Ecological Economics 69 (2010) 623–631

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

Sulfur dioxide allowances: Trading and technological progress

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ARTICLE INFO

Article history:
Received 15 January 2009
Received in revised form 11 August 2009
Accepted 24 September 2009
Available online 19 October 2009

Keywords:
Sulfur dioxide allowances trading
Technological progress
Environmental policy
Distance function

ABSTRACT

The US Clean Air Act Amendments introduce an emissions trading system to regulate SO_2 emissions. This study finds that changes in SO_2 emissions prices are related to innovations induced by these amendments. We find that electricity-generating plants are able to increase electricity output and reduce emissions of SO_2 and NO_x from 1995 to 2007 due to the introduction of the allowance trading system. However, compared to the approximate 8% per year of exogenous technological progress, the induced effect is relatively small, and the contribution of the induced effect to overall technological progress is about 1–2%.

1. Introduction

Title IV of the 1990 Clean Air Act Amendments (1990 CAAA) introduces an emission permit trading system to regulate SO_2 emissions from US thermal power plants. The policy was implemented to reduce damage from acidification while achieving the lowest compliance costs.[1] The often-cited measure of the success of the program is that the market allowance prices were substantially lower than the marginal compliance costs initially predicted. The decline in compliance costs can be attributed to three factors: (i) a decline in fuel prices coupled with a reduction in rail transportation costs for low sulfur western coal, (ii) exogenous technological progress that would have occurred in the absence of the program, and (iii) the technological progress that has been ignited by the allowance trading program (Burtraw et al., 2005). Using a production frontier approach, this study disentangles these effects by estimating exogenous (i.e., the aggregate of (i) and (ii)) [2] and technological progress induced by the allowance system (i.e., (iii)) that occurred from 1995 to 2007.

Environmental policy is designed to enhance incentives for the development and utilization of environmentally friendly technologies beyond static efficiency (Kneese and Schulze, 1975; Managi et al., 2005; Akao and Managi, 2007).[3] Firms change their technology in various directions depending upon prices and costs, which may be influenced by environmental regulations. Several theoretical studies show the advantages of market-based instruments (MBIs) over command and control regulations for inducing technological progress.[4] Some recent studies have empirically examined the dynamic effects of environmental policy in the US electricity sector (Bellas, 1998; Keohane, 2002; Popp, 2003). Bellas (1998), for example, has found non-significant evidence of technological change in abatement regarding the installation of scrubbers. Keohane (2002) has found an increase in the adoption of new scrubber technology after the 1990 CAAA. Popp (2003) used patent data to measure the level of innovation. He found that while successful patent applications for flue gas desulfurization units were higher before the introduction of the 1990 CAAA, the post-1990 CAAA had more positive environmental effects. However, Lange and Bella (2005) find that while scrubbers installed under the 1990 CAAA are less expensive

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[1] The allowance trading program was divided in two phases. Phase I affected 110 of the dirtiest plants and remained operative from 1995 to 1999. Units in phase I could emit at a rate of 2.5 lb of SO_2 emissions per million British Thermal Units (mBTUs) of heat input. All other units of fossil-fueled power plants could annually emit at the rate of 1.2 lb of SO_2 emissions per mBTUs of heat input. Phase II has been in operation since January 2000. In this phase, all major plants can emit at a rate of 1.2 lb of SO_2 emissions per mBTUs of heat input. Under the emissions trading system, the firms have an incentive to find the lowest-cost means of achieving compliance and to reap financial rewards for developing these means. Some recent studies (Carlson et al., 2000; Swinton, 2004) empirically examine the cost effectiveness of allowance trading systems.

[2] Relative change in input or/and output prices causes substitution effect and thereby affects the compliance costs in addition to technological changes. We try to distinguish between the effects on compliance costs of the introduction of SO_2 trading and all other causes.

[3] "Over the long haul, perhaps the most important single criterion on which to judge environmental policies is the extent they spur new technology towards the efficient conservation of environmental quality" (van Soest, 2005, pp. 236).

[4] See Requate (2005) for a survey of theoretical literature on dynamic incentives provided by various environmental policy instruments. Jaffe et al. (2003) has reviewed the literature on environmental policy and technological change.

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doi:10.1016/j.ecolecon.2009.09.013

to purchase and operate than older scrubbers, these cost reductions appear as a one-time drop rather than a continual decline.

Innovations under SO_2 allowance trading do not remain limited to scrubbing; rather, other abatement options, such as organizational changes at the firm, market, and regulatory level as well as process changes, are also allowed (Burtraw, 2000). Kolstad and Turnovsky (1998) and Considine and Larson (2006) showed that technological change has reduced the emissions of sulfur, thereby supporting the notion that technological progress has been responsible, at least in part, for the drop in the abatement costs of SO_2 emissions. Similarly, Carlson et al. (2000) found the approximate 20% declines in marginal abatement costs from 1985 to 1995 can be attributed to exogenous technological changes. However, these studies do not distinguish the technological progress that is exogenous (that is, technological progress that happened even in the absence of allowance trading) and the technological changes that were ignited by allowance trading. This study fills this void by decomposing the technological progress into exogenous and induced components so that the contribution of the allowance trading system can be explicitly recognized.

Technological change can be decompos1ed into two components: innovation and diffusion. The transformation function[5] is best suited to measure technological change (see Jaffe et al., 2003); it represents "best practice," i.e., what an electricity-generating plant would produce if all innovations made to date had fully diffused. Therefore, a shift in the transformation function captures innovations. The role of diffusion would then arise if some plants are not adopting the "best practice" but rather operating at points inside the transformation frontier. The movement of these plants toward the frontier can be termed as a "catch-up" effect, technological diffusion, or efficiency change (EC).[6] This study extends the literature on induced technological progress by measuring both innovations and diffusion.

There is a considerable theoretical and empirical literature on the measurement of the induced innovation hypothesis.[7] That literature typically analyzes the induced effect in terms of conventional representations of production technology, such as costs, production, or profit functions. However, distinctions between factor or output substitution and shifts in production technology frontiers cannot be addressed by conventional representations. In conventional representations, when current and long-run prices appear along with input–output vectors, the comparative static relations of the stated price-induced innovation model do not follow traditional forms, because the direct derivatives of the demand and supply functions with respect to prices are unsigned, given the presence of the cross derivatives (Celikkol and Stefanou, 1999; Paris and Caputo, 2001). Moreover, the traditional measures of productivity do not account for the production of harmful by-products such as SO_2 emissions, which may lead to environmental damage. Some recent studies[8] have included environmental externalities and have found that these measures differ from traditional measures.

We use a directional output distance function as a representation of production technology in order to simultaneously expand good output and contract bad outputs. It is particularly well suited to measure technical efficiency in the input–output space and satisfies all the properties that are required by conventional representations.

We measure technological change (TC) for US thermal power plants from 1995 to 2007. TC is similar in nature to any investment process, as it requires time and adjustment that is not instantaneous, and the choice of technology is influenced by long-term prices. TC is decomposed into two parts, namely, exogenous technological change (ETC) and induced technological change (ITC). A time trend variable is used to measure exogenous innovation.[9] Similarly, the inclusion of long-term allowance prices, as a factor accounting for shifts in the transformation function, is used to measure the induced innovation effect.[10]

The paper is organized as follows. Section 2 outlines the theoretical structure of the study. Section 3 presents the empirical model for the stochastic estimation of directional output distance function, and the data are described in Section 4. Section 5 discusses the main results of the study, and conclusions are presented in Section 6.

2. Measurement of technological progress

2.1. The directional output distance function

Suppose that an electricity-generating plant employs a vector of inputs $x \in \Re^K_+$ to produce a vector of good outputs (e.g., electricity output) $y \in \Re^N_+$, and bad outputs $b \in \Re^N_+$ (e.g., SO_2 and NO_x) (see Managi and Kaneko, 2009). Let $P(x)$ be the feasible output set for a given input vector x. The technology set is defined as:

$$T = \{(x, y, b) : x \text{ can produce } (y, b)\} \tag{1}$$

Production technology can be modeled in other ways. The output is strongly or freely disposable if $(y, b) \in P(x)$ and $(y', b') \leq (y, b) \Rightarrow (y', b') \in P(x)$. This implies that if an observed output vector is feasible, then any output vector smaller than that is also feasible. This assumption prevents production processes that generate poor outputs and are costly to dispose. For example, pollutants should not be considered to be freely disposable. In such cases, poor outputs are considered weakly disposable: $(y, b) \in P(x)$ and $0 \leq \theta \leq 1 \Rightarrow (\theta y, \theta b) \in P(x)$. This implies that pollution is costly to dispose and that abatement activities typically divert resources away from the production of desirable outputs, thus leading to lower desirable outputs given the inputs. Moreover, desirable outputs are assumed to be null-joint with the undesirable outputs.[11] Formally, the directional output distance function is defined as:

$$D(x, y, b; g) = \max_{\beta} \{\beta : (y + \beta \cdot g_y, b - \beta \cdot g_b) \in P(x)\} \tag{2}$$

This function requires a simultaneous reduction in pollutants and expansion in electricity output. The computed value of β, β^* provides the maximum expansion of electricity production and the maximum contraction of pollutants if a firm is to operate efficiently given the directional vector g. The vector $g = (g_y - g_b)$ specifies the direction an output vector (y,b) $P(x)$ is scaled so as to reach the output boundary set at point $(y + \beta^* \cdot g_y, b - \beta^* \cdot g_b)$ $P(x)$ by expanding electricity production and contracting pollutants, where $\beta^* = D(x, y, b; g)$.

The directional output distance function derives its properties from the output possibility set P(x) (Färe et al., 2005, 2007). These properties include monotonicity conditions for desirable and poor outputs as well as a translation property, which is the additive

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[5] The transformation function describes a frontier of production possibility, that is, a set of combinations of inputs and outputs that is technically feasible at a point in time.

[6] The directional distance function constitutes a transformation function by using the data of the countries under study. Thus, it is a relative measure of technical inefficiency across countries. It can identify the practices adopted by the most efficient country that are diffused to other countries. This is not equivalent to saying that most efficient country uses only the latest innovations, i.e., directional distance function cannot say anything about diffusion within a country.

[7] See Hayami and Ruttan (1971), Binswanger (1974, 1978), and Thirtle and Ruttan (1987) for a literature review.

[8] See, for example, Hailu and Veeman (2001); Färe et al. (2005), and Kumar (2006).

[9] Technological progress occurs due to both inducements and advancements in general science and technology. Therefore, a time trend is included to account for the impact of scientific innovation on production technology (Lansink et al., 2000, pp. 500, footnote 1).

[10] The notion that long-run prices may serve as a stimulating factor for innovation is a critical component of the price-induced innovation model. Changes in current prices induce factor substitution, whereas changes in long-run prices induce the development of new technologies and may lead to shifts in the technology frontier.

[11] Null-jointness implies that a firm cannot produce desirable outputs in the absence of undesirable outputs, i.e., if $(y, b) \in P(x)$ and $b = 0$ then $y = 0$.

counterpart to the homogeneity property of the Shepherd distance functions. The translation property implies that:

$$D(x, y+\alpha, b-\alpha; g_y, -g_b) + \alpha = D(x, y, b; g_y, -g_b) \tag{3}$$

The translation property implies that if we add $\alpha(g_y)$ to the desirable outputs and subtract $\alpha(g_b)$ from undesirable outputs, measured inefficiency declines by α, where α is a constant. The advantage of this function is that it allows one to consider non-proportional changes in output and makes possible the expansion of one output in tandem with the contraction of other outputs. This property is very useful in studying input–output choices of a pollutant for which a firm faces environmental regulations. The distance function takes the value of zero for technically efficient output vectors on the frontier, whereas positive values imply inefficient output vectors below the frontier. The higher the value is, the more inefficient is the output vector.

2.2. Malmquist–Luenberger productivity indicators

We extend the Malmquist–Luenberger (ML) measure of productivity change (PC) to a measure that also accounts for induced technological change (ITC). The ML productivity indicator can be decomposed into two component measures: efficiency change (EC) and technological change (TC), where EC + TC = PC. We further decompose TC into exogenous technological change (ETC) and ITC so that ETC + *I* TC = TC. EC measures how close an observation is to the technology frontier, and TC measures the shift in the technology frontier over a period of time as well as changes in allowance prices.

Following Färe et al. (2005), the directional output distance function is parameterized using an additive quadratic flexible functional form.

$$\begin{aligned}D^{kt}(x^{kt}, y^{kt}, b^{kt}; g, t, q) &= \alpha_0 + \sum_{n=1}^{3}\alpha_n x_n^{kt} + \beta_0 y^{kt} + \sum_{m=1}^{2}\beta_m b_m^{kt} \\ &+ \gamma_1 t + \gamma_2 q^t + \frac{1}{2}\sum_{n=1}^{3}\sum_{n'=1}^{3}\alpha_{nn'}x_n^{kt}x_{n'}^{kt} + \sum_{n=1}^{3}\delta_{n0}x_n^{kt}y^{kt} \\ &+ \sum_{m=1}^{2}\sum_{n=1}^{3}\delta_{nm}x_n^{kt}b_m^{kt} + \sum_{n=1}^{3}\eta_{n1}x_n^{kt}t + \sum_{n=1}^{3}\eta_{n2}x_n^{kt}q^t + \frac{1}{2}\beta_{00}y^{kt}y^{kt} \\ &+ \sum_{m=1}^{2}\beta_{0m}y^{kt}b_m^{kt} + \mu_{y1}y^{kt}t + \mu_{y2}y^{kt}q^t + \frac{1}{2}\sum_{m=1}^{2}\sum_{m'=1}^{2}\beta_{mm'}b_m^{kt}b_{m'}^{kt} \\ &+ \sum_{m=1}^{2}\mu_{m1}b_m^{kt}t + \sum_{m=1}^{2}\mu_{m2}b_m^{kt}q^t + \frac{1}{2}\gamma_{11}t^2 + \phi t q^t + \frac{1}{2}\gamma_{22}q^{t2}\end{aligned} \tag{4}$$

We include one desirable output y (electricity production), two undesirable outputs b_m (SO_2 and NO_x), three inputs x_n, time trend t as a proxy for exogenous technological changes, and long-run SO_2 allowance price q as a proxy for ITC.

Accounting for direction vectors and the translation property, the following parameter restrictions must be satisfied:

$$\beta_0 - \sum_{m=1}^{2}\beta_m = -1; \beta_{0m} - \sum_{m=1}^{2}\beta_{mm'} = 0; \beta_{00} - \sum_{m=1}^{2}\beta_{0m} = 0; \delta_{n0} - \sum_{m=1}^{2}\delta_{nm} = 0; \; m = 1, 2.$$

In addition to translation, we impose following symmetry condition:

$$\alpha_{nn'} = \alpha_{n'n}; \beta_{mm'} = \beta_{m'm}; m, m' = 1, 1; n, n' = 1, 2, 3,$$

where t is a time-trend, and q is the long-run SO_2 allowance price. Specification (4) allows for neutral and biased technological changes. The effect of a neutral ETC is captured by coefficients γ_1 and γ_{11}, and the effect of neutral ITC is captured by coefficients γ_2 and γ_{22}. The extent of input-biased ETC and ITC is estimated by coefficients η_{n1} and η_{n2}, respectively. The effects of changes in output due to ETC and ITC (i.e., output-biased technological change) are estimated by coefficients μ_{y1}, μ_{b1}, μ_{y2}, and μ_{b2}, respectively. In addition, the interaction between ITC and ETC is captured by coefficient φ.

We parameterize the directional output distance function in quadratic form so that we are able to apply Diewert's (1976) Quadratic Identity Lemma.[12] Using this lemma, changes in the directional output distance function (4) from one period to the next can be written as:

$$\begin{aligned}(D^t - D^{t+1}) &= 0.5\left[\frac{\partial D^t}{\partial y} + \frac{\partial D^{t+1}}{\partial y}\right](y^{t+1} - y^t) + 0.5\sum_{m=1}^{2}\left[\frac{\partial D^t}{\partial b} + \frac{\partial D^{t+1}}{\partial b}\right](b^{t+1} - b^t) \\ &+ 0.5\sum_{n=1}^{3}\left[\frac{\partial D^t}{\partial x_n} + \frac{\partial D^{t+1}}{\partial x_n}\right](x_n^{t+1} - x_n^t) + 0.5\left[\frac{\partial D^{t+1}}{\partial t} + \frac{\partial D^t}{\partial t}\right] \\ &+ 0.5\left[\frac{\partial D^{t+1}}{\partial q} + \frac{\partial D^t}{\partial q}\right](q^t - q^{t+1})\end{aligned} \tag{5}$$

where D^t is short for $D(x^t, y^t, b^t; g, t, q)$. Using Eq. (5), PC can be written as:

$$\begin{aligned}PC &= -0.5\left[\frac{-\partial D^{t+1}}{\partial y} + \frac{-\partial D^t}{\partial y}\right](y^{t+1} - y^t) + 0.5\sum_{m=1}^{2}\left[\frac{\partial D^t}{\partial b} + \frac{\partial D^{t+1}}{\partial b}\right](b^{t+1} - b^t) \\ &+ 0.5\sum_{n=1}^{3}\left[\frac{\partial D^{t+1}}{\partial x_n} + \frac{\partial D^t}{\partial x_n}\right](x_n^{t+1} - x_n^t)\end{aligned} \tag{6}$$

This PC index can be broadly defined as the difference between the weighted average rates of change in outputs and inputs, where the weights are derivatives of the directional output distance function with respect to (negative) desirable outputs and (positive) undesirable outputs and inputs, respectively. Rearranging Eq. (6), PC can be decomposed as:

$$PC = \underbrace{(D^{t+1} - D^t)}_{EC} \underbrace{- 0.5\left[\frac{\partial D^{t+1}}{\partial t} + \frac{\partial D^t}{\partial t}\right]}_{ETC} \underbrace{- 0.5\left[\frac{\partial D^{t+1}}{\partial q} + \frac{\partial D^t}{\partial q}\right].(q^{t+1} - q^t)}_{ITC} \tag{7}$$

Eq. (7) provides a decomposition of PC into EC, ETC, and ITC. Negative values of the derivatives of the directional output distance function with respect to the time trend and the openness index imply positive changes in ETC and ITC, respectively. Therefore, the negative value of each component of the productivity index implies a positive change in total factor productivity (TFP).[13]

3. Estimation

The directional output distance function can be computed either using linear programming (LP) or stochastic techniques. Estimating distance functions econometrically have several advantages over LP approach. Other than allowing for an appropriate treatment of measurement errors and random shocks, several statistical hypotheses can be tested. These include significance of parameters, separability between outputs and inputs and between good and bad outputs, and monotonicity properties of distance functions.[14] In the analysis, an appropriate functional form has to be selected, and we chose the quadratic functional form (4). This functional form allows us to model

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[12] Diewert (1976) showed that that a difference in a quadratic function of *N* variables evaluated at two points is exactly equal to the sum of the arithmetic average of the first-order partial derivatives of the function evaluated at the two points of difference in the independent variables. Orea (2002) employed the Quadratic Identity Lemma for parametric decomposition of the Malmquist productivity index using an output distance function, and Kumar and Managi (2009) used the Lemma for decomposing the Malmquist–Luenberger index into EC, ETC and ITC.

[13] In the discussion of our results, we multiply each of the components by minus one for the sake of clarity.

[14] However, the stochastic methods have their own disadvantages, such as distributional assumptions for the inefficiency and error terms, and the problem of imposing nonlinear monotonicity constraints in the estimation process.

second-order effects and the imposition of a translation condition. Furthermore, the inefficiency component (value of the directional distance function) can be easily calculated.

The stochastic specification of the directional output distance function takes the form:

$$0 = D(x, y, b; 1, -1) + \varepsilon, \tag{8}$$

To estimate Eq. (9), we utilize the translation property of the directional output distance function. By substituting $D(x, y+\alpha, b-\alpha; 1, -1)+\alpha$ for $D(x, y, b; 1, -1)$ in Eq. (8) and moving α to the left hand side, we obtain:

$$-\alpha = D(x, y + \alpha, b - \alpha; 1, -1) + \varepsilon, \tag{9}$$

where $D(x, y+\alpha, b-\alpha; 1, -1)$ is the quadratic form given by Eq. (4) with α added to y and subtracted from b. Therefore, one is able to obtain variation on the left hand side by choosing an α that is specific to each plant. In this study, it is electricity output, the good output. The form of Eq. (9) to be estimated is:

$$\begin{aligned}
-\alpha = {} & \alpha_0 + \sum_{n=1}^{3} \alpha_n x_n^{kt} + \beta_0(y^{kt} + \alpha) + \sum_{m=1}^{2} \beta_m(b_m^{kt} - \alpha) \\
& + \gamma_1 t + \gamma_2 q^t + \frac{1}{2}\sum_{n=1}^{3}\sum_{n'=1}^{3} \alpha_{nn'} x_n^{kt} x_{n'}^{kt} + \sum_{n=1}^{3} \delta_{n0} x_n^{kt}(y^{kt} + \alpha) \\
& + \sum_{m=1}^{2}\sum_{n=1}^{3} \delta_{nm} x_n^{kt}(b_m^{kt} - \alpha) + \sum_{n=1}^{3} \eta_{n1} x_n^{kt} t + \sum_{n=1}^{3} \eta_{n2} x_n^{kt} q^t \\
& + \frac{1}{2}\beta_{00}(y^{kt} + \alpha)(y^{kt} + \alpha) + \sum_{m=1}^{2} \beta_{0m}(y^{kt} + \alpha)(b_m^{kt} - \alpha) \\
& + \varphi_{y1}(y^{kt} + \alpha)t + \varphi_{y2}(y^{kt} + \alpha)q^t + \frac{1}{2}\sum_{m=1}^{2}\sum_{m'=1}^{2} \beta_{mm'}(b_m^{kt} - \alpha) \\
& \times (b_{m'}^{kt} - \alpha) + \sum_{m=1}^{2} \varphi_{m1}(b_m^{kt} - \alpha)t + \sum_{m=1}^{2} \varphi_{m2}(b_m^{kt} - \alpha)q^t + \frac{1}{2}\gamma_{11} t^2 \\
& + \varphi t q^t + \frac{1}{2}\gamma_{22} q^{t2} + v - \mu
\end{aligned} \tag{10}$$

where the term μ is the inefficiency component of the error term, $\varepsilon = v - \mu$. To recover the inefficiency component of the composite error term, one needs to assume a distribution structure for μ. It is assumed one sided error term is exponential distributed, and the error term v follows the distribution such as $v \sim N(0, \sigma_v^2)$. This study adopts a Maximum Likelihood (ML) estimation approach, while assuming an exponential distribution for the one-sided error term.

4. Data

We measure technological progress in US electricity-generating plants since the inception of the SO_2 trading system. We restrict our attention to plants for which each generating unit has had a minimum installed nameplate generating capacity of 25 megawatts.[15] To minimize the effect of outliers, we examine the ratios of each output to each input and compare descriptive statistics across periods. If we observed any abnormality for any plant for a specific year, we exclude that plant from our data set. As a result, we use an unbalanced panel data set of about 50 electric generating plants from 1995 to 2007.[16] Out of these plants, nine plants had units that participated in the Phase I SO_2 emission trading system.[17]

Table 1
Summary statistics of the variables used in the study, 1995–2007.

Variable	Unit	Mean	Standard deviation	Maximum	Minimum
Electricity output	kWh (millions)	5170.10	5264.66	50,151.86	52.79
SO_2 emissions	Short tons	26,921.88	29,374.77	185,712.90	131.00
NO_x emissions	Short tons	11,142.20	11,587.34	105,691.70	40.69
Heat	Btu (billions)	52,511.21	48,316.31	265,410.31	489.21
Labor	Workers (employees)	134.13	102.76	567.00	7.00
Capital	Millions of 1995$	268.58	250.65	1243.25	8.74

The data come primarily from two sources: the Federal Energy Regulatory Commission (FERC) and the US Environmental Protection Agency (EPA). The FERC maintains an online database of FERC Form 1 from 1994 to the present. Form 1 provides annual information regarding electricity production activities at the plant level. From this source, we obtained plant-level statistics regarding variables such as electricity output, number of employees and capital stock. The EPA maintains an emissions database for all majors US pollution sources. Its Aerometric Information Retrieval System (AIRS) database is the source of air pollution data for SO_2, NO_x and heat input from 1995 to the present. The 1990 CAAA required all affected power plants to install a continuous emission monitoring system (CEMS) by 1995. Consequently, all air pollution data since 1995 are available from CEMS readings.

Capital is measured in millions of 1995 dollars. We use this measure rather than the installed nameplate capacity, because it provides information not only regarding the generating capacity of a plant, but also provides data about the extent to which plants have invested in equipment to reduce air pollution emissions. FERC Form 1 collects data on the historical plant-level costs, including land and land rights, structures and their improvements and equipment costs. For the sake of comparison, we consider only structures and improvements and equipment costs, since for some plants, the figures for land and land rights are zero or missing. Until 2002, FERC form 1 collected these figures only for costs regarding plants and equipment. And only since 2003 has it collected information for asset retirement costs, that is, depreciation costs. Therefore, we assume changes in these costs reflect net investment (NI) until 2002. Following that, the historical cost data are converted into constant 1995-dollar values using the Handy-Whitman Index (HWI) (Whitman, Requardt & Associates, 2007). This is the same procedure employed by Yaisawarng and Klein (1994, p. 453, footnote 30) and Carlson et al. (2000, p. 1322). In the first year of its operation, the net investment of a power plant is equivalent to the total value of the physical plant and equipment. The descriptive statistics of variables used in the estimation of the directional output distance function are provided in Table 1.

4.1. Long-term emission prices

The EPA holds auctions of allowances each year, and electric utilities and brokers can also sell their allowances at these auctions. The auctions are held in two categories: (1) a spot allowance auction

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[15] This is because only the units for which their generating nameplate capacity is greater than 25 MW are covered under the allowance program.

[16] The distribution of plants is given as follows:

Year	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Number of plants	54	55	52	56	50	40	44	49	49	48	49	48	47

[17] The nine plants are Allen, Asbury, Brunner Island, Coffeen, Grand Tower, High Bridge, Northport, Petersburg, and Shawville.

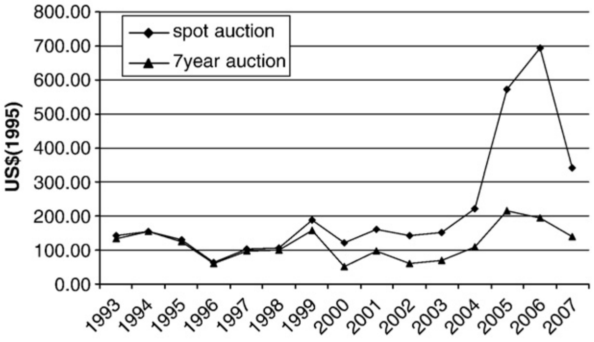

Fig. 1. Allowance prices (1995$).
Source: http://www.epa.gov/airmarkets//trading/auction.html (for current prices).

and (2) an advance allowance auction. The first category consists of allowances that are sold and can be used in the same year for compliance purposes, while the latter category includes allowances that become usable for compliance seven years after the transaction date, although they can be traded earlier. Thus, the spot allowance auction prices can be considered current prices, and the advance auction prices may be used as long-term emission prices.[18]

Fig. 1 shows both spot and advanced allowance prices in constant values (1995 dollars). Current values are converted into constant values using the Handy–Whitman Index. The movements in allowance prices may help in understanding the evolution of the allowance trading market. At the opening of Phase I of the program in 1995, the average spot prices were about US$ 130 per ton and fell to about US$ 65 per ton in 1996. Thereafter, allowance prices experienced an upward trend, and in 1999, they reached US$ 190 per ton[19]. Again, we find that allowance prices continuously increased to US$ 695 but then in 2007 declined to US$ 341. The seven-year advance auction price increased during 2002 to 2005 and reached its highest value at US$ 216 in 2005 but then declined. Some studies (Carlson et al., 2000) have shown that the rate of increase in allowance prices corresponds roughly to the opportunity cost of holding emission allowances in the bank.

5. Results

Following Färe et al. (2005), we estimate the directional output distance function as specified in Eq. (4) by using normalized values of outputs and inputs.[20] Table 2 provides the parameter estimates for the directional distance function. A first look at the production technology parameters in Table 2 indicates that the first-order coefficients on outputs and inputs have the expected values regarding economic behavior. Looking at the signs of second-order parameters suggests interesting results. These parameters, however, require a more detailed analysis than can be presented here in order to measure their significance. Thus, using the estimated coefficients, we are able to verify that the resulting distance function satisfies the regularity conditions of convexity for inputs and concavity for outputs for the majority of observations. We conduct *t*-test for equality of means for evaluating the statistical significance of the difference between the means of all observation and means of observations satisfying monotonicity conditions. On the basis of '*t*-test' statistics we are not able to reject the null hypothesis of equality of means. The results based on all observations are presented in the Appendix A, which show similar results and conclusions remain same.

Table 2
Quadratic directional distance function parameter estimates.

Variable/parameter	Coefficient	Std. Err.	Variable/ parameter	Coefficient	Std. Err.
$y_1, \beta_1 = -1 + \beta_2 + \beta_3$	−0.5348		y_2x_2, δ_{22}	0.0148	0.0182
y_2, β_2	0.1594*	0.0384	y_2x_3, δ_{23}	−0.1100*	0.0205
y_3, β_3	0.3058*	0.0426	y_2t, μ_{11}	−0.0239*	0.0048
x_1, α_1	−0.4876*	0.0619	y_2q, μ_{12}	0.0001	0.0002
x_2, α_2	−0.2588*	0.0470	y_3x_1, δ_{31}	0.0627***	0.0336
x_3, α_3	−0.0817***	0.0436	y_3x_2, δ_{32}	−0.0948*	0.0243
t, γ_1	−0.0324*	0.0079	y_3x_3, δ_{33}	−0.0153	0.0216
q, γ_2	−0.0010***	0.0006	y_3t, μ_{21}	−0.0149*	0.0052
$y_1^2, \beta_{11} = \beta_{12} + \beta_{13}$	−0.0511		y_3q, μ_{22}	−0.0007**	0.0003
y_2^2, β_{22}	−0.1828*	0.0318	x_1x_2, α_{12}	−0.2163*	0.0320
y_3^2, β_{33}	−0.1037*	0.0159	x_1x_3, α_{13}	−0.1968*	0.0248
x_1^2, α_{11}	0.3510*	0.0525	x_1t, η_{11}	−0.0385*	0.0056
x_2^2, α_{22}	0.0262	0.0287	x_1q, η_{12}	−0.0004	0.0004
x_3^2, α_{33}	0.0482	0.0306	x_2x_3, α_{23}	0.1807*	0.0242
t^2, γ_{11}	0.0054*	0.0013	x_2t, η_{21}	0.0206*	0.0052
q^2, γ_{22}	0.00001	0.0000	x_2q, η_{22}	0.0009*	0.0003
$y_1y_2, \beta_{12} = \beta_{22} + \beta_{23}$	−0.0651		x_3t, η_{31}	0.0037	0.0043
$y_1y_3, \beta_{13} = \beta_{23} + \beta_{33}$	0.0140		x_3q, η_{32}	−0.0004***	0.0002
$y_1x_1, \delta_{11} = \delta_{21} + \delta_{31}$	0.1826		tq, Φ	−0.0001	0.0001
$y_1x_2, \delta_{12} = \delta_{22} + \delta_{32}$	−0.0799		Constant	0.2231*	0.0494
$y_1x_3, \delta_{13} = \delta_{23} + \delta_{33}$	−0.1253		σ_V	0.0687*	0.0076
y_1t, μ_{y1}	−0.0388		σ_U	0.1693*	0.0112
$y_1q, \mu y_2$	−0.0006		σ^2	0.0334*	0.0032
y_2y_3, β_{23}	0.1177*	0.0272	λ	2.4642*	0.0171
y_2x_1, δ_{21}	0.1199*	0.0334			
Log likelihood					274.38
Loglikelihood ration test of $\sigma_U = 0$, χ^2 (*p*-value)					260 (0.00)
Number of observations					641

Note: underlined parameters were calculated using the translation property. *, **, *** indicate the coefficient is statistically different from zero at 1, 5 and 10% respectively. y_1, electricity output, y_2, SO_2 emissions, y_3, NO*x* emissions, x_1, heat input, x_2, labor and x_3, capital stock.

The estimated parameters associated with the time trend and long-term emission price variables are of specific interest. Negative parameters indicate positive changes in technology; a positive parameter indicates technological decline. We find the presence of neutral ETC, since the coefficients of time trend variable are statistically significant, as well as the presence of biased or embodied ETC, since some of the coefficients of the interaction terms between the time trend, outputs and inputs are statistically significant.[21] The coefficient of long-term allowance prices is negative and statistically significant, but its quadratic coefficient is statistically insignificant, indicating the presence of neutral, progressive ITC. The coefficients of interaction terms between outputs and allowance prices and between heat input and allowance prices also indicate progressive embodied ITC. This observation is consistent with the theoretical literature on the dynamic impacts of incentive-based environmental regulation.

5.1. Levels of inefficiency and the presence of a catch-up effect

Plant-specific estimates of technological inefficiency, catch-up effects, ITC, ETC, TC and total factor productivity change (PC) are generated each year over from 1995 to 2001. Average measures of inefficiency and adjunct-year measures of other components through 1995 to 2007 are reported in Table 3.[22] We find that the pooled sample average for the directional distance function is 0.1. This

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[18] Allowance auction price information was obtained from the EPA website (http://www.epa.gov/airmarkets/auctions/factsheet.html) on December 23, 2008.

[19] The temporarily jump in allowance prices in 1999 can be attributed in part to the planning for Phase-II of the program as well as to the tightening of particulate matter ambient health standards (Burtraw et al., 2005).

[20] We normalized the data for each output and each input by their mean values before estimation.

[21] Kolstad and Turnovsky (1998), Carlson et al. (2000) and Considine and Larson (2006) have found the absence of neutral and presence of biased exogenous technical progress.

[22] Plant- and time-specific inefficiency as well as components of total factor productivity are not reported because of space restrictions. Similarly, plant-specific results concerning the direction of technological change are not reported here. The results are available from the authors upon request.

Table 3
Productivity change and its components, 1995–2007.

	Inefficiency	EC	ETC	ITC	TC	PC	ITC/TC%
1995	0.1722						
1995/1996	0.1242	0.0480	0.0799	0.0008	0.0807	0.1287	1.0018
1996/1997	0.1491	−0.0250	0.0842	0.0012	0.0854	0.0604	1.3822
1997/1998	0.1074	0.0417	0.0894	0.0012	0.0906	0.1323	1.3235
1998/1999	0.1017	0.0057	0.0829	0.0009	0.0838	0.0895	1.0796
1999/2000	0.1520	−0.0502	0.0726	0.0011	0.0737	0.0235	1.5015
2000/2001	0.0941	0.0578	0.0617	0.0014	0.0630	0.1208	2.1584
2001/2002	0.0794	0.0148	0.0503	0.0013	0.0517	0.0664	2.5847
2002/2003	0.0730	0.0064	0.0555	0.0018	0.0572	0.0636	3.0664
2003/2004	0.0674	0.0056	0.0851	0.0021	0.0872	0.0928	2.4404
2004/2005	0.0550	0.0123	0.1136	0.0018	0.1153	0.1277	1.5587
2005/2006	0.0522	0.0028	0.1148	0.0014	0.1161	0.1189	1.1661

Note: EC: efficiency change, ETC: exogeneous technological change, ITC: induced technological change: TC: technological change (=ETC + ITC), PC: productivity change (=EC + TC).

Table 4
Productivity change and its components, 1995–1999.

	Inefficiency	EC	ETC	ITC	TC	PC	ITC/TC%
Phase I plants							
1995	0.1814						
1995/1996	0.1690	0.0124	0.0776	0.0008	0.0784	0.0908	1.0248
1996/1997	0.1129	0.0561	0.1174	0.0019	0.1193	0.1754	1.6287
1997/1998	0.1064	0.0066	0.1128	0.0019	0.1147	0.1213	1.6545
1998/1999	0.1424	−0.0360	0.0584	0.0007	0.0591	0.0231	1.1783
Non-phase I plants							
1995	0.1709						
1995/1996	0.1174	0.0535	0.0802	0.0008	0.0810	0.1345	0.9984
1996/1997	0.1561	−0.0387	0.0778	0.0010	0.0789	0.0401	1.3111
1997/1998	0.1075	0.0486	0.0841	0.0011	0.0852	0.1337	1.2453
1998/1999	0.0964	0.0111	0.0859	0.0009	0.0868	0.0979	1.0721

implies that a representative plant that is operating with an average value of inputs and outputs has the potential to simultaneously increase electricity and decrease quantities of SO_2 and NO_x emissions by 10%. We observe that the level of inefficiency decreases over the period (Table 3, column 2). A similar trend is observed during Phase I of the allowance trading system. The average level of inefficiency is higher for plants that are required to participate in the program relative to other plants, as these plants are considered “dirty” plants (Table 4, column 2). However, the difference in the inefficiency estimates is statistically insignificant.[23]

During the period under study, we observe the presence of catch-up effects across the US thermal power plants. Efficiency changes about 1% per year. Except for two years (1996–1997 and 1999–2000), the catch-up effect is positive for each year (Table 3, column 3). The catch-up effect is stronger for non-Phase I plants in comparison to plants required to participate in Phase I, but it is statistically insignificant (Table 4, column 3).

5.2. Magnitude of exogenous and induced technological progress

The estimates of adjunct-year total factor productivity (TFP) are presented by year in Table 3. Table 3 presents the results for all plants and Table 4 presents the results during Phase I for the plants that were required to participate in Phase I as well as those that were not required to participate. The notable feature that emerges from the decomposition of PC is that the overall growth in PC is based on growth in TC.

We decompose TC into two components: ETC and ITC. Overall, we observe a positive ETC effect of the magnitude of about 8% per year from 1995 to 2007. During the initial years, we observe an increasing trend in ETC, but then it starts to decline and reaches its lowest growth rate of about 5% in 2001–2002. Afterward, it starts to increase at a rate of about 11.5% in 2005–2006 (Table 3). Similarly, during Phase I, we observe significant growth in ETC for both plants required to participate in Phase I and plants not required to do so; the ETC growth rate is higher for the group required to participate in Phase I. That is, the growth rate of ETC was about 9% per year for the plants that participated in Phase I, while other plants observed an ETC growth rate of about 8% per year, but the difference in the means of two groups is not statistically significant. The positive and substantial contribution of ETC to TFP indicates that the progress of general science and technological made a significant contribution during these time periods. This finding is contrary to the findings of Gollop and Roberts (1983) which show both positive and negative productivity growth at different times over their sample periods.

Measurement of technological progress induced by the allowance trading system is our main concern. We observe that electricity-generating plants experience positive ITC effects during the period under study, i.e., electricity-generating plants are able to increase electricity production and reduce the emissions of SO_2 and NO_x from 1995 to 2007 due to introduction of an allowance trading system. Yearly results indicate that the growth rate of ITC is about 0.14% per year (Table 3). Moreover, from Table 4, it is also evident that the growth rate of ITC is higher during Phase II of the program relative to Phase I. Here it should be noted that the contribution of ITC to TC increases over the period under study. At the beginning of the allowance trading system, the contribution of ITC to TC was about 1%; this rate has increased to about 2% by 2006.

Both Phase I and non-Phase I groups witnessed positive ITC effects during Phase I of the allowance trading program. The ITC growth rate is higher for plants required to participate in allowance trading during Phase I in comparison to their non-Phase I counterparts and the difference in the means of the growth rate of two groups is statistically significant at 10% level. The ITC growth rates are about 0.13 and 0.10% per year for these Phase I and non-Phase I groups, respectively. Moreover, we observe that the contribution of ITC to TC is higher in the former group relative to the latter group. For the plants that participated during Phase I, the contribution of ITC to TC is about 1.5% per year, whereas for the other group, it is about 1.2% per year on average (see Table 4).

The pattern of technological change in these two groups of plants is consistent with the pattern of SO_2 emission reductions during Phase I. Ellerman et al. (2000) found that the SO_2 emissions not only substantially fall to previous levels, but they also fall relative to levels that would have seemingly been achieved in the absence of allowance trading during Phase I of the program. Recall that Phase II of the trading program started in January 2000, and since then, all electricity-generating plants were required to participate in the trading. That is, they are now restricted to emitting 1.2 lb of SO_2 per million BTUs of heat input. From 2000 to 2001, electricity-generating plants experienced increased ITC effects of about 0.14%. In addition, the performance of Phase I plants is slightly higher in comparison to other plants from 1998 to 1999. This finding is in accordance with the estimates of the patterns of emissions reductions between these two groups. Ellerman (2003) found that about 83% of the reductions in SO_2 emissions in 2001 from the projected baseline occurred at large, dirty plants, that is, Phase I plants.

Moreover, we observe that the timing of ITC effects is in line with economic theory. ITC effects are larger in years that have seen higher long-term allowance prices of the seven-year allowance auction price (Fig. 1). For example, the long-term prices are higher in Phase II relative to Phase I, and the ITC effect is 0.15% per year during Phase II relative to 0.10% per year during Phase I. The ITC effect is higher during years when long-term allowance prices are higher than in the preceding years (Fig. 2).

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[23] We conduct ‘*t*-test’ for comparing the means of two groups of plants.

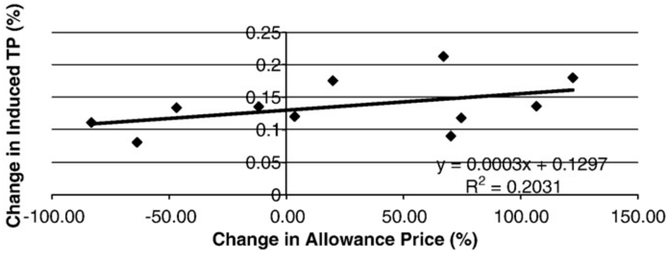

Fig. 2. Relationship between change in allowance price and included technological progress.

5.3. The direction of exogenous and allowance price induced technological progress

TC, either exogenous or induced, can be further decomposed into two categories. One involves changes resulting from shifts in the transformation function. The other involves changes in output decisions regarding the production of a particular output or, alternatively, changes in allowance prices along the new transformation function caused by allowance trading. Shifts in the transformation function can be subdivided into two categories: neutral TC and biased TC. Neutral TC implies a shift in the technological frontier such that it becomes possible to produce fewer undesirable outputs and more desirable outputs with the same quantities of inputs. Biased TC implies that the change in the slope of the frontier at the decision point of the firm is not on the ray, even when relative prices are constant.

Antle (1984) developed a profit function-based multifactor measure of biased TC. He defined the impact of technological progress on input decisions for factor *n* as the proportionate change in the cost-share of the elasticity of factor *n* due to proportionate change in exogenous variables and long-run prices.

One can derive the output supply function as the derivative of the revenue function with respect to output prices. Similarly, we can derive the inverse of the output supply function as the derivative of the directional output distance function with respect to output quantities. The measures of output bias (B_{it}) for exogenous and induced technological change can be expressed as follows:

$$B_{\text{it}}^{\text{ETC}} = \frac{\partial \ln(\varepsilon_i / \varepsilon)}{\partial \ln t}$$
$$B_{\text{it}}^{\text{ITC}} = \frac{\partial \ln(\varepsilon_i / \varepsilon)}{\partial \ln q} \qquad (11)$$

where

$$\frac{\varepsilon_i}{\varepsilon} = -\frac{\partial \ln D}{\partial \ln y_i} \Bigg/ \left(-\sum_{i=1}^{3} \frac{\partial \ln D}{\partial \ln y_i}\right)$$

The output bias associated with technological progress is:

$$i^{\text{th}}\,output \begin{Bmatrix} Reducing \\ Neutral \\ Increasing \end{Bmatrix} \text{as}\, B_{it} \begin{Bmatrix} > \\ = \\ < \end{Bmatrix} 0,$$

where y_i is electricity output, SO_2, and NO_x. We treat desirable and undesirable outputs asymmetrically; therefore, a positive sign indicates a reduction in electricity production and an increase in pollution.

Output bias results arising from ETC and ITC are shown in Tables 5 and 6. Exogenous TC output bias results indicate that from 1995 to 2007, ETC effects increased electricity output and reduced emissions except for the initial two years. In 1995 and 1996, ETC effects reduced both electricity production and emissions. ETC output bias results also show that over the period under study, technological progress increased electricity output less so but reduced emissions more so, as the magnitude of bias reduces electricity production and increases emissions over time in absolute terms. Similar results are obtained regarding induced technological progress. In general, the magnitude of bias arising from exogenous forces is higher than the bias arising from allowance prices, thus suggesting that exogenous innovations effects dominate price-induced technological progress.

Exogenous output bias results indicate that the Phase I plants experienced technological progress that increased electricity output and NO_x emissions and reduced SO_2 emissions during Phase I. However, in this group, exogenous technological progress reduced electricity output and increased emissions in 1995. ETC continued to increase NO_x emissions only up to 1997, after which it reduces NO_x emissions. Similar trends are observed with respect to induced technological progress. Among non-Phase I plants, exogenous technological change increases electricity production and reduces emissions, except in 1996. In 1996, ETC reduces both electricity output and emissions. These findings are in line with the observed behavior of SO_2 and NO_x emissions. Output bias resulting from induced innovation indicates that allowance price changes lead to technological progress, which in turn results in an increase in electricity and a reduction in emissions. Note that the differences in the means of the biases in technological progress either it is exogenous or induced are found to be statistically significant at 5% level.

Table 5
Direction of technological change, 1995–2007.

	Electricity output biased ETC	SO_2 emissions biased ETC	NO_x emissions biased ETC	Electricity output biased ITC	SO_2 emissions biased ITC	NO_x emissions biased ITC
1995	0.0441	−0.2633	−0.1256	−0.4431	−1.3395	−1.1244
1996	0.1385	−1.0840	−0.0366	0.0443	−0.8612	−0.0850
1997	−0.6353	−2.3201	−0.7971	−0.3695	−1.7000	−0.4590
1998	−0.5391	−2.5649	−1.0352	−0.2621	−1.4926	−0.6429
1999	−0.3479	−5.5599	−2.1159	−0.2363	−4.2777	−2.3047
2000	−0.4435	−6.5661	−1.5267	−0.0923	−1.4108	−0.4128
2001	−0.3544	−18.0116	−2.2436	−0.1264	−6.2354	−1.0795
2002	−0.4249	−36.3963	−2.4538	−0.0869	−6.9114	−0.6423
2003	−0.3074	−8.2479	−3.8671	−0.0683	−1.5947	−1.1110
2004	−0.3237	−8.0080	−4.1374	−0.0988	−2.1347	−1.6370
2005	−0.0330	−7.0810	−2.0121	−0.0184	−3.3617	−1.3272
2006	−0.0237	−1.9136	−2.4519	−0.0146	−7.7409	−1.3889

Table 6
Direction of technological change, 1995—1999.

	Electricity output biased ETC	SO_2 emissions biased ETC	NO_x emissions biased ETC	Electricity output biased ITC	SO_2 emissions biased ITC	NO_x emissions biased ITC
Phase I plants						
1995	0.9391	0.7256	0.6805	−0.2896	−0.8973	−1.4342
1996	−0.7872	−1.9480	0.1409	−0.4478	−1.3093	0.7772
1997	−0.3859	−1.1832	0.8953	−0.3048	−0.9109	1.5000
1998	−0.4489	−1.5479	−0.3232	−0.2820	−0.9293	−0.0356
1999	−0.2944	−2.5935	−0.8682	−0.2355	−1.9833	−0.7965
Non phase I plants						
1995	−0.0875	−0.4087	−0.2441	−0.4656	−1.4046	−1.0788
1996	0.2788	−0.9531	−0.0635	0.1189	−0.7934	−0.2156
1997	−0.6833	−2.5387	−1.1226	−0.3819	−1.8517	−0.8357
1998	−0.5491	−2.6779	−1.1143	−0.2599	−1.5552	−0.7104
1999	−0.3548	−5.9468	−2.2787	−0.2365	−4.5770	−2.5014

6. Conclusions

The decreasing compliance costs of the 1990 CAAA can be attributed to (i) a decline in fuel prices coupled with a reduction in rail transportation costs for low sulfur western coal, (ii) exogenous technological progress that would have occurred in the absence of the program, and (iii) the technological progress ignited by the allowance trading program (Burtraw et al., 2005).

This study finds that the changes in SO_2 emissions prices are related to technological innovations induced by the allowance trading system. That is, we have tested whether an increase in the prices leads to a reduction in pollution emissions. We observe that electricity-generating plants experience positive induced technological change. That is, electricity-generating plants are able to increase electricity output and reduce the emissions of SO_2 and NO_x from 1995 to 2007 due to the introduction of an allowance trading system. However, compared to the approximate 8% per year of exogenous technological progress, the induced effect is relatively small, though it is increasing over time. Moreover, the contribution of an induced effect to overall technological progress is about 1–2%. Economists often cite market-based solution to reduce the emission of pollution and the significance of subsequent induced effects on technological change. Our study contributes to this literature by distinguishing between induced and exogenous technological progress, thereby showing the significance of the induced effect in practice.

Appendix A

Table A1
Level of inefficiency, 1995–2007 (all observations).

Year	Number of plants	Inefficiency	Standard deviation
1995	54	0.163756	0.150253
1996	55	0.127066	0.119815
1997	52	0.163747	0.172244
1998	56	0.130343	0.134573
1999	50	0.142092	0.162557
2000	40	0.155423	0.157658
2001	44	0.131347	0.154355
2002	49	0.100838	0.058375
2003	49	0.117929	0.112023
2004	48	0.117872	0.105239
2005	49	0.14217	0.128282
2006	48	0.129379	0.111924
2007	47	0.141594	0.109697

Table A2
Level of inefficiency, 1995–1999 (all observations).

Year	Number of plants	Inefficiency
Phase I plants		
1995	9	0.1586
1996	9	0.1466
1997	9	0.1402
1998	8	0.0978
1999	8	0.1226
Non phase I plants		
1995	46	0.1648
1996	47	0.1232
1997	43	0.1687
1998	44	0.1366
1999	42	0.1458

Table A3
Productivity change and its components, 1995–2007(all observations).

	EC	ETC	ITC	TC	PC	ITC/TC%
1995/1996	0.037	0.107	0.001	0.108	0.145	0.964
1996/1997	−0.037	0.108	0.001	0.110	0.073	1.206
1997/1998	0.033	0.111	0.001	0.112	0.146	1.132
1998/1999	−0.012	0.105	0.001	0.106	0.094	0.971
1999/2000	−0.013	0.103	0.001	0.104	0.091	1.371
2000/2001	0.024	0.099	0.002	0.100	0.125	1.781
2001/2002	0.031	0.092	0.002	0.094	0.124	1.858
2002/2003	−0.017	0.086	0.002	0.088	0.071	2.208
2003/2004	0.000	0.083	0.002	0.085	0.085	2.098
2004/2005	−0.024	0.084	0.001	0.085	0.061	1.349
2005/2006	0.013	0.078	0.001	0.079	0.092	0.962
2006/2007	−0.012	0.066	0.001	0.067	0.055	1.684

Table A4
Productivity change and its components, 1995–1999 (all observations).

	EC	ETC	ITC	TC	PC	ITC/TC%
Phase I units						
1995/1996	0.0120	0.1378	0.0015	0.1392	0.1513	1.0486
1996/1997	0.0065	0.1147	0.0014	0.1161	0.1226	1.2376
1997/1998	0.0424	0.1076	0.0013	0.1089	0.1513	1.1761
1998/1999	−0.0249	0.0996	0.0010	0.1006	0.0758	1.0322
Non-phase-I units						
1995/1996	0.0415	0.1010	0.0010	0.1020	0.1435	0.9413
1996/1997	−0.0454	0.1070	0.0013	0.1083	0.0628	1.1991
1997/1998	0.0321	0.1119	0.0013	0.1132	0.1453	1.1237
1998/1999	−0.0092	0.1060	0.0010	0.1070	0.0978	0.9606

Table A5
Direction of technological progress, 1995–2007 (all observations).

Year	Electricity output biased ETC	SO_2 emissions biased ETC	NO_x emissions biased ETC	Electricity output biased ITC	SO_2 emissions biased ITC	NO_x emissions biased ITC
1995	0.0078	0.1068	−0.1604	−0.3509	−0.5984	−1.0373
1996	0.0415	−0.5930	−0.1516	0.0112	−0.4443	−0.1466
1997	−0.4768	−0.9393	−0.7329	−0.2449	−0.5790	−0.4672
1998	−0.4226	−0.6382	−1.0024	−0.1696	0.0467	−0.6444
1999	−0.3192	−2.1189	−2.3654	−0.1659	−1.0489	−2.5975
2000	−0.3396	−1.2602	−0.5564	−0.0595	−0.2397	−0.0801
2001	−0.2794	−4.8343	−2.1630	−0.0737	−1.1404	−1.0332
2002	−0.2945	−1.2927	−1.9950	−0.0430	−0.0120	−0.5047
2003	−0.2783	1.3425	5.8153	−0.0410	0.3862	1.9461
2004	−0.2552	1.1258	−1.7532	−0.0489	0.3626	−0.6068
2005	−0.2060	1.1649	15.0165	−0.0669	0.6649	12.0430
2006	−0.2044	−2.6124	−3.1008	−0.0580	−0.9741	−1.7914
2007	−0.2125	1.0981	−26.1338	−0.0389	0.3504	−10.9931
Average	−0.2492	−0.7270	−1.4833	−0.1039	−0.2482	−0.4549

Table A6
Direction of technological progress, 1995–1999 (all observations).

Year	Electricity output biased ETC	SO_2 emissions biased ETC	NO_x emissions biased ETC	Electricity output biased ITC	SO_2 emissions biased ITC	NO_x emissions biased ITC
Phase I plants						
1995	0.5084	0.4018	0.3290	−0.1663	−0.4469	−0.9326
1996	−0.4692	−1.0021	−0.0391	−0.2542	−0.6363	0.3480
1997	−0.3357	−0.3861	0.1749	−0.1691	−0.1697	0.6078
1998	−0.4786	0.7199	−1.0427	−0.1656	0.6315	−0.6313
1999	−0.4173	0.3750	−0.9414	−0.1728	1.8896	−0.6858
Non phase I plants						
1995	−0.0923	0.0478	−0.2583	−0.3879	−0.6287	−1.0582
1996	0.1414	−0.5130	−0.1737	0.0632	−0.4068	−0.2434
1997	−0.5064	−1.0551	−0.9229	−0.2608	−0.6646	−0.6922
1998	−0.4119	−0.8983	−0.9946	−0.1704	−0.0653	−0.6469
1999	−0.3005	−2.5940	−2.6366	−0.1646	−1.6086	−2.9616

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