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Applying an Efficiency Measure of Desirable and Undesirable Outputs in DEA to U.S. Electric Utilities

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Abstract

The measure proposed in this paper is a new nonparametric data envelopment analysis (DEA) scheme, the hybrid measure, for determining efficiency in the presence of radial and nonradial inputs or outputs. Further extension of the scheme occurred to address nonseparable desirable and undesirable outputs. Applying the model to measure the overall efficiency of U.S. electric utilities in the presence of both desirable and undesirable outputs indicated that the utilities had improved their overall management and environmental efficiency between 1996 and 2000.

Keywords: Hybrid measure, radial, nonradial, environmental factors, undesirable outputs, nonseparable outputs, U.S. electric utilities, DEA

JEL Classification codes: C67, D24, Q56

In accordance with global environmental conservation awareness, undesirable outputs of production and social activities (e.g., air pollutants and hazardous waste) have harmful social and environmental dimensions. Thus, development of technologies with less undesirable outputs is important in every area of production. Data envelopment analysis (DEA) usually indicates that producing more outputs relative to fewer input resources is a criterion of efficiency. In the presence of undesirable outputs, however, one should recognize technologies with more good (desirable) outputs and fewer bad (undesirable) outputs relative to fewer input resources as efficient.

Addressing the problem included integrating the radial and nonradial measures of efficiency in DEA into a unified framework called the hybrid measure. The extension of the model followed to address desirable (good) and undesirable (bad) outputs where separable and nonseparable goods and bads in input and output items were evident. Conducting the empirical study involved applying the model to 30 U.S. electric utilities over five years (1996-2000) using two inputs, total generation capacity (separable) and fuel consumption (nonseparable), and four outputs, nonfossil power generation (separable good), fossil power generation (nonseparable good), nitrogen oxide emissions (nonseparable bad), and sulfur dioxide emissions (nonseparable bad).

Reducing bad outputs is an important objective of the electric utilities but not their only goal. Utilities have to supply electricity to their customers, manage efficient production, and make a profit. The purpose of this study was to measure overall efficiency, taking into account not only environmental but also management efficiency. The results indicate that the U.S. utilities under study improved their overall management and environmental efficiency considering both good and bad outputs between 1996 and 2000; thus, the environmental index proposed in this paper serves as a reasonable means of measuring environmental performance. The current research is the first literature available on an environmental performance index that accounts systematically for the existence of separable and nonseparable goods and bads in a unified framework.

In his valuable works, Tyteca (1996) surveyed parametric and nonparametric approaches for environmental performance indicators. Further, Tyteca (1997) proposed linear programming models for environmental performance measurements. The approach in the current paper differs from Tyteca's models in the recognition of separable and nonseparable inputs and outputs (and the related indicators). Färe, Grosskopf, and Hernandez-Sancho (2004) proposed an environmental performance index using distance functions. Their index results from a pair of ratios of distance functions. However, one can obtain the index proposed in the current paper by solving only one unified linear programming model.

The following section reflects an introduction to the hybrid measure of efficiency. Next, the model is extended to an undesirable outputs case. An application of the model to U.S. electric utilities between 1996 and 2000 follows before the presentation of the conclusions.

A Hybrid Measure of Efficiency

Two types of measures or approaches are apparent in DEA: *radial* and *nonradial*. Differences exist in the characterization of input or output items. Suppose that there are four inputs, x_1, x_2, x_3, and x_4, in the concerned problem, where x_1 and x_2 are radial, and x_3 and x_4 are nonradial, that is, (x_1, x_2) are subject to change proportionally, such as $(\theta x_1, \theta x_2)$ (with $\theta > 0$), while x_3 and x_4 are subject to change nonradially. Such differences should be evident in the evaluation of efficiency.

The radial input part (x_1, x_2) satisfies the efficiency status if there is no proportionally reduced input $(\theta x_1, \theta x_2)$ (with $1 > \theta > 0$) that can produce the observed outputs. The nonradial input part x_3 (x_4) satisfies the efficiency status if no reduced x_3 (x_4) exists that can produce the observed outputs. Analogously, one can divide the output part into radial and nonradial outputs.

The CCR (Charnes, Cooper, & Rhodes, 1978) and BCC (Banker, Charnes, & Cooper, 1984) models represent the radial approach. The shortcoming of the radial approach is the neglect of the nonradial input or output slacks. Russell (1985); Pastor, Ruiz, & Sirvent (1999); and Tone (2001) proposed the nonradial approach, which addresses slacks directly but neglects the radial characteristics of inputs and/or outputs. The application in this paper follows the slacks-based measure (SBM) model (Tone, 2001). An integration of these approaches into a unified framework resulting in the proposition of a hybrid measure of efficiency is evident in the following sections.

Definition of a Hybrid Measure

Let the observed input and output data matrices be $X \in R^{m \times n}$ and $Y \in R^{s \times n}$, respectively, where n, m, and s designate the number of decision-making units (DMUs), inputs, and outputs. Decompose the input matrix into the radial part, X^RÎ $R^{m_1 \times n}$, and nonradial part, X^{NR}Î $R^{m_2 \times n}$, with $m = m_1 + m_2$, as follows:

$$X = \begin{pmatrix} X^R \\ X^{NR} \end{pmatrix}. \tag{1}$$

Decompose the output matrix Y into the radial part, Y^RÎ $R^{s_1 \times n}$, and nonradial part, Y^{NR}Î $R^{s_2 \times n}$, with $s = s_1 + s_2$, as follows:

$$Y = \begin{pmatrix} Y^R \\ Y^{NR} \end{pmatrix}. \tag{2}$$

The assumption is that the data set is positive (i.e., $X > 0$, and $Y > 0$). The production possibility set P is defined by

$$P = \{(x, y) | x \geq X\lambda, y \leq Y\lambda, \lambda \geq 0\}, \tag{3}$$

where λ is a nonnegative vector in R^n.

An expression for describing a certain DMU_o $(x_o, y_o) = (x_o^R, x_o^{NR}, y_o^R, y_o^{NR}) \in P$ is

$$\begin{aligned} \theta x_o^R &= X^R\lambda + s^{R-} \\ x_o^{NR} &= X^{NR}\lambda + s^{NR-} \\ \varphi y_o^R &= Y^R\lambda - s^{R+} \\ y_o^{NR} &= Y^{NR}\lambda - s^{NR+} \end{aligned} \tag{4}$$

with $\theta \leq 1, \varphi \geq 1, \lambda \geq 0, s^{R-} \geq 0, s^{NR-} \geq 0, s^{R+} \geq 0, s^{NR+} \geq 0.$

The vectors s^{R-} Î R^{m_1} and s^{NR-} Î R^{m_2} indicate the *excesses* for the radial and nonradial inputs, respectively, while s^{R+} Î R^{s_1} and s^{NR+} Î R^{s_2} specify the *shortfalls* for the radial and nonradial outputs, respectively. These excesses and shortfalls are called *slacks*.

As such, $\theta = 1$, $\varphi = 1$, $\text{l}_o = 1$, $\text{l}_j = 0$ ($\forall j$ ¹ o), with all slacks being zero, is a feasible expression. Based on Equation 4, define an index ρ, applying the nonoriented SBM form, as

$$\rho = \frac{1 - \frac{m_1}{m}(1-\theta) - \frac{1}{m}\sum_{i=1}^{m_2} s_i^{NR-} / x_{io}^{NR}}{1 + \frac{s_1}{s}(\phi - 1) + \frac{1}{s}\sum_{r=1}^{s_2} s_r^{NR+} / y_{ro}^{NR}}. \tag{5}$$

Index ρ is designed to decrease with respect to decreases in θ and increases in φ, s_i^{NR-} ($\forall i$) and s_r^{NR+} ($\forall r$), but not to be affected by s^{R-} and s^{R+} directly, reflecting free disposability of these radial slacks.[1] The index is also units invariant (i.e., invariant with respect to the measurement units of the data).

The hybrid efficiency status of the DMU_o $(x_o, y_o) = (x_o^R, x_o^{NR}, y_o^R, y_o^{NR}) \in P$ is defined as follows.

Definition 1 [hybrid efficient status]. The DMU_o (x_o, y_o) is hybrid efficient if and only if $\rho = 1$ for every feasible expression of Equation 4 (i.e., $\theta = 1$, $\varphi = 1$, $s^{NR-} = 0$, $s^{NR+} = 0$).

One can identify hybrid efficiency status by solving the following program with the variables θ, φ, λ, s^{NR-}, s^{NR+}, s^{R-}, and s^{R+}.

$$[\text{Hybrid}] \quad \rho^* = \text{Min} \frac{1 - \frac{m_1}{m}(1-\theta) - \frac{1}{m}\sum_{i=1}^{m_2} s_i^{NR-} / x_{io}^{NR}}{1 + \frac{s_1}{s}(\varphi - 1) + \frac{1}{s}\sum_{r=1}^{s_2} s_r^{NR+} / y_{ro}^{NR}}$$

s.t.

$$\begin{aligned} \theta x_o^R &= X^R\lambda + s^{R-}, \\ x_o^{NR} &= X^{NR}\lambda + s^{NR-}, \\ \varphi y_o^R &= Y^R\lambda - s^{R+}, \\ y_o^{NR} &= Y^{NR}\lambda - s^{NR-}, \end{aligned} \tag{6}$$

with $\theta \leq 1, \varphi \geq 1, \lambda \geq 0, s^{R-} \geq 0, s^{NR-} \geq 0, s^{R+} \geq 0, s^{NR+} \geq 0.$

Let an optimal solution for this program be θ^*, φ^*, l^*, s^{NR-*}, s^{NR+*}, s^{R-*}, and s^{R+*}.

Theorem 1. The DMU_o (x_o, y_o) is hybrid-efficient if and only if $\rho^* = 1$ (i.e., $\theta^* = 1$, $\varphi^* = 1$, $s^{NR-*} = 0$, and $s^{NR+*} = 0$.

One can transform the [Hybrid] into a linear program using the Charnes-Cooper (1962) transformation (as cited in Tone, 2001).

For a hybrid-inefficient DMU (i.e., $\rho^* < 1$), the hybrid projection is given by

$$
\begin{aligned}
&\bar{x}_o^R \leftarrow \theta^* x_o^R \\
&\bar{x}_o^{NR} \leftarrow x_o^{NR} - s^{NR-*} \\
&\bar{y}_o^R \leftarrow \varphi^* y_o^R \\
&\bar{y}_o^{NR} \leftarrow y_o^{NR} + s^{NR+*}.
\end{aligned}
\tag{7}
$$

Notice that the radial slacks s^{R-*} and s^{R+*}, if they exist, are not accounted for in the above projection because they are assumed to be freely disposable and have no effect on efficiency evaluation.

Theorem 2. The projected DMU_o $(\bar{x}_o^R, \bar{x}_o^{NR}, \bar{y}_o^R, \bar{y}_o^{NR})$ is hybrid-efficient.

Decomposition of Hybrid Efficiency

Using the optimal solution (θ^*, φ^*, l^*, s^{NR-*}, s^{NR+*}, s^{R-*}, s^{R+*}), decompose the hybrid efficiency indicator ρ^* into four factors as follows:

$$
\begin{aligned}
&\text{Radial input inefficiency:} && \alpha_1 = 1 - \theta^* \\
&\text{Nonradial input inefficiency:} && \alpha_2 = \frac{1}{m_2}\sum_{i=1}^{m_2} s_i^{NR-*} / x_{io}^{NR} \\
&\text{Radial output inefficiency:} && \beta_1 = \varphi^* - 1 \\
&\text{Nonradial output inefficiency:} && \beta_2 = \frac{1}{s_2}\sum_{r=1}^{s_2} s_r^{NR+*} / y_{ro}^{NR}.
\end{aligned}
\tag{8}
$$

In addition, define input and output inefficiencies as

$$
\begin{aligned}
&\text{Input inefficiency: } \alpha = \frac{m_1\alpha_1 + m_2\alpha_2}{m} \\
&\text{Output inefficiency: } \beta = \frac{s_1\beta_1 + s_2\beta_2}{s}.
\end{aligned}
\tag{9}
$$

Then one can express ρ^* as

$$
\rho^* = \frac{1-\alpha}{1+\beta}. \tag{10}
$$

This expression is useful for finding the sources of inefficiency and the magnitude of their influence on the efficiency score ρ^*.

A Hybrid Model with Undesirable Outputs

Development of technologies with less undesirable outputs is important in every area of production. In DEA literature, several authors have proposed methods to deal with the problem (e.g., Färe, Grosskopf, Lovell, & Pasurka, 1989; Korhonen & Luptacik, 2004; Scheel, 2001; Seiford & Zhu, 2002). The following sections show that one can address the problem by applying the hybrid model proposed in the preceding section.

Nonseparable Good and Bad Outputs

Derivation of some undesirable outputs (bads) often accompanies some desirable outputs (goods), such as air pollutants and motorization. Such outputs have a nonseparable relationship, and in most cases, their yields are proportional. In contrast, separable goods and bads may exist in outputs. For example, nuclear power generation is free of nitrogen oxide (NO_x) and sulfur dioxide (SO_2) emissions. Thus, one can classify output variables into nonseparable goods (NSG), nonseparable bads (NSB), separable goods (SG), and separable bads (SB).

On the input side, some inputs are not separable from outputs. For example, fossil fuel consumption (input) is nonseparable from fossil-fueled power generation (NSG) and air pollutants (NSB). Hence, one can classify input variables into separable (S) and nonseparable (NS) variables.

Decompose inputs/outputs data set matrices $X \in R^{m\times n}$ and $Y \in R^{s\times n}$ as follows:

$$X = \begin{pmatrix} X^{S} \\ X^{NS} \end{pmatrix}, \quad Y = \begin{pmatrix} Y^{SG} \\ Y^{SB} \\ Y^{NSG} \\ Y^{NSB} \end{pmatrix}, \tag{11}$$

where X^{S}Î $R^{m_1\times n}$ and X^{NS}Î $R^{m_2\times n}$ denote separable and nonseparable input data matrices, respectively, and Y^{SG}Î $R^{s_1\times n}$, Y^{SB}Î $R^{s_2\times n}$, Y^{NSG}Î $R^{s_3\times n}$, and Y^{NSB}Î $R^{s_4\times n}$ denote separable good, separable bad, nonseparable good, and nonseparable bad outputs, respectively.

The behavior of the nonseparable outputs Y^{NSG} and Y^{NSB} needs special attention. A reduction of the nonseparable bad outputs y^{NSB} is designated by θy^{NSB} with $0 \le \theta \le 1$, which is accompanied by a proportionate reduction in the good outputs y^{NSG} as denoted by θy^{NSG}. Although, in this case, the same proportionate rate θ in bad and good outputs is assumed, one could set other relationships between the two, for example, θy^{NSB} and fy^{NSG} with $0 \le \theta \le 1$, $0 \le \varphi \le 1$, along with an additional relationship between θ and φ.

In accordance with the reduction of bad outputs, on the input side, the nonseparable input x^{NS} is assumed to be reduced to θx^{NS}. Now, the new production possibility set P_{NS} is defined by

$$\begin{aligned} P_{NS} = \{ & (x^{S}, x^{NS}, y^{SG}, y^{SB}, y^{NSG}, y^{NSB}) \\ & | x^{S} \ge X^{S}\lambda, x^{NS} \ge X^{NS}\lambda, \\ & y^{SG} \le Y^{SG}\lambda, y^{SB} \ge Y^{SB}\lambda, y^{NSG} \le Y^{NSG}\lambda, y^{NSB} \ge Y^{NSB}\lambda \}. \end{aligned} \tag{12}$$

This definition is a natural extension of P in Equation 3.

A DMU_o $(x_o^{S}, x_o^{NS}, y_o^{SG}, y_o^{SB}, y_o^{NSG}, y_o^{NSB})$ Î P_{NS} can be expressed as

$$\begin{aligned} & x_o^{S} = X^{S}\lambda + s^{S-} \\ & \theta x_o^{NS} = X^{NS}\lambda + s^{NS-} \\ & y_o^{SG} = Y^{SG}\lambda - s^{SG+} \\ & y_o^{SB} = Y^{SB}\lambda + s^{SB+} \\ & \theta y_o^{NSG} = Y^{NSG}\lambda - s^{NSG+} \\ & \theta y_o^{NSB} = Y^{NSB}\lambda + s^{NSB+} \\ & \lambda \ge 0, 0 \le \theta \le 1, \\ & s^{S-} \ge 0, s^{NS-} \ge 0, s^{SG+} \ge 0, s^{SB+} \ge 0, s^{NSG+} \ge 0, s^{NSB+} \ge 0, \end{aligned} \tag{13}$$

where s^{S-}, s^{NS-}, s^{SG+}, s^{SB+}, s^{NSG+}, and s^{NSB+} are slacks to respective inputs/outputs. This expression is a variant of the hybrid model (6) as follows:

1. Nonseparable inputs and outputs are linked via the reduction rate variable θ ($0 \le \theta \le 1$), and they are *radial*.
2. Nonseparable bad outputs (NSB) have slacks (s^{NSB+}) with the *reverse* sign to nonseparable good outputs (NSG) because less bad outputs are to be expected.
3. Separable inputs and outputs are *nonradial*.

The definition of the efficiency status in the nonseparable case is altered as follows.

Definition 2 [NS-efficient]. A DMU_o ($x_o^S, x_o^{NS}, y_o^{SG}, y_o^{SB}, y_o^{NSG}, y_o^{NSB}$) is NS-efficient if and only if, for any θ ($0 \le \theta < 1$), one has

(1) $(x_o^S, \theta x_o^{NS}, y_o^{SG}, y_o^{SB}, \theta y_o^{NSG}, \theta y_o^{NSB}) \notin P_{NS}$, and

(2) there is no ($x^S, x^{NS}, y^{SG}, y^{SB}, y^{NSG}, y^{NSB}$) Î P_{NS} such that

$x_o^S \ge x^S$, $y_o^{SG} \le y^{SG}$, $y_o^{SB} \ge y^{SB}$

(with at least one strict inequality within these $m_1 + s_1 + s_2$ inequalities)

and

$x_o^{NS} \ge x^{NS}$, $y_o^{NSG} \le y^{NSG}$, $y_o^{NSB} \ge y^{NSB}$

(with at least one strict inequality for these three inequalities).

The Basic Undesirable Output Model

The basic undesirable output model with separable and nonseparable inputs or outputs can be implemented by the program in *l*, s^{S-}, s^{NS-}, s^{SG+}, s^{SB+}, s^{NSG+}, s^{NSB+}, and θ as below,

[Basic Undesirable Output Model]

$$\rho^* = \text{Min} \frac{1 - \frac{1}{m}\left(\sum_{i=1}^{m_1} \frac{s_i^{S-}}{x_{io}^S} + m_2(1-\theta)\right)}{1 + \frac{1}{s}\left(\sum_{r=1}^{s_1} \frac{s_r^{SG+}}{y_{ro}^{SG}} + \sum_{r=1}^{s_2} \frac{s_r^{SB+}}{y_{ro}^{SB}} + (s_3 + s_4)(1-\theta)\right)}$$

$$\begin{aligned} \text{s.t. } & x_o^S = X^S\lambda + s^{S-}, \\ & \theta x_o^{NS} = X^{NS}\lambda + s^{NS-}, \\ & y_o^{SG} = Y^{SG}\lambda - s^{SG+}, \\ & y_o^{SB} = Y^{SB}\lambda + s^{SB+}, \\ & \theta y_o^{NSG} = Y^{NSG}\lambda - s^{NSG+}, \\ & \theta y_o^{NSB} = Y^{NSB}\lambda + s^{NSB+}, \\ & s^{S-} \ge 0, s^{NS-} \ge 0, s^{SG+} \ge 0, s^{SB+} \ge 0, s^{NSG+} \ge 0, s^{NSB+} \ge 0, \\ & \lambda \ge 0, 0 \le \theta \le 1, \end{aligned} \tag{14}$$

where $m = m_1 + m_2$, and $s = s_1 + s_2 + s_3 + s_4$.

The objective function decreases strictly monotonically with respect to s_i^{S-} ($\forall i$), s_r^{SG+} ($\forall r$), s_r^{SB+} ($\forall r$), and θ. Let an optimal solution for the [Basic Undesirable Output Model] be (ρ^*, l^*, s^{S-*}, s^{NS-*}, s^{SG+*}, s^{SB+*}, s^{NSG+*}, s^{NSB+*}, θ^*); then one has $0 \le \rho^* \le 1$, and the following theorem holds.

Theorem 3. The DMU_o is NS-efficient if and only if $\rho^* = 1$ (i.e., $s^{S-*} = 0$, $s^{SG+*} = 0$, $s^{SB+*} = 0$, and $\theta^* = 1$).

If the DMU_o is NS-inefficient (i.e., $\rho^* < 1$), it can improve and become NS-efficient through the following NS projection:

$$\begin{aligned} x_o^S &\Leftarrow x_o^S - s^{S-*} \\ x_o^{NS} &\Leftarrow \theta^* x_o^{NS} - s^{NS-*} \\ y_o^{SG} &\Leftarrow y_o^{SG} + s^{SG+*} \\ y_o^{SB} &\Leftarrow y_o^{SB} - s^{SB+*} \\ y_o^{NSG} &\Leftarrow \theta^* y_o^{NSG} + s^{NSG+*} \\ y_o^{NSB} &\Leftarrow \theta^* y_o^{NSB} - s^{NSB+*}. \end{aligned} \tag{15}$$

Note that some of the slacks in nonseparable good and bad outputs (inputs) may remain positive even after the projection and that these slacks, if any, are not accounted for in the NS-efficiency score because one assumes weak disposability in these outputs. Thus, apply the SBM model for the separable outputs but employ the radial approach for the nonseparable inputs and outputs.

Variations of the Basic Model

This section involves modifying the basic model in the objective function as well as the constraints.

Accounting for radial slacks into the objective function

In the basic model, the assumption is that slacks for radial inputs and outputs are freely disposable. However, on some occasions, one needs to consider them in terms of efficiency, especially for the slacks in nonseparable good and bad outputs. Thus, the remaining slacks, s^{NS-}, s^{NSG+}, and s^{NSB+}, appear in the objective function as follows:

$$\rho^* = \text{Min} \frac{1 - \frac{1}{m}\left(\sum_{i=1}^{m_1} \frac{s_i^{S-}}{x_{io}^S} + m_2(1-\theta) + \sum_{i=1}^{m_2} \frac{s_i^{NS-}}{x_{io}^{NS}} \right)}{1 + \frac{1}{s}\left(\sum_{r=1}^{s_1} \frac{s_r^{SG+}}{y_{ro}^{SG}} + \sum_{r=1}^{s_2} \frac{s_r^{SB+}}{y_{ro}^{SB}} + (s_3+s_4)(1-\theta) + \sum_{r=1}^{s_3} \frac{s_r^{NSG+}}{y_{ro}^{NSG}} + \sum_{r=1}^{s_4} \frac{s_r^{NSB+}}{y_{ro}^{NSB}} \right)}, \tag{16}$$

where m_1 and m_2 are numbers of separable and nonseparable inputs, s_1 and s_2 are numbers of separable good and bad outputs, and s_3 and s_4 are numbers of nonseparable good and bad outputs, respectively.

Additional constraints

Adding some other constraints to the production possibility set, reflecting the characteristics of problems concerned, will make the model more realizable:

1. Keeping the total output amount status quo: Because the nonseparable good outputs are proportional to the nonseparable bad outputs, a reduction in the bads is accompanied by a reduction in nonseparable good outputs. Hence, the total amount of good outputs will decrease if one does not increase the separable good outputs. Coping with this problem requires adding a constraint to the basic model that demands the total output amount remain at the current level as follows:

$$\sum_{r=1}^{s_1} y_r^{SG} + \sum_{r=1}^{s_3} y_r^{NSG} = \sum_{r=1}^{s_1} y_{ro}^{SG} + \sum_{r=1}^{s_3} y_{ro}^{NSG} \tag{17}$$

The assumption is that the units of measurement for all good and bad outputs are the same.

2. Setting upper bound to the expansion of separable good outputs: In the above scenario, however, some upper bound to the expansion of separable good outputs exists. Thus, add constraints,

$$y_r^{SG} \le (1+\delta) y_{ro}^{SG} \quad (r = 1, \ldots, s_1), \tag{18}$$

where δ is an expansion ratio given externally.

3. Imposing returns to scale: Impose the variable returns-to-scale assumption on the basic model using the following constraint:

$$\sum_{j=1}^{n} \lambda_j = 1.$$

Decomposition of Inefficiency

In the same way described in the Decomposition of Hybrid Efficiency section, decompose the efficiency score (Equation 16) into the respective inefficiencies as follows:

$$\rho^* = \frac{1-\alpha}{1+\beta}, \tag{19}$$

where

$$\begin{aligned}
\alpha &= \frac{m_1\alpha_1 + m_2\alpha_2}{m} \\
\beta &= \frac{s_1\beta_1 + s_2\beta_2 + s_3\beta_3 + s_4\beta_4}{s} \\
\alpha_1 &= \frac{1}{m_1}\sum_{i=1}^{m_1} s_i^{S-*} / x_{io}^{S} : \text{Separable inputs inefficiency} \\
\alpha_2 &= \frac{1}{m_2}(1-\theta^*) + \frac{1}{m_2}\sum_{i=1}^{m_2} s_i^{NS-*} / x_{io}^{NS} : \text{Nonseparable inputs inefficiency} \\
\beta_1 &= \frac{1}{s_1}\sum_{r=1}^{s_1} s_r^{SG+*} / y_{ro}^{SG} : \text{Separable good outputs inefficiency} \\
\beta_2 &= \frac{1}{s_2}\sum_{r=1}^{s_2} s_r^{SB+*} / y_{ro}^{SB} : \text{Separable bad outputs inefficiency} \\
\beta_3 &= \frac{1}{s_3}(1-\theta^*) + \frac{1}{s_3}\sum_{r=1}^{s_3} s_r^{NSG+*} / y_{ro}^{NSG} : \text{Nonseparable good outputs inefficiency} \\
\beta_4 &= \frac{1}{s_4}(1-\theta^*) + \frac{1}{s_4}\sum_{r=1}^{s_4} s_r^{NSB+*} / y_{ro}^{NSB} : \text{Nonseparable bad outputs inefficiency.}
\end{aligned} \tag{20}$$

Furthermore, define the notations as follows:

$$\begin{aligned}
\bar{\alpha}_i &= \frac{m_i}{m}\alpha_i \quad (i = 1, 2) \\
\bar{\beta}_r &= \frac{s_r}{s}\beta_r \quad (r = 1, 2, 3, 4).
\end{aligned} \tag{21}$$

Using them, one can express Equation 19 as

$$\rho^* = \frac{1-\alpha}{1+\beta} = \frac{1-\bar{\alpha}_1-\bar{\alpha}_2}{1+\bar{\beta}_1+\bar{\beta}_2+\bar{\beta}_3+\bar{\beta}_4}. \tag{22}$$

An Empirical Study of U.S. Electric Utilities

The following sections reflect an application of the aforementioned model to U.S. electric utilities and an evaluation of their performance in the presence of both desirable (good) and undesirable (bad) outputs.

Data

Several researchers have studied the efficiency performance of electric utilities (Jamasb and Pollitt, 2001). Most of the studies included electric power sales by demand category and number of customers as outputs, which are desirable outputs (goods) of electric utilities. In contrast, the electric industry produces several kinds of undesirable outputs (bads). Typical bads are emission gases from fossil power plants (e.g., NO_x and SO_2), which cause smog and acid rain. CO_2 emitted from power plants is also a bad because CO_2 is one of the greenhouse gases that leads to climate change. Fly ash, mercury compounds, and nuclear fuel waste are further undesirable outputs of electric power plants. From the viewpoint of the electric supply service, blackouts and brownouts are undesirable outputs.

The current study included a focus on the NO_x and SO_2 emissions of electric power plants as bad outputs.[2] The electric power industry is responsible for a large share of the air emissions in the United States, specifically 23% of NO_x emissions and 67% of SO_2 emissions. Power plants emit NO_x by burning coal, oil, and natural gas and release SO_2 by burning coal and oil.

Electric utilities can take several measures to reduce NO_x and SO_2 emissions. One effective measure is using sulfur and nitrogen removal equipment. Utilities can further reduce emission of such gases by choosing high-quality fuel that includes less sulfur. Furthermore, changing the generation technology from fossil fuel to nonfossil fuel power, such as nuclear, hydraulic, and renewable power generation, would have a big impact.

Reducing NO_x and SO_2 emissions is an important objective but not the only goal for electric utilities. Utilities have to supply electricity to customers, manage the production process efficiently, and make a profit. The purpose of the proposed model is to measure overall efficiency of electric utilities considering both goods and bads.

The data source (1996-2000) for the current study was the Emissions & Generation Resource Integrated Database (eGRID), which is "a comprehensive source of data on the environmental characteristics of almost all electric power generated in the United States" (Environmental Protection Agency, 2011, para. 1). Inputs included the total generation capacity (megawatts: MW) and the amount of fuel consumption (British thermal units: BTU). Desirable (good) outputs were the annual net generation of fossil plants (megawatt hour: MWh) and net generation of nonfossil plants (MWh), while undesirable (bad) outputs were the annual NO_x and SO_2 emissions (tons).

Fuel input, fossil power generation, and NO_x and SO_2 emissions are closely related. If utilities reduce the amount of fuel input, the fossil power generation and emission gases will also decrease more or less. Therefore, one should consider them as nonseparable input, output, and bads, respectively. In contrast, total generation capacity and nonfossil power generation are separable inputs and outputs, respectively (see Table 1).

Table 1
Inputs and Outputs

Notation	Type of inputs and outputs	Data explanation
x_1	Separable input	Total generation capacity (MW)
x_2	Nonseparable input	Fuel consumption (BTU)
y_1	Separable good output	Nonfossil power generation (MWh)
y_2	Nonseparable good output	Fossil power generation (MWh)
y_3	Nonseparable bad output 1	NO_x emission (ton)
y_4	Nonseparable bad output 2	SO_2 emission (ton)

eGRID includes operational data for more than 100 companies. The current study included only companies that operate both fossil and nonfossil power plants. In general, outlier data influence DEA results a good deal. Screening all data by box plot aided in eliminating the influence of outliers. See Table 2 for the 30 DMUs on which balanced panel data were obtained for the five years, 1996 to 2000. The following analysis involved addressing these 150 (=30*5) DMUs as independent entities.

Table 2
The Sample DMUs

	DMU		DMU
1	Alabama Power Company	16	Northern Indiana Public Service Company
2	Appalachian Power Company	17	Northern States Power Company
3	Arizona Public Service Company	18	Ohio Power Company
4	Carolina Power & Light Company	19	PacifiCorp East
5	Consumers Energy Company	20	Portland General Electric
6	Detroit Edison Company	21	Psi Energy, Inc
7	Duke Power Company	22	Public Service Company of Colorado
8	Entergy Arkansas, Inc	23	Public Service Company of New Hampshire
9	Florida Power & Light Company	24	Rochester Gas & Electric Corporation
10	Georgia Power Company	25	South Carolina Electric & Gas Company
11	Holyoke Water Power Company	26	Union Electric Company
12	Indiana Michigan Power	27	Virginia Electric & Power Company
13	Kentucky Utilities Company	28	Wisconsin Electric Power Company
14	Louisville Gas & Electric Company	29	Wisconsin Power & Light Company
15	Minnesota Power & Light Company	30	Wisconsin Public Service Corporation

Model

The study involved applying the undesirable output model in the Variations of the Basic Model section to the 150 DMUs. The procedure included minimizing the objective function (Equation 16) subject to Equations 14, 17, and 18 under the constant returns-to-scale assumption. The expansion ratio of separable good outputs (in this case, nonfossil power generation) was chosen in Equation 18 as $\delta = 0.2$. No separable bad output was evident in this case. The minimized objective function value ρ^* represents the overall management and environmental performance index.

Empirical Results

The following sections include a description of the results and an observation of the relationship of the overall efficiency index with other key indices in the industry.

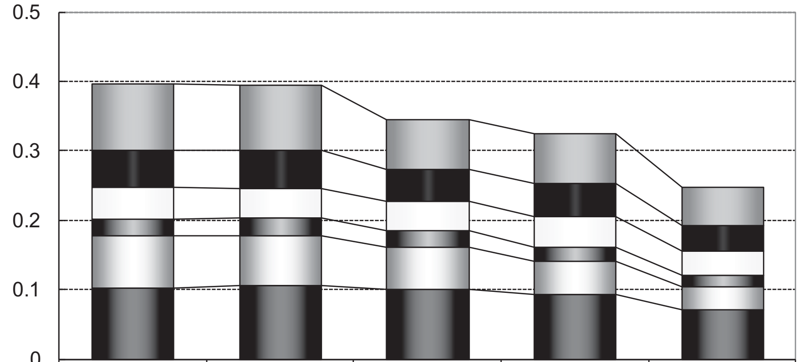
Trends of overall efficiency over time

Table 3 shows the averages of the overall efficiency scores over time. The 30 utilities have improved in overall efficiency considering good and bad outputs on average over the five years. Specifically, the advance in 2000 (a 16% improvement from 1996) is remarkable.

Table 3
Yearly Averages of the Overall Efficiency Score ρ^*

	1996	1997	1998	1999	2000	Change rate
Average (ρ^*)	0.69	0.70	0.73	0.74	0.80	16%

The next step was decomposing the efficiency score ρ^* in terms of inefficiencies regarding each input and output item using Equation 20. Figure 1 depicts the result of decomposition. The numbers in the figure indicate the average inefficiency scores of each input/output item of the year as measured by Equation 21. The figure shows that all input and output items reduced their inefficiency steadily from 1996 to 1999 and steeply in 2000. Figure 2 illustrates the movements of inefficiencies of each item, taking 1996 as the base year. The two bad outputs, NO_x and SO_2, reflected reduced inefficiencies at a relatively higher rate, while the inefficiencies of the two good outputs, fossil generation and nonfossil generation, reduced slowly.



	1996	1997	1998	1999	2000
x1: Total Generation Capacity	0.0953	0.0933	0.0716	0.0710	0.0561
x2: Fuel Consumption	0.0539	0.0564	0.0469	0.0476	0.0356
y1: Nonfossil Power Generation	0.0445	0.0417	0.0422	0.0437	0.0367
y2: Fossil Power Generation	0.0253	0.0264	0.0224	0.0207	0.0150
y3: NOx Emission	0.0750	0.0716	0.0609	0.0478	0.0329
y4: SO2 Emission	0.1028	0.1063	0.1021	0.0944	0.0729

Figure 1. Decomposition of ρ^* (yearly average).

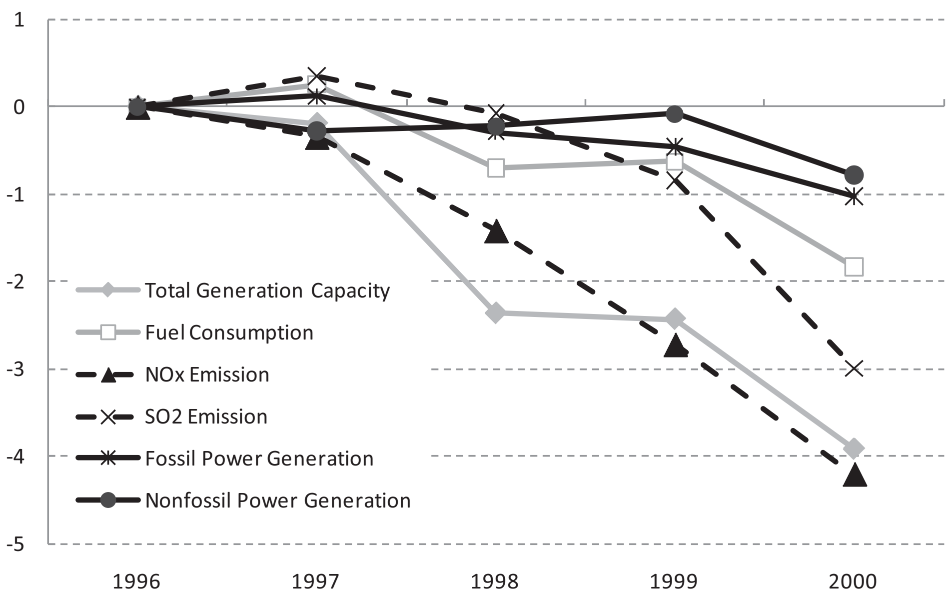


Figure 2. Reduction of inefficiencies from 1996.

Comparisons with other indices

The DEA overall efficiency score ρ^* is an integrated measure incorporating multiple input and output factors. This section reflects an attempt to verify that the DEA score actually confirms the trends of several traditional key indices (i.e., the thermal efficiency, the fossil power ratio, and the NO_x and SO_2 emission factors) as exhibited in Table 4 and Figure 3.

Table 4
Comparisons with Traditional Key Indices

	1996	1997	1998	1999	2000	Change rate
Average ρ^*	0.69	0.70	0.73	0.74	0.80	16%
Capacity factor (good)	0.53	0.54	0.57	0.57	0.58	8%
Thermal efficiency (good)	0.30	0.30	0.31	0.31	0.32	3%
Fossil power ratio (bad)	0.75	0.76	0.77	0.77	0.78	4%
No_x emission factor (bad)	3.07	3.02	2.74	2.53	2.27	-26%
SO_2 emission factor (bad)	6.41	6.37	6.19	5.92	5.44	-15%

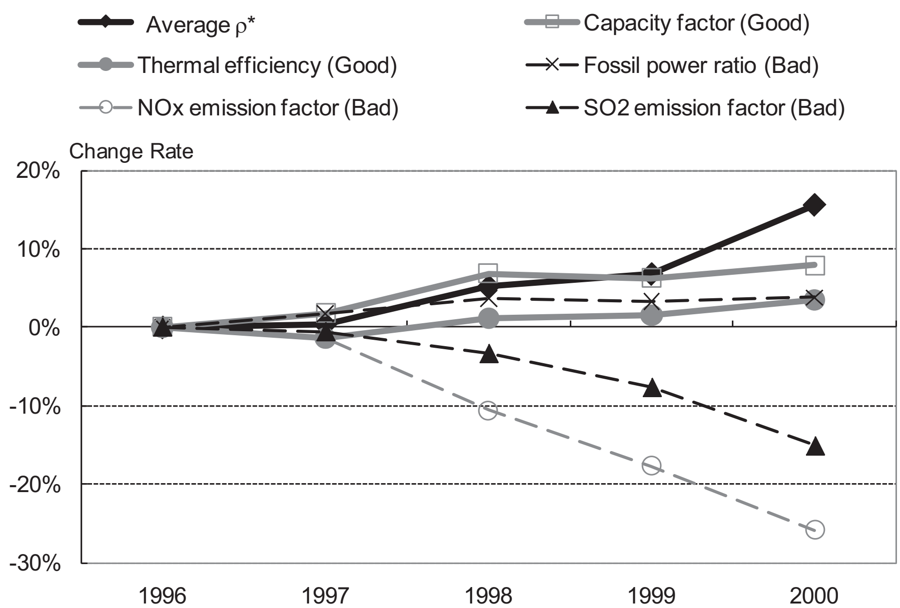


Figure 3. Comparisons with other indices (change rate from 1996).

Main observations are as follows.

1. Comparison with the capacity factor: Capacity factor is defined by "total electric power generation (MWh) / (generation capacity (MW) * 365 * 24)". Capacity factor reflects an aspect of the utilization of capital inputs, and overall efficiency is expected to increase if capacity factor increases. Table 4 indicates the average capacity factor for the total DMUs over the five years. Figure 3 shows its change rate from 1996. The trend of ρ^* runs parallel with that of the capacity factor until 1999, which indicates that the capacity factors are consistently integrated into the overall efficiency ρ^*.

2. Comparison with the thermal efficiency: Thermal efficiency is defined by "fossil power generation (MWh) / (fuel consumption (BTU) * $2.93*10^{-7}$)". If thermal efficiency increases, one could expect more good outputs with less fuel consumption and, consequently, less bad outputs. Table 4 shows the thermal efficiency over time. The total average increased about 3% from 1996 to 2000, whereas the overall efficiency ρ^* increased 16%. One may attribute the gap to performance improvements induced by other factors. However, both indices demonstrate a similar pattern of movements over the five years.

3. Comparison with the fossil power ratio: Fossil power ratio is defined by "fossil power generation (MWh) / total electric power generation (MWh)". If this ratio increases, the fuel consumption (input) will increase; hence, the emissions of NO_x and SO_2 will increase. The ratio negatively affects the overall efficiency index. Table 4 reflects the ratio over the five years. Although the trend is slowly increasing (4%), their effects on ρ^* were set off by the sharp decreases in the bad output emission factors, as described in the next point.

4. Comparison with the NO_x emission factor: NO_x emission factor is defined by "NO_x emission (ton) / fossil power generation (kWh)". This factor negatively affects the overall efficiency index. Table 4 shows its trend. Comparing this trend with that of NO_x inefficiency in Figure 2, both reduction rates are consistent.

5. Comparison with the SO_2 emission factor: SO_2 emission factor is defined as "SO_2 emission (ton) / fossil power generation (kWh)". Similar to the NO_x emission factor, the SO_2 emission factor behaves negatively in relation to the overall efficiency index. Table 4 indicates its trend. Figure 3 shows diagrammatically the trend of this factor, which matches the trend in Figure 2.

Environmental performance

Figure 4 plots all 150 DMUs, taking the NO_x emission factor as the horizontal axis and the NO_x inefficiency obtained by the decomposition of ρ^* as the vertical axis. As the approximate curve therein indicates, higher NO_x emissions correspond to larger NO_x inefficiencies.[3] The finding reflects collateral evidence that the proposed environmental performance index ρ^* can serve as a reasonable environmental index.

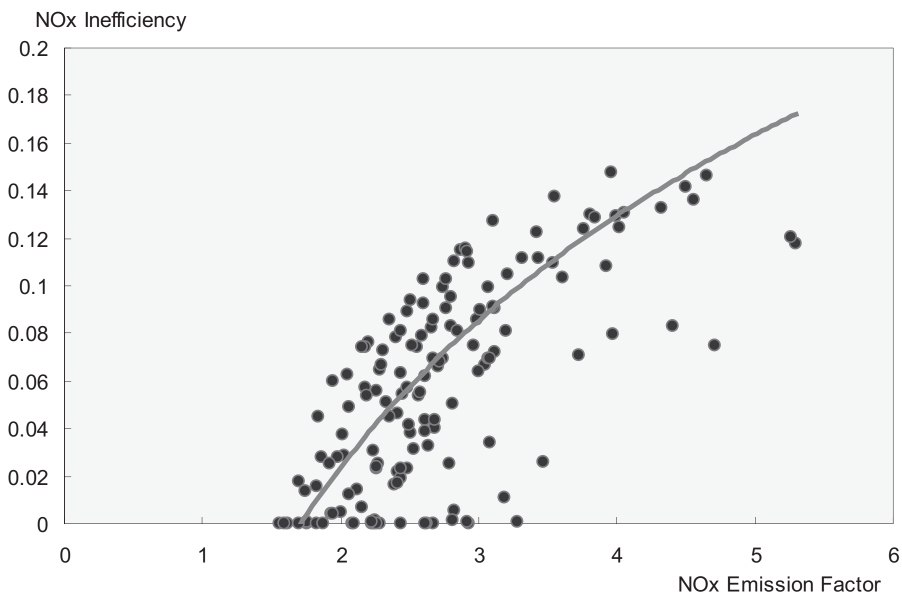


Figure 4. Comparison of NO_x inefficiency index and NO_x emission factor.

Concluding Remarks

The focus of this paper was the proposal of a new efficiency measure that can address both desirable (good) outputs and undesirable (bad) outputs in a unified framework under conditions in which certain nonseparable associations between some inputs and outputs exist. The paper included an application of the model to 30 U.S. electric utilities between 1996 and 2000. The results indicate about 16% improvement in the overall efficiency on average from 1996 to 2000, which means that the utilities have made progress in efficiency regarding both desirable outputs (fossil and nonfossil generations) and undesirable outputs (NO_x and SO_2) during the period. Furthermore, demonstration of the rationality of the proposed model is evident through a comparison of efficiency scores with other traditional managerial and environmental indices. Based on the findings, the proposed model can function as an effective tool for measuring environmental performance in the presence of both good and bad outputs.

Even under the liberalized competitive market, the electric power industry remains a public utility. Hence, evaluation of its performance should occur in a multifaceted fashion (i.e., managerial and environmental aspects). Both managers and regulating authorities need an appropriate evaluation method for this purpose. The proposed model may serve as a valid theoretical basis for addressing such eco-efficiency relationships. A future extension of this work would be a cost-efficiency model that accounts for both production and de-contamination costs.

Footnotes

1 In this model, the assumption is that radial slacks are freely disposable, but modification of the definition occurs in the Variations of the Basic Model section.

2 The correlation between fossil fuel consumption and CO_2 emission is nearly 100%. Therefore, no big difference might exist among utilities on performance of CO_2 emission reduction, so CO_2 emission was not employed as a bad output in the proposed model.

3 Similar results were observed for SO_2.

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Research supported by Grant-in-Aid for Scientific Research (C), Japan Society for the Promotion of Science.

We are grateful to an anonymous referee for pointing out several mistakes in the first draft and for suggesting improvements.