about 17% in 2010. Transformer capacity above 35kV operated by the SGCC was 449.81 GVA at the end of 1997, and it increased to 2,308.99 GVA at the end of 2010. The average growth rate is 13.33%. The detailed data are shown in Figure 4. Similar with the transmission lines' voltage degree structure, there was a trend in the percentage of transformer capacity to a high voltage degree as shown in Figure 5. The proportion of transformer capacity above 330kV was nearly 30% in 2010.

Figure 1. The organization of the State Power Grid (SGCC).

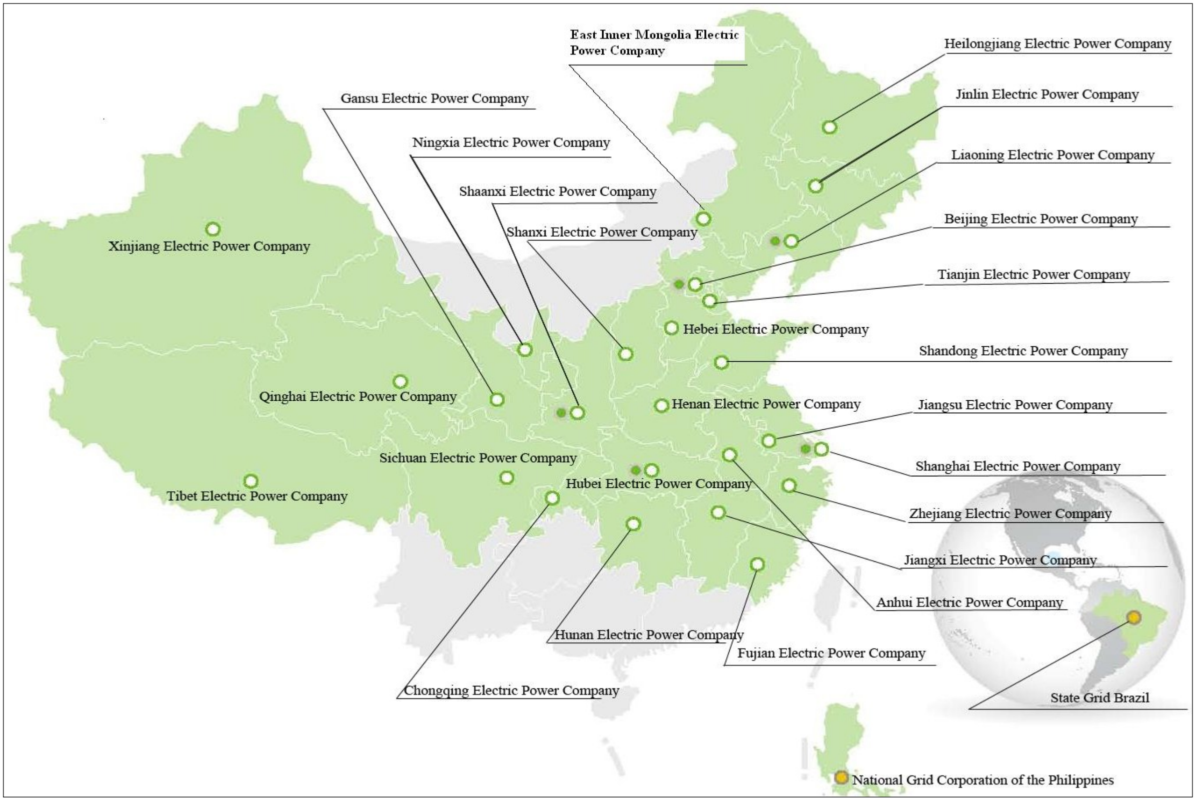


Figure 2. The total length of the transmission lines above 35 kV of the SGCC and its growth rate.

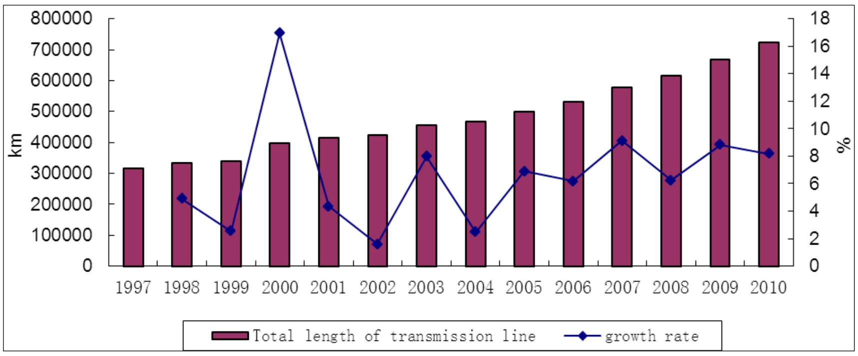


Figure 3. The voltage degrees percentage of the transmission lines of the SGCC in 1997 and 2010.

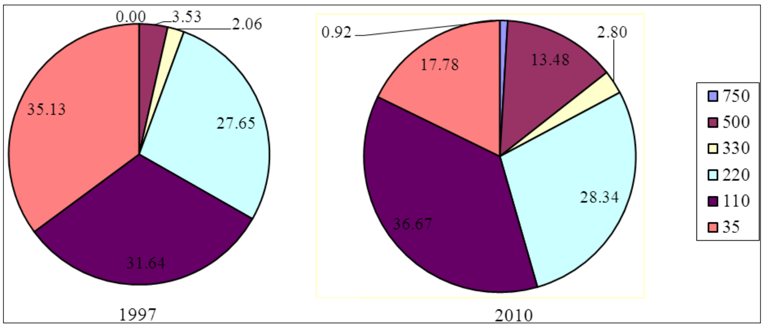


Figure 4. The total transformer capacity above 35 kV of the SGCC and its growth rate.

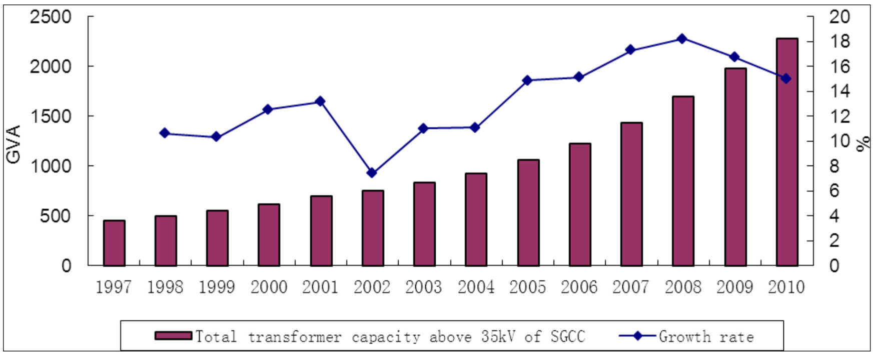
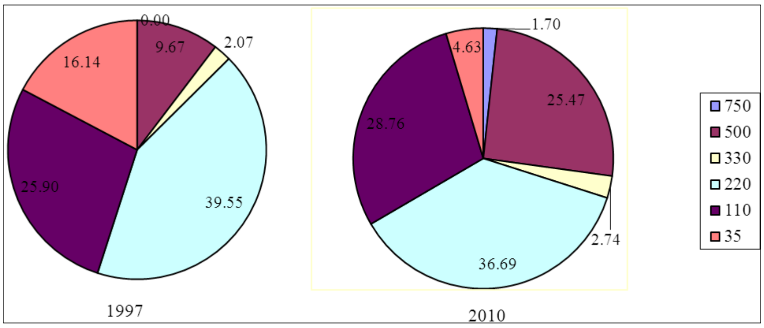


Figure 5. The voltage degrees percentage of transformer capacity of the SGCC in 1997 and 2010.



3. Literature Survey

Since the early 1990s, DEA has gradually become a popular benchmarking tool for studying the efficiency of electricity distribution utilities (Weyman-Jones [9]). Until now, much research has appeared in the literature and the study scope has also expanded from a single country case to an international one. Such published papers are shown in Table 1. It is an important step in the DEA method to choose the input-output variables. As shown in Table 1, the most frequently used outputs are units of energy delivered, number of customers, and size of the service area. The most widely used inputs are the number of employees, transformer capacity, and network length. In some papers, the transmission line loss was also taken as an input (Raul Perez-Reyes, Beatriz Tovar [10], and Ramos-Real *et al.* [11]) or output variable (Tooraj Jamasb and Michael Pollitt [12]). There are altogether four efficiency analysis methodologies used in these papers, including DEA, Malmquist index, DEA-PCA and DEA-COLS-SFA.

Table 1. Information on input-output variables and methods in related papers.

Author(s)	Data	Inputs	Outputs	Sources	Methods
Abbott (2006) [13]	Australia's electricity supply industry in 1969–1999	Capital stock Energy used (in TJ) Labor employed	Electricity consumed	Energy Economics	DEA
Wang *et al.* (2007) [14]	Hong Kong electricity supply industry in 1978–2003	Capital expenditure Labor	Sales of electricity delivered Customer density (customer/km^2)	Energy Policy	Malmquist index
Vinod Kumar Yadav, N.P. Padhy, H.O. Gupta (2010) [15]	29 Electricity Distribution Divisions Uttarakhand	Operation & Maintenance Cost (Rs Million) Number of employees	Energy sold (Million Units) Number of customers Average duration of interruption (Hours) Distribution line length (Circuit kilometer) Transformer capacity	Energy	DEA
Dag Fjeld Edvardsen, Finn R. Førsund (2003) [16]	Denmark, Finland, Norway, Sweden and The Netherlands in 1997	Total operating and maintenance costs the loss in MWh the replacement value	Number of customers Total lines Energy delivered	Resource and Energy Economics	DEA; Malmquist productivity index
Kaoru Tonea, Miki Tsutsui (2007) [17]	Japanese-US electric utility	generation capacity transmission line length distribution transformer capacity index of capital stock total cost for capital input total number of employees fuel data	Net electricity power sales	Socio-Economic Planning Sciences	DEA

Table 1. *Cont.*

Author(s)	Data	Inputs	Outputs	Sources	Methods
A.Azadeh, S.F.Ghaderi, H.Omrani, H.Eivazy (2009) [18]	38 electricity distribution units in Iran	Network length (km) Transformers capacity (MWA) Number of employees	Number of customers Total electricity sales	Energy policy	DEA-COLS-SFA
Vinod KumarYadav, N.P.Padhy, H.O.Gupta (2011) [19]	29 Electricity Distribution Divisions of an Indian state–Uttarakhand	O & M cost Number of employees	Energy sold (MillionUnit) Number of customers Duration of interruption/feeder	Energy Policy	DEA
Carlos Pombo, Rodrigo Taborda [20]	12 distribution companies from 1985 to 2001 of Colombia	Employees in power distribution + commercialization Number of transformers + substations Power lines network (km) Regional GDP per capita National installed capacity in electricity generation	Total sales (GWh) Total customers Urban area served	Energy Economics	DEA
Marcos Pereira Estellita Lins, Maria Karla Vervloet Sollero, Guilherme Marques Caloba, Angela Cristina Moreira da Silva (2007) [21]	Brazilian electricity sector	Operational cost Number of employees Losses System Average Interruption Duration Index Network size	Number of Consumers Delivered energy Service Area	European Journal of Operational Research	DEA

4. Model Descriptions

4.1. Data Envelopment Analysis

Data envelopment analysis (DEA) is a non-parametric technique to assess the relative efficiencies of multi-input and multi-output production units. DEA uses linear programming methodology to define a production frontier for decision-making units (DMUs), then like Stochastic Frontier Analysis (SFA), DEA identifies a "frontier" on which the relative performance of all utilities in the sample can be compared: DEA benchmarks DMU only against the best producers. It can be characterized as an extreme point method which assumes that if a DMU can produce a certain level of output utilizing specific input levels, another DMU of equal scale could be capable of doing the same [22].

Since the introduction of DEA by Charnes *et al.*, several alternative models that preserve the upper bound of one for efficiency scores have been proposed. The main differences among these models are whether they are input or output oriented and whether they stipulate a constant or a variable return to scale. The original output-oriented DEA model which introduced by Adler, Friedman, and Sinuany-Stern [23] and Cook and Seiford [24] is as follows:

$$\begin{aligned}
&\theta^* = \min \theta_o \\
&s.t. \\
&\sum_{j=1}^{n} \lambda_j \bar{x}_{ij} \le \theta_o \bar{x}_{io} \quad i = 1,\ldots \\
&\sum_{j=1}^{n} \lambda_j \bar{y}_{rj} \ge \bar{y}_{ro} \quad r = 1,\ldots \\
&\lambda_j \ge 0 \quad j = 1,\ldots
\end{aligned} \tag{1}$$

The Model (1) evaluates the relative efficiencies of n DMUs, with each DMU using m inputs $\bar{x}_{ij}$ ($i = 1,\ldots$) and generating s outputs $\bar{y}_{rj}$ ($r = 1,\ldots$). Also, the score of the DMU under consideration is θ_o. The DMUs cannot be ranked exactly since there are several DMUs which take score 1 by Model (1). To overcome this problem, Andersen and Petersen [25] proposed a new approach which leads to a concept called "super-efficiency".

4.2. Super-Efficiency DEA (SDEA) Model

In the super-efficiency DEA model, the efficiency scores from the model are obtained by eliminating the data of the DMU to be evaluated from the solution set. The super-efficiency model is defined as follows:

$$\begin{aligned}
&\theta_S^* = \min \theta_o^S \\
&s.t. \\
&\sum_{\substack{j=1 \\ j \ne o}}^{n} \lambda_j x_{ij} \le \theta_o^S x_{io} \quad i = 1,\ldots \\
&\sum_{\substack{j=1 \\ j \ne o}}^{n} \lambda_j y_{rj} \ge y_{ro} \quad r = 1,\ldots \\
&\lambda_j \ge 0 \quad j = 1,\ldots
\end{aligned} \tag{2}$$

Model (2) computes the score of the DMU by removing it from constraints. Although Model (2) is introduced to rank efficient DMUs obtained by the model (1), we can use it to evaluate and rank all DMUs.

4.3. Unified Efficiency DEA Model

To deal with the undesirable (bad) outputs in assessing the operational and environmental performance of energy firms, Fare *et al.* [26] (pp. 473–474) proposed the following directional distance function:

$$Max\{\theta \mid (G+\beta\zeta_g, B-\beta\zeta_b) \in P(X)\} \tag{3}$$

Here, P(X) = {(G, B): X can produce (G, B)}. The P(X) indicates a production possibility set, which has a column vector of inputs (X) that can produce not only a column vector of desirable outputs (G) but also a column vector of undesirable outputs (B). In Equation (3), $\xi = (\xi_g, -\xi_b)$ represents a directional vector for desirable and undesirable outputs, β is a magnitude of how much each DMU can simultaneously increase its desirable outputs and decrease its undesirable outputs within the production possibility set. The directional vector $\xi = (\xi_g, -\xi_b)$ is suggested as $(1, 1, \ldots, 1, -1, -1, \ldots, -1)^T$ which contains s + h components.

Mandal and Madheswaran [27] assumed that if the firm's objective is to simultaneously expand the desirable output and reduce the undesirable one by same proportion without increasing the inputs, the directional technology distance function becomes:

$$\vec{D}_T(x, y, b, 0, y, -b) = \sup[\beta : [(1+\beta)y, (1-\beta)b] \in P(x)] \tag{4}$$

Here, the value β represents technical inefficiency. The direction vector $g = (g_x, g_y, -g_b) = (0, y, -b)$ determines the direction in which efficiency is measured. Given the technology and direction vector, the directional distance function measures the maximum feasible expansion of desirable output and contraction of undesirable output. For an efficient firm, which operates on the frontier, the value of the directional distance function β is zero. The directional distance function β is obtained by solving the maximization problem in model (5).

$$\begin{aligned}
&\max \beta \\
&s.t.\ \sum_{j=1}^{n} x_{ij}\lambda_j \le x_{ik} && (i = 1, \ldots \\
&\sum_{j=1}^{n} g_{rj}\lambda_j \ge g_{rk} + \beta g_{rk} && (r = 1, \ldots \\
&\sum_{j=1}^{n} b_{fj}\lambda_j \le b_{fk} - \beta b_{fk} && (f = 1, \ldots \\
&\sum_{j=1}^{n} \lambda_j = 1 \\
&\beta \ge 0, \lambda_j \ge 0 && (j = 1, \ldots
\end{aligned} \tag{5}$$

Here, the outputs regarding the *jth* DMU are separated into desirable outputs (g_{rk}) and undesirable outputs (b_{fk}). This model can measure the efficiency by $\theta = 1 - \beta$, where β is obtained from optimality of Model (5).

In addition to Model (5), Zhou and Ang [28] proposed the following model to measure the unified efficiency of the energy firms:

$$
\begin{aligned}
& Min\theta \\
& s.t. \quad \sum_{j=1}^{n} x_{ij}\lambda_j \le x_{ik} \quad (i = 1,\ldots \\
& \qquad \sum_{j=1}^{n} e_{qj}\lambda_j \le \theta e_{qk} \quad (q = 1,\ldots \\
& \qquad \sum_{j=1}^{n} g_{rj}\lambda_j \ge g_{rk} \quad (r = 1,\ldots \\
& \qquad \sum_{j=1}^{n} b_{fj}\lambda_j = b_{fk} \quad (f = 1,\ldots \\
& \qquad \theta \ge 0 and \lambda_j \ge 0 \quad (j = 1,\ldots
\end{aligned}
\tag{6}
$$

Here, inputs regarding the *jth* DMU are separated into non-energy ($x_{ij} : i = 1,\ldots$) and energy related inputs ($e_{qj} : q = 1,\ldots$). Model (6) can be considered as an extension of CCR (Charnes–Cooper–Rhodes) and the production possibility set of Model (6) is shaped by constant RTS (returns to scale). The USDEA model we proposed in this paper is on the basis of Model (6), which is illustrated in Section 4.4 of the paper.

4.4. The Unified Super DEA Model

The Model (6) cannot realize the comparison of the efficient DMUs. In order to solve this problem, we proposed a new model: the unified super DEA (USDEA) model, which is a combination of unified efficiency DEA model (Model (6)) and the super-efficiency DEA model (Model (2)). The USDEA model has the following formulation:

$$
\begin{aligned}
& \min \theta \\
& s.t. \quad \sum_{\substack{j=1 \\ j\ne k}}^{n} x_{ij}\lambda_j \le \theta x_{ik} \quad (i = 1,\ldots \\
& \qquad \sum_{\substack{j=1 \\ j\ne k}}^{n} g_{rj}\lambda_j \text{-} s^{+} = g_{rk} \quad (r = 1,\ldots \\
& \qquad \sum_{\substack{j=1 \\ j\ne k}}^{n} b_{fj}\lambda_j + \mathrm{s}^{-} = b_{fk} \quad (f = 1,\ldots \\
& \qquad \theta \ge 0, \lambda_j \ge 0, s^{+} \ge 0, s^{-} \ge 0 \quad (j = 1,\ldots
\end{aligned}
\tag{7}
$$

Here, unified super DEA Model (7) computes the score of the DMU by removing itself from constraints, which is realized by letting the j ≠ k in the formula. s^{+} is the slack variable related to desirable output. s^{-} is the slack variable related to undesirable output.

5. The Unified Efficiency of Chinese Electric Power Supply Companies

5.1. The Efficiency Analysis Indexes of the Electric Power Supply Company

At the point of production, the input efficiency indexes of electric power supply companies were chosen based on human input (e.g., input 3), cost of production (e.g., input 4) and material resources (e.g., inputs 1 and 2). The output indexes were chosen based on the considerations of economic benefit (e.g., output 1), social benefit (e.g., outputs 2 and 3) and environmental benefit (e.g., output 4). Among the four outputs, outputs1, 2, and 3 are the desirable outputs, while output 4 (line loss) is an undesirable output. In this paper, four variables were used as inputs and four variables were used as outputs. The variables were listed as below.

Inputs:

Input1 (x1): network length above 35 kV (km)

Input2 (x2): transformers capacity above 35 kV (MVA)

Input3 (x3): number of employees

Input4 (x4): cost of the main business (10^4 RMB)

Outputs:

Economic variables:

Output1 (y1): Electric power supply amount (10^8 kWh)

Social variables:

Output2 (y2): Power supply reliability (%)

Output3 (y3): The quality of the voltage (%)

Environmental variables

Output4 (y4): Line loss (%)

5.2. Data Collection

We studied the data of 24 electric power supply subsidiary companies of SGCC except East Inner Mongolia and Tibet Electric Power Supply Companies. Table 2 showed the raw data of 24 companies from 2003–2010. This study combined the data sets in the eight annual periods together into a single panel data set for our DEA application. Data have been gathered from China Electric Power Yearbooks, China Statistical Yearbooks and other various sources.

Table 2. Descriptive statistics.

Input or Output		**x1**	**x2**	**x3**	**x4**	**y1**	**y2**	**y3**	**y4**
Statistics	**Year**	**km**	**MVA**	**person**	**10^4 RMB**	**10^8 kWh**	**%**	**%**	**%**
Avg.	2003	17,988.21	32,585,447.29	27,882	1,852,066.5	494.28	99.85	98.923	7.33
	2005	18,660.04	38,841,223.33	26,873	2,713,685.1	636.94	99.92	99.357	6.99
	2008	21,619.95	54,380,961.41	30,823	4,356,075.8	896.08	99.86	99.094	6.71
	2010	23,331.50	63,781,929.07	31,420	5,827,761.3	1,132.99	99.94	99.145	6.46
Max.	2003	30,032.00	81,142,925	57,890	5,070,172.0	1,186.20	99.99	99.750	9.68
	2005	32,498.00	101,646,300	53,975	8,429,622.0	1,700.44	99.99	99.910	9.82
	2008	42,296.60	148,898,407	50,000	12,854,647.3	2,467.00	99.98	99.726	9.64
	2010	48,378.20	179,084,565	58,569	16,960,404.0	3,117.35	99.99	99.771	10.03
Min.	2003	5,623.00	6,199,795	7,775	357,199.0	129.06	99.29	97.960	5.00
	2005	6,090.00	8,266,095	7,590	510,641.0	170.04	99.65	98.807	4.80
	2008	6,734.60	15,712,429.5	8,553	843,629.9	270.00	99.54	98.276	3.96
	2010	7,085.80	18,310,338.5	8,638	1,361,123.0	380.60	99.85	98.336	3.65
S.D.	2003	7,943.12	19,174,585.21	13,162	1,258,966.1	303.92	0.18	0.414	1.29
	2005	8,174.88	25,411,117.08	13,041	1,943,449.3	419.35	0.09	0.327	1.32
	2008	10,071.58	36,669,123.61	12,460	2,977,477.4	612.86	0.09	0.430	1.38
	2010	11,409.58	44,375,521.66	13,421	4,025,598.2	783.34	0.04	0.426	1.50

5.3. The Unified Efficiency of 24 Electric Power Supply Subsidiary Companies of SGCC

We studied the unified efficiency by USDEA and the economic efficiency through SDEA, respectively, in order to explore the difference between them. We used inputs (x1, x2, x3, and x4) and outputs (y1, y2, y3, and y4) to calculate the unified efficiency. We used inputs (x1, x2, x3, and x4) and output (y1) to calculate the economic efficiency. We presented the unified efficiency scores and the economic efficiency scores of 24 electric power supply subsidiary companies in Table 3 and Table 4, separately. The ranking of the efficiency was based on the average of eight years' efficiency. What we found from comparing unified efficiency with economic efficiency was listed as below: (i) The ranking of unified efficiency and economic efficiency was different based solely on outputs. The unified efficiency took into consideration environmental and social benefit, whereas the economic efficiency did not. (ii) Tianjin, Qinghai, Jiangxi and Chongqing power supply companies had a great improvement in ranking, their achievements in the social and environmental outputs were reflected. (iii) The unified efficiencies of 24 electric power supply companies did not show a clear trend but all displayed a fluctuation during the observed periods (2003–2010).

Table 3. Unified efficiency scores of the 24 distribution units.

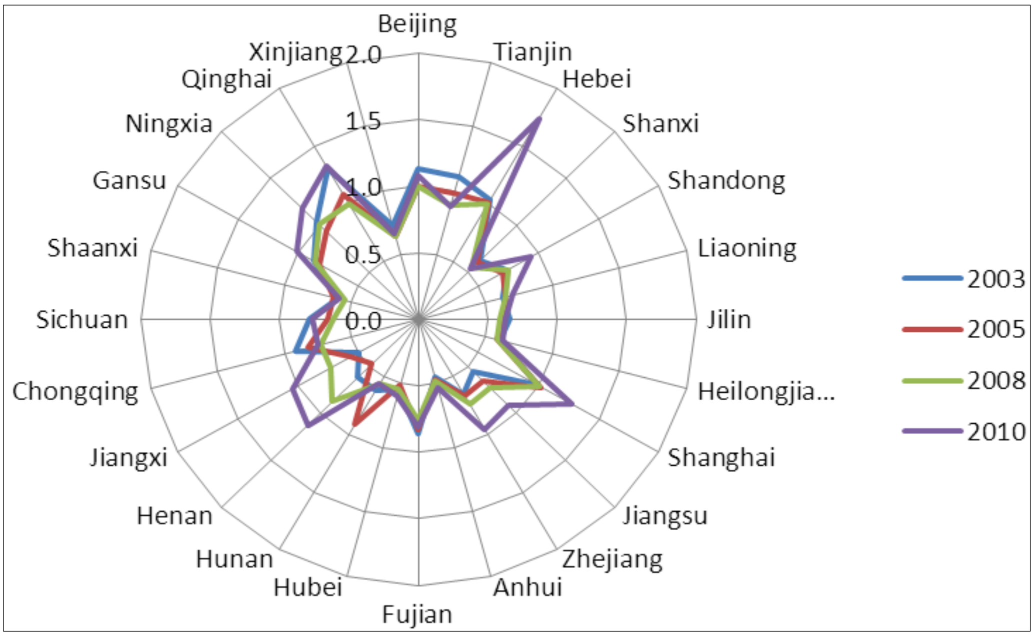
Firm	2003	2004	2005	2006	2007	2008	2009	2010	Average	S.D.	Ranking
Beijing	1.131	0.975	0.997	1.091	1.003	1.002	0.996	1.083	1.035	0.058	5
Tianjin	1.110	0.951	0.982	0.943	0.899	0.887	0.867	0.878	0.940	0.080	6
Hebei	1.031	1.021	1.013	1.017	1.029	0.998	1.020	1.735	1.108	0.254	2
Shanxi	0.625	0.621	0.601	0.573	0.586	0.548	0.502	0.533	0.574	0.043	22
Shandong	0.731	0.701	0.704	0.696	0.779	0.743	0.743	0.930	0.753	0.077	11
Liaoning	0.624	0.650	0.650	0.658	0.664	0.650	0.637	0.700	0.654	0.022	16
Jilin	0.657	0.625	0.613	0.592	0.575	0.586	0.582	0.626	0.607	0.028	19
Heilongjiang	0.610	0.590	0.590	0.588	0.563	0.589	0.596	0.631	0.594	0.020	20
Shanghai	0.991	1.030	1.022	1.014	1.023	1.009	0.994	1.272	1.045	0.093	4
Jiangsu	0.562	0.685	0.651	0.658	0.661	0.726	0.724	0.913	0.698	0.101	13
Zhejiang	0.648	0.638	0.665	0.707	0.688	0.737	0.808	0.957	0.731	0.106	12
Anhui	0.445	0.463	0.468	0.460	0.452	0.479	0.489	0.531	0.473	0.027	24
Fujian	0.859	0.863	0.831	0.817	0.775	0.763	0.764	0.807	0.810	0.040	8
Hubei	0.547	0.534	0.513	0.531	0.509	0.544	0.554	0.599	0.541	0.028	23
Hunan	0.618	0.637	0.910	0.573	0.566	0.556	0.544	0.565	0.621	0.121	18
Henan	0.618	0.613	0.477	0.737	0.779	0.873	0.922	1.126	0.768	0.205	10
Jiangxi	0.501	0.591	0.562	0.542	0.551	0.724	0.831	1.045	0.668	0.188	14
Chongqing	0.920	0.941	0.826	0.758	0.719	0.733	0.715	0.752	0.795	0.090	9
Sichuan	0.789	0.665	0.651	0.598	0.524	0.611	0.629	0.761	0.654	0.086	17
Shaanxi	0.605	0.598	0.630	0.574	0.549	0.544	0.546	0.590	0.580	0.032	21
Gansu	0.871	0.783	0.828	0.802	0.810	0.859	0.895	1.015	0.858	0.074	7
Ningxia	1.043	0.960	0.939	1.338	1.103	1.004	0.993	1.181	1.070	0.134	3
Qinghai	1.304	1.030	1.084	1.005	1.267	1.005	1.281	1.333	1.164	0.145	1
Xinjiang	0.729	0.660	0.648	0.671	0.658	0.649	0.653	0.663	0.666	0.026	15

Table 4. Economic efficiency scores of the 24 distribution units.

Firm	2003	2004	2005	2006	2007	2008	2009	2010	Average	S.D.	Ranking
Beijing	0.816	0.763	0.758	0.808	0.745	0.773	0.799	0.866	0.791	0.039	4
Tianjin	0.556	0.528	0.516	0.552	0.572	0.574	0.575	0.631	0.563	0.035	20
Hebei	1.010	1.021	1.013	1.008	1.019	0.993	1.014	1.149	1.028	0.049	1
Shanxi	0.600	0.613	0.601	0.573	0.586	0.548	0.502	0.533	0.569	0.039	19
Shandong	0.705	0.667	0.675	0.661	0.751	0.723	0.726	0.855	0.720	0.063	8
Liaoning	0.624	0.650	0.650	0.658	0.664	0.650	0.635	0.694	0.653	0.021	10
Jilin	0.614	0.603	0.594	0.579	0.566	0.584	0.581	0.626	0.594	0.020	15
Heilongjiang	0.573	0.570	0.581	0.588	0.563	0.589	0.596	0.631	0.586	0.021	17
Shanghai	0.807	0.880	0.920	0.923	0.943	0.949	0.954	1.117	0.936	0.087	2
Jiangsu	0.559	0.675	0.632	0.645	0.658	0.659	0.689	0.812	0.666	0.071	9
Zhejiang	0.596	0.565	0.580	0.610	0.663	0.642	0.667	0.772	0.637	0.066	13
Anhui	0.413	0.448	0.457	0.460	0.451	0.471	0.481	0.519	0.463	0.030	24
Fujian	0.657	0.664	0.618	0.617	0.591	0.637	0.660	0.727	0.646	0.041	12
Hubei	0.511	0.520	0.508	0.531	0.509	0.541	0.550	0.597	0.534	0.030	22
Hunan	0.577	0.611	0.910	0.564	0.554	0.556	0.544	0.564	0.610	0.123	14
Henan	0.606	0.605	0.452	0.737	0.778	0.871	0.918	1.080	0.756	0.201	6
Jiangxi	0.450	0.486	0.458	0.470	0.493	0.545	0.587	0.742	0.529	0.098	23
Chongqing	0.763	0.618	0.563	0.524	0.513	0.518	0.510	0.562	0.571	0.086	18
Sichuan	0.771	0.665	0.651	0.598	0.524	0.611	0.629	0.761	0.651	0.083	11
Shaanxi	0.554	0.562	0.608	0.558	0.536	0.544	0.546	0.590	0.562	0.025	21
Gansu	0.788	0.722	0.805	0.785	0.810	0.828	0.846	0.949	0.817	0.065	3
Ningxia	0.748	0.743	0.691	1.096	0.705	0.740	0.690	0.769	0.773	0.134	5
Qinghai	0.781	0.813	0.762	0.683	0.744	0.668	0.677	0.752	0.735	0.053	7
Xinjiang	0.543	0.534	0.539	0.585	0.595	0.616	0.633	0.663	0.588	0.048	16

In order to analyze the changes in the unified efficiency dynamically for each company during our research period, we selected four time points with an interval of one or two years between them—2003, 2005, 2008 and 2010—to illustrate 24 province electric power supply subsidiary companies' unified efficiencies. The result was displayed in Figure 6. It could be seen that: (i) The unified efficiency of Hebei electric power supply company showed the biggest deviation among the four time points, which standard deviation (S.D.) was 0.2535 (Table 3). (ii) The unified efficiency of 24 electric power supply companies in 2003, 2005 and 2008 did not change a lot, but the unified efficiency in 2010 showed a significant change. This result implied that 24 province electric power supply subsidiary companies experienced a great improvement in their social and environmental performance in 2010. This is due to the optimization of the grid structure and grid operation. We will collect and use related data to realize quantitative analysis of the unified efficiency.

Figure 6. The radar map of the 24 provinces' electric power supply subsidiary companies.



6. Conclusions

This study discussed a new DEA approach to measure the economic and unified efficiency of electric power supply companies. Since the former unified DEA models did not realize the comparison among the efficient DMUs, we modified the unified DEA model taking into account super DEA. Then, we used the unified super DEA (USDEA) model to measure the performance of the 24 electric power supply subsidiary companies of SGCC. The results indicated that the combination of a unified efficiency model and applying a robust super-efficiency data envelopment analysis model can be more reliable for unified efficiency estimating and ranking strategies.

The results showed that although the subsidiary companies of SGCC have made great progress in the grid scale, such as in transmission line and transformer capacity, their overall performance is poor. There are only five subsidiary companies with unified efficiencies above 1 among the 24 subsidiary companies. Meanwhile, it is possible that electric power supply companies will not only pay attention to improving economic outputs but will also place more emphasis on the social and environmental outputs after learning of our unified efficiency measure method. This is an embodiment of sustainable development in electric power supply companies.

Future studies are encouraged to gain more insight into the companies in this study in order to draw more generalized conclusions. Meanwhile, a greater amount of data might also be needed.

Acknowledgments

The authors thank the two reviewers whose comments improved the quality of this study. This work has been supported by "the Fundamental Research Funds for the Central Universities Nos.12MS74", "Beijing Higher Education Young Elite Teacher Project Nos. YETP0709" and "China Postdoctoral Science Foundation Nos. 2012M520221".

Author Contributions

Jinchao Li established the USDEA model and made the analysis results. Jinchao Li and Fengting Zheng completed the paper in English together. Jinying Li gave many good research advices.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Charnes, A.; Cooper, W.W.; Rhodes, E. Measuring the efficiency of decision making units. *Eur. J. Oper. Res.* **1978**, *2*, 429–444.
2. Bagdadioglu, N.; Price, C.M.W.; Weyman-Jones, T.G. Efficiency and ownership in electricity distribution: A nonparametric model of the Turkish experience. *Energy Econ.* **1996**, *18*, 1–23.
3. Hjalmarsson, L.; Veiderpass, A. Productivity in Swedish electricity retail distribution. *J. Econ.* **1992**, *94*, 193–205.
4. Zhang, Y.; Bartels, B. The effect of sample size on the mean efficiency in DEA with an application to electricity distribution in Australia, Sweden and New Zealand. *J. Prod. Anal.* **1998**, *9*, 187–204.
5. Pacudan, R.; de Guzman, E. Impact of energy efficiency policy to productive efficiency of electricity distribution industry in the Philippines. *Energy Econ.* **2002**, *24*, 41–54.
6. Giannakis, D.; Jamasb, T.; Pollitt, M. Benchmarking and incentive regulation of quality of service: An application to the UK electricity distribution networks. *Energ. Policy* **2005**, *33*, 2256–2271.
7. Chien, C.F.; Lo, F.Y.; Lin, J.T. Using DEA to measure the relative efficiency of the service center and improve operation efficiency through reorganization. *IEEE. T. Power Syst.* **2003**, *18*, 366–373.
8. Agrell, P.J.; Bogetoft, P. Economic and environmental efficiency of district heating plants. *Energ. Policy* **2005**, *33*, 1351–1362.
9. Weyman-Jones, T.G. Productive efficiency in a regulated industry: The area electricity boards of England and Wales. *Energy Econ.* **1991**, *13*, 116–122.
10. Perez-Reyes, R.; Tovar, B. Measuring efficiency and productivity change (PTF) in the Peruvian electricity distribution companies after reforms. *Energ. Policy* **2009**, *37*, 2249–2261.
11. Ramos-Real, F.J.; Tovar, B.; Iootty, M.; de Almeida, E.F.; Pinto, H.Q., Jr. The evolution and main determinants of productivity in Brazilian electricity distribution 1998–2005: An empirical analysis. *Energy Econ.* **2009**, *31*, 298–305.
12. Jamasb, T.; Pollitt, M. International benchmarking and regulation: An application to European electricity distribution utilities. *Energ. Policy* **2003**, *31*, 1609–1622.
13. Abbott, M. The productivity and efficiency of the Australian electricity supply industry. *Energy Econ.* **2006**, *28*, 444–454.
14. Wang, J.H.; Ngan, H.W.; Engriwan, W.; Lo, K.L. Performance based regulation of the electricity supply industry in Hong Kong: An empirical efficiency analysis approach. *Energ. Policy* **2007**, *35*, 609–615.

15. Yadav, V.K.; Padhy, N.P.; Gupta, H.O. A micro level study of an Indian electric utility for efficiency enhancement. *Energy* **2010**, *35*, 4053–4063.
16. Edvardsen, D.F.; Forsund, F.R. International benchmarking of electricity distribution utilities. *Res. Energy Econ.* **2003**, *25*, 353–371.
17. Tone, K.; Tsutsui, M. Decomposition of cost efficiency and its application to Japanese-US electric utility comparisons. *Socioecon. Plann. Sci.* **2007**, *41*, 91–106.
18. Azadeh, A.; Ghaderi, S.F.; Omrani, H.; Eivazy, H. An integrated DEA–COLS–SFA algorithm for optimization and policy making of electricity distribution units. *Energ. Policy* **2009**, *37*, 2605–2618.
19. Yadav, V.K.; Padhy, N.P.; Gupta, H.O. Performance Evaluation and Improvement Directions for an Indian Electric Utility. *Energ. Policy* **2011**, *39*, 7112–7120.
20. Pombo, C.; Taborda, R. Performance and efficiency in Colombia's power distribution system: Effects of the 1994 reform. *Energy Econ.* **2006**, *28*, 339–369.
21. Lins, M.P.E.; Sollero, M.K.V.; Caloba, G.M.; da Silva, A.C.M. Integrating the regulatory and utility firm perspectives, when measuring the efficiency of electricity distribution. *Eur. J. Oper. Res.* **2007**, *181*, 1413–1424.
22. Lovell, C.A.K.; Schmidt, P. A comparison of alternative approaches to the measurement of productive efficiency. *Appl. Mod. Prod. Theor.: Eff. Prod.* **1988**, *9*, 3–32.
23. Adler, N.; Friedman, L.; Sinuany-Stern, Z. Review of ranking methods in the data envelopment analysis context. *Eur. J. Oper. Res.* **2002**, *140*, 249–265.
24. Cook, W.D.; Seiford, L.M. Data envelopment analysis (DEA)—Thirty years on. *Eur. J. Oper. Res.* **2009**, *192*, 1–17.
25. Andersen, P.; Petersen, N.C. A procedure for ranking efficient units in data envelopment analysis. *Manage. Sci.* **1993**, *39*, 1261–1264.
26. Färe, R.; Grosskopf, S.; Noh, D.; Weber, W. Characteristics of a polluting technology: Theory and practice. *J. Econ.* **2005**, *126*, 469–492.
27. Mandal, S.K.; Madheswaran, S. Environmental efficiency of the Indian cement industry: An interstate analysis. *Energ. Policy* **2010**, *38*, 1108–1118.
28. Zhou, P.; Ang, B.W. Linear programming models for measuring economy-wide energy efficiency performance. *Energ. Policy* **2008**, *36*, 2911–2916.