Hampf, Benjamin

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Benjamin Hampf

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Separating Environmental Efficiency into Production and Abatement Efficiency - A Nonparametric Model with Application to U.S. Power Plants

by

Benjamin Hampf*†

Darmstadt University of Technology

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Abstract

In this paper we present a new approach to evaluate the environmental efficiency of decision making units. We propose a model that describes a two-stage process consisting of a production and an end-of-pipe abatement stage with the environmental efficiency being determined by the efficiency of both stages. Taking the dependencies between the two stages into account, we show how nonparametric methods can be used to measure environmental efficiency and to decompose it into production and abatement efficiency. For an empirical illustration we apply our model to an analysis of U.S. power plants.

JEL classification: C14, L94, Q53

Keywords: nonparametric efficiency analysis, pollution abatement, network DEA, materials balance condition, fosil-fueled power plants

* Department of Law and Economics, Residenzschloss, Marktplatz 15, D-64283 Darmstadt, Germany, Tel.:+49 6151 165319, Fax: +49 6151 163897, E-Mail: hampf@vwl.tu-darmstadt.de

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1 Introduction

In the last two decades the measurement of environmental efficiency of decision making units (DMUs) has become one of the major issues in the field of nonparametric efficiency evaluation (see Zhou et al. (2008) for a survey). Since the traditional approaches like data envelopment analysis (DEA) proposed by Charnes et al. (1978) do not account for the unintended production of undesirable outputs like pollutants, different methods to incorporate emissions in nonparametric efficiency analysis (see Scheel (2001) for an overview) have been proposed. These approaches include among others the incorporation of the inverse of the undesirable outputs (see Lovell et al. (1995)), the translation approach where the undesirable outputs are subtracted from a sufficient large positive number (see Seiford and Zhu (2002)) and the approach of incorporating them as weak disposable outputs (see Färe et al. (1989)).
Most of these approaches treat the DMUs as black boxes (see figure 1) which use inputs (X) and produce desirable (Y) and undesirable outputs (U) (e.g. power plants use coal and produce electricity and SO_2 emissions). Environmental efficiency is analyzed without taking into account that the DMUs produce desirable outputs and try to abate undesirable outputs in different stages, which is the basic idea behind classic end-of-pipe abatement technologies (e.g. scrubber technologies). Moreover, these approaches have in common that they neither formulate an explicit production nor an abatement process of the undesirable outputs (see Førsund (2009) for critical remarks).

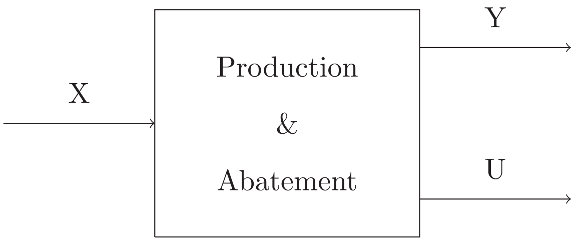

Figure 1: Environmental "black box"

As a result, little research has been conducted to reveal sources of possible inefficiencies with regard to the environment. For instance a DMU might be inefficient because it uses too much of a polluting input in the production stage or the amount of emissions which are abated using an abatement technology is too low. The existing literature that presents more detailed analyses of environmental efficiency also has some drawbacks. Hua and Bian (2008) propose a network based efficiency measure incorporating undesirable outputs but no production theoretical background of this measure is presented. Yang et al. (2008) propose an analysis with both a production and an abatement stage, but they do not separate the efficiencies of these stages. Coelli et al. (2007) suggest an approach where technical and environmental allocative efficiency is analyzed. However, abatement efficiency is only shortly noted and not included in their analysis.

In this paper we propose a new model to evaluate the environmental efficiency of DMUs and to separate it into production and abatement efficiency. In contrast to the existing literature, we explicitly formulate a production theoretical model of production and pollution abatement activities. Furthermore, an environmental efficiency measure is proposed that can be decomposed into the effects of production and abatement inefficiencies on environmental efficiency and we show how nonparametric methods can be used to estimate this measure and its components. To show the empirical applicability of our new approach, we analyze the environmental efficiency of U.S. coal-fired power plants in the year 2009 with regard to sulfur dioxide (SO_2) emissions.

This paper is structured as follows: Section 2 presents the theory of the production and the abatement technology, while a new measure for environmental efficiency regarding these technologies is discussed in section 3. In section 4 the new approach is applied to an analysis of U.S. power plants and section 5 concludes the paper.

2 Modelling the Technologies

In our model we assume that the production process of a DMU can be divided into two stages, the production stage with technology T_1 and the abatement stage with technology T_2. In the first stage, the DMUs use inputs x_1^F, x^P and x_1^S to produce outputs y. x_1^F denotes pollution free (or non-polluting) inputs, which means that the use of these inputs does not lead to any pollution (e.g. labor), while pollution containing (or polluting) inputs are denoted by x^P (e.g. coal).[1] x_1^S denotes the amount of shared inputs x^S(inputs which are used in both stages) used in the production stage. The desirable outputs of the DMUs consist of final outputs y^f and intermediate inputs y^2, which are inputs of the abatement stage. The use of the pollution containing inputs x^P to produce outputs $y = y^f + y^2$ leads to a production of undesirable outputs u' (e.g. carbon dioxide emissions).[2] These undesirable outputs are inputs of the abatement process (e.g. scrubbers) where they are reduced using non-polluting inputs x_2^F, the amount x_2^S of the shared inputs and the intermediate inputs y^2 to the final amount of undesirable outputs u'' which are emitted to the environment. The structure of this production process is depicted in figure 2.

To formally define the technology consider n DMUs that are using m inputs $x \in \mathbb{R}_+^m$ which can be split into m^F pollution free, m^P pollution containing and m^S shared inputs, to produce k desirable outputs $y \in \mathbb{R}_+^k$.[3] m_1^F non-polluting inputs are used in the production stage and m_2^F are used in the abatement stage. As a result of the use of polluting inputs to produce y in the first stage, s undesirable outputs $u' \in \mathbb{R}_+^s$ are produced. They are reduced to $u'' \in \mathbb{R}_+^s$ in the abatement process. We further define $l \equiv u' - u'' \in \mathbb{R}_+^s$ as the amount of abated pollution. Given the definitions above the first stage of the overall

[1] Since we assume that polluting inputs are only used in the first stage, they do not have subscripts.

[2] Note that we assume that neither y^2 nor x^S contains any pollution, so that no additional pollution can be created at the abatement stage.

[3] The notation $\mathbb{R}_+^{\cdot}$ means that the vector contains only non-negative elements.

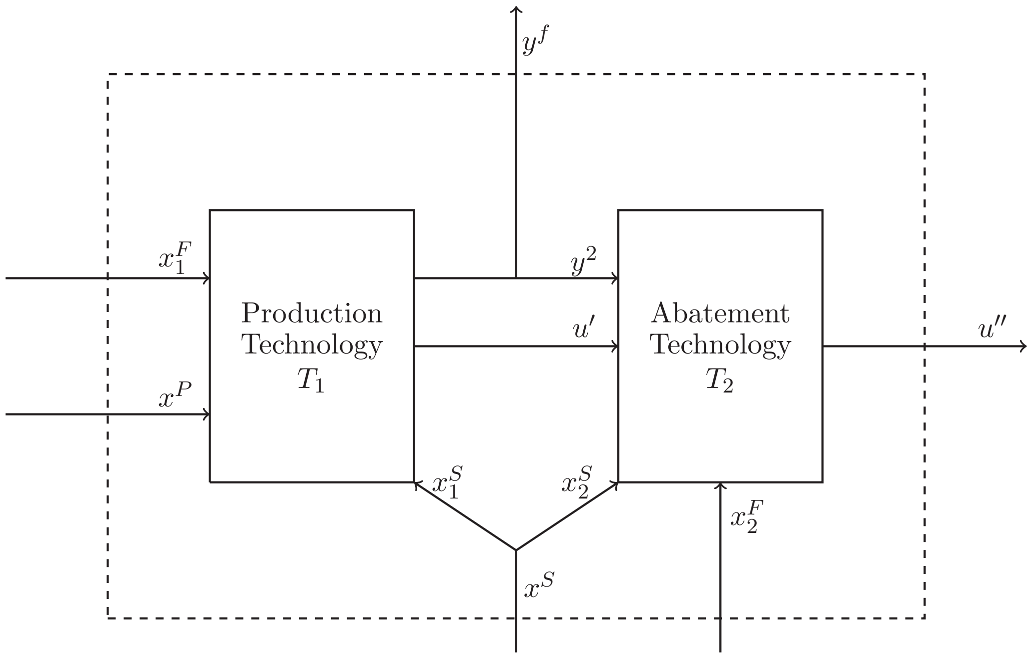

Figure 2: Structure of the two-stage production process

technology, the production technology T_1, can be defined as

$$T_1 = \{(x_1^F, x^P, x_1^S, y, u') \in \mathbb{R}_+^{m_1^F+m^P+m^S+k+s} : (x_1^F, x^P, x_1^S) \text{ can produce } (y, u')\}. \quad (1)$$

In our model we treat the pollutants u' as the residuals of the production stage.[4] A practical problem arises from the fact that in general u' is not observable for the researcher. To overcome this problem we assume that no abatement activities are conducted in the production stage. Therefore, the amount of undesirable outputs that are the inputs of the abatement stage can be derived from the materials balance condition (MBC).[5] This concept, introduced by Ayers and Kneese (1969), can be simplified as "what goes in must come out". It is based on fundamental physical laws and states that the amount of materials bounded in the inputs must be equal to those that are bounded in the desirable and undesirable outputs.[6] Therefore, we can estimate the amount of pollutants resulting from the first stage by the equality

$$u' = \Omega x^P - \Phi y^f, \quad (2)$$

where Ω is a $s \times m^P$ matrix of factors that indicate the amount of undesirable outputs bounded in the polluting inputs and Φ is a $s \times k$ matrix of factors that indicates the

[4] See Pethig (2006) for microeconomic foundations of the residual generation in production processes.

[5] Of course the MBC also holds if abatement activities are introduced in the production stage. But in this case the amount of abatement would have to be considered in the MBC resulting in an equivalent data problem.

[6] See Lauwers (2009) for a discussion and Coelli et al. (2007) for an application of the MBC in nonparametric efficiency analysis.

amount of pollutants bounded in the final outputs.[7] Note that the matrices Ω and Φ can differ among the DMUs since the inputs and outputs might not be completely homogenous e.g. the quality of coal and hence the sulfur content of it may differ among power plants. Since we assume that the amount of u' follows this equality as a residual of the production we can split the production technology in two parts.[8] The production of the desirable outputs y,

$$T_1^y = \{(x_1^F, x^P, x_1^S, y) \in \mathbb{R}_+^{m_1^F+m^P+m^S+k} : (x_1^F, x^P, x_1^S) \text{ can produce } y\}, \tag{3}$$

and the resulting pollution according to the MBC

$$T_1^{u'} = \{(x^P, y^f, u') \in \mathbb{R}_+^{m^P+k+s} : u' = \Omega x^P - \Phi y^f\}. \tag{4}$$

We assume that the technology T_1^y satisfies the following axioms proposed by Shephard (1970) (see Färe and Primont (1995) for a discussion):

1.1 Inactivity:
$\forall (x_1^F, x^P, x_1^S) \in \mathbb{R}_+^{m_1^F+m^P+m^S}$, $(x_1^F, x^P, x_1^S, 0) \in T_1^y$.
It is possible for any amount of inputs to produce no output.

1.2 No free-lunch:
$(x_1^F, x^P, x_1^S, y) \notin T_1^y$ if $x_1^F = x_1^P = x_1^S = 0$ and $y \geq 0$.[9]
It is not possible to produce positive amounts of any output without using positive amounts of at least one input.

1.3 Strong disposability of inputs:
If $(x_1^F, x^P, x_1^S, y) \in T_1^y$ and $(\tilde{x}_1^F, \tilde{x}^P, \tilde{x}_1^S) \geq (x_1^F, x^P, x_1^S)$ then $(\tilde{x}_1^F, \tilde{x}^P, \tilde{x}_1^S, y) \in T_1^y$.
For any given combination (x_1^F, x^P, x_1^S, y) the same amount of output is attainable by using more inputs.

1.4 Strong disposability of outputs:
If $(x_1^F, x^P, x_1^S, y) \in T_1^y$ and $\tilde{y} \leq y$ then $(x_1^F, x^P, x_1^S, \tilde{y}) \in T_1^y$.
For any given combination of (x_1^F, x^P, x_1^S, y) it is possible to produce less output holding (x_1^F, x^P, x_1^S) constant.

1.5 Convexity: T_1^y is convex.
For example, if $(x_{1a}^F, x_a^P, x_{1a}^S, y_a) \in T_1^y$ and $(x_{1b}^F, x_b^P, x_{1b}^S, y_b) \in T_1^y$ then
$\alpha(x_{1a}^F, x_a^P, x_{1a}^S, y_a) + (1-\alpha)(x_{1b}^F, x_b^P, x_{1b}^S, y_b) \in T_1^y \ \forall \alpha \in [0,1]$.

1.6 The technology exhibits variable returns to scale (VRS).

[7] By assumption, the intermediate inputs do not contain any pollution.
[8] For a detailed discussion of the splitting of a technology into the production of good output and the residual generation see Murty and Russell (2010).
[9] Here and in the following "$\geq$" means that at least one element of the vector satisfies strict inequality while "$\geqq$" means that all elements can hold with equality.

1.7 Compactness: T_1^y is a compact set.
 That means it is a closed and bounded set.

Given the observed combinations $(x_{1i}^F, x_i^P, x_{1i}^S, y_i^f, y_i^2)$ for $i = 1, ..., n$ the DEA estimation of the production technology reads as:

$$T_1^y = \{(x_1^F, x^P, x_1^S, y) \in \mathbb{R}_+^{m_1^F+m^P+m^S+k} : x_1^F \geqq X_1^F\lambda, x^P \geqq X^P\lambda, x_1^S \geqq X_1^S\lambda, \\ y^f + y^2 \leqq \left(Y^f + Y^2\right)\lambda, 1^T\lambda = 1, \lambda \geq 0\} \tag{5}$$

where X_1^F represents the $m_1^F \times n$ matrix of non-polluting inputs, X^P represents the $m^P \times n$ matrix of polluting inputs, X_1^S denotes the $m^S \times n$ matrix of the amount of shared inputs in the production stage. The outputs consist of a $k \times n$ matrix Y^f of final outputs and a $k \times n$ matrix Y^2 of intermediate inputs. λ denotes a $n \times 1$ vector of weight factors, with $1^T\lambda = 1$ indicating variable returns to scale. In the second stage an abatement technology is used to reduce the undesirable outputs that are residuals of the use of polluting inputs and the production of final outputs according to $T_1^{u'}$. The abatement technology T_2 can be defined as

$$T_2 = \{(x_2^F, x_2^S, y^2, u', l) \in \mathbb{R}_+^{m_2^F+m^S+k+2s} : (x_2^F, x_2^S, y^2, u') \text{ can produce } l\} \tag{6}$$

where $l = u' - u''$ and hence has the same dimension as the s undesirable outputs. We use l as the output of the abatement stage since in contrast to u'' it is a desirable output (see Coelli et al. (2007, p. 9)).
This technology is assumed to satisfy the following axioms:

2.1 Inactivity:
 $\forall (x_2^F, x_2^S, y^2, u') \in \mathbb{R}_+^{m_2^F+m^S+k+s}$, $(x_2^F, x_2^S, y^2, u', 0) \in T_2$.
 It is possible to abate no emissions using some inputs, hence $u' = u''$ and $l = 0$.

2.2 No free-lunch: $(x_2^F, x_2^S, y^2, u', l) \notin T_2$ if $x_2^F = x_2^S = y^2 = u' = 0$ and $l \geq 0$.

2.3 Strong disposability of inputs:
 If $(x_2^F, x_2^S, y^2, u', l) \in T_2$ and $(\tilde{x}_2^F, \tilde{x}_2^S, \tilde{y}^2, \tilde{u})' \geq (x_2^F, x_2^S, y^2, u')$ then $(\tilde{x}_2^F, \tilde{x}_2^S, \tilde{y}^2, \tilde{u}', l) \in T_2$.
 Strong disposability of u' means that an increase of the emissions that are an input to the abatement stage results in an equal increase in u'', such that none of the additional emissions are abated.

2.4 Strong disposability of outputs:
 If $(x_2^F, x_2^S, y^2, u', l) \in T_2$ and $\tilde{l} \leq l$ then $(x_2^F, x_2^S, y^2, u', \tilde{l}) \in T_2$.
 It is possible to increase the amount of emissions u'' until they are equal to u'. This boundary follows from the non-negativity of l.

2.5 Convexity: T_2 is convex.
For example, if $(x_{2a}^F, x_{2a}^S, y_a^2, u_a', l_a) \in T_2$ and $(x_{2b}^F, x_{2b}^S, y_b^2, u_b', l_b) \in T_2$ then $\alpha(x_{2a}^F, x_{2a}^S, y_a^2, u_a', l_a) + (1-\alpha)(x_{2b}^F, x_{2b}^F, y_b^2, u_b', l_b) \in T_2 \; \forall \alpha \in [0,1]$.

2.6 The technology exhibits variable returns to scale.

2.7 Compactness: T_2 is a compact set.

The DEA estimation of this technology is created using observations of $(x_{2i}^F, x_{2i}^S, y_i^2, u_i'')$ and estimations of u_i' and l_i by the MBC for $i = 1, \ldots, n$ and reads as :

$$T_2 = \{(x_2^F, x_2^S, y^2, u', l) \in \mathbb{R}_+^{m_2^F + m^S + k + 2s} : x_2^F \geqq X_2^F z, x_2^S \geqq X_2^S z, y^2 \geqq Y^2 z, u' \geqq U' z, \\ l \leqq Lz, 1^T z = 1, z \geq 0\} \tag{7}$$

where X_2^F denotes the $m_2^F \times n$ matrix of non-polluting inputs, X_2^S represents the $m^S \times n$ matrix of shared inputs used in the abatement stage, U' denotes the $s \times n$ matrix of undesirable outputs and L represents the $s \times n$ matrix of abated undesirable outputs. z denotes the $n \times 1$ vector of weight factor. Note that these weight factors do not have to equal the λ-values of the first stage. Hence, the reference observations may differ.
The overall technology of the two-stage production process T_N is constructed by combining all three subtechnologies ($T_1^y, T_1^{u'}$ and T_2) to one network DEA technology and reads as:

$$T_N = \{\left(x^P, x_1^F, x_1^S, x_2^F, x_2^S, x^S, y^f, y^2, u', u''\right) :$$

$$\begin{array}{rcll}
x^P & \geqq & X^P \lambda & \\
x_1^F & \geqq & X_1^F \lambda & \\
x_1^S & \geqq & X_1^S \lambda & \\
y^f + y^2 & \leqq & \left(Y^f + Y^2\right) \lambda & T_1^y \\
1^T \lambda & = & 1 & \\
\lambda & \geq & 0 & \\
u' & = & x^P \Omega - y^f \Phi & \} \quad T_1^{u'} \\
y^2 & \geqq & Y^2 z & \\
x_2^F & \geqq & X_2^F z & \\
x_2^S & \geqq & X_2^S z & \\
u' & \geqq & U' z & T_2 \\
u' - u'' & \leqq & (U' - U'') z & \\
1^T z & = & 1 & \\
z & \geq & 0 & \\
x_1^S + x_2^S & \leqq & x^S \quad \} & \} \quad \text{Shared inputs}
\end{array} \tag{8}$$

In addition to the three subtechnologies the last inequality is included which states that the sum of shared inputs used in both stages can not exceed an exogenous total amount of shared inputs. Our technology is similar to the one presented in Färe and Grosskopf

(1996) which also contains shared and intermediate inputs but is not constructed for the analysis of environmental efficiency. The possibility of using network DEA to estimate environmental efficiency is mentioned in Färe et al. (2007a) but is not worked out in detail there. In the next section we will show how this technology can be used to estimate the environmental efficiency of DMUs.

3 Measuring and Separating Environmental Efficiency

In this section we present a new possibility to evaluate the environmental efficiency of the DMUs given the technologies defined in the last section and to separate it into production and abatement efficiency. As described above, we assume that the production process has a two-stage structure with the production of desirable outputs in the first stage and the reduction of the undesirable outputs, which are the residuals of the output production, in the second stage.

In the literature of environmental economics different measures for environmental efficiency have been proposed (see e.g Tyteca (1996) for an overview of different measures). For a nonparametric analysis of environmental efficiency incorporating undesirable outputs as weak disposable outputs (see the introduction to this paper) Färe et al. (2004) have developed an index that is based on the ratio of good to bad outputs. But to our knowledge there exists no measure that allows to evaluate the environmental efficiency of DMUs and to decompose possible inefficiencies into production and abatement inefficiencies. Therefore, we define a new measure of environmental efficiency (EEM) as :

$$\frac{w^T u''^*}{w^T u''} = \underbrace{\frac{w^T u'^*}{w^T u'}}_{\text{PE}} \cdot \underbrace{\frac{w^T u''^*}{w^T u'^*} \cdot \left[\frac{w^T u''}{w^T u'}\right]^{-1}}_{\text{AE}} \tag{9}$$

This measure is defined by the ratio of the weighted minimal amount of emissions ($w^T u''^*$) released to the environment to the equally weighted actual observed amount of emissions ($w^T u''$) of the DMU with a value less then 1 indicating environmental inefficiency. w^T denotes the $1 \times s$ vector of weight factors for which possible choices might be global warming potentials to convert different emissions into CO_2 equivalents or (in a monetary setting) emission allowance prices.[10] In case of a single pollutant w^T can be set to 1.

The environmental efficiency measure can be decomposed into the product of two efficiency effects. The first term $\left(\frac{w^T u'^*}{w^T u'}\right)$ captures the effect of production inefficiency (PE) on the environmental efficiency. If the term is less than 1 the production is inefficient (the amount of u'^* is lower than u') and hence the DMU can increase its environmental efficiency by reducing its produced emissions from the production stage. The second term measures the effect of abatement inefficiency (AE) and is the quotient of two ratios: the first measuring the ratio of weighted minimal final emissions $\left(w^T u''^*\right)$ to the weighted minimum of emission

[10] For example, the global warming potential of methan (CH_4) is 25. That means, that if the DMU emmits 1 ton of CO_2 and 1 ton of CH_4 the EEM aggregates the pollutants to 26 tons of CO_2.

input $\left(w^T u'^*\right)$ while the second measures the initial ratio of weighted emission output $\left(w^T u''\right)$ to the initial weighted emission input $\left(w^T u'\right)$. If this quotient is smaller than 1 then the DMU is abatement inefficient. If there are no abatement activities present, the environmental efficiency measures equals the measure of the productive efficiency.

To obtain the environmental efficiency measure we use the network technology defined in the last section and estimate the weighted minimum of emissions released to the environment. Given a sample of DMUs ($i = 1, \ldots, n$) the activity analysis or data envelopment analysis model reads as:

$$
\begin{array}{llll}
\min\limits_{x^P, x_1^S, x_2^S, y^f, y_1^2, u', u'', \lambda, z} & w^T u'' & & \\
\text{s.t.} \quad
\begin{array}{rcl}
x^P & \geqq & X^P \lambda \\
x_{1i}^F & \geqq & X_1^F \lambda \\
x_1^S & \geqq & X_1^S \lambda \\
y^f + y^2 & \leqq & \left(Y^f + Y^2\right) \lambda \\
1^T \lambda & = & 1 \\
\lambda & \geq & 0
\end{array} & \left.\vphantom{\begin{array}{c}a\\a\\a\\a\\a\\a\end{array}}\right\} & T_1^y \\
\begin{array}{rcl}
u' & = & x^P \Omega - y^f \Phi
\end{array} & \} & T_1^{u'} \\
\begin{array}{rcl}
y^2 & \geqq & Y^2 z \\
x_{2i}^F & \geqq & X_2^F z \\
x_2^S & \geqq & X_2^S z \\
u' & \geqq & U' z \\
u' - u'' & \leqq & \left(U' - U''\right) z \\
1^T z & = & 1 \\
z & \geq & 0
\end{array} & \left.\vphantom{\begin{array}{c}a\\a\\a\\a\\a\\a\\a\end{array}}\right\} & T_2 \\
\begin{array}{rcl}
x_1^S + x_2^S & \leqq & x_i^S
\end{array} & \} & \text{Shared inputs}
\end{array}
\tag{10}
$$

This linear program minimizes the weighted sum of emissions by simultaneously conducting the following steps. The production technology is used to minimize the polluting inputs and to maximize the final outputs to achieve productive efficiency with regard to the minimum amount of emissions u'^* that is technically feasible according to the MBC. Therefore, the minimization also incorporates u'. The efficient amount of pollutants released to the environment (u''^*) given u'^* is estimated using the technology of the abatement stage. Moreover, in this estimation the shared inputs are possibly reallocated and the intermediate inputs are increased to minimize emissions. The resulting minimal emission amount u''^* is used together with u'^* to measure the environmental efficiency as well as the effects of the production and the abatement efficiency.

Note that without shared and intermediate inputs it is not necessary to estimate the efficiency using this network DEA. Without this additional interaction between the production and the abatement stage it is possible to estimate the productive and the abatement efficiency separatly. This could be done by first estimating the efficient amount of u'^*

using the production technology T_1^y and the materials balance condition and in a second step computing u''^* using the abatement technology T_2.
The estimation and the decomposition of the environmental efficiency measure can be graphically explained using the following figures 3 and 4.

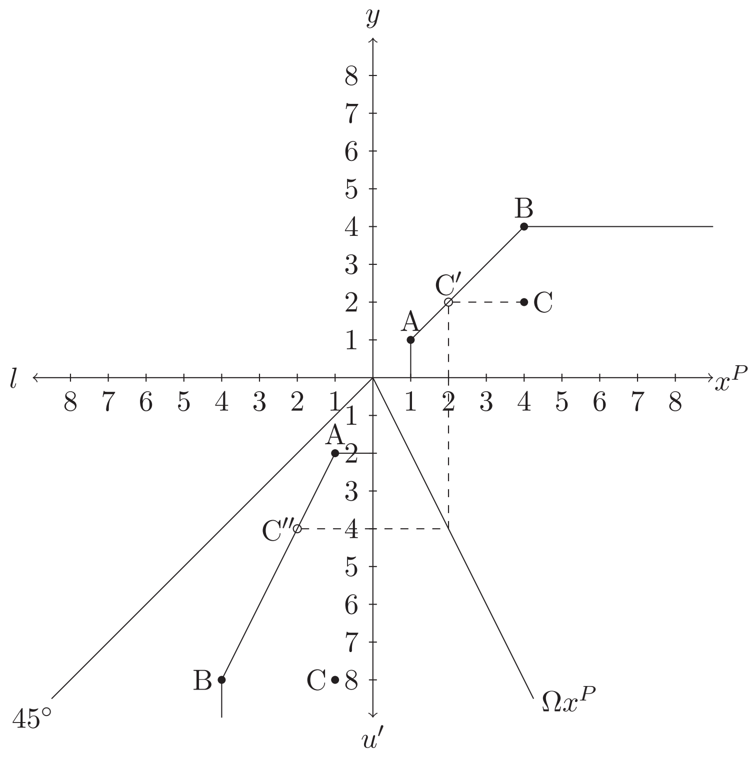

Figure 3: Measurement of environmental effficiency

Figure 3 shows the efficiency analysis of the production and the abatement stage. The upper right quadrant showst the production technology, where the three DMUs (A,B,C) are using one polluting input x^P to produce the desirable output y. The upper boundary of the technology is given by the connecting line between A and B, the vertical extension to A and the horizontal extension to B. The production of y results in the generation of a single pollutant u'. The amount of this pollutant is given by the materials balance equation $u' = \Omega x^P$, depicted by the ray through the origin in the lower right quadrant. To keep the graphical example as simple as possible we assume that the output y does not contain any pollution, hence $\Phi = 0$. Moreover, we assume that x^P is completely homogenous which implies that Ω is a constant factor for all three observations. The lower left quadrant shows the abatement technology. The input u' is reduced to u'', hence the output is $l = u' - u''$.[11] The 45° line shows the physical boundary of the technology, since for every point on it $l = u'$ holds and thus $u'' = 0$. Since we assume $u'' \geq 0$ no point left to this line can be attained. The technical boundary of this technology is given by the connecting line between A and B, the horizontal extension to A and the vertical extension

[11] Since abatement without any costs is an unrealistic assumption, we may assume that each observation uses in addition to u' 1 unit of a non-polluting input x_2^F in the abatement stage.

to B. The environmental efficiency analysis can be seen from following the dashed line from C to C$''$. From the graph of the production technology it is clearly visible that DMU C lies in the interior of the technology and is therefore productive inefficient. Since y does not contain any pollution we measure the productive efficiency in input orientation. Given the production technology, C should reduce its input x^P from 4 to 2 units keeping the output constant to become productive efficient. According to the MBC the use of 2 units of x^P leads to the production of 4 units of u'. Given 4 units of u', the maximal amount of abatement is 2 units according to the abatement technology (see C$''$). Hence, the minimal amount of u'' is $u''^* = u'^* - l^* = 4 - 2 = 2$. In the former situtation C abated 1 of 8 units of u' resulting in $u'' = 8 - 1 = 7$ units of released emissions. Thus, the environmental efficiency measure takes the value $\frac{u''^*}{u''} = \frac{2}{7} \approx 0.286$. This means that C could lower its emissions to 28.6% if it would operate its production and abatement stage efficiently.

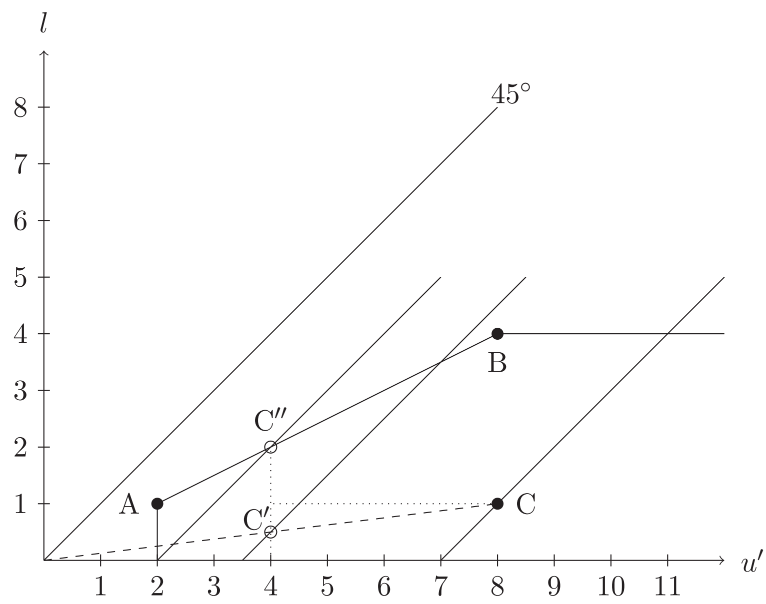

Figure 4: Decomposition of environmental efficiency

The decomposition of the environmental efficiency of DMU C into production and abatement efficiency is depicted in figure 4 which shows the lower left quadrant of figure 3 mirrored at the l-axis. In addition, the figure includes three parallel lines (one through each point C, C$'$ and C$''$) with slope 1. The intersection of each line with the u'-axis indicates the amount of u'' associated with the points C, C$'$ and C$''$ since $l = u' - u''$. For example, point C represents $u' = 8$ and $l = 1$ and the intersection point gives $u' - l = u'' = 7$. The dashed line from the origin to C contains all combinations of u' and l with the same ratio $\frac{u''}{u'}$ as in point C. As explained above, the efficient amount of u' is given by $u'^* = 4$ and the optimal amount of abatement is $l^* = 2$ (see C$''$). The intersection of the parallel through this point and the u'-axis is (2,0), hence $u''^* = 2$. Therefore the environmental efficiency is $\frac{2}{7} \approx 0.286$. The point C$'$ is estimated by combining the productive efficient amount of

emission input $u'^{*} = 4$ and the ratio $\frac{u''}{u'}$ given at point C. The intersection of the parallel line through the point C$'$ and the u'-axis gives the amount of emissions released to the environment if the production stage operates efficiently but the abatement stage remains unchanged. We denote this amount $u''^{\#}$. The production efficiency is therefore given by $\frac{u''^{\#}}{u''} = \frac{3.5}{7} = 0.5$ which by using the intersection theorem is the same as $\frac{u'^{*}}{u'} = \frac{4}{8} = 0.5$, where the last equation is the definition of production efficiency in our environmental efficiency measure. Given the productive efficient point, C$'$ could further lower its emissions by increasing l to 2 units keeping u' constant to become abatement efficient. This would lead to an evironmentally efficient amount of 2 units of u'' and the abatement efficiency is then given by $\frac{u''^{*}}{u''^{\#}} = \frac{2}{3.5} \approx 0.571$. But note that we would not obtain point C$'$ as a solution of the network DEA model which only gives u'^{*} and u''^{*}. But by using the points C and C$''$ as well as again the intersection theorem we find that $\frac{u''^{*}}{u''^{\#}} = \frac{u''^{*}}{u'^{*}} \cdot \left[\frac{u''}{u'}\right]^{-1}$ with the right hand side of this equation representing the term for abatement efficiency in our environmental efficiency measure. Finally, this measure is given by the product of production and abatement efficiency $0.5 \cdot 0.571 \approx 0.286$.
In the next section we show how this measure can be applied to an analysis of U.S. power plants.

4 Application to U.S. Power Plants

For an empirical illustration we apply our model to an efficiency analysis of U.S. coal-fired power plants in the year 2009. These plants have been adressed by several previous studies (e.g. Färe et al. (2005), Färe et al. (2007b), and Sueyoshi et al. (2010)) analyzing their environmental efficiency as described in the introduction to this paper. The amount of available data, especially for abatement activities, has significantly increased in the last years enabling us to conduct a detailed analysis of the potential sources of environmental inefficiency. We analyze the environmental efficiency with regard to the sulfur dioxide (SO_2) emissions of the power plants. The reason for choosing SO_2 emissions in our analysis is twofolded. Firstly, coal fired power plants contribute 73% of all SO_2 emissions in the United States (EPA (2011b)) and therefore their efficiency has a significant influence on the total generation of SO_2 emissions in the U.S.. Secondly, the abatement of these emissions by flue gas desulfurization units (FGDs) exists as an end-of-pipe technology and hence can be analyzed with our network model (see Srivastava and Josewicz (2001) for a description of FGDs). Due to their large contribution to overall SO_2 emissions, the power plants are regulated by the U.S. Environmental Protection Agency (EPA). The Acid Rain Program (ARP) Phase II which was implemented in the year 2000 and covers all plants with a capacity $>$ 25 megawatts introduced a cap and trade program with a total amount of allowances for 8.95 million tons of SO_2 emissions per year (see EPA (2011a)). In addition, the Clean Air Interstate Rule (CAIR) which includes 28 eastern states of the U.S. and the district of Colombia was implemented in 2010 to reduce SO_2 emissions to 57% of the

amount in 2003 by 2015 (see EPA (2005)). In our analysis we will test, whether the plants which are additionally regulated by the CAIR program have shown significant differences with regard to their environmental efficiency before the regulation compared with those which are only regulated by the ARP.
The sources of the data used in our study are the files EIA-860 and EIA-923 of the U.S. Energy Information Agency (EIA), where EIA-923 provides detailed information on the inputs and outputs of the production stage of the power plants, whereas EIA-860 contains data on their abatement activities. These files contain the data on boiler and generator level (EIA-923), respectively on FGD unit level (EIA-860). In addition to the data from EIA we use the Clean Air Markets data from the EPA which provides data on the amount of SO_2 emissions released to the environment by each boiler of the plants. Finally, we include plant-level labor data from Form 1 of the Federal Energy Regulatory Commission (FERC). Since the data are reported on different levels we had to aggregate them to estimate plant-level efficiency. This aggregation was done as follows: In the first step, we excluded all observations (boilers, generators and FGDs) with missing data (see the paragraph below for a description of the used inputs and outputs). We also excluded boilers for which coal contributes to less than 95% of the used heat content of the fuels and those for which fuels other than coal, oil or gas contribute to more than 0.0001% of the used heat content.[12] FGDs were excluded if they either were non-operating or if the generators linked with these units have an installed capacity that is lower than 100 megawatts. The last exclusion is due to previous studies (see Eastern Research Group (2009)) which find that while medium ($100-500$ MW) and large (>500 MW) FGDs are comparable e.g. with regard to capital cost per capacity, smaller (<100 MW) FGDs show significant differences to large and medium FGDs. To avoid this comparison we excluded those observations. The remaining observation were checked if all linked units were still included in the data set (e.g. if all boilers that are linked to one generator are still part of the data). If the data were complete, we summed the single parts up to estimate the data on power plant level, otherwise we did not include the data. As a result of this procedure, not necessecarly all generators, boilers and FGDs of a power plant were included in our analysis. However, we prefered this method to simply summing up all boilers, generators and FGDs to one plant since this would lead to more serious problems. For example, our approach avoids comparing the environmental efficiency of boilers and generators without FGDs with those that are equipped with FGDs using the same estimated technology set.

For our efficiency analysis we use the following input and output variables. In the production stage we include the sum of the heat content (measured by british thermal units (BTUs)) [13] of the fuels used by the power plants (coal, oil and natural gas) as the pollution-containing input.[14] We do not include the different fuels separately because this would

[12] This step was done following the definition of a power plant as coal-fired by Färe et al. (2007b).
[13] A BTU is the amount of thermal energy needed to raise the temperature of one pound of water by $1^{\circ}F$.
[14] In our analysis coal consists of anthracite and bituminous (BIT), lignite (LIG) and subbituminous (SUB) coal. Oil consists of destillate (DFO) and residual fuel (RFO) oil.

lead to zeros in the input data since many observations do not use oil or natural gas additional to coal. To avoid zeros in the data (see e.g. Thanassoulis et al. (2008) for an overview of this problem in DEA methods) we aggregate all used fuels by multiplying the physical quantities of the fuels with their heat content which is also reported in the file EIA-923 and sum up the results to one input (total heat content). The non-polluting input of the production stage is given by the installed capacity of the generators measured in megawatts (MW). The output of the production stage, the produce amount of electricity, can be split up into two parts. The first part, the net generation of electricity, is the amount (measured in gigawatt hours (GWh)) of electricity produced by the plant excluding the amount of electricity used by the plant. The second part is the amount of electricity used by the FGD units to abate SO_2 emissions. Since this electricity is both an output of the production stage and an input of the abatement stage, it can be viewed as an intermediate input. To estimate the amount of SO_2 emissions (in tons) that are generated in the production stage we multiply the physical quantites of the used fuels by their sulfur content and by the uncontrolled emission factors that are reported in appendix A of the Electric Power Annual Report (EIA (2011)). Beside these emissions and the electricity used by the FGD units, the inputs of the abatement stage consist of the operating costs as well as the costs of the installed FGD structures. The operating costs consist of the costs of land acquisition, waste disposal, chemicals and other maintenance material. To present the costs of installed FGD structures in the year 2009 we use inflation data from the Bureau of Labor Statistics. We assume that no additional equipment was installed to the FGD unit after the year it came into service and hence assume that the costs of the structures did not change after that year. We have to assume this, because we lack data for these costs before the year 1985 and so we cannot observe changes in the costs for structures over the whole operating period of some of the FGD units.[15] The single output of the abatement stage is the amount of abated SO_2 emissions which we obtain by substracting the amount of released SO_2 emissions (given by the EPA data) from the estimated amount of SO_2 emissions produced in the first stage. In addition to the inputs described above which are only used by either the production or the abatement stage, we also include one shared input, the number of employed workers. Two problems arise from the fact that FERC data only report the overall number of worker employed at the power plant. Firstly, our dataset does not necessarily cover the whole plants as explained above. Therefore, we assumed that the number of workers of the plants is proportional to the plants capacity and hence the total amount of labor in our dataset is estimated by

$$\text{Number of workers (total)} = \text{Number of workers (FERC)} \cdot \frac{\text{MW}_{\text{Data}}}{\text{MW}_{\text{Total}}} \quad (11)$$

where MW_{Data} is the capacity of the plant in our dataset and MW_{Total} is the total capacity of the plant. Secondly, we had to attribute the total amount of workers to the production and the abatement stage. To estimate the amount of workers operating the FGD units

[15] The historical data back to the year 1985 can be obtained from the file EIA-767.

we used two power laws which were developed by Srivastava (2000) to estimate the cost of operating labor for FGD units.[16] For wet scrubbers the amount is estimated by

$$\text{Number of workers (FGD)} = 41.69041 \cdot \text{MW}^{-0.322307} \cdot \frac{\text{MW}}{100} \tag{12}$$

and for dry scrubbers by

$$\text{Number of workers (FGD)} = (18.25 - 2.278 \cdot \ln(\text{MW})) \cdot \frac{\text{MW}}{100} \tag{13}$$

where MW denotes the capacity of the generators linked to the FGD unit. The difference of the estimated total number of workers and the estimated FGD operating labor is attributed to the production stage. Table 1 presents the descriptive statistics for the data used in the production and the abatement stage, respectively.

Table 1: Descriptive statistics of the production process

$n = 23$ Power Plants	Min	Mean	Median	Max	SD
Production stage					
Inputs					
Total heat content (Bio. BTUs)	9049.93	47413.73	32816.74	127135.37	33232.20
Capacity (MW)	191.70	883.38	644.60	2160.20	589.47
Output					
Net generation (GWh)	1108.39	5035.63	3450.75	14664.33	3717.50
Abatement stage					
Inputs					
SO_2 emissions (tons)	971.80	7032.16	4570.78	40129.08	8919.37
Operation costs (1000$)	1316.00	7399.52	5473.00	21619.00	6045.30
Costs of structures (1000$, 2009)	11323.52	211254.71	122746.99	692319.67	170881.04
Output					
Abated SO_2 emissions (tons)	2102.27	78471.06	41399.25	280130.00	83419.18
Intermediate input					
FGD electricity (GWh)	5.79	78.92	46.62	314.60	81.56
Shared input					
Labor total (worker)	55.00	140.17	118.00	398.00	79.36
Labor production (worker)	25.00	102.26	88.00	330.00	65.65
Labor FGD (worker)	12.00	37.91	31.00	76.00	19.05

[16] These equations are also implemented in the EPA CueCost program, a computer software to estimate the capital cost of power plants.

The descriptive statistics show, that although we excluded observations with a capacity lower than 100 MW, our sample covers a broad range of power plant sizes as can be seen by the minimal and maximal amounts of installed capacity. The relatively small sample size (23 power plants) is largely driven by the FERC data since for many power plants no labor data was available. The costs for the FGD structures appear to be very large (the maximum is near to 700 Mio.$) but they are in accordance with the average costs as presented by the EPA (see EPA (2003)).
We estimate the environmental efficiency of the power plants by solving the linear program defined in section 3. To solve this problem we use the package "lpSolve" for the statistical software R. Since the final output (net generation of electricity) does not contain any pollution, we do not minimize the emissions over this variable. The Ω matrix is estimated for each plant by the weighted average sulfur dioxide emission input (u') per BTU of used heat content. The detailed results of the environmental efficiency as well as the decomposition into production and abatement efficiency for each plant can be found in table 3 in the appendix of this paper. Table 2 contains the descriptive statistics of the results while figure 5 contains the related boxplots. A boxplot can be read as follows. The box shows the interquartile range of the efficiency estimates with the lower end indicating the first quartile and the upper end indicating the third quartile. The bold line shows the median value. The whiskers span to the most extreme observations that lie within 1.5 times the interquartile range.

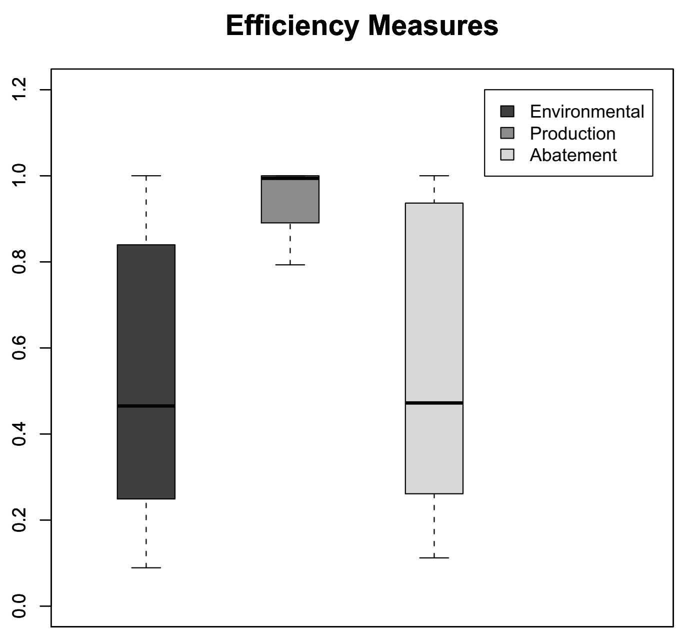

Figure 5: Boxplots of the efficiency estimates

Table 2: Descriptive statistics of efficency measures

Efficiency	Min	Mean	Median	Max	SD	# Efficient
Environmental	0.089	0.522	0.465	1.000	0.341	4
Production	0.793	0.942	0.994	1.000	0.073	10
Abatement	0.112	0.542	0.472	1.000	0.343	5

Our efficiency analysis shows that ten power plants are productive and five are abatement efficient. Four plants are efficient regarding both the production and the abatement stage and are therefore environmentally efficient. One observation, the power plant Cayuga, is abatement but not productive efficient, hence its environmental efficiency equals its production efficiency. Moreover, our results show that while the efficiency of the production is high among the DMUs (average efficency 94.2%), the abatement efficiency is quite low (average efficiency 54.2%). It is clearly visible from the boxplots that the low abatement efficiency of the plants largely influences their environmental efficiency which is also relativly low (mean value 52.2%). To analyze whether the plants which are regulated by the EPA CAIR program show significant differences in their environmental performance compared to the plants which are only regulated by the ARP program, we tested for these potentials differences using the Wilcoxon-Test. While we find no differences among the power plants with respect to the environmental and the abatement efficiency, we find that the CAIR regulated plants show significant lower productive efficiency results. This result indicates that the CAIR program comprises a subgroup of ARP regulated plants which have significant potentials to lower their emissions created in the production stage. This reduction would lead to a catch-up of these plants to the rest of the ARP regulated power plants.

To summerize our results we find that the power plants in the year 2009 show significant potentials to reduce their SO_2 emissions. This supports the EPA decision to implement further regulatory actions on the plants (as the CAIR program). Using the possibility to separate the environmental efficiency into its components, we find that environmental inefficiencies are largely driven by abatement inefficiencies. Therefore, an optimal regulation should adress the abatement activities of the power plants to exploit the potentials for SO_2 reductions.

5 Conclusion

In this paper we have presented a new approach to evaluate the environmental efficiency of decision making units. Since the existing literature of nonparametric efficiency analysis does not account for explicit abatement activities of the DMUs we proposed a technology that incorporates a production as well as an abatement stage, which are linked using intermediate and shared inputs. Furthermore, we showed how the materials balance condition can be incorporated to estimate the amount of emissions before the abatement process. We proposed a new measure for environmental efficiency and showed how it can be decomposed into the effects of production and abatement efficiency. Moreover, a network DEA model was introduced which can be used to estimate the efficiency measure and its components. Our application of the new model to U.S. power plants shows that there are significant potentials to reduce SO_2 emissions which could be achieved by more efficient abatement activities of the plants. We find significant differences in the production efficiency of power plants which are in addition to the Acid Rain Program of the EPA regulated by the Clean Air Interstate Rule. These differences which existed in the year 2009 and hence before the regulation started, can be interpreted as potential sources for an catch-up to the plants which are not regulated by the CAIR. But we want to point out, that since our sample only consists of 23 power plants these results might be due to the small sample size. This problem could be adressed in future reseach by applying the presented model on different datasets. Empirical research with regard to the coal-fired power plants may analyze sources of the large abatement inefficiencs which could be used to identify the targets of environmental regulation more precisely. Since the detailed data for empirical environmental analyses as performed in this paper are lacking for many interesting real-world problems, future theoretical research may enhance the presented model to allow a detailed analysis without the necessity of a large amount of data.

6 References

Ayers, R.U. and A.V. Kneese (1969). "Production, Consumption, and Externalities". In: *The American Economic Review* 59(3), pp. 282–297.

Charnes, A., W.W. Cooper, and E. Rhodes (1978). "Measuring the Efficiency of Decision Making Units". In: *European Journal of Operational Research* 2, pp. 429–444.

Coelli, T., L. Lauwers, and G. Van Huylenbroeck (2007). "Environmental Efficiency Measurement and the Materials Balance Condition". In: *Journal of Productivity Analysis* 28, pp. 3–12.

Eastern Research Group (2009). *Electricity Framework 5 Years Review - Control Technologies Review.*

EIA (2011). *Electric Power Annual 2009.* Report DOE/EIA-0348(2009).

EPA (2003). *Air Pollution Control Technology Fact Sheet.* EPA-452/F-03-034.

— (2005). *Fact Sheet - Clean Air Interstate Rule (CAIR).*

— (2011a). *Acid Rain Program - Basic Information.* [Retrieved August 09, 2011]. URL: http://www.epa.gov/airmarkets/progsregs/arp/basic.html.

— (2011b). *Sulfur Dioxide.* [Retrieved August 09, 2011]. URL: http://www.epa.gov/oaqps001/sulfurdioxide/.

Førsund, F. R. (2009). "Good Modelling of Bad Outputs: Pollution and Multiple-Output Production". In: *International Review of Environmental and Resource Economics* 3, pp. 1–38.

Färe, R. and S. Grosskopf (1996). *Intertemporal Production Frontiers: With Dynamic DEA.* Norwell, Massachusetts (U.S.): Kluwer Academic Publishers.

Färe, R. and D. Primont (1995). *Multi-Output Production and Duality: Theory and Applications.* Boston/London/Dordrecht: Kluwer Academic Publishers.

Färe, R., S. Grosskopf, C. A. K. Lovell, and C. Pasurka (1989). "Multilateral Productivity Comparisons When Some Outputs are Undesirable: A Nonparametric Approach". In: *The Review of Economics and Statistics* 71(1), pp. 90–98.

Färe, R., S. Grosskopf, and F. Hernandez-Sancho (2004). "Environmental Performance: An Index Number Approach". In: *Resource and Energy Economics* 26, pp. 343–352.

Färe, R., S. Grosskopf, D.-W. Noh, and W. Weber (2005). "Characteristics of a Polluting Technology: Theory and Practice". In: *Journal of Econometrics* 126, pp. 469–492.

Färe, R., S. Grosskopf, and G. Whittaker (2007a). "Network DEA". In: *Modeling Data Irregularities and Structural Complexities in Data Envelopment Analysis.* Ed. by J. Zhu and W. D. Cook. Springer: New York, pp. 209–240.

Färe, R., S. Grosskopf, and C. A. Pasurka (2007b). "Pollution Abatement Activities and Traditional Productivity". In: *Ecological Economics* 62, pp. 673–682.

Hua, Z. and Y. Bian (2008). "Performance Measurement for Network DEA with Undesirable Factors". In: *International Journal of Management and Decision Making* 9(2), pp. 141–153.

Lauwers, L. (2009). "Justifying the Incorporation of the Materials Balance Principle into Frontier-Based Eco-Efficiency Models". In: *Ecological Economics* 68, pp. 1605–1614.

Lovell, C. A. K., J. T. Pastor, and J. A. Turner (1995). "Measuring Macroeconomic Performance in the OECD: A Comparison of European and Non-European Countries". In: *European Journal of Operational Research* 87, pp. 507–518.

Murty, S. and R. R. Russell (2010). "On Modeling Pollution-Generating Technologies". Warwick Economic Research Papers No. 931.

Pethig, R. (2006). "Non-Linear Production, Abatement, Pollution and Materials Balance Reconsidered". In: *Journal of Environmental Economics and Management* 51, pp. 185–204.

Scheel, H. (2001). "Undesirable Outputs in Efficiency Valuations". In: *European Journal of Operational Research* 13, pp. 400–410.

Seiford, L. M. and J. Zhu (2002). "Modeling Undesirable Factors in Efficiency Evaluation". In: *European Journal of Operational Research* 142, pp. 16–20.

Shephard, R. W. (1970). *Theory of Cost and Production Functions*. Princeton: Princeton University Press.

Srivastava, R. K. (2000). "Contolling SO_2 Emissions: A Review of Technologies". In: *U.S. Environmental Protection Agency, Office of Research and Development, EPA/600/R-00/093*.

Srivastava, R. K. and W. Josewicz (2001). "Flue Gas Desulfurization: The State of the Art". In: *Journal of the Air & Waste Management Association* 51, pp. 1676–1688.

Sueyoshi, T., M. Goto, and T. Ueno (2010). "Performance Analysis of US Coal-Fired Power Plants by Measuring Three DEA Efficiencies". In: *Energy Policy* 38, pp. 1675–1688.

Thanassoulis, E., M. C. A. S. Portela, and O. Despić (2008). "Data Envelopment Analysis: The Mathematical Programming Approach to Efficiency Analysis". In: *The Measurement of Productive Efficiency and Productivity Growth*. Ed. by H.O. Fried, C.A.K. Lovell, and S.S. Schmidt. Oxford University Press, pp. 251–420.

Tyteca, D. (1996). "On the Measurement of the Environmental Performance of Firms - A Literature Review and a Productive Efficiency Perspective". In: *Journal of Environmental Management* 46, pp. 281–308.

Yang, C-C., C.-K. Hsaio, and M.-M. Yu (2008). "Technical Efficiency and Impact of Environmental Regulations in Farrow-to-Finish Swine Production in Taiwan". In: *Agricultural Economics* 39, pp. 51–61.

Zhou, P., B. W. Ang, and K. L. Poh (2008). "A Survey of Data Envelopment Analysis in Energy and Environmental Studies". In: *European Journal of Operational Research* 189, pp. 1–18.

7 Appendix

Table 3: Plant results of the efficiency analysis

Plant ID	Plant Name	Environmental	Production	Abatement
51	Dolet Hills	0.089	0.796	0.112
469	Cherokee	0.176	1	0.176
470	Comanche	0.473	1	0.473
477	Valmont	1	1	1
645	Big Bend	0.263	0.89	0.295
990	Harding Street	0.358	0.899	0.399
994	AES Petersburg	0.244	0.891	0.274
1001	Cayuga	0.901	0.901	1
1356	Ghent	0.269	1	0.269
1363	Cane Run	0.135	0.869	0.155
1364	Mill Creek	0.778	0.889	0.875
1915	Allen S King	0.661	1	0.661
2727	Marshall	0.997	0.999	0.998
3797	Chesterfield	0.707	0.943	0.75
4078	Weston	1	1	1
4162	Naughton	0.267	0.994	0.268
6071	Trimble County	1	1	1
6085	R M Schahfer	0.095	0.817	0.116
6137	A B Brown	0.186	0.793	0.235
8042	Belews Creek	0.465	0.985	0.472
8066	Jim Bridger	0.254	1	0.254
8069	Huntington	0.695	1	0.695
8224	North Valmy	1	1	1