Decomposing NO_x and SO_2 Electric Power Plant Emissions in a "By-production" Framework: A Nonparametric DEA Study

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Abstract

Recently, Murty, Russell, and Levkoff [2011] introduced the concept of *by-production* as a non-conventional approach for modeling pollution-generating technologies. This approach differs significantly from traditional treatments with regards to: 1) disposability properties of goods associated with pollution and 2) the use of separate production relations to model pollution generation. Using a panel data set of input-output observation for coal-fired electric power plants, this study applies the by-production approach to a quadripartite index decomposition (ID) model to analyze productivity factors associated with emissions variations among polluting firms as well as the behavior of these firms when they face binding regulation requiring future emissions reductions. Indexes that are decomposable into measures of both environmental and intended output efficiency are computed by nonparametrically estimating the by-production technologies via data envelopment (DEA) methods.

1 Introduction

In a recent paper, Murty, Russell, and Levkoff [2011] (MRL) take an non-conventional approach to modeling the joint production activities of technologies that produce both good and bad outputs and introduce the concept of a *by-production* technology. Technologies that exhibit the property of by-production satisfy a *costly disposability* condition with respect to by-products,[1] such as pollution, and violate standard free disposability with respect to goods associated with the generation of the by-product, such as the burning of fossil fuels. In addition, MRL show that in general, more than one implicit production relation is needed in order to properly capture all of the technological trade-offs associated with the physical processes of by-production and that conventional single relation approaches assuming weak disposability of unintended outputs fail to get the job done. MRL propose a by-production technology set defined as the intersection of a standard technology set and nature's residual generation

[1] We use the terms *by-product*, *residual*, *pollutant*, *unintended output*, and *bad output* interchangeably, admittedly with some abuse.

set whose reduced form satisfies the correct technological tradeoffs associated with the physical processes implied by the by-production phenomenon.[2] The necessity of more than one implicit production relation to model by-production technologies has direct implications on the nonparametric estimation of the DEA technology and the algorithms employed for computing efficiency measurements. This study models by-production technologies of coal-fired electric power plants - technologies that generate both electricity, an intended output, and pollutants, by-products resulting from the use of fuel inputs. The model is then used in an application analyzing the factor decomposition of emissions variations of these power plants over time. In parallel with Pasurka [2006], this study takes a distance function approach to modeling the joint by-production of both good and bad outputs, but with multiple production relations and non-conventional technological assumptions related to the disposability properties associated with the generation of unintended outputs. Furthermore, we examine variations in bad output production resulting from variations in technical efficiency, technical progress, and the input-output mix in a manner similar to growth accounting studies of changes in total factor productivity.

The remainder of the study is organized as follows: The rest of the first section provides background on disposability and conducts a survey of previous decomposition studies related to firm emissions. Section 2 explains the derivation of the joint by-production model used in decomposing emissions via data envelopment analysis

[2]Pethig [2006] also takes a non-conventional approach to modeling pollution-generating technologies utilizing the materials balance condition with a network technology.

(DEA) under the assumption of residual by-production. Section 3 outlines the algorithms utilized to calculate indexes for the factor decomposition and discusses some issues related to modeling technological dynamics when complications arise from using a mixed-period Malmquist-Luenberger distance functions with panel data. Section 4 presents the results of the index decomposition for the various technological assumptions and concludes with a discussion related to firm response to the 1990 Clean Air Act Amendment. The study concludes with Section 5.

1.1 Previous Studies

The literature on decomposing factors associated with changes in pollution emissions has been extensive. Many of these studies have carried out analyses related to carbon emissions variations using either index decomposition (ID) models[3] similar to the one herein or structural decomposition analysis (SDA) models,[4] which utilize input-output tables.[5] While carbon emissions are of great importance in the environmental literature, this study focuses specifically on NO_x and SO_2 emissions. NO_x and SO_2 emissions are now subject to federal cap and trade policy under the Acid Rain Ruling, which was established under Title IV of the 1990 Clean Air Act Amendment to reduce acid deposition in the environment. Unlike studies analyzing only carbon emissions,

[3]See Lin and Chang [1996], Selden et al. [1999], Viguier [1999], Hammer and Lofgren [2001], Bruvoll and Medin [2003], and Cherp et al. [2003].

[4]See Leontief and Ford [1972], Meyer and Stahmer [1989], Wier [1998], Wier and Hasler [1999].

[5]For a comparison of these models, see Hoekstra and ven der Bergh [2003]

where the production frontier consists of a single combination of good and bad output production for a given technology and input/intended output combination due to the absence of abatement activities, when NO_x and SO_2 emissions are generated, abatement options allow for multiple combinations of good and bad outputs to be produced for a given technology and input vector. Reducing carbon emission resulting from the burining of fossil fuels, on the other hand, requires either substitution between types of less emission intense fuels or substitution of non-fuel inputs for fuel inputs. Aiken and Pasurka [2002] specify a joint production model and attempt to quantify variations in SO_2 emissions associated with changes in technical efficiency, the output mix, and production levels in the United States manufacturing sector during the 80's and 90's. Pasurka [2003] extends this analysis by calculating the change in SO_2 emissions associated with the lack of free disposability of pollutants. Throughout the remainder of the paper, the standard technology set will be denoted by T, input vectors are denoted by $x \in R^I_+$, intended output vectors by $y \in R^J_+$, and unintended output vectors by $z \in R^K_+$.

1.2 Disposability

Past studies focused on capturing the positive relationship between intended production and residual generation of unintended outputs typically treated pollution in one of two fashions: either as a standard input,[6] or as a weakly disposable, null-joint

[6]See Baumol and Oates [1975], Cropper and Oates [1992], Pittman [1981], and Barbera and McConnell [1990].

output.[7]

A technology satisfies weak disposability of outputs if[8]

$$\langle x, y, z \rangle \in T \implies \langle x, \lambda y, \lambda z \rangle \in T \;\; \forall \;\; \lambda \in [0, 1].$$

This implies that while pollution is not freely disposable, it is possible to reduce, in tandem, pollution and intended outputs.

Null-jointness is satisfied if

$$\langle x, y, z \rangle \in T \wedge z = 0 \implies y = 0.$$

This condition implies that any positive level of intended production always generates some residual by-product.

This study takes the position of MRL, that weak disposability of unintended outputs is inconsistent with the trade offs implied by the physical processes associated with the by-production phenomenon. It is reasonable to purport that, in the case of pollution generating firms, there are specific characteristics about stages in the production process of applying a technology to a set of inputs to produce some desired output that can set reactions in motion in nature that will inevitably result in the generation of pollution as a by-product (e.g., the use of gas, fuel, or coal generates NO_x and SO_2 emissions which in turn react to the atmosphere causing acid rain). MRL define these natural reactions that occur contemporaneously with intended production

[7] See Pittman [1983], Fare, Grosskopf, Lovell, and Pasurka[1989], Pasurka[2006], and Fare, Grosskopf, and Pasurka [1986].

[8] This was first formalized by Shephard [1953].

as nature's residual generation mechanism. In the case of technologies exhibiting the by-production property, we argue that one can observe a certain minimal amount of the by-product for a particular level of input/intended output bundle. Inefficiencies arising in the production process through nature's residual generation mechanism can lead to excess generation of the by-product above the minimal lower bound implied by physical feasibility. This means that the technology should satisfy a much different technological assumption known as costly disposability[9]

$$\langle x, y, z \rangle \in T \wedge \bar{z} \geq z \implies \langle x, y, \bar{z} \rangle \in T.$$

Thus, this non-conventional definition implies some *minimal* feasible vector of residuals for a given combination of inputs/intended outputs in a manner similar to how much of the conventional literature on modeling intended output production utilizes production functions defining the *maximal* feasible set of output vectors associated with a fixed input bundle.

As a preliminary discussion, let's first consider the flaw associated with utilizing only one implicit production relation if we accept that the technology satisfies costly disposability. The standard technology set is defined as[10]

$$T = \{\langle x, y, z \rangle \in R_{+}^{I+J+K} | f(x, y, z) \leq 0\},$$

where f is differentiable and vectors satisfying $f(x, y, z) = 0$ are (weakly efficient)

[9] This condition was first formalized by Murty [2010] and is similar to free input disposability.

[10] We abstract from including abatement output in this study as we lack data on abatement activities in our application. For a theoretical discussion including abatement output, see MRL.

points on the boundary of the technology set. Any vectors satisfying $f(x, y, z) < 0$ are inefficient production vectors. The standard differential restrictions imposed on the technology are

$$f_x(x, y, z) \leq 0,$$

$$f_y(x, y, z) \geq 0,$$

$$f_z(x, y, z) \leq 0.$$

The first two differential restrictions are the standard free disposability of inputs and intended outputs, respectively

$$\langle x, y, z \rangle \in T \wedge \bar{x} \geq x \implies \langle \bar{x}, y, z \rangle \in T,$$

$$\langle x, y, z \rangle \in T \wedge \bar{y} \leq y \implies \langle x, \bar{y}, z \rangle \in T.$$

The third differential restriction captures the costly disposability condition.

Next, consider an efficient vector $\langle \hat{x}, \hat{y}, \hat{z} \rangle$ such that $f(\hat{x}, \hat{y}, \hat{z}) = 0$ and $f_z(\hat{x}, \hat{y}, \hat{z}) < 0$. Then by the implicit function theorem, there exist neighborhoods $U \subseteq R_+^{I+J+K-1}$ and $V \subseteq R_+$ around $\langle \hat{x}, \hat{y}, \hat{z_{-k}} \rangle \in R_+^{I+J+K-1}$ and $\hat{z_k} \in R_+$ and a function $\varphi : U \to V$ such that

$$\hat{z_k} = \varphi(\hat{x}, \hat{y}, \hat{z_{-k}})$$

and

$$f(x, y, \varphi(x, y, z_{-k}), z_{-k}) = 0,$$

where z_{-k} is the vector z with the kth element purged.

Then the ceteris paribus trade off between any input and unintended by-product z_k implied by the implicit function theorem is given by

$$\frac{\partial \varphi(x, y, z_{-k})}{\partial x_i} = -\frac{f_x(x, y, z)}{f_z(x, y, z)} \leq 0 \ \ \forall \ \ i, k.$$

Clearly, this non-positive trade off between inputs and residuals is inconsistent with the phenomena of by-production, especially in the case where usage of input i results in residual generation of by-product k. That is, if pollution is generated as a by-product of input usage, then the usage of inputs should be positively correlated with the residual generation of pollution, not negatively.

Likewise, the ceteris paribus trade off between any intended output and unintended by-product z_k implied by the implicit function theorem is given by:

$$\frac{\partial \varphi(x, y, z_{-k})}{\partial y_j} = -\frac{f_y(x, y, z)}{f_z(x, y, z)} \geq 0 \ \ \forall \ \ j, k.$$

If the trade off between intended production and pollution is strictly positive, this implies the existence of a wide variety of technically efficient $\langle y, z \rangle$ combinations that are possible with fixed levels of all inputs. This is also incongruent with the by-production phenomena since by-production itself implies that only one technically efficient, minimal level of pollution should exist given a fixed level of inputs[11] combinations.

Finally, the implied trade off between one pollutant and another along the effi-

[11]Unless abatement activities are present, which would permit a rich menu of $\langle y, z \rangle$ combinations.

cient frontier is given by:

$$\frac{\partial \varphi(x,y,z_{-k})}{\partial z_{-k}} = -\frac{f_z(x,y,z)}{f_z(x,y,z)} \leq 0 \;\; \forall \;\; k.$$

This implies that pollutants are substitutable for one another and that there exists a rich menu of $\langle z_k, z_{-k} \rangle$ for a given input and intended production vector. Again, this trade off is not consistent with the fact that the residual generation mechanism may be specific to the utilization of particular inputs (ie: coal) and one combination of inputs may not be able to produce such a rich menu of unintended by-product.

Clearly, these trade offs are not consistent with the phenomena of by-production. Moreover, it seems that the single equation implicit specification of a pollution generating technology seems to treat residual generation like any other input: increases in levels of the by-product holding all other inputs fixed increases output; secondly, pollution is a substitute for all other inputs in the production process so that decreases in non-polluting inputs can be easily substituted with pollution to generate the same level of output.

To reconcile this seeming paradox between by-production and implicit trade offs, we follow MRL and utilize multiple production relations to model the residual generation mechanism and intended production process as two separate technology sets. The by-production technology is then defined as the the set of feasible vectors in the intersection of these two technology sets. Under the by-production specification, the reduced form technology satisfies free disposability with respect to intended outputs and non-pollution causing inputs. It violates free disposability with respect to pollution causing inputs and satisfies the costly disposability condition with respect to residually generated, unintended outputs. A few studies have already explored using multiple relations.[12]

The next section describes the technology under the by-production assumption and the implications for estimating the technology set utilizing data envelopment analysis.

2 By-production Technology

In order to correct for the aforementioned trade off implications that arise under the single equation, implicit production relation when costly disposability is invoked, we specify a by-production technology as the intersection of two technological mechanisms: one governing the intended production process and another governing the residual generation mechanism. The subsequent reduced form by-production technology properly accounts for the trade offs that the single equation formulation fails to capture.[13] Partition the input vector $x = \langle x_{-\imath}, x_\imath \rangle$ where $x_{-\imath}$ is the input vector purged of the first $I' \leq I$ inputs that are associated with the pollutants z and let $x_\imath$ denote the subset of the input vector that are associated with the residual generation

[12] Frisch [1965] and more recently, Forsund [2009] provide some foundation on using multiple production relations.

[13] See MRL for a proof of this proposition.

of pollutants.[14] The by-production technology is specified as

$$T_{BP} = T_1 \cap T_2,$$

where

$$T_1 = \left\{ \langle x_{-\imath}, x_\imath, y, z \rangle \in \mathbf{R}_+^{I+J+K} \mid f(x_{-\imath}, x_\imath, y) \leq 0 \right\},$$

$$T_2 = \left\{ \langle x_{-\imath}, x_\imath, y, z \rangle \in \mathbf{R}_+^{I+J+K} \mid g(z, x_\imath) \geq 0 \right\},$$

and f and g are continuously differentiable functions.[15] T_1 is the standard technology set specifying the ways in which inputs are transformed into intended outputs. The standard free disposal properties can be imposed on this set by assuming that

$$f_x(x, y) \leq 0 \quad \forall \quad i = 1 \ldots I$$

$$f_y(x, y) \geq 0 \quad \forall \quad j = 1 \ldots J.$$

T_2 is nature's residual-generation set reflecting the physical and chemical mechanism underlying the production of pollutants. T_2 satisfies costly disposability with respect

[14] In general, we need not restrict ourselves to the case where only input usage causes pollution. For example, the production of cheese causes an unintended odor from the presence of the output, not necessarily from input usage. See MRL for a discussion of altering the model to accommodate for this type of situation.

[15] We assume that T_{BP} is non-empty. In fact, as long as a production vector in T_1 is feasible given the same component of pollution generating input causes some amount of pollution through T_2, then the intersection will be non-empty. If the no free lunch assumption holds, then the zero vector lies in both T_1 and T_2, so that T_{BP} is non-empty.

to pollution as the function $g(z, x_\imath)$ defines the minimum level[16] of bad outputs generated by a given level of input usage and satisfies

$$g_{x_\imath}(z, x_\imath) \leq 0 \;\; \forall \;\; \imath = 1 \ldots I'$$

$$g_z(z, x_\imath) \geq 0 \;\; \forall \;\; k = 1 \ldots K$$

to reflect the fact that increases in input usage associate with bad output production will increase this minimal amount. However, notice that T_2 violates standard free disposability of inputs that are associated with pollution and satisfies a completely different condition with respect to these inputs:

$$\langle x_{-\imath}, x_\imath, y, z \rangle \in T_2 \wedge \bar{z} \geq z \wedge \bar{x}_\imath \leq x_\imath \implies \langle x_{-\imath}, \bar{x}_\imath, y, \bar{z} \rangle \in T_2.$$

This condition reflects that fact that inefficiencies arising in the residual generation process imply that it may be possible to either reduce input usage to generate the same level of pollutant or reduce pollution generation for a given level of input usage.

Thus, we can infer that T_{BP} satisfies free disposability with respect to all intended outputs and inputs not associated with residual generation. However, the reduced form by-production technology violates standard free disposability with respect to inputs associated with residual generation and satisfies costly disposability with respect to residual generation of pollutants.

[16]We could equivalently allow some function $\bar{g}$ to instead define the maximal level of by-product feasible for a given input/intended output combination, but abstract from this issue here as it is not empirically binding in our estimation techniques.

2.1 Constructing the DEA Technologies

In this section, we describe the fundamental differences between the weak disposability/null-jointness and by-production approaches with respect to the nonparametric estimation of the convex DEA technology. We consider the case where input usage is associated with pollution, since this is the case relevant to our data set utilized in the factor decomposition. Construction of the DEA technologies requires the following elements:

(i) D decision making units (DMUs), indexed by d.

(ii) J intended outputs, indexed by j, with quantity vector $y \in R^J_+$. Let Y be the $D \times K$ matrix of intended output observations.

(iii) I inputs, indexed by i. The first I' are inputs associated with causing pollution, indexed by $\imath$. The remaining $I - I'$ inputs are non pollution-generating. The quantity vector is $x = \langle x^{\imath}, x^{-\imath} \rangle$. The $D \times I$ matrix of input observations is then partitioned into $X = \langle X^{\imath}, X^{-\imath} \rangle \in R^I_+$.

(iv) K pollutants indexed by k, with quantity vector $z \in R^K_+$. Let Z be the $D \times K$ matrix of pollution observations.

The standard DEA construction of a pollution-generating technology satisfying weak disposability and null-jointness, as formulated by Fare, Grosskopf, and Pasurka [1986] is given by[17]

$$T_{WD} = \left\{ \langle x, y, z \rangle \in R^{I+J+K}_+ | \lambda X \leq x \wedge \lambda Y \geq y \wedge \lambda Z = z \text{ for some } \lambda \in R^D_+ \right\}.$$

[17] Their study assumes constant returns to scale and we maintain this assumption herein. The assumption can be easily modified by altering the non-negativity constraints on λ.

The by-production technology is constructed in three stages.

(i) T_1 is constructed by

$$T_1 = \left\{ \langle x, y, z \rangle \in R_+^{I+J+K} | \lambda X \leq x \wedge \lambda Y \geq y \ \text{ for some } \ \lambda \in R_+^D \right\}.$$

(ii) T_2 is constructed by

$$T_2 = \left\{ \langle x^\imath, x^{-\imath} y, z \rangle \in R_+^{I+J+K} | \mu X^\imath \geq x^\imath \wedge \mu Z \leq z \ \text{ for some } \ \mu \in R_+^D \right\}.$$

(iii) The by-production technology is defined as the intersection of T_1 and T_2

$$T_{BP} = \left\{ \langle x^\imath, x^{-\imath} y, z \rangle \in R_+^{I+J+K} | \lambda [X^\imath \ X^{-\imath}] \leq \langle x^\imath, x^{-\imath} \rangle \ \wedge \ \lambda Y \geq y \ \wedge \ \mu X^\imath \geq x^\imath \ \wedge \ \mu Z \leq z \right.$$
$$\left. \text{for some } \ \langle \lambda, \mu \rangle \in R_+^{2D} \right\}.$$

The following sections discuss the choice of distance functions to be used in the quadripartite decomposition.

3 Efficiency Measurement and Decomposition

This study will utilize two different types of distance functions in implementing the quadripartite decomposition:[18] The popular hyperbolic index and a modification of the Fare, Grosskopf, and Lovell [1985] coordinate-wise efficiency index as utilized by MRL to characterize efficiencies specifically in by-production technologies. The advantage of the latter index is that it satisfies an indication axiom,[19] which the

[18]Although, within these two categories of distance functions, we will actually compute seven different indexes, five of which utilize mixed-period distance functions to run the decomposition.

[19]Indication is satisfied if the index takes on the value of one if and only if an observation is technically efficient in the strict Koopmans sense.

hyperbolic does not. Furthermore, the coordinate-wise index is readily decomposable into measures of efficiency in intended production and (in)efficiency in unintended residual generation of by-products.

3.1 Distance Functions: Weak Disposability vs. By-production

The most popular efficiency index used in decomposition studies is the hyperbolic efficiency index. Pasurka [2006] measures producer efficiency under weak disposability and null jointness by employing the hyperbolic index

$$D_{HYP}^{-1}(x, y, z, T_{WD}) = \max_{\beta > 0} \{\beta | \langle x, y\beta, \beta z\rangle \in T_{WD}\}.$$

That is, efficiency is measured by crediting the producer for expanding both intended and unintended outputs to the boundary of the technology set. However, this implies, that the index will give a relatively higher ordinal ranking to a producer if that producer is able to generate more (not less) pollution relative to others. First,we modify the direction of measurement under weak disposability by employing the subsequent decomposition utilizing a variation of the hyperbolic efficiency index that credits the producer for simultaneously expanding and retracting intended and unintended outputs, respectively.

$$D_{HYP}^{-1}(x, y, z, T_{WD}) = \min_{\beta > 0} \{\beta | \langle x, y/\beta, \beta z\rangle \in T_{WD}\}.$$

However, measurement under the by-production framework is less straight forward since the presence of multiple technological mechanisms implies measurement relative to not one, but two different frontiers. Thus, two notions of efficiency arise under by-production: efficiency in intended production, as measured by the expansion of an intended output vector toward the production possibilities frontier, and environmental efficiency, as measured by retracting unintended pollution to its minimally possible level given an input/intended output vector. We calculate the hyperbolic index for the by-production technology by solving the following optimization problem:

$$
\begin{aligned}
D_{HYP}(x, y, z, T_{BP}) &= \min_{\beta>0} \{\beta |\ \langle x, y/\beta, \beta z\rangle \in T_{BP}\} \\
&= \min_{\beta>0} \{\beta | \langle x, y/\beta, \beta z\rangle \in T_1 \text{ and } \langle x, y/\beta, \beta z\rangle \in T_2\} \\
&= \max\{\beta_1, \beta_2\} \quad \text{where} \\
\beta_1 &= \min_{\beta>0} \{\beta | \langle x, y/\beta, z\rangle \in T_1\} =: D_H^1(x, y, z, T_{BP}) \\
\beta_2 &= \min_{\beta>0} \{\beta | \langle x, y, \beta z\rangle \in T_2\} =: D_H^2(x, y, z, T_{BP}).
\end{aligned}
$$

The equalities after the first equation follow from the independence of T_1 and T_2[20]. Note that β_1 measures efficiency in intended production while β_2 measures environmental efficiency. That is, if $D_{HYP} = \beta_1$, then the reference point in the by-production technology set is efficient (weakly) in intended production, but not environmentally efficient. If $D_{HYP} = \beta_2$, then the reference point in the by-production technology set is environmentally efficient (weakly), but not output efficient. Therefore, it is important for policy makers and researchers to distinguish between these two notions of efficiency as the objectives of producers and policy makers may not coincide.

[20]Note that $\langle x, y, z\rangle \in T_1 \implies \langle x, y, \bar{z}\rangle \in T_1 \ \forall \ \bar{z}$. This assumption would need to be relaxed if pollution adversely affected labor productivity.

The second distance function that will be used in computing efficiency is a modification of a coordinate-wise graph space [21] index, first introduced by Fare, Grosskopf, and Lovell [1985].[22] Define $y \oslash \beta = \langle y_1/\beta_1, \ldots, y_J/\beta_J \rangle$ and $\gamma \otimes z = \langle \gamma_1 z_1, \ldots, \gamma_K z_K \rangle$. In the case of by-production and assuming independence of T_1 and T_2 the by-production index proposed by MRL decomposes as follows:

$$
\begin{aligned}
D_{FGL}(x, y, z, T_{BP}) &:= \frac{1}{2} \min_{\beta,\gamma} \left\{ \frac{\sum_j \beta_j}{J} + \frac{\sum_k \gamma_k}{K} \middle| \, \langle x, y \oslash \beta, \gamma \otimes z \rangle \in T_{BP} \right\} \\
&= \frac{1}{2} \min_{\beta,\gamma} \left\{ \frac{\sum_j \beta_j}{J} + \frac{\sum_k \gamma_k}{K} \middle| \, \langle x, y \oslash \beta, \gamma \otimes z \rangle \in T_1 \ \wedge \ \langle x, y \oslash \beta, \gamma \otimes z \rangle \in T_2 \right\} \\
&= \frac{1}{2} \min_{\beta} \left\{ \frac{\sum_j \beta_j}{J} \ \middle| \ \langle x, y \oslash \beta, z \rangle \in T_1 \right\} + \frac{1}{2} \min_{\gamma} \left\{ \frac{\sum_k \gamma_k}{K} \ \middle| \ \langle x, y, \gamma \otimes z \rangle \in T_2 \right\} \\
&=: \frac{1}{2} \left[D^1_{FGL}(x, y, z, T_1) + D^2_{FGL}(x, y, z, T_2) \right].
\end{aligned}
$$

This index differs significantly from the hyperbolic in that no "slack" is left in the technology.[23] With the hyperbolic index, only one constraint involving β binds with equality. However, D_{FGL} is measured through coordinate-wise expansions and contractions of intended output and pollution respectively. That is, D_{FGL} takes up all of the slack in the technology,[24] whereas the hyperbolic does not.

[21] Graph space refers to the full space of inputs and outputs.

[22] This particular type of index is frequently referred to as a "Russell" measure in the operations research literature.

[23] The weight of 1/2 is used here. Any weights on (0,1) would suffice to preserve the indication property for by-production technologies.

[24] See Levkoff, Russell, and Schworm [2010] for a discussion of this property and its relationship to the FGL index.

3.2 Quadripartite and Pentipartite Emissions Decomposition

We first examine a quadripartite decomposition and extended it further by decomposing fuel growth into two factors: fuel and non fuel input growth. Let z_k^{t+1}/z_k^t represent the gross rate of change in pollutant k between periods t and $t+1$. Then, using distance functions, we can rewrite the gross rate of emissions change as follows:

$$\frac{z_k^{t+1}}{z_k^t} = \frac{D(x^{t+1}, y^{t+1}, z^{t+1}, T_{BP}^{t+1})(z_k^{t+1}/D(x^{t+1}, y^{t+1}, z^{t+1}, T_{BP}^{t+1}))}{D(x^t, y^t, z^t, T_{BP}^t)(z_k^t/D(x^t, y^t, z^t, T_{BP}^t))}$$

which can be rewritten as

$$\begin{aligned}
\frac{z_k^{t+1}}{z_k^t} &= \left[\left(\frac{D(x^{t+1}, y^{t+1}, z^{t+1}, T_{BP}^{t+1})}{D(x^t, y^t, z^t, T_{BP}^t)}\right)\right] \times \left[\left(\frac{D(x^t, y^t, z^t, T_{BP}^t)}{D(x^t, y^t, z^t, T_{BP}^{t+1})}\right)\left(\frac{D(x^{t+1}, y^{t+1}, z^{t+1}, T_{BP}^t)}{D(x^{t+1}, y^{t+1}, z^{t+1}, T_{BP}^{t+1})}\right)\right]^{1/2} \\
&\times \left[\left(\frac{D(x^t, y^t, z^t, T_{BP}^{t+1})}{D(x^{t+1}, y^t, z^t, T_{BP}^{t+1})}\right)\left(\frac{D(x^t, y^{t+1}, z^{t+1}, T_{BP}^t)}{D(x^{t+1}, y^{t+1}, z^{t+1}, T_{BP}^t)}\right)\right]^{1/2} \\
&\times \left[\left(\frac{z_k^{t+1}/D(x^{t+1}, y^{t+1}, z^{t+1}, T_{BP}^{t+1})}{z_k^t/D(x^{t+1}, y^t, z^t, T_{BP}^{t+1})}\right)\left(\frac{z_k^{t+1}/D(x^t, y^{t+1}, z^{t+1}, T_{BP}^t)}{z_k^t/D(x^t, y^t, z^t, T_{BP}^t)}\right)\right]^{1/2} \\
&= TECHEFF_t^{t+1} \times TECHCHANGE_t^{t+1} \times INPUTGROWTH_t^{t+1} \times OUTPUTMIX_{t,k}^{t+1}
\end{aligned}$$

where $TECHEFF_t^{t+1}$ is the index component associated with variations in technical efficiency (movements toward or away from the frontier), $TECHCHANGE_t^{t+1}$ is the index component associated with technical change (shifting of the frontier), $INPUTGROWTH_t^{t+1}$ is the index component associated with variations in input usage, and $OUTPUTMIX_t^{t+1}$ is the index component associated with changes in the output mixture (movements along the frontier). It is important to note that $TECHEFF_t^{t+1}$, $TECHCHANGE_t^{t+1}$, and $INPUTGROWTH_t^{t+1}$ have equal effects on all pollutants being emitted by a given producer and only the k subscript appears on $OUTPUTMIX_{t,k}^{t+1}$). Thus, the $OUTPUTMIX_{t,k}^{t+1}$ component accounts for all variation in emissions across bad outputs for a producer. If any of the components have a value larger than unity, then increased emissions of the pollutant are associated with that component. If the component's value is less than unity, this indicates decreased bad output production associated with the component. $INPUTGROWTH_t^{t+1}$ can be further decomposed to analyze factors related to growth of fuel and non-fuel inputs:

$$INPUTGROWTH_t^{t+1} = \left[\left(\frac{D(x_F^t, x_{NF}^t, y^t, z^t, T_{BP}^{t+1})}{D(x_F^t, x_{NF}^{t+1}, y^t, z^t, T_{BP}^{t+1})}\right)\left(\frac{D(x_F^t, x_{NF}^{t+1}, y^t, z^t, T_{BP}^{t+1})}{D(x_F^{t+1}, x_{NF}^{t+1}, y^t, z^t, T_{BP}^{t+1})}\right)\right]^{1/2}$$
$$\times \left[\left(\frac{D(x_F^t, x_{NF}^t, y^{t+1}, z^{t+1}, T_{BP}^t)}{D(x_F^t, x_{NF}^{t+1}, y^{t+1}, z^{t+1}, T_{BP}^t)}\right)\left(\frac{D(x_F^t, x_{NF}^{t+1}, y^{t+1}, z^{t+1}, T_{BP}^t)}{D(x_F^{t+1}, x_{NF}^{t+1}, y^{t+1}, z^{t+1}, T_{BP}^t)}\right)\right]^{1/2}$$

where the set of inputs $x = \langle x_F, x_{NF} \rangle$ is partitioned into the set of fuel inputs x_F and non-fuel inputs x_{NF}. We can also rewrite this expression as:

$$INPUTGROWTH_t^{t+1} = \left[\left(\frac{D(x_F^t, x_{NF}^t, y^t, z^t, T_{BP}^{t+1})}{D(x_F^t, x_{NF}^{t+1}, y^t, z^t, T_{BP}^{t+1})}\right)\left(\frac{D(x_F^t, x_{NF}^t, y^{t+1}, z^{t+1}, T_{BP}^t)}{D(x_F^t, x_{NF}^{t+1}, y^{t+1}, z^{t+1}, T_{BP}^t)}\right)\right]^{1/2}$$
$$\times \left[\left(\frac{D(x_F^t, x_{NF}^{t+1}, y^t, z^t, T_{BP}^{t+1})}{D(x_F^{t+1}, x_{NF}^{t+1}, y^t, z^t, T_{BP}^{t+1})}\right)\left(\frac{D(x_F^t, x_{NF}^{t+1}, y^{t+1}, z^{t+1}, T_{BP}^t)}{D(x_F^{t+1}, x_{NF}^{t+1}, y^{t+1}, z^{t+1}, T_{BP}^t)}\right)\right]^{1/2}$$
$$= NONFUEGROWTH_t^{t+1} \times FUELGROWTH_t^{t+1}$$

to observe how changes in fuel usage are associated with emissions reductions. Note that both of the above decompositions utilize the mixed-period distance function: using production vectors from period t and the technology form period $t+1$ or vice versa. Using mixed period distance functions presents complications with solution feasibility when calculating indexes under the assumption of weak disposability, and are addressed in the next section.

3.3 Modeling the Best Practice Frontier Using Panel Data

As was discussed in the previous section, the pentipartite decomposition employs seven different distance functions for a given technological specification, five of which involve mixed periods. As is true for Malmquist-Luenberger productivity indexes, some of the solutions to the mixed period distance functions may be infeasible.[25] To mitigate this problem, Pasurka [2006] "pools" the technology by using a three period rolling window, so that the technology in period t is derived from observations from periods t, $t-1$, and $t-2$. While this treatment mitigates the frequency of the in-feasibility problem,[26] it doesn't completely eliminate it. The problem still exists and is further exacerbated by the large number of different mixed period distance functions utilized for each pair of years. If any one out of the five has an infeasible solution for any given year, then the firm must be removed from the sample as the decomposition between those two years cannot be calculated.[27] Another drawback to using the rolling window technology is that the size of the window restricts the researcher by preventing the use of all years of data in the decomposition.[28]

[25] There may exist vectors such that $\langle y_{t+1}, z_{t+1} \rangle \notin T_t(x_{t+1})$. If β is bounded above by unity, then solutions to these programs will not be feasible.

[26] Relative to using only a one period window.

[27] Pasurka [2006], for example was restricted to using only 80% of firms in the sample as a consequence of this issue, dramatically limiting the analytical power of the subsequent results.

[28] A rolling window pooling W periods of observations in constructing the technology means that the first period that can be fully analyzed in implementing the decomposition is period W and information is lost from periods before W.

There are three alternatives to remedy this problem. The first, is allowing the efficiency scores to exceed unity, and characterizing hyper-efficient[29] points in the technology set. However, interpretation of this notion is not clearly understood in applications to the decomposition literature.

Another solution is to allow observations from the entire panel horizon to define the best practice technology for any period. This guarantees never running into an in-feasibility problem. However, it removes all dynamics from the frontier. Because the frontier is generated from all observations across the panel, it will not change from period to period and hence, will not allow researchers to assess changes in technical progress.[30] Moreover, if the panel horzon is sufficiently long, it may not make sense to include output observations from the very far future in determinig the technology set in the current period.

The third solution, and the one employed herein, is to use the sequential technology so that the technology in period t includes observations from the current and all previous periods. Unlike the pooled window specification, which allows for the possibility of technological regress or implosion of the technology set, the sequential technology assumes no possibility of technological implosion - if a vector was feasible in the past, then it is feasible in the present so that all future technology sets contain, as subsets, all past technology sets. There may be some applications where allowing

[29]Not technologically feasible in a given period.

[30]In fact, there is vacuously no technological progress if all observations are used in constructing the technology.

for implosion is warranted.[31] Some may argue that government regulation may prevent past observations from being feasible. However, this argument doesn't address technological feasibility, but rather policy feasibility.[32] Unlike the pooled, rolling window production set, another advantage of using the sequential production set is that it no longer limits the time period in which we can begin conducting a decomposition analysis. We immediately extend Pasurka [2006] to the sequential technology and show that his results are robust to the choice of technological dynamics. For the remainder of the study, the sequential frontier is employed.[33]

4 Data Analysis and Results

This section describes the data utilized in the analysis of the by-production model. Observations from 92 coal-fired power plants from the years 1985 through 1995 are used to construct the efficiency indexes and to estimate the by-production technology.[34]

[31] However, for our purposes herein, it is not likely that technological regress has occurred in the electricity generation industry.

[32] We can reconcile this argument by defining another set of policy feasible vectors and define the by-production technology over the intersection of the production set and the feasible policy vector set, the latter of which may implode.

[33] We have calculated, but have not included a reporting of the results for the three-period rolling window for each index as the results appear to be robust to the choice of sequential or pooled frontier.

[34] We are indebted to Carl Pasurka for providing access to the data.

4.1 Description of the Data

Each DMU (electrical plant) produces one intended output, net electrical generation, measured in kWh, and two unintended outputs, sulfur dioxide (SO_2) and nitrogen oxides (NO_x), measured in short tons. The inputs used by each plant consist of the capital stock, the number of employees, and the heat content of coal, oil, and natural gas, measured in Btus.[35] In order to model homogeneous production technologies via data envelopment, coal must provide a minimum of 95 % of the Btu of fuels consumed by each plant[36].

One difficulty with empirically implementing the by-production approach is that it requires, as a priori, that the researcher have enough knowledge to partition the sets T_1 and T_2 properly. This study assumes that all inputs are utilized in the T_1 mechanism to produce energy but only coal, oil, and natural gas contribute to the joint production of NO_x and SO_2, all through the T_2 mechanism.[37]

The number of employees is calculated as an average taken from data in the U.S. Federal Energy Regulatory Commission Form 1 survey. Additionally, the FERC 1 survey also collects information on the historical cost of plants and equipment and does not consider investment expenditures. Thus, variation in the value of plants

[35]This study ignores the consumption of fuel inputs other than coal, oil, and natural gas if the consumption of these fuel inputs constitutes less than .0001 % of a plant's total fuel consumption.

[36]Otherwise, the firm is not considered to be a coal-fired electric plant. DEA assumes that technologies are homogeneous across decision making units

[37]This analysis could be extended to include a separate mechanism distinguishing NO_x generation from SO_2 generation, but we leave this as an extension.

and equipment reflect the value of additional plant and equipment less the value of depreciated plant and equipment. In constructing the capital stock in each period for each plant, this study assumes that changes in the costs of plants and equipment reflect net investment.[38] Historical costs are converted to constant dollar values via the HWI,[39] The net constant dollar capital stock is then the sum of the ratios of net investment to HWI over all previous years. Thus, in the first year of operation, the net investment of a power plant is equal to the aggregate value of its plant and equipment.

The U.S. Department of Energy's Form EIA-767 survey provides the information on fuel consumption and net electrical output, which is utilized to derive estimates of SO_2 and NO_x emissions.[40]

4.2 Hyperbolic Index Under Weak Disposability and Null Jointness

The hyperbolic index program under weak disposability and null jointness, as implemented by Pasurka [2006], is calculated by solving the following optimization problem

[38] Yaisawarng and Klein [1994], Carlson et al. [2000], and Pasurka [2006] are studies that also measure the capital stock in the same capacity.

[39] See Whitman, Requardt, and Associates, LLP [2002]

[40] A common criticism of DEA in this type of environment is that it does not consider measurement error, of which there most likely is in deriving emissions estimates based on observables in the production process.

using the sequential frontier:[41]

For each plant d' and for each year τ, solve:

$$D_{HYP}^{d',\tau}(x, y, z, T_{WD}) = \max_{\lambda,\beta} \beta \qquad s.t.$$

$$\sum_{t=1}^{\tau}\sum_{d=1}^{D} \lambda_{d,t} y_{d,t}^{j} \geq \beta y_{d',t}^{j} \quad \forall j = 1 \ldots J$$

$$\sum_{t=1}^{\tau}\sum_{d=1}^{D} \lambda_{d,t} x_{d,t}^{i} \leq x_{d',t}^{i} \quad \forall i = 1 \ldots I$$

$$\sum_{t=1}^{\tau}\sum_{d=1}^{D} \lambda_{d,t} z_{d,t}^{k} = \beta z_{d',t}^{k} \quad \forall k = 1 \ldots K$$

$$\lambda \geq 0.$$

Results of computing the decomposition factors for this index are listed in the appendix in Table 1.[42] Table 1 contains geometric means of each decomposition component across all years for each firm. Table 2 shows geometric means across all firms in the sample for each factor in the decomposition by two-year pairs. The relative magnitudes and impacts of the factors using the sequential frontier are the same using the pooled frontier.[43] The bottom rows labeled AVG in Tables 1 and 2 confirm that technical change, on average, is associated with increased emissions. Moreover, these results are consistent with Pasurka [2006] in that changes in the output mix are most

[41]Note that for each of the following programs, changing the index range on the first summation in any constraint from $t = 1$ to $t = \tau - W + 1$ where W is the rolling window size, will correspond to the same index calculated under the rolling window, pooled technology.

[42]We maintain the assumption of constant returns to scale throughout this study.

[43]In fact, this is the case with every index calculated in considering the decomposition. We report only the sequential frontier results as there is minimal in-feasibility problem to consider.

associated with emissions reductions. Changes in bad outputs per unit of intended output can be the result of a regulatory induced change, requiring the producer to mitigate pollutants relative to intended production. Again, the results suggest that changes in the output mix, or movements along the production frontier, account for greater reductions in SO_2 than for NO_x emissions.

Note that the above program[44] credits producers for expanding both intended and unintended output production as increases in efficiency. However, under by-production, being able to produce more pollutant for a given input vector is not more efficient, but less. Accordingly, we alter the direction of measurement, maintaining weak disposability, by considering crediting a producer for expanding intended outputs and contracting unintended outputs by solving:

For each plant d' and for each year τ, solve:

$$
\begin{aligned}
D_{HYP}^{d',\tau}(x, y, z, T_{WD}) = \min_{\lambda,\beta} \beta \qquad & s.t. \\
& \sum_{t=1}^{\tau}\sum_{d=1}^{D} \lambda_{d,t} y_{d,t}^{j} \geq y_{d',t}^{j}/\beta \quad \forall j = 1 \ldots J \\
& \sum_{t=1}^{\tau}\sum_{d=1}^{D} \lambda_{d,t} x_{d,t}^{i} \leq x_{d',t}^{i} \quad \forall i = 1 \ldots I \\
& \sum_{t=1}^{\tau}\sum_{d=1}^{D} \lambda_{d,t} z_{d,t}^{k} = \beta z_{d',t}^{k} \quad \forall k = 1 \ldots K \\
& \lambda \geq 0.
\end{aligned}
$$

Results for this program are reported in Table 3.[45] The one clear difference after

[44] as in Pasurka [2006]

[45] Since this problem is non-linear in the constraint set, and due to the size of the choice variable

making the switch to crediting producers for retracting unintended outputs is that input growth of fuel inputs is now associated with increased emissions. Again, the results from Table 3 suggest that changes in the output mix account for greater reductions in SO_2 than for NO_x emissions, but the effect of the output mix for SO_2 is slightly lower under retractions of pollutants and the effect of the output mix for NO_x is slightly higher. Thus, by not retracting output, the weakly disposable, null-joint index decomposition tends to understate the effect of fuel growth on emissions increases over the panel horizon, understate the effects of output mix changes on reductions of NO_x, and overstate the effects of the output mix on reductions of SO_2 emissions, relative to the case where producers are credited for retracting unintended outputs.

set, we use a first order Taylor series approximation to the output constraint around $\beta = 1$ as is standard practice and utilized in Fare, Grosskopf, Lovell, and Pasurka [1989]. Blank cells indicate firms with some component of the decomposition yielding an infeasible LP problem.

4.3 Hyperbolic Index Under By-production

Under the assumption of by-production, and crediting producers for expanding outputs and retracting unintended outputs, the hyperbolic index is calculated as follows:

For each plant d' and for each year τ, solve:

$$D_{HYP}^{d',\tau}(x, y, z, T_{BP}) = \max\{\beta_1, \beta_2\} \quad \text{where}$$

$$\begin{aligned}
\beta_1 = \min_{\lambda,\beta} \beta \qquad & s.t. \\
& \sum_{t=1}^{\tau}\sum_{d=1}^{D} \lambda_{d,t} y_{d,t}^j \geq y_{d',t}^j/\beta \quad \forall j = 1 \dots J \\
& \sum_{t=1}^{\tau}\sum_{d=1}^{D} \lambda_{d,t} x_{d,t}^i \leq x_{d',t}^i \quad \forall i = 1 \dots I \\
& \lambda \geq 0.
\end{aligned}$$

and

$$\begin{aligned}
\beta_2 = \min_{\mu,\beta} \beta \qquad & s.t. \\
& \sum_{t=1}^{\tau}\sum_{d=1}^{D} \mu_{d,t} z_{d,t} \leq \beta z_{d',t}^k \quad \forall k = 1 \dots K \\
& \sum_{t=1}^{\tau}\sum_{d=1}^{D} \mu_{d,t} x_{d,t} \geq x_{d',t}^i \quad \forall i = 1 \dots I' \\
& \mu \geq 0.
\end{aligned}$$

If the $\max\{\beta_1, \beta_2\} = \beta_1$, then the counter factual reference point on the frontier is efficient in intended output, but inefficient in unintended output. That is, in minimizing β, the constraint on intended output binds before the constraint on unintended output. If $\max\{\beta_1, \beta_2\} = \beta_2$, then the counter factual reference point on the frontier is efficient in retracting unintended output to its minimally necessary level, but it is inefficient in expansions of intended output. It is important to note that in this study, we do not take the max when running the decomposition. This is because mixing notions of intended and unintended efficiency does not make sense when evaluating relative distance functions. However, we report the decomposition results for β_1 and β_2 separately as it is crucial to differentiate between these notions of efficiency. The results for these two hyperbolic indexes are reported in Tables 4-5 by two year pairs, and in Tables 7-8 by firm averaged across years.

4.4 The By-production Coordinate-wise Index: A Modification of the FGL Index

Lastly, we calculate, for by-production technologies, a proposed modification of the Fare, Grosskopf, and Lovell [1985] graph space index that measures a coordinate-wise average of intended output expansions and unintended output retractions. This index measures joint efficiency by taking a weighted average of efficiency scores for intended and unintended production. However, this index is easily decomposable into intended output efficiency (D^1_{FGL}) and unintended output efficiency (D^2_{FGL}). The algorithm for computing this index is given by:

For each plant d' and for each year τ, solve:

$$D_{FGL}^{d',\tau}(x,y,z,T_{BP}) = \min_{\beta,\gamma,\lambda,\mu} \frac{1}{2}\left\{\frac{\sum_{j=1}^{J}\beta_j}{J} + \frac{\sum_{k=1}^{K}\gamma_k}{K}\right\} \quad \text{s.t.}$$

$$\sum_{t=1}^{\tau}\sum_{d=1}^{D}\lambda_{d,t}y_{d,t}^{j} \geq y_{d',t}^{j}/\beta_j \quad \forall j = 1\ldots J$$

$$\sum_{t=1}^{\tau}\sum_{d=1}^{D}\lambda_{d,t}x_{d,t}^{i} \leq x_{d',t}^{i} \quad \forall i = 1\ldots I$$

$$\sum_{t=1}^{\tau}\sum_{d=1}^{D}\mu_{d,t}z_{d,t}^{k} \leq \gamma_k z_{d',t}^{k} \quad \forall k = 1\ldots K$$

$$\sum_{t=1}^{\tau}\sum_{d=1}^{D}\mu_{d,t}x_{d,t}^{i} \geq x_{d',t}^{i} \quad \forall i = 1\ldots I'$$

$$\lambda, \mu \geq 0.$$

In general, this problem is non-linear. However, since we have only one intended output in our data set, and by independence of T_1 from T_2 , D_{FGL}^{1} and D_{FGL}^{2} can be calculated separately by running the following linear programs:

$$[D_{FGL}^{1,d',\tau}(x,y,z,T_{BP})]^{-1} = \max_{\beta,\lambda}\beta \quad \text{s.t.}$$

$$\sum_{t=1}^{\tau}\sum_{d=1}^{D}\lambda_{d,t}y_{d,t}^{j} \geq \beta y_{d',t}^{j}$$

$$\sum_{t=1}^{\tau}\sum_{d=1}^{D}\lambda_{d,t}x_{d,t}^{i} \leq x_{d',t}^{i} \quad \forall i = 1\ldots 5$$

$$\lambda \geq 0$$

$$D^{2,d',\tau}_{FGL}(x,y,z,T_{BP}) = \min_{\gamma,\mu} \frac{\gamma_1+\gamma_2}{2} \qquad \text{s.t.}$$

$$\sum_{t=1}^{\tau}\sum_{d=1}^{D}\mu_{d,t}z^k_{d,t} \le \gamma_k z^k_{d',t} \ \ \forall k=1,2$$

$$\sum_{t=1}^{\tau}\sum_{d=1}^{D}\mu_{d,t}x^i_{d,t} \ge x^i_{d',t} \ \ \forall i=3,4,5$$

$$\mu \ge 0$$

Then $D_{FGL} = \frac{1}{2}D^1_{FGL} + \frac{1}{2}D^2_{FGL}$. Again, we give equal weights to intended output efficiency and unintended output efficiency, but the policy maker is free to choose weights more appropriate for any particular use.[46] Results for the coordinate-wise modification of the FGL index are reported in Table 6 by two-year pairs and in Table 9 by firms geometrically averaged across all years.

4.5 Efficiencies of By-production Technologies

Perhaps the most striking difference between the treatment of technologies as weakly disposable and null-joint verses by-production, is the size of the efficient frontier. Since the by-production technology lies at the intersection of two manifolds implied by T_1 and T_2, the efficient frontier is smaller in dimension[47]. This results in far fewer firms operating efficiently. In fact, there is no single firm in the sample that received an efficiency score of unity for both β_1 and β_2 using the hyperbolic and no firm with an efficiency score of unity using the coordinate-wise index. Moreover, Table

[46] A regulator interested in environmental efficiency may choose to put greater weight on D^2_{FGL}

[47] See MRL for a discussion related to this issue.

10 includes both rank and product moments between intended output efficiency and unintended output efficiency for both the hyperbolic and coordinate-wise indexes. The large negative correlations provides evidence consistent with the idea that firms in general, face a trade off between efficiency in intended and unintended output. That is, firms that tend to operate efficiently in terms of intended output expansions tend to operate relatively inefficiently in terms of unintended output reductions and vice versa, indicative of the fact that abatement is a costly activity.

4.6 Evidence of Firm Response to Title IV of the 1990 Clean Air Act Amendment

The use of fossil fuels in energy generation is one of the primary sources of NO_x and SO_2 atmospheric by-products that lead to the creation of acid rain when they react with water in the air. While Title IV of the 1990 Clean Air Act Amendment was passed in 1990, the first phases of action required by firms related to emissions reductions was not mandated until January of 1995. The Acid Rain Ruling specifically mandated emissions reductions in two phases, requiring aggregate reductions of 10 million tons per year of SO_2 and 2 million tons per year of NO_x relative to the levels prevailing in the 1980's. In the 10 years following the implementation of Phase I in 1995, annual emissions of SO_2 fell by almost 23% while annual emissions of NO_x fell by more than 33%. Currently, both NO_x and SO_2 allowances are subject to the federal cap and trade system under the 2005 Clean Air Interstate Rule (CAIR)[48]. End-of-pipe abatement efforts and fuel switching are important methods utilized by electricity generating firms to remain in compliance with the Acid Rain Ruling. Phase I required very specific reductions in SO_2 across 110 power plants in the United States listed in Table A of section 404 of U.S.7651c 1990 Clean Air Act. Fortunately, 34 of the 92 plants in our sample are present on this list and are highlighted in the rows of the appendix tables. Also at the bottom of Tables 2-5, we have considered the geometric averages across firms and decomposition components before and after the initial 1990 ruling. However, while the first phase of mandated reductions did not go into effect until 1995, the firms that would be forced to comply were made aware of the necessity when the ruling was made in 1990. Thus, the timing of the data set at hand provides us with an interesting perspective to identify whether or not firms would anticipate and adjust their emissions earlier to be ready for the 1995 implementation of Phase I. Unfortunately, Phase I also mandated specific NO_x reductions for specific firms, but there is not information available on the levels of reduction specific to a given firm as the mandated reduced levels depend on the various types of boilers used.

Observing tables 2, 4, 5, and 6, it is clear that regardless of how the technology is specified, the variations in the output mix play a much more significant role in explaining reductions after the 1990 Amendment was announced. For the weak disposability technology as used in Pasurka [2006], the OM factors drop from .9920

[48]despite the fact that the program was suspended and then re-implemented in 2008

and .9973 between 1985-1990 to .9452 and .9727 between 1990-1995 for SO_2 and NO_x, respectively. The decomposition under the three by-production indexes shares this trend as well. Table 3, considers only efficiency in intended output, but signals decreases in the OM components from .9965 and 1.0018 between 1985-1990 to .9573 and .9851 from 1990-1995 for SO_2 and NO_x, respectively. Measuring only environmental efficiency in Table 4, we can also see the effects of the output mix for both pollutants contributes dramatically to the reduction in emissions during the 1990-1995 period from .9982 and 1.0035 in 1985-1990 to .9015 and .9277 during 1990-1995 for SO_2 and NO_x, respectively. In fact, all by-production decompositions in Tables 4-6 share this trend, even when joint efficiency is considered in Table 6. However, the decomposition factors when only considering environmental efficiency contradict one another for the by-production technologies with respect to the effects of input growth before and after the policy change. From 1985-1990, the IG component of Table 5 switches from contributing to reductions in emissions to contributing to increases during the 1990-1995 period.

However, there is one major respect that the weakly disposable, null-joint technological specification and decomposition differs from its by-production counterparts. Observing Table 2, note that the OM effect contributes to reductions of both pollutants over both the 1985-1990 and 1990-1995 periods. However, Tables 4-6 illustrate that the OM effect for NO_x was actually contributing to increased emissions during the 1985-1990 period, and the direction of this effect changed after the 1990 Clean

Air Act Amendment was passed.

5 Conclusion

This study not only implements a previous decomposition with a novel modeling philosophy for pollution-generating technologies, but it also contributes to the discussion of efficiency measurement when some outputs are not necessarily socially desirable. We have extended Pasurka [2006] to the sequential frontier, and show that his results are, for the most part, robust to the sequential technological specification over the entire sample duration relative to when the three period, pooled, rolling window was used. Moreover, we have extended the analysis by implementing the same decomposition under by-production, and show that efficiency measurement for by-production technologies is not straightforward. The criteria used to measure producer efficiency has direct implications on analyzing how firms respond to regulatory emissions reduction mandates. The final section of the results provided some evidence of anticipatory firm responses to the 1990 Clean Air Act Amendment related to Title IV's Acid Rain Rule, despite the fact that Phase I of the program was not implemented until 1995.

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Weak Disposability/Null Jointness Technology

Hyperbolic Index (Expanding Pollutants)

Table 1

Plant Name	DELTA_SO2	DELTA_NOx	TE	TC	IG	IG_NF	IG_F	OM_SO2	OM_NOx
Barry	1.0336	1.0120	0.9930	1.0080	1.0130	1.0000	1.0130	1.0193	0.9980
Gorgas	1.0573	1.0163	0.9918	1.0153	1.0160	1.0002	1.0158	1.0336	0.9935
Comanche	0.9886	1.0127	1.0013	1.0007	1.0116	1.0000	1.0116	0.9753	0.9991
Brandon Shores	1.1312	1.1323	0.9999	1.0024	1.1307	0.9997	1.1310	0.9981	0.9990
Crist	0.8818	0.9539	0.9764	1.0200	0.9839	0.9998	0.9840	0.8999	0.9735
Hammond	0.8934	0.9157	0.9703	1.0317	0.9353	1.0000	0.9353	0.9542	0.9780
Harllee Branch	0.9737	0.9831	0.9905	1.0044	0.9790	0.9999	0.9791	0.9998	1.0095
Yates	0.8227	0.8911	0.9598	1.0327	0.9213	1.0000	0.9213	0.9009	0.9757
E.D. Edwards	1.0641	0.9933	0.9840	1.0153	1.0160	1.0000	1.0160	1.0483	0.9785
Coffeen	0.8525	0.9791	0.9805	1.0199	0.9792	0.9999	0.9792	0.8707	0.9999
Grand Tower	0.9711	0.9674	0.9673	1.0324	0.9664	1.0000	0.9664	1.0062	1.0024
Hustonville	0.9048	0.8770	0.9608	1.0325	0.9092	1.0000	0.9092	1.0031	0.9723
Meredosia	0.9643	0.9781	0.9674	1.0321	0.9773	1.0000	0.9773	0.9881	1.0023
Kincaid	0.7620	0.9199	0.9879	1.0102	0.9307	0.9998	0.9309	0.8204	0.9903
Powerton	0.9327	0.9858	0.9856	1.0107	0.9787	0.9999	0.9787	0.9567	1.0111
Joppa Steam	0.8710	1.0160	0.9917	1.0107	1.0197	0.9997	1.0200	0.8522	0.9940
Baldwin	0.9952	0.9872	0.9841	1.0134	0.9932	0.9998	0.9934	1.0047	0.9966
Clifty Creek	0.9012	1.0090	0.9909	1.0131	0.9917	0.9979	0.9937	0.9054	1.0136
Tanners Creek	0.9435	1.0054	0.9839	1.0180	1.0144	1.0011	1.0133	0.9287	0.9896
H.T. Pritchard	0.9462	0.9805	0.9682	1.0321	0.9992	1.0000	0.9992	0.9477	0.9820
Petersburgh	1.0298	1.0309	0.9920	1.0080	1.0459	0.9999	1.0460	0.9845	0.9856
Edwardsport	0.9525	0.9744	0.9633	1.0321	0.9745	1.0000	0.9745	0.9831	1.0057
R. Gallagher	0.9535	0.9790	0.9827	1.0136	1.0213	0.9997	1.0216	0.9373	0.9624
F.B. Culley	0.8068	0.9639	0.9949	1.0051	0.9992	0.9968	1.0024	0.8075	0.9647
Lansing	0.9854	0.9444	0.9698	1.0181	0.9760	1.0000	0.9760	1.0225	0.9800
Lawrence	0.9735	0.9916	0.9963	1.0096	1.0220	1.0000	1.0220	0.9470	0.9646
E.W. Brown	0.9278	0.9369	0.9835	1.0168	0.9718	0.9998	0.9720	0.9548	0.9641
Ghent	0.9461	1.0314	1.0011	1.0042	1.0558	1.0002	1.0556	0.8913	0.9717
Green River	0.9865	0.9527	0.9676	1.0262	0.9732	1.0000	0.9732	1.0209	0.9860
Mill Creek	1.1458	0.9992	0.9878	1.0133	1.0166	0.9999	1.0166	1.1260	0.9820
R.P. Smith	0.9285	0.8934	0.9836	1.0321	0.9162	1.0000	0.9162	0.9984	0.9605
Mount Tom	0.9680	0.9609	1.0086	1.0273	0.9565	1.0000	0.9565	0.9768	0.9697
B.C. Cobb	1.0312	1.0636	0.9814	1.0199	1.0515	1.0000	1.0515	0.9797	1.0105
Trenton Channel	0.9914	1.0258	0.9727	1.0277	1.0040	0.9990	1.0050	0.9877	1.0220
Hoot Lake	0.8964	1.0111	0.9756	1.0316	1.0025	1.0000	1.0025	0.8885	1.0021
Montrose	0.7142	0.9554	1.0177	1.0221	0.9767	1.0000	0.9767	0.7029	0.9403
Labadie	0.9141	0.9869	0.9915	1.0096	1.0057	0.9997	1.0060	0.9081	0.9803
Sioux	0.9770	0.9831	0.9877	1.0182	1.0315	1.0000	1.0315	0.9419	0.9477
Goudey	0.9483	0.9251	0.9993	1.0146	0.9429	0.9990	0.9438	0.9919	0.9677
Greenidge	0.9310	0.9216	0.9872	1.0252	0.9396	0.9963	0.9431	0.9791	0.9692
Milliken	0.9047	1.0045	0.9865	1.0150	1.0123	1.0001	1.0122	0.8926	0.9910
C.R. Huntley	0.9758	0.9773	0.9966	1.0085	0.9755	0.9848	0.9905	0.9952	0.9968
Dunkirk	0.9960	0.9628	0.9772	1.0369	0.9919	0.9969	0.9950	0.9910	0.9579
Rochester	0.9838	0.9843	0.9647	1.0321	0.9870	1.0000	0.9870	1.0011	1.0016
Asheville	1.0368	1.0232	0.9938	1.0084	1.0187	1.0000	1.0187	1.0156	1.0023
G.G. Allen	1.0220	1.0061	0.9849	1.0115	1.0432	0.9993	1.0440	0.9833	0.9681
Cliffside	1.0124	0.9817	0.9843	1.0188	1.0108	0.9988	1.0119	0.9988	0.9685
Marshall	1.0347	0.9959	1.0000	1.0015	1.0304	0.9997	1.0307	1.0026	0.9650
R.M. Heskett	0.8701	0.8981	0.9864	1.0068	0.9400	1.0000	0.9400	0.9320	0.9621
J.M. Stuart	0.9487	0.9859	0.9895	1.0098	0.9973	1.0001	0.9972	0.9520	0.9894
R.E. Burger	0.9375	0.9488	0.9941	1.0048	0.9466	0.9987	0.9478	0.9916	1.0035

Weak Disposability/Null Jointness Technology

Hyperbolic Index (Expanding Pollutants)

Table 1

Plant Name	DELTA_SO2	DELTA_NOx	TE	TC	IG	IG_NF	IG_F	OM_SO2	OM_NOx
Muskingum River	0.9255	0.9574	0.9744	1.0226	0.9770	1.0000	0.9771	0.9507	0.9835
Kyger Creek	0.9128	0.9920	0.9974	1.0020	1.0004	1.0000	1.0004	0.9130	0.9923
Elrama	1.0683	1.0068	0.9798	1.0243	1.0498	0.9999	1.0500	1.0139	0.9556
Seward	0.9927	0.9731	0.9821	1.0192	0.9950	0.9991	0.9959	0.9968	0.9770
Shawville	0.9879	0.9617	0.9926	1.0079	0.9956	0.9990	0.9966	0.9918	0.9655
New Castle	0.9815	0.9750	0.9871	1.0238	0.9732	0.9973	0.9758	0.9979	0.9912
Brunner Island	0.9681	0.9463	0.9974	1.0062	0.9825	0.9988	0.9837	0.9818	0.9597
Montour	1.0231	0.9596	0.9961	1.0036	0.9917	0.9991	0.9926	1.0320	0.9680
Armstrong	0.9537	0.9241	0.9996	1.0248	0.9378	1.0000	0.9378	0.9926	0.9619
Watertree	1.0237	1.0250	0.9979	1.0046	1.0254	1.0001	1.0253	0.9959	0.9971
Big Brown	1.0315	0.9973	0.9845	1.0160	0.9907	1.0066	0.9842	1.0409	1.0064
Carbon	1.0758	1.1008	1.0003	1.0040	1.1020	1.0000	1.1021	0.9721	0.9946
Clinch River	1.0160	1.0150	0.9939	1.0077	1.0107	0.9999	1.0107	1.0037	1.0027
Glen Lyn	1.0116	0.9776	0.9687	1.0272	1.0181	0.9997	1.0184	0.9985	0.9650
Potamac River	0.9721	0.9792	0.9715	1.0290	0.9812	1.0001	0.9811	0.9910	0.9983
Bremo	1.0388	1.0260	0.9785	1.0274	1.0174	1.0000	1.0174	1.0156	1.0030
Kanawha River	0.9796	0.9816	0.9696	1.0263	0.9914	1.0000	0.9914	0.9930	0.9950
Rivesville	0.9178	0.9195	0.9634	1.0322	0.9218	1.0000	0.9218	1.0013	1.0031
Willow Island	1.0007	0.9913	1.0187	1.0127	0.9641	1.0000	0.9641	1.0061	0.9967
Kammer	0.9774	0.9978	0.9959	1.0020	1.0019	1.0000	1.0019	0.9775	0.9980
Mitchell	0.9507	0.9608	0.9941	1.0078	0.9979	0.9999	0.9980	0.9508	0.9610
Nelson Dewey	0.8331	0.9272	0.9884	1.0111	1.0021	0.9990	1.0030	0.8320	0.9259
Pulliam	0.8519	1.0576	1.0041	1.0032	1.0472	1.0000	1.0472	0.8077	1.0027
Dave Johnston	0.9793	1.0291	0.9960	1.0077	1.0164	1.0000	1.0164	0.9600	1.0088
Naughton	1.0052	1.0189	0.9954	1.0057	1.0167	1.0000	1.0166	0.9877	1.0011
J.H. Miller Jr.	1.1362	1.1543	0.9986	1.0066	1.1368	1.0000	1.1367	0.9944	1.0102
Pleasants	1.2178	0.9974	1.0106	1.0086	0.9937	0.9999	0.9938	1.2024	0.9847
Duck Creek	0.9956	1.0076	0.9888	1.0142	1.0081	1.0000	1.0081	0.9848	0.9967
Newton	1.0660	1.0316	0.9904	1.0130	1.0274	0.9998	1.0276	1.0342	1.0008
Sooner	1.0493	1.0218	0.9986	1.0046	1.0407	0.9980	1.0428	1.0050	0.9787
Welsh	0.9780	0.9593	0.9912	1.0055	0.9980	0.9994	0.9985	0.9832	0.9644
Martin Lake	1.0840	1.0064	0.9996	1.0064	1.0048	1.0001	1.0047	1.0723	0.9956
Monticello	0.9540	0.9758	0.9776	1.0289	0.9631	1.0013	0.9619	0.9848	1.0073
Rush Island	0.9425	0.9830	0.9880	1.0047	1.0107	1.0000	1.0108	0.9394	0.9798
Coleto Creek	1.0170	0.9797	0.9950	1.0133	0.9916	0.9854	1.0063	1.0174	0.9800
Harrington	1.0193	0.9881	1.0000	1.0504	0.9608	0.9879	0.9725	1.0099	0.9790
Pawnee	1.0399	0.9917	0.9946	1.0081	1.0120	1.0000	1.0120	1.0248	0.9773
Mountaineer	0.9787	0.9748	0.9868	1.0125	0.9744	0.9999	0.9745	1.0053	1.0012
Belews Creek	0.9785	1.0058	0.9992	1.0287	0.9777	0.9918	0.9858	0.9736	1.0007
Gen. J.M. Gavin	0.8000	1.0107	0.9937	1.0114	1.0094	1.0002	1.0092	0.7885	0.9962
Cheswick	1.0046	0.9671	1.0030	1.0073	0.9964	1.0000	0.9964	0.9979	0.9606
AVG	**0.9680**	**0.9846**	**0.9878**	**1.0159**	**0.9962**	**0.9992**	**0.9969**	**0.9683**	**0.9849**

TABLE 2									
WD/NJ	**HYP**								
Year	**DELTA_SO2**	**DELTA_NOx**	**TE**	**TC**	**IG**	**IG_NF**	**IG_F**	**OM_SO2**	**OM_NOx**
1985-1986	0.9538	0.9587	0.9792	1.0196	0.9570	0.9991	0.9579	0.9983	1.0034
1986-1987	0.9878	0.9908	1.0025	1.0018	0.9971	0.9999	0.9972	0.9865	0.9894
1987-1988	1.0284	1.0586	1.0041	1.0018	1.0548	0.9996	1.0553	0.9692	0.9977
1988-1989	1.0573	1.0493	1.0010	1.0014	1.0384	1.0003	1.0380	1.0159	1.0082
1989-1990	0.9592	0.9564	0.9964	1.0063	0.9654	1.0001	0.9653	0.9909	0.9880
1990-1991	0.9331	0.9444	0.9965	1.0020	0.9516	1.0001	0.9515	0.9821	0.9939
1991-1992	0.9924	0.9741	1.0049	1.0001	0.9960	0.9998	0.9962	0.9914	0.9731
1992-1993	1.0141	1.0294	1.0002	1.0011	1.0458	0.9999	1.0459	0.9684	0.9830
1993-1994	0.9663	0.9185	0.9988	1.0003	0.9795	0.9979	0.9816	0.9874	0.9385
1994-1995	0.8099	0.9752	0.8990	1.1315	0.9824	0.9955	0.9868	0.8104	0.9759
AVG(pre-1990)	**0.9965**	**1.0018**	**0.9966**	**1.0062**	**1.0018**	**0.9998**	**1.0020**	**0.9920**	**0.9973**
AVG(post-1990)	**0.9403**	**0.9676**	**0.9790**	**1.0257**	**0.9906**	**0.9986**	**0.9919**	**0.9452**	**0.9727**
AVG	**0.9680**	**0.9846**	**0.9878**	**1.0159**	**0.9962**	**0.9992**	**0.9969**	**0.9683**	**0.9849**

Weak Disposability/Null Jointness Technology

Hyperbolic Index (Retracting Pollutants)

Table 3

Plant Name	DELTA_SO2	DELTA_NOx	TE	TC	IG	IG_NF	IG_F	OM_SO2	OM_NOx
Barry	1.0336	1.0120	0.9911	1.0097	1.0064	0.9998	1.0066	1.0263	1.0048
Gorgas	1.0573	1.0163	0.9986	1.0111	1.0077	1.0001	1.0076	1.0393	0.9990
Comanche	0.9886	1.0127	1.0078	0.9382	1.0668	1.0048	1.0617	0.9801	1.0041
Brandon Shores	1.1312	1.1323	1.0003	1.0084	1.0465	0.9980	1.0485	1.0716	1.0726
Crist	0.8818	0.9539	0.9789	1.0151	0.9574	1.0001	0.9573	0.9268	1.0026
Hammond	0.8934	0.9157	0.9813	1.0204	0.9569	1.0003	0.9566	0.9324	0.9557
Harllee Branch	0.9737	0.9831	0.9898	1.0059	0.9899	1.0002	0.9897	0.9879	0.9975
Yates	0.8227	0.8911	0.9866	1.0113	0.9659	1.0001	0.9658	0.8537	0.9246
E.D. Edwards	1.0641	0.9933	0.9825	1.0158	1.0190	1.0000	1.0190	1.0464	0.9767
Coffeen	0.8525	0.9791	0.9589	1.0354	0.9750	1.0002	0.9748	0.8807	1.0115
Grand Tower	0.9711	0.9674	0.9747	1.0247	1.0124	1.0000	1.0124	0.9604	0.9567
Hustonville	0.9048	0.8770	0.9825	1.0182	0.9722	1.0000	0.9722	0.9302	0.9016
Meredosia	0.9643	0.9781	0.9813	1.0137	1.0000	1.0000	1.0000	0.9693	0.9832
Kincaid	0.7620	0.9199	1.0000	0.9028	1.0583	1.0143	1.0434	0.7976	0.9628
Powerton	0.9327	0.9858	0.9889	0.9768	1.0098	1.0014	1.0085	0.9562	1.0106
Joppa Steam	0.8710	1.0160	0.9972	1.0113	1.0100	0.9999	1.0101	0.8551	0.9974
Baldwin	0.9952	0.9872	1.0000	0.9952	1.0073	1.0037	1.0037	0.9927	0.9847
Clifty Creek	0.9012	1.0090	1.0000	0.9721	1.0135	1.0010	1.0125	0.9148	1.0241
Tanners Creek	0.9435	1.0054	0.9736	1.0260	1.0111	1.0023	1.0088	0.9342	0.9955
H.T. Pritchard	0.9462	0.9805	0.9847	1.0131	0.9979	1.0000	0.9979	0.9505	0.9849
Petersburgh	1.0298	1.0309	0.9876	1.0201	1.0065	1.0001	1.0065	1.0155	1.0166
Edwardsport	0.9525	0.9744	0.9652	1.0274	1.0168	1.0000	1.0168	0.9445	0.9662
R. Gallagher	0.9535	0.9790	0.9823	1.0120	1.0379	1.0000	1.0379	0.9241	0.9489
F.B. Culley	0.8068	0.9639	0.9976	0.9827	1.0393	1.0110	1.0280	0.7918	0.9460
Lansing	0.9854	0.9444	0.9534	1.0131	1.0157	0.9860	1.0301	1.0043	0.9626
Lawrence									
E.W. Brown	0.9278	0.9369	0.9886	1.0191	0.9929	1.0015	0.9914	0.9275	0.9366
Ghent	0.9461	1.0314	1.0076	1.0172	1.0145	1.0011	1.0133	0.9099	0.9919
Green River	0.9865	0.9527	0.9854	1.0173	0.9700	1.0000	0.9700	1.0145	0.9798
Mill Creek	1.1458	0.9992	0.9973	1.0247	1.0129	0.9943	1.0187	1.1070	0.9654
R.P. Smith	0.9285	0.8934	1.0075	1.0095	0.9676	1.0000	0.9676	0.9435	0.9078
Mount Tom									
B.C. Cobb	1.0312	1.0636	0.9812	1.0157	1.0264	0.9998	1.0266	1.0081	1.0398
Trenton Channel	0.9914	1.0258	0.9769	1.0141	1.0078	1.0000	1.0078	0.9930	1.0275
Hoot Lake	0.8964	1.0111	0.9785	1.0433	0.9287	1.0000	0.9287	0.9454	1.0664
Montrose									
Labadie	0.9141	0.9869	0.9818	1.0166	1.0004	0.9981	1.0023	0.9156	0.9884
Sioux	0.9770	0.9831	0.9679	1.0311	0.9667	1.0001	0.9666	1.0127	1.0190
Goudey	0.9483	0.9251	1.0085	1.0119	0.9673	1.0000	0.9673	0.9606	0.9371
Greenidge	0.9310	0.9216	1.0022	1.0127	0.9651	0.9999	0.9652	0.9505	0.9409
Milliken	0.9047	1.0045	0.9901	1.0174	0.9975	0.9998	0.9978	0.9004	0.9997
C.R. Huntley									
Dunkirk									
Rochester	0.9838	0.9843	0.9794	1.0151	0.9928	1.0000	0.9928	0.9967	0.9972
Asheville	1.0368	1.0232	0.9931	1.0092	1.0140	1.0004	1.0136	1.0202	1.0068
G.G. Allen	1.0220	1.0061	1.0018	1.0111	1.0255	0.9998	1.0257	0.9838	0.9685
Cliffside	1.0124	0.9817	1.0000	1.0116	1.0010	1.0000	1.0010	0.9997	0.9694
Marshall	1.0347	0.9959	1.0000	1.0260	0.9959	0.9963	0.9997	1.0125	0.9746
R.M. Heskett	0.8701	0.8981	0.9999	1.0360	0.9792	0.9978	0.9814	0.8578	0.8854
J.M. Stuart	0.9487	0.9859	0.9844	1.0154	0.9961	1.0004	0.9956	0.9529	0.9903
R.E. Burger	0.9375	0.9488	0.9833	1.0076	0.9935	0.9995	0.9940	0.9525	0.9640

Plant Name	DELTA_SO2	DELTA_NOx	TE	TC	IG	IG_NF	IG_F	OM_SO2	OM_NOx
Muskingum River	0.9255	0.9574	0.9702	1.0051	0.9923	1.0010	0.9913	0.9564	0.9894
Kyger Creek	0.9128	0.9920	0.9963	0.9926	1.0062	1.0005	1.0057	0.9173	0.9969
Elrama									
Seward	0.9927	0.9731	0.9931	1.0108	1.0003	1.0000	1.0003	0.9886	0.9691
Shawville	0.9879	0.9617	0.9964	1.0050	0.9914	1.0000	0.9914	0.9951	0.9687
New Castle	0.9815	0.9750	0.9851	1.0262	0.9738	1.0000	0.9738	0.9970	0.9903
Brunner Island	0.9681	0.9463	0.9988	1.0205	0.9857	1.0005	0.9852	0.9636	0.9419
Montour	1.0231	0.9596	1.0000	1.0302	0.9869	0.9989	0.9880	1.0064	0.9439
Armstrong	0.9537	0.9241	1.0084	1.0256	0.9476	1.0002	0.9475	0.9730	0.9429
Watertree	1.0237	1.0250	0.9982	1.0044	1.0131	0.9998	1.0133	1.0079	1.0091
Big Brown	1.0315	0.9973	0.9941	1.0467	0.9650	0.9779	0.9868	1.0274	0.9933
Carbon	1.0758	1.1008	1.0100	1.0080	1.0075	1.0000	1.0075	1.0489	1.0733
Clinch River	1.0160	1.0150	0.9916	1.0084	1.0196	0.9998	1.0197	0.9966	0.9956
Glen Lyn	1.0116	0.9776	0.9872	1.0089	1.0194	1.0000	1.0194	0.9963	0.9629
Potamac River	0.9721	0.9792	0.9898	1.0068	0.9965	1.0002	0.9964	0.9788	0.9860
Bremo	1.0388	1.0260	0.9679	1.0280	1.0455	1.0004	1.0450	0.9987	0.9863
Kanawha River	0.9796	0.9816	0.9635	1.0292	1.0018	1.0000	1.0018	0.9861	0.9881
Rivesville	0.9178	0.9195	0.9806	1.0146	1.0148	1.0000	1.0148	0.9091	0.9108
Willow Island	1.0007	0.9913	1.0175	1.0322	0.9974	1.0000	0.9974	0.9553	0.9463
Kammer	0.9774	0.9978	0.9929	1.0101	1.0103	1.0072	1.0031	0.9646	0.9848
Mitchell	0.9507	0.9608	0.9917	1.0102	0.9862	0.9999	0.9863	0.9623	0.9726
Nelson Dewey									
Pulliam									
Dave Johnston	0.9793	1.0291	1.0239	0.9485	1.0261	0.9998	1.0263	0.9827	1.0328
Naughton	1.0052	1.0189	1.0020	1.0043	1.0035	1.0002	1.0033	0.9955	1.0090
J.H. Miller Jr.	1.1362	1.1543	0.9988	1.0104	1.0528	0.9997	1.0531	1.0694	1.0864
Pleasants	1.2178	0.9974	1.0086	0.7392	1.2904	1.0009	1.2892	1.2658	1.0367
Duck Creek	0.9956	1.0076	0.9867	1.0094	1.0086	1.0000	1.0086	0.9911	1.0031
Newton	1.0660	1.0316	0.9939	1.0085	1.0065	1.0000	1.0065	1.0566	1.0225
Sooner	1.0493	1.0218	1.0000	1.0455	0.9759	1.0006	0.9753	1.0284	1.0015
Welsh	0.9780	0.9593	0.9991	1.0121	0.9948	0.9999	0.9949	0.9723	0.9538
Martin Lake	1.0840	1.0064	0.9909	1.0130	0.9950	0.9999	0.9951	1.0853	1.0076
Monticello	0.9540	0.9758	0.9816	1.0139	0.9902	1.0010	0.9891	0.9681	0.9902
Rush Island	0.9425	0.9830	0.9931	1.0076	1.0072	1.0000	1.0072	0.9351	0.9754
Coleto Creek	1.0170	0.9797	1.0000	1.0254	0.9738	0.9858	0.9878	1.0185	0.9811
Harrington									
Pawnee	1.0399	0.9917	0.9799	0.9284	1.1108	1.0086	1.1014	1.0290	0.9813
Mountaineer	0.9787	0.9748	0.9848	1.0132	0.9816	1.0006	0.9810	0.9992	0.9952
Belews Creek	0.9785	1.0058	1.0000	0.9900	1.0236	1.0055	1.0180	0.9656	0.9925
Gen. J.M. Gavin	0.8000	1.0107	1.0000	0.9909	1.0203	1.0044	1.0159	0.7913	0.9997
Cheswick									
AVG	**0.9721**	**0.9853**	**0.9906**	**1.0059**	**1.0046**	**1.0001**	**1.0045**	**0.9712**	**0.9843**

TABLE 4									
BP TECH	**HYP**	**OUTPUT EFF**							
Year	**DELTA_SO2**	**DELTA_NOx**	**TE**	**TC**	**IG**	**IG_NF**	**IG_F**	**OM_SO2**	**OM_NOx**
1985-1986	0.9538	0.9587	0.9792	1.0196	0.9435	1.0048	0.9391	1.0125	1.0177
1986-1987	0.9878	0.9908	1.0025	1.0018	0.9955	1.0001	0.9954	0.9881	0.9910
1987-1988	1.0284	1.0586	1.0041	1.0018	1.0537	1.0003	1.0534	0.9703	0.9988
1988-1989	1.0573	1.0493	1.0010	1.0014	1.0371	1.0004	1.0367	1.0171	1.0094
1989-1990	0.9592	0.9564	0.9964	1.0063	0.9610	1.0018	0.9592	0.9954	0.9925
1990-1991	0.9331	0.9444	0.9965	1.0020	0.9497	1.0001	0.9496	0.9840	0.9959
1991-1992	0.9924	0.9741	1.0049	1.0001	0.9959	0.9998	0.9961	0.9915	0.9731
1992-1993	1.0141	1.0294	1.0002	1.0011	1.0447	1.0000	1.0448	0.9694	0.9840
1993-1994	0.9663	0.9185	0.9988	1.0003	0.9792	0.9978	0.9814	0.9877	0.9388
1994-1995	0.8099	0.9752	0.8990	1.1315	0.9252	1.0585	0.8741	0.8605	1.0362
AVG(pre-1990)	**0.9965**	**1.0018**	**0.9966**	**1.0062**	**0.9973**	**1.0015**	**0.9958**	**0.9965**	**1.0018**
AVG(post-1990)	**0.9403**	**0.9676**	**0.9790**	**1.0257**	**0.9781**	**1.0110**	**0.9675**	**0.9573**	**0.9851**
AVG	**0.9680**	**0.9846**	**0.9878**	**1.0159**	**0.9876**	**1.0062**	**0.9816**	**0.9767**	**0.9934**
TABLE 5									
BP TECH	**HYP**	**ENV EFF**							
Year	**DELTA_SO2**	**DELTA_NOx**	**TE**	**TC**	**IG**	**IG_NF**	**IG_F**	**OM_SO2**	**OM_NOx**
1985-1986	0.9538	0.9587	0.9758	1.0267	1.0391	1.0128	1.0260	0.9163	0.9210
1986-1987	0.9878	0.9908	1.0038	1.0090	0.9966	1.0026	0.9940	0.9786	0.9815
1987-1988	1.0284	1.0586	0.8770	1.1460	0.9418	1.0695	0.8806	1.0864	1.1184
1988-1989	1.0573	1.0493	0.9701	1.0075	0.9753	1.0027	0.9727	1.1092	1.1008
1989-1990	0.9592	0.9564	0.9915	1.0288	1.0254	1.0143	1.0110	0.9171	0.9144
1990-1991	0.9331	0.9444	1.0379	1.0004	1.0264	0.9998	1.0265	0.8756	0.8861
1991-1992	0.9924	0.9741	0.9756	1.0057	1.0358	1.0025	1.0332	0.9765	0.9584
1992-1993	1.0141	1.0294	1.0177	1.0148	0.9456	1.0075	0.9386	1.0384	1.0540
1993-1994	0.9663	0.9185	1.0175	1.0629	0.9972	1.0285	0.9696	0.8959	0.8516
1994-1995	0.8099	0.9752	1.0180	1.0333	1.0284	1.0164	1.0117	0.7487	0.9016
AVG(pre-1990)	**0.9965**	**1.0018**	**0.9626**	**1.0423**	**0.9950**	**1.0201**	**0.9754**	**0.9982**	**1.0035**
AVG(post-1990)	**0.9403**	**0.9676**	**1.0132**	**1.0232**	**1.0061**	**1.0109**	**0.9953**	**0.9015**	**0.9277**
AVG	**0.9680**	**0.9846**	**0.9875**	**1.0327**	**1.0005**	**1.0155**	**0.9853**	**0.9486**	**0.9649**
TABLE 6									
BP TECH	**CW**	**JOINT EFF**							
Year	**DELTA_SO2**	**DELTA_NOx**	**TE**	**TC**	**IG**	**IG_NF**	**IG_F**	**OM_SO2**	**OM_NOx**
1985-1986	0.9538	0.9587	0.9613	1.0416	0.9765	1.0169	0.9602	0.9754	0.9805
1986-1987	0.9878	0.9908	1.0064	1.0012	0.9942	0.9995	0.9947	0.9861	0.9890
1987-1988	1.0284	1.0586	1.0021	1.0046	1.0114	1.0016	1.0098	1.0101	1.0398
1988-1989	1.0573	1.0493	0.9903	1.0006	1.0142	0.9999	1.0142	1.0521	1.0442
1989-1990	0.9592	0.9564	0.9976	1.0103	0.9825	1.0042	0.9784	0.9687	0.9658
1990-1991	0.9331	0.9444	1.0121	1.0012	0.9745	0.9999	0.9746	0.9450	0.9564
1991-1992	0.9924	0.9741	0.9956	1.0011	1.0127	1.0002	1.0124	0.9833	0.9651
1992-1993	1.0141	1.0294	1.0047	1.0076	0.9989	1.0033	0.9956	1.0029	1.0180
1993-1994	0.9663	0.9185	1.0149	1.0127	0.9800	1.0039	0.9762	0.9595	0.9120
1994-1995	0.8099	0.9752	0.9485	1.0876	0.9676	1.0388	0.9315	0.8113	0.9770
AVG(pre-1990)	**0.9965**	**1.0018**	**0.9914**	**1.0115**	**0.9956**	**1.0044**	**0.9913**	**0.9980**	**1.0033**
AVG(post-1990)	**0.9403**	**0.9676**	**0.9948**	**1.0215**	**0.9866**	**1.0091**	**0.9777**	**0.9378**	**0.9651**
AVG	**0.9680**	**0.9846**	**0.9931**	**1.0165**	**0.9911**	**1.0068**	**0.9844**	**0.9675**	**0.9840**

Plant Name	DELTA_SO2	DELTA_NOx	TE	TC	IG	IG_NF	IG_F	OM_SO2	OM_NOx
Barry	1.0336	1.0120	0.9930	1.0080	1.0081	1.0028	1.0053	1.0243	1.0029
Gorgas	1.0573	1.0163	0.9918	1.0153	1.0096	1.0092	1.0004	1.0400	0.9997
Comanche	0.9886	1.0127	1.0013	1.0007	1.0113	1.0004	1.0109	0.9755	0.9994
Brandon Shores	1.1312	1.1323	0.9999	1.0024	1.1295	1.0008	1.1286	0.9991	1.0001
Crist	0.8818	0.9539	0.9764	1.0200	0.9738	1.0093	0.9649	0.9092	0.9835
Hammond	0.8934	0.9157	0.9703	1.0317	0.9212	1.0162	0.9065	0.9688	0.9930
Harllee Branch	0.9737	0.9831	0.9905	1.0044	0.9770	1.0015	0.9755	1.0018	1.0115
Yates	0.8227	0.8911	0.9598	1.0327	0.9066	1.0162	0.8921	0.9155	0.9916
E.D. Edwards	1.0641	0.9933	0.9840	1.0153	1.0082	1.0075	1.0007	1.0564	0.9861
Coffeen	0.8525	0.9791	0.9805	1.0199	0.9676	1.0077	0.9602	0.8811	1.0119
Grand Tower	0.9711	0.9674	0.9673	1.0324	0.9510	1.0159	0.9361	1.0225	1.0187
Hustonville	0.9048	0.8770	0.9608	1.0325	0.8946	1.0160	0.8806	1.0194	0.9881
Meredosia	0.9643	0.9781	0.9674	1.0321	0.9620	1.0159	0.9470	1.0038	1.0183
Kincaid	0.7620	0.9199	0.9879	1.0102	0.9263	1.0051	0.9216	0.8243	0.9951
Powerton	0.9327	0.9858	0.9856	1.0107	0.9735	1.0053	0.9684	0.9617	1.0165
Joppa Steam	0.8710	1.0160	0.9917	1.0107	1.0157	1.0055	1.0101	0.8556	0.9979
Baldwin	0.9952	0.9872	0.9841	1.0134	0.9880	1.0074	0.9808	1.0100	1.0019
Clifty Creek	0.9012	1.0090	0.9909	1.0131	0.9799	0.9993	0.9806	0.9162	1.0258
Tanners Creek	0.9435	1.0054	0.9839	1.0180	1.0044	1.0103	0.9942	0.9379	0.9994
H.T. Pritchard	0.9462	0.9805	0.9682	1.0321	0.9835	1.0159	0.9681	0.9628	0.9977
Petersburgh	1.0298	1.0309	0.9920	1.0080	1.0419	1.0041	1.0377	0.9883	0.9893
Edwardsport	0.9525	0.9744	0.9633	1.0321	0.9592	1.0159	0.9442	0.9987	1.0217
R. Gallagher	0.9535	0.9790	0.9827	1.0136	1.0140	1.0058	1.0082	0.9440	0.9693
F.B. Culley	0.8068	0.9639	0.9949	1.0051	0.9976	1.0023	0.9953	0.8088	0.9663
Lansing	0.9854	0.9444	0.9698	1.0181	0.9670	1.0087	0.9586	1.0321	0.9891
Lawrence	0.9735	0.9916	0.9963	1.0096	1.0171	1.0048	1.0123	0.9515	0.9692
E.W. Brown	0.9278	0.9369	0.9835	1.0168	0.9620	1.0061	0.9562	0.9645	0.9740
Ghent	0.9461	1.0314	1.0011	1.0042	1.0537	1.0027	1.0509	0.8931	0.9736
Green River	0.9865	0.9527	0.9676	1.0262	0.9578	1.0100	0.9483	1.0372	1.0018
Mill Creek	1.1458	0.9992	0.9878	1.0133	1.0099	1.0066	1.0033	1.1335	0.9885
R.P. Smith	0.9285	0.8934	0.9836	1.0321	0.9018	1.0159	0.8877	1.0143	0.9758
Mount Tom	0.9680	0.9609	1.0086	1.0273	0.9315	1.0002	0.9313	1.0030	0.9957
B.C. Cobb	1.0312	1.0636	0.9814	1.0199	1.0388	1.0076	1.0310	0.9917	1.0229
Trenton Channel	0.9914	1.0258	0.9727	1.0277	0.9917	1.0131	0.9788	1.0000	1.0347
Hoot Lake	0.8964	1.0111	0.9756	1.0316	0.9868	1.0153	0.9720	0.9026	1.0181
Montrose	0.7142	0.9554	1.0177	1.0221	0.9614	1.0061	0.9556	0.7141	0.9553
Labadie	0.9141	0.9869	0.9915	1.0096	1.0014	1.0048	0.9967	0.9120	0.9845
Sioux	0.9770	0.9831	0.9877	1.0182	1.0254	1.0119	1.0133	0.9475	0.9534
Goudey	0.9483	0.9251	0.9993	1.0146	0.9384	1.0078	0.9311	0.9967	0.9724
Greenidge	0.9310	0.9216	0.9872	1.0252	0.9295	1.0067	0.9233	0.9896	0.9797
Milliken	0.9047	1.0045	0.9865	1.0150	1.0072	1.0095	0.9977	0.8972	0.9961
C.R. Huntley	0.9758	0.9773	0.9966	1.0085	0.9704	0.9881	0.9821	1.0004	1.0021
Dunkirk	0.9960	0.9628	0.9772	1.0369	0.9713	1.0108	0.9609	1.0120	0.9782
Rochester	0.9838	0.9843	0.9647	1.0321	0.9715	1.0159	0.9563	1.0170	1.0176
Asheville	1.0368	1.0232	0.9938	1.0084	1.0153	1.0050	1.0102	1.0190	1.0056
G.G. Allen	1.0220	1.0061	0.9849	1.0115	1.0375	1.0045	1.0329	0.9887	0.9734
Cliffside	1.0124	0.9817	0.9843	1.0188	1.0023	1.0080	0.9944	1.0072	0.9767
Marshall	1.0347	0.9959	1.0000	1.0015	1.0297	1.0003	1.0294	1.0033	0.9657
R.M. Heskett	0.8701	0.8981	0.9864	1.0068	0.9370	1.0035	0.9337	0.9350	0.9652
J.M. Stuart	0.9487	0.9859	0.9895	1.0098	0.9928	1.0049	0.9880	0.9563	0.9939
R.E. Burger	0.9375	0.9488	0.9941	1.0048	0.9450	0.9996	0.9454	0.9933	1.0052

Plant Name	DELTA_SO2	DELTA_NOx	TE	TC	IG	IG_NF	IG_F	OM_SO2	OM_NOx
Muskingum River	0.9255	0.9574	0.9744	1.0226	0.9660	1.0109	0.9556	0.9616	0.9948
Kyger Creek	0.9128	0.9920	0.9974	1.0020	0.9997	1.0007	0.9990	0.9137	0.9930
Elrama	1.0683	1.0068	0.9798	1.0243	1.0377	1.0122	1.0252	1.0258	0.9668
Seward	0.9927	0.9731	0.9821	1.0192	0.9855	1.0077	0.9780	1.0064	0.9865
Shawville	0.9879	0.9617	0.9926	1.0079	0.9926	1.0028	0.9898	0.9948	0.9684
New Castle	0.9815	0.9750	0.9871	1.0238	0.9641	1.0088	0.9557	1.0074	1.0006
Brunner Island	0.9681	0.9463	0.9974	1.0062	0.9804	1.0016	0.9788	0.9840	0.9618
Montour	1.0231	0.9596	0.9961	1.0036	0.9905	1.0006	0.9900	1.0332	0.9691
Armstrong	0.9537	0.9241	0.9996	1.0248	0.9242	1.0098	0.9152	1.0072	0.9760
Watertree	1.0237	1.0250	0.9979	1.0046	1.0229	1.0024	1.0204	0.9984	0.9996
Big Brown	1.0315	0.9973	0.9845	1.0160	0.9789	1.0114	0.9678	1.0536	1.0186
Carbon	1.0758	1.1008	1.0003	1.0040	1.1001	1.0018	1.0982	0.9737	0.9963
Clinch River	1.0160	1.0150	0.9939	1.0077	1.0069	1.0038	1.0031	1.0075	1.0065
Glen Lyn	1.0116	0.9776	0.9687	1.0272	1.0039	1.0123	0.9917	1.0126	0.9786
Potamac River	0.9721	0.9792	0.9715	1.0290	0.9668	1.0141	0.9534	1.0058	1.0132
Bremo	1.0388	1.0260	0.9785	1.0274	1.0060	1.0159	0.9902	1.0271	1.0144
Kanawha River	0.9796	0.9816	0.9696	1.0263	0.9783	1.0126	0.9661	1.0064	1.0084
Rivesville	0.9178	0.9195	0.9634	1.0322	0.9073	1.0159	0.8931	1.0173	1.0191
Willow Island	1.0007	0.9913	1.0187	1.0127	0.9637	1.0124	0.9520	1.0065	0.9970
Kammer	0.9774	0.9978	0.9959	1.0020	1.0020	1.0005	1.0015	0.9775	0.9979
Mitchell	0.9507	0.9608	0.9941	1.0078	0.9939	1.0037	0.9903	0.9546	0.9648
Nelson Dewey	0.8331	0.9272	0.9884	1.0111	0.9947	1.0015	0.9932	0.8381	0.9327
Pulliam	0.8519	1.0576	1.0041	1.0032	1.0441	1.0003	1.0438	0.8100	1.0056
Dave Johnston	0.9793	1.0291	0.9960	1.0077	1.0127	1.0040	1.0087	0.9634	1.0125
Naughton	1.0052	1.0189	0.9954	1.0057	1.0144	1.0034	1.0110	0.9899	1.0033
J.H. Miller Jr.	1.1362	1.1543	0.9986	1.0066	1.1344	1.0043	1.1295	0.9965	1.0123
Pleasants	1.2178	0.9974	1.0106	1.0086	0.9895	1.0041	0.9855	1.2075	0.9889
Duck Creek	0.9956	1.0076	0.9888	1.0142	1.0012	1.0073	0.9940	0.9915	1.0036
Newton	1.0660	1.0316	0.9904	1.0130	1.0211	1.0064	1.0147	1.0405	1.0070
Sooner	1.0493	1.0218	0.9986	1.0046	1.0399	0.9996	1.0403	1.0058	0.9794
Welsh	0.9780	0.9593	0.9912	1.0055	0.9970	1.0042	0.9928	0.9841	0.9654
Martin Lake	1.0840	1.0064	0.9996	1.0064	1.0002	1.0020	0.9982	1.0772	1.0001
Monticello	0.9540	0.9758	0.9776	1.0289	0.9499	1.0174	0.9337	0.9986	1.0213
Rush Island	0.9425	0.9830	0.9880	1.0047	1.0077	1.0014	1.0063	0.9422	0.9827
Coleto Creek	1.0170	0.9797	0.9950	1.0133	0.9794	0.9863	0.9930	1.0300	0.9922
Harrington	1.0193	0.9881	1.0000	1.0504	0.9073	0.9838	0.9222	1.0695	1.0367
Pawnee	1.0399	0.9917	0.9946	1.0081	1.0082	1.0043	1.0039	1.0287	0.9810
Mountaineer	0.9787	0.9748	0.9868	1.0125	0.9670	1.0047	0.9625	1.0130	1.0089
Belews Creek	0.9785	1.0058	0.9992	1.0287	0.9508	0.9922	0.9583	1.0012	1.0291
Gen. J.M. Gavin	0.8000	1.0107	0.9937	1.0114	1.0037	1.0061	0.9976	0.7929	1.0018
Cheswick	1.0046	0.9671	1.0030	1.0073	0.9922	1.0029	0.9893	1.0021	0.9646
AVG	**0.9680**	**0.9846**	**0.9878**	**1.0159**	**0.9876**	**1.0062**	**0.9816**	**0.9767**	**0.9934**

Plant Name	DELTA_SO2	DELTA_NOx	TE	TC	IG	IG_NF	IG_F	OM_SO2	OM_NOx
Barry	1.0336	1.0120	0.9496	1.0281	1.0088	1.0131	0.9957	1.0494	1.0275
Gorgas	1.0573	1.0163	0.9554	1.0399	0.9871	1.0200	0.9677	1.0783	1.0365
Comanche	0.9886	1.0127	0.9893	1.0233	0.9878	1.0097	0.9783	0.9885	1.0127
Brandon Shores	1.1312	1.1323	0.9495	1.0173	0.9140	1.0086	0.9062	1.2813	1.2825
Crist	0.8818	0.9539	1.0299	1.0329	0.9878	1.0172	0.9711	0.8392	0.9078
Hammond	0.8934	0.9157	1.0065	1.0504	1.0468	1.0222	1.0240	0.8073	0.8274
Harllee Branch	0.9737	0.9831	0.9710	1.0334	1.0209	1.0164	1.0044	0.9504	0.9596
Yates	0.8227	0.8911	1.0102	1.0484	1.0751	1.0215	1.0524	0.7226	0.7827
E.D. Edwards	1.0641	0.9933	0.9803	1.0200	0.9843	1.0116	0.9730	1.0812	1.0092
Coffeen	0.8525	0.9791	1.0000	1.0366	1.0275	1.0182	1.0091	0.8005	0.9193
Grand Tower	0.9711	0.9674	0.9648	1.0482	1.0231	1.0241	0.9991	0.9385	0.9350
Hustonville	0.9048	0.8770	1.0123	1.0496	1.0733	1.0230	1.0492	0.7933	0.7690
Meredosia	0.9643	0.9781	0.9763	1.0863	0.9739	1.0215	0.9534	0.9335	0.9469
Kincaid	0.7620	0.9199	1.0339	1.0493	1.0644	1.0268	1.0366	0.6600	0.7967
Powerton	0.9327	0.9858	0.9942	1.0362	1.0127	1.0174	0.9954	0.8941	0.9451
Joppa Steam	0.8710	1.0160	1.0086	1.0457	0.9604	1.0216	0.9401	0.8599	1.0030
Baldwin	0.9952	0.9872	0.9611	1.0456	1.0080	1.0223	0.9860	0.9825	0.9746
Clifty Creek	0.9012	1.0090	0.9874	1.0454	1.0002	1.0218	0.9789	0.8728	0.9772
Tanners Creek	0.9435	1.0054	0.9796	1.0238	1.0047	1.0093	0.9955	0.9364	0.9978
H.T. Pritchard	0.9462	0.9805	0.9561	1.0390	1.0294	1.0197	1.0095	0.9253	0.9588
Petersburgh	1.0298	1.0309	0.9682	1.0417	0.9569	1.0190	0.9391	1.0669	1.0681
Edwardsport	0.9525	0.9744	1.0003	1.0653	0.9657	1.0353	0.9328	0.9256	0.9469
R. Gallagher	0.9535	0.9790	1.0078	1.0508	0.9641	1.0279	0.9379	0.9339	0.9589
F.B. Culley	0.8068	0.9639	1.0477	1.0445	0.9975	1.0217	0.9764	0.7391	0.8830
Lansing	0.9854	0.9444	1.0006	1.0000	1.0245	0.9993	1.0252	0.9612	0.9212
Lawrence	0.9735	0.9916	1.0000	1.0417	0.9709	1.0122	0.9592	0.9625	0.9804
E.W. Brown	0.9278	0.9369	0.9931	1.0475	1.0261	1.0245	1.0015	0.8693	0.8779
Ghent	0.9461	1.0314	1.0008	1.0385	0.9558	1.0186	0.9383	0.9524	1.0383
Green River	0.9865	0.9527	0.9748	1.0463	1.0291	1.0226	1.0064	0.9399	0.9077
Mill Creek	1.1458	0.9992	0.9709	1.0172	0.9858	1.0050	0.9810	1.1769	1.0264
R.P. Smith	0.9285	0.8934	1.0053	1.0354	1.0698	1.0184	1.0504	0.8338	0.8022
Mount Tom	0.9680	0.9609	0.9886	1.0333	1.0200	1.0153	1.0046	0.9291	0.9223
B.C. Cobb	1.0312	1.0636	0.9661	1.0279	0.9546	1.0142	0.9413	1.0878	1.1220
Trenton Channel	0.9914	1.0258	0.9570	1.0233	1.0030	1.0143	0.9889	1.0092	1.0443
Hoot Lake	0.8964	1.0111	1.0133	1.0088	0.9958	0.9911	1.0048	0.8805	0.9932
Montrose	0.7142	0.9554	1.0406	1.0310	1.0347	1.0068	1.0278	0.6434	0.8606
Labadie	0.9141	0.9869	0.9771	1.0504	0.9928	1.0266	0.9671	0.8971	0.9685
Sioux	0.9770	0.9831	1.0141	1.0353	0.9644	1.0152	0.9499	0.9649	0.9710
Goudey	0.9483	0.9251	0.9728	1.0323	1.0767	1.0160	1.0597	0.8771	0.8556
Greenidge	0.9310	0.9216	0.9701	1.0371	1.0777	1.0155	1.0612	0.8587	0.8501
Milliken	0.9047	1.0045	0.9977	1.0468	0.9802	1.0224	0.9588	0.8837	0.9811
C.R. Huntley	0.9758	0.9773	0.9649	1.0456	1.0192	1.0190	1.0002	0.9490	0.9506
Dunkirk	0.9960	0.9628	1.0014	1.0544	0.9837	1.0255	0.9593	0.9590	0.9270
Rochester	0.9838	0.9843	0.9593	1.0499	1.0087	1.0262	0.9829	0.9684	0.9689
Asheville	1.0368	1.0232	0.9728	1.0231	0.9829	1.0116	0.9716	1.0599	1.0460
G.G. Allen	1.0220	1.0061	1.0060	1.0254	0.9635	1.0133	0.9508	1.0283	1.0123
Cliffside	1.0124	0.9817	0.9888	1.0326	0.9862	1.0174	0.9694	1.0053	0.9748
Marshall	1.0347	0.9959	0.9858	1.0320	0.9778	1.0182	0.9603	1.0401	1.0011
R.M. Heskett	0.8701	0.8981	1.0000	1.0540	1.0644	1.0303	1.0331	0.7755	0.8005
J.M. Stuart	0.9487	0.9859	0.9936	1.0402	1.0028	1.0207	0.9824	0.9152	0.9512
R.E. Burger	0.9375	0.9488	0.9556	1.0452	1.0552	1.0226	1.0319	0.8895	0.9002

Plant Name	DELTA_SO2	DELTA_NOx	TE	TC	IG	IG_NF	IG_F	OM_SO2	OM_NOx
Muskingum River	0.9255	0.9574	0.9789	1.0484	1.0176	1.0228	0.9949	0.8861	0.9167
Kyger Creek	0.9128	0.9920	0.9876	1.0440	0.9994	1.0206	0.9792	0.8859	0.9627
Elrama	1.0683	1.0068	1.0000	0.9770	0.9631	0.9759	0.9869	1.1353	1.0700
Seward	0.9927	0.9731	0.9535	1.0420	1.0297	1.0190	1.0104	0.9704	0.9512
Shawville	0.9879	0.9617	0.9886	1.0498	0.9974	1.0243	0.9737	0.9544	0.9291
New Castle	0.9815	0.9750	0.9660	1.0296	1.0311	1.0177	1.0132	0.9571	0.9507
Brunner Island	0.9681	0.9463	0.9904	1.0558	1.0105	1.0253	0.9856	0.9162	0.8956
Montour	1.0231	0.9596	0.9911	1.0513	0.9989	1.0232	0.9762	0.9830	0.9220
Armstrong	0.9537	0.9241	0.9757	1.0488	1.0560	1.0240	1.0313	0.8825	0.8551
Watertree	1.0237	1.0250	0.9542	1.0227	0.9987	1.0106	0.9882	1.0505	1.0518
Big Brown	1.0315	0.9973	0.9858	1.0370	0.9794	1.0137	0.9662	1.0303	0.9961
Carbon	1.0758	1.1008	0.9890	1.0132	0.9114	1.0080	0.9042	1.1779	1.2052
Clinch River	1.0160	1.0150	0.9824	1.0137	0.9894	1.0059	0.9835	1.0313	1.0302
Glen Lyn	1.0116	0.9776	0.9631	1.0234	1.0327	1.0145	1.0179	0.9938	0.9605
Potamac River	0.9721	0.9792	0.9761	1.0234	1.0236	1.0108	1.0126	0.9507	0.9577
Bremo	1.0388	1.0260	0.9629	1.0123	0.9977	1.0097	0.9881	1.0683	1.0551
Kanawha River	0.9796	0.9816	0.9981	1.0144	1.0099	1.0078	1.0020	0.9582	0.9601
Rivesville	0.9178	0.9195	0.9955	1.0145	1.0716	1.0079	1.0632	0.8480	0.8496
Willow Island	1.0007	0.9913	0.9640	1.0197	1.0252	1.0098	1.0153	0.9931	0.9837
Kammer	0.9774	0.9978	0.9599	1.0463	0.9978	1.0228	0.9755	0.9752	0.9956
Mitchell	0.9507	0.9608	1.0021	1.0251	1.0158	1.0157	1.0001	0.9110	0.9208
Nelson Dewey	0.8331	0.9272	1.0881	1.0214	0.9968	1.0088	0.9881	0.7521	0.8370
Pulliam	0.8519	1.0576	1.0188	1.0458	0.9477	1.0275	0.9224	0.8437	1.0474
Dave Johnston	0.9793	1.0291	0.9917	1.0289	0.9835	1.0124	0.9714	0.9759	1.0255
Naughton	1.0052	1.0189	0.9900	1.0157	0.9808	1.0078	0.9732	1.0192	1.0330
J.H. Miller Jr.	1.1362	1.1543	0.9559	1.0263	0.8876	1.0077	0.8808	1.3050	1.3257
Pleasants	1.2178	0.9974	0.9533	1.0292	1.0044	1.0151	0.9894	1.2359	1.0121
Duck Creek	0.9956	1.0076	0.9916	1.0138	0.9923	1.0067	0.9857	0.9981	1.0102
Newton	1.0660	1.0316	0.9697	1.0264	0.9772	1.0187	0.9592	1.0960	1.0607
Sooner	1.0493	1.0218	0.9867	1.0095	0.9603	1.0045	0.9561	1.0969	1.0682
Welsh	0.9780	0.9593	1.0051	1.0165	1.0035	1.0062	0.9973	0.9539	0.9357
Martin Lake	1.0840	1.0064	0.9590	1.0059	0.9925	1.0034	0.9892	1.1322	1.0512
Monticello	0.9540	0.9758	0.9794	1.0157	1.0318	1.0090	1.0226	0.9295	0.9507
Rush Island	0.9425	0.9830	1.0044	1.0409	0.9902	1.0196	0.9711	0.9105	0.9496
Coleto Creek	1.0170	0.9797	0.9938	1.0058	0.9991	1.0024	0.9967	1.0184	0.9810
Harrington	1.0193	0.9881	0.9831	1.0117	0.9931	1.0035	0.9896	1.0319	1.0003
Pawnee	1.0399	0.9917	1.0323	1.0149	0.9246	1.0053	0.9197	1.0734	1.0237
Mountaineer	0.9787	0.9748	0.9834	1.0169	1.0284	1.0096	1.0187	0.9517	0.9479
Belews Creek	0.9785	1.0058	0.9922	1.0202	0.9951	1.0108	0.9845	0.9713	0.9984
Gen. J.M. Gavin	0.8000	1.0107	1.0268	1.0493	0.9879	1.0243	0.9645	0.7516	0.9496
Cheswick	1.0046	0.9671	0.9988	1.0380	0.9975	1.0212	0.9767	0.9715	0.9352
AVG	**0.9680**	**0.9846**	**0.9875**	**1.0327**	**1.0005**	**1.0155**	**0.9853**	**0.9486**	**0.9649**

Plant Name	DELTA_SO2	DELTA_NOx	TE	TC	IG	IG_NF	IG_F	OM_SO2	OM_NOx
Barry	1.0336	1.0120	0.9832	1.0095	1.0044	1.0030	1.0014	1.0368	1.0151
Gorgas	1.0573	1.0163	0.9845	1.0156	1.0033	1.0092	0.9941	1.0540	1.0131
Comanche	0.9886	1.0127	0.9964	1.0110	1.0016	1.0051	0.9965	0.9797	1.0037
Brandon Shores	1.1312	1.1323	0.9797	1.0081	1.0251	1.0028	1.0223	1.1173	1.1183
Crist	0.8818	0.9539	1.0055	1.0177	0.9808	1.0095	0.9716	0.8786	0.9504
Hammond	0.8934	0.9157	0.9892	1.0229	0.9606	1.0153	0.9461	0.9192	0.9421
Harllee Branch	0.9737	0.9831	0.9896	1.0074	0.9896	1.0035	0.9862	0.9869	0.9964
Yates	0.8227	0.8911	0.9956	1.0240	0.9626	1.0127	0.9505	0.8383	0.9079
E.D. Edwards	1.0641	0.9933	0.9835	1.0138	1.0002	1.0070	0.9933	1.0670	0.9960
Coffeen	0.8525	0.9791	0.9920	1.0191	0.9810	1.0079	0.9733	0.8596	0.9872
Grand Tower	0.9711	0.9674	0.9780	1.0245	0.9736	1.0095	0.9644	0.9954	0.9917
Hustonville	0.9048	0.8770	0.9870	1.0233	0.9568	1.0103	0.9470	0.9363	0.9076
Meredosia	0.9643	0.9781	0.9909	1.0443	0.9610	1.0100	0.9515	0.9696	0.9835
Kincaid	0.7620	0.9199	1.0060	1.0144	0.9593	1.0085	0.9512	0.7784	0.9397
Powerton	0.9327	0.9858	0.9891	1.0197	0.9890	1.0087	0.9805	0.9351	0.9883
Joppa Steam	0.8710	1.0160	1.0105	1.0166	1.0022	1.0078	0.9944	0.8460	0.9868
Baldwin	0.9952	0.9872	0.9834	1.0149	0.9924	1.0082	0.9844	1.0047	0.9966
Clifty Creek	0.9012	1.0090	0.9951	1.0160	0.9829	1.0023	0.9806	0.9069	1.0153
Tanners Creek	0.9435	1.0054	0.9898	1.0172	1.0030	1.0090	0.9940	0.9343	0.9956
H.T. Pritchard	0.9462	0.9805	0.9712	1.0249	1.0104	1.0154	0.9951	0.9407	0.9748
Petersburgh	1.0298	1.0309	0.9929	1.0112	1.0103	1.0054	1.0049	1.0152	1.0163
Edwardsport	0.9525	0.9744	0.9958	1.0356	0.9582	1.0145	0.9445	0.9639	0.9860
R. Gallagher	0.9535	0.9790	1.0062	1.0120	0.9970	1.0053	0.9918	0.9392	0.9644
F.B. Culley	0.8068	0.9639	1.0221	1.0122	0.9955	1.0058	0.9897	0.7834	0.9359
Lansing	0.9854	0.9444	0.9825	1.0126	0.9909	1.0059	0.9851	0.9995	0.9579
Lawrence	0.9735	0.9916	0.9983	1.0162	1.0039	1.0013	1.0026	0.9557	0.9736
E.W. Brown	0.9278	0.9369	0.9995	1.0168	0.9864	1.0062	0.9803	0.9255	0.9346
Ghent	0.9461	1.0314	1.0150	1.0098	1.0163	1.0058	1.0105	0.9083	0.9902
Green River	0.9865	0.9527	0.9743	1.0246	0.9774	1.0099	0.9679	1.0110	0.9765
Mill Creek	1.1458	0.9992	0.9776	1.0149	0.9985	1.0067	0.9919	1.1567	1.0087
R.P. Smith	0.9285	0.8934	1.0003	1.0209	0.9804	1.0067	0.9738	0.9275	0.8924
Mount Tom	0.9680	0.9609	1.0084	1.0246	0.9532	1.0022	0.9511	0.9830	0.9758
B.C. Cobb	1.0312	1.0636	0.9802	1.0204	1.0031	1.0077	0.9955	1.0278	1.0601
Trenton Channel	0.9914	1.0258	0.9696	1.0223	1.0000	1.0121	0.9881	1.0001	1.0349
Hoot Lake	0.8964	1.0111	0.9998	1.0212	0.9895	1.0089	0.9808	0.8873	1.0008
Montrose	0.7142	0.9554	1.0471	1.0216	0.9910	1.0070	0.9841	0.6737	0.9012
Labadie	0.9141	0.9869	1.0023	1.0105	0.9984	1.0058	0.9926	0.9040	0.9759
Sioux	0.9770	0.9831	1.0009	1.0161	1.0103	1.0102	1.0001	0.9509	0.9568
Goudey	0.9483	0.9251	0.9963	1.0148	0.9780	1.0073	0.9709	0.9591	0.9357
Greenidge	0.9310	0.9216	0.9897	1.0215	0.9723	1.0083	0.9643	0.9471	0.9375
Milliken	0.9047	1.0045	1.0034	1.0179	0.9970	1.0109	0.9863	0.8885	0.9864
C.R. Huntley	0.9758	0.9773	0.9937	1.0118	0.9828	0.9949	0.9879	0.9875	0.9891
Dunkirk	0.9960	0.9628	0.9892	1.0344	0.9764	1.0130	0.9639	0.9969	0.9636
Rochester	0.9838	0.9843	0.9732	1.0262	0.9863	1.0150	0.9717	0.9987	0.9993
Asheville	1.0368	1.0232	0.9889	1.0103	1.0036	1.0056	0.9980	1.0340	1.0204
G.G. Allen	1.0220	1.0061	0.9997	1.0117	1.0074	1.0049	1.0025	1.0030	0.9874
Cliffside	1.0124	0.9817	0.9934	1.0158	0.9988	1.0072	0.9916	1.0044	0.9740
Marshall	1.0347	0.9959	1.0011	1.0063	1.0087	1.0027	1.0059	1.0182	0.9801
R.M. Heskett	0.8701	0.8981	1.0111	1.0175	1.0011	1.0074	0.9937	0.8448	0.8720
J.M. Stuart	0.9487	0.9859	0.9960	1.0122	0.9960	1.0064	0.9897	0.9448	0.9819
R.E. Burger	0.9375	0.9488	0.9896	1.0103	0.9697	1.0030	0.9668	0.9671	0.9787

Plant Name	DELTA_SO2	DELTA_NOx	TE	TC	IG	IG_NF	IG_F	OM_SO2	OM_NOx
Muskingum River	0.9255	0.9574	0.9858	1.0211	0.9752	1.0101	0.9655	0.9428	0.9753
Kyger Creek	0.9128	0.9920	1.0025	1.0062	1.0001	1.0029	0.9972	0.9049	0.9834
Elrama	1.0683	1.0068	0.9917	1.0056	0.9935	0.9986	0.9948	1.0782	1.0162
Seward	0.9927	0.9731	0.9797	1.0188	1.0023	1.0063	0.9960	0.9923	0.9727
Shawville	0.9879	0.9617	1.0000	1.0098	0.9967	1.0049	0.9918	0.9817	0.9556
New Castle	0.9815	0.9750	0.9868	1.0201	0.9828	1.0085	0.9746	0.9921	0.9855
Brunner Island	0.9681	0.9463	1.0036	1.0122	0.9933	1.0059	0.9875	0.9593	0.9377
Montour	1.0231	0.9596	0.9992	1.0104	0.9922	1.0046	0.9877	1.0214	0.9580
Armstrong	0.9537	0.9241	0.9984	1.0231	0.9581	1.0090	0.9496	0.9744	0.9442
Watertree	1.0237	1.0250	0.9868	1.0080	1.0172	1.0042	1.0129	1.0119	1.0131
Big Brown	1.0315	0.9973	0.9802	1.0172	0.9881	1.0102	0.9781	1.0472	1.0124
Carbon	1.0758	1.1008	0.9931	1.0122	1.0069	1.0048	1.0020	1.0629	1.0876
Clinch River	1.0160	1.0150	0.9890	1.0110	1.0015	1.0059	0.9957	1.0146	1.0136
Glen Lyn	1.0116	0.9776	0.9627	1.0243	1.0223	1.0123	1.0098	1.0035	0.9698
Potamac River	0.9721	0.9792	0.9772	1.0204	0.9972	1.0097	0.9876	0.9776	0.9848
Bremo	1.0388	1.0260	0.9730	1.0225	1.0028	1.0144	0.9886	1.0412	1.0283
Kanawha River	0.9796	0.9816	0.9795	1.0211	0.9917	1.0110	0.9809	0.9877	0.9897
Rivesville	0.9178	0.9195	0.9794	1.0213	0.9774	1.0077	0.9699	0.9389	0.9406
Willow Island	1.0007	0.9913	1.0061	1.0132	0.9810	1.0116	0.9697	1.0008	0.9914
Kammer	0.9774	0.9978	0.9940	1.0060	1.0014	1.0025	0.9989	0.9760	0.9964
Mitchell	0.9507	0.9608	1.0041	1.0090	0.9977	1.0046	0.9932	0.9404	0.9505
Nelson Dewey	0.8331	0.9272	1.0200	1.0162	0.9921	1.0048	0.9874	0.8102	0.9016
Pulliam	0.8519	1.0576	1.0183	1.0177	1.0096	1.0071	1.0025	0.8142	1.0107
Dave Johnston	0.9793	1.0291	0.9950	1.0143	0.9996	1.0074	0.9923	0.9707	1.0202
Naughton	1.0052	1.0189	0.9914	1.0107	0.9995	1.0055	0.9941	1.0037	1.0173
J.H. Miller Jr.	1.1362	1.1543	0.9733	1.0187	1.0158	1.0065	1.0093	1.1281	1.1460
Pleasants	1.2178	0.9974	0.9815	1.0136	0.9934	1.0063	0.9873	1.2322	1.0091
Duck Creek	0.9956	1.0076	0.9890	1.0150	0.9976	1.0078	0.9898	0.9942	1.0063
Newton	1.0660	1.0316	0.9812	1.0127	0.9978	1.0060	0.9918	1.0751	1.0404
Sooner	1.0493	1.0218	0.9936	1.0099	1.0069	1.0039	1.0030	1.0385	1.0113
Welsh	0.9780	0.9593	0.9979	1.0094	1.0001	1.0058	0.9943	0.9708	0.9523
Martin Lake	1.0840	1.0064	0.9785	1.0080	0.9953	1.0026	0.9927	1.1041	1.0251
Monticello	0.9540	0.9758	0.9819	1.0209	0.9844	1.0136	0.9712	0.9669	0.9889
Rush Island	0.9425	0.9830	1.0034	1.0089	1.0008	1.0036	0.9972	0.9302	0.9702
Coleto Creek	1.0170	0.9797	0.9921	1.0137	0.9881	0.9955	0.9926	1.0234	0.9859
Harrington	1.0193	0.9881	0.9918	1.0403	0.9364	0.9935	0.9426	1.0550	1.0227
Pawnee	1.0399	0.9917	1.0105	1.0119	0.9749	1.0070	0.9682	1.0431	0.9947
Mountaineer	0.9787	0.9748	0.9858	1.0119	0.9900	1.0039	0.9862	0.9911	0.9871
Belews Creek	0.9785	1.0058	0.9974	1.0259	0.9641	0.9971	0.9669	0.9919	1.0195
Gen. J.M. Gavin	0.8000	1.0107	1.0183	1.0150	0.9986	1.0081	0.9906	0.7751	0.9792
Cheswick	1.0046	0.9671	1.0031	1.0144	0.9911	1.0080	0.9832	0.9962	0.9589
AVG	**0.9680**	**0.9846**	**0.9931**	**1.0165**	**0.9911**	**1.0068**	**0.9844**	**0.9675**	**0.9840**

TABLE 10	**Rolling Window**			
	Pearson		**Spearman**	
Year	**HYP**	**CW**	**HYP**	**CW**
1987	-0.1151	-0.1107	-0.0624	-0.0437
1988	-0.207	-0.1879	-0.1721	-0.1318
1989	-0.2204	-0.2252	-0.2154	-0.2031
1990	-0.2353	-0.2402	-0.253	-0.2537
1991	-0.2027	-0.1895	-0.2003	-0.1639
1992	-0.1877	-0.1463	-0.1842	-0.1332
1993	-0.2067	-0.21	-0.1662	-0.1541
1994	-0.141	-0.1836	-0.1574	-0.1693
1995	-0.0625	-0.1035	-0.0523	-0.0851
AVG	**-0.175377778**	**-0.17743**	**-0.162589**	**-0.14866**
	Sequential Technology			
	Pearson		**Spearman**	
Year	**HYP**	**CW**	**HYP**	**CW**
1985	-0.1057	-0.0688	-0.0824	-0.0124
1986	-0.1446	-0.1429	-0.12	-0.1003
1987	-0.1151	-0.1107	-0.0624	-0.0437
1988	-0.2034	-0.1869	-0.1691	-0.133
1989	-0.2195	-0.1781	-0.1991	-0.1335
1990	-0.2605	-0.2239	-0.2832	-0.208
1991	-0.1814	-0.1833	-0.192	-0.1551
1992	-0.184	-0.1597	-0.1913	-0.1415
1993	-0.1948	-0.195	-0.1705	-0.165
1994	-0.1157	-0.1617	-0.1219	-0.1464
1995	-0.0615	-0.0854	-0.0398	-0.0621
AVG	**-0.162381818**	**-0.15422**	**-0.148336**	**-0.11827**