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ESTIMATING MARGINAL ABATEMENT COSTS OF SPM: AN APPLICATION TO THE THERMAL POWER SECTOR IN INDIA

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ABSTRACT

This paper provides estimates of firm specific marginal abatement costs of suspended particulate matters (SPM) for the thermal power sector in India. To derive these costs, the duality of the output distance function and the revenue function is used. This study uses the output distance function framework to estimate marginal abate-

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ment costs or shadow prices of the pollutant for individual plants. The average shadow price in 1991-92 of SPM emissions for 33 thermal power plants in India has been estimated to be 145 rupees per kilogram. This figure can be used for designing market-based instruments for controlling pollution in the thermal power sector in India since there is wide variation in the shadow prices across the plants. Moreover, this study also finds that switching to lower ash content coal has more cost advantages for controlling pollution in the Indian thermal power sector.

INTRODUCTION

Industrial pollution is considered a detrimental externality in economic analysis. Economists have advocated the use of markets to force firms to internalize the costs of pollution. Pigou (1932) advocated the introduction of taxes or subsidies, whereas Dales (1968) suggested the use of tradable pollution permits for pollution control. When markets are competitive and information is perfect, market based instruments (MBI) can achieve given environmental standards at a lower cost than the command and control policies. (Tietenberg, 1985; Baumol and Oates, 1988). According to Krupnick (1997) these MBI are even more suited to developing economies. Hence more and more countries are adopting these instruments for the control of industrial pollution.

Economic theory states that the equalization of marginal abatement costs across firms would minimize the total cost of abatement of pollutants at the aggregate level. This paper estimates the marginal abatement costs (or shadow prices) of SPM for individual thermal power plants in India to analyze the cost effectiveness of MBI to meet environmental standards. In general, reliable data on abatement costs and the resulting reduction in effluents is not available. How can one estimate this cost for a competitive firm facing environmental regulation? It has to be estimated by studying the decision-making behavior of firms regarding pollution loads and the choice of pollution abatement technologies. In some recent studies, the technology of a polluting firm is modeled on one of the two basic approaches using the conventional methods of the theory of production: (a) Considering effluent as an additional input in the production or profit function; and (b) By including abatement capital as an additional input in a cost function. In some studies, the pollution abatement technology is modeled with the assumption that it is non-separable from the technology of the main products while in others it is modeled with the assumption it is separable. In response to environmental regulations firms may adopt different types of technologies to reduce pollution. Jorgenson and Wilcoxen (1990) identify three different responses of firms. First, the firm may substitute less polluting inputs for more polluting ones. Second, the firm may change the production process to reduce emissions. Third, the firm may invest in pollution abatement devices. In practice, a firm may adopt a mix of these methods. The first two methods are non-separable with the production processes of main products while the third method, known as an end-of-the pipe method, is separable. Thus, one must try to infer the marginal abatement costs indirectly.

One possible way to derive these costs indirectly is to use the duality of the output distance function and the revenue function. The idea originally came from Shephard (1970). Shephard (1970, 1974) noted that the conventional assumptions and models of producer behavior should be modified in cases where the production process generates undesirable outputs that are not strongly disposable (free of cost). According to Shephard (1974) "...for the future where unwanted outputs of technology are not likely to be freely disposable it is inadvisable to enforce free disposal of inputs and outputs. Since production function is a technological statement, all outputs, whether economic goods are wanted or not, should be spanned by the output vector y"(p.205).

This study uses the output distance function framework, first employed by Fare et al. (1993) and later by Coggins and Swinton (1996), Hetemaki (1996) and Kumar (1999) to derive marginal abatement costs or shadow prices for individual plants. This approach also provides information on the production technology of the plants. Employing a weak disposability assumption, we specify and estimate a parametric output distance function that can be used to calculate production efficiencies for each plant. Using the duality argument, the estimated distance function can be combined with electricity price information, to derive the abatement cost of SPM.

It may be noted that Fare et al. (1993) and Coggins and Swinton (1996) used parametric linear programming to estimate the output distance function whereas Hetemaki (1996) employed both parametric linear programming and stochastic estimation methods. Moreover, the earlier two studies assumed that prices of undesirable outputs are non-positive, but Hetemaki relaxes this assumption and makes one more assumption that increasing inputs, with a fixed level of output cannot increase the value of the output distance function. Due to the problem of lack of data we employ the parametric linear programming technique rather than stochastic estimation. It should be noted here that the shadow prices of SPM are not the virtual shadow price of the undesirable output but that they represent the scaled value of the marginal productivity of coal as the social opportunity cost of reducing pollution.

The development of the power sector in India has proceeded so far without paying much attention to its environmental implications. Such a course of development, however, seems difficult to continue in the face of growing degradation of environmental quality and the increasing public awareness of environmental problems in the country. The share of the thermal power sector is about 66 percent of the total production of electricity in India. The thermal power sector, largely based on coal, contributes substantially to air pollution in India (Shreshtha and Acharya, 1992). Air pollution adversely affects the welfare of society and can be viewed as a negative externality. We need to have energy, but we also need to meet environmental standards to keep the environment clean. Market based instruments (MBI) are usually advocated for their cost-effectiveness in meeting environmental standards. The efficient designing of these instruments requires information on firm specific costs of abatement of pollution for effective implementation. The purpose of this paper is to compute estimates of firm specific marginal abatement costs of suspended particulate matter (SPM), which is the main pollutant from the thermal power sector. The remainder of the paper is organized as follows. Section 2 contains the theoretical model; data, estimation procedure and results are presented in section 3. Section 4 concludes the paper.

THEORETICAL MODEL

The conventional production function defines the maximum output that can be produced from an exogeneously given input vector while the cost function defines the minimum cost to produce the exogeneously given output. The output and input distance functions generalise these notions to a multi-output case. The output distance function describes "how far" an output vector is from the boundary of the representative output set, given the fixed input vector.

Suppose that a thermal power plant employs a vector of inputs $x Î Â^{N}_{+}$ to produce a vector of outputs; $y Î Â^{M}_{+}$, $Â^{N}_{+}$, $Â^{M}_{+}$, are non-negative *N*- and *M*-dimensional Euclidean spaces, respectively. Let *P (x)* be the feasible output set for the given input vector *x* and *L (y)* is the input requirement set for a given output vector *y*. Now the technology set is defined as

$$T = \{(y, x)\ Î Â^{M+N}_{+};\ x \ can\ produce\ y\}. \qquad (1)$$

The output distance function is defined as,

$$D_o(x, y) = min\ \{\theta > 0 : (y/\theta)\ Î P(x)\}\ \forall x\ Î Â^{N}_{+}. \qquad (2)$$

Equation (2) characterizes the output possibility set by the maximum equi-proportional expansion of all outputs consistent with the technology set (1). We now turn to the properties of the output distance function, which are used for the estimation of the distance function.

The output distance function can be used to measure the Debreu-Farrell technical efficiency (DF). In terms of the above output set, the Debreu-Farrell measure can be defined as $DF(y, x) = max\ \{\theta : \theta y Î P(x)\}$; and in terms of the output distance function $DF(y, x) = 1/D_o(y, x)$. Thus, the DF measure is the reciprocal of the value of the distance function and it gives the factor by which all output could be expanded proportionately if the production units were operating on the frontier. It is clear that $D_o (y, x) \leq 1$. If $D_o (y, x) = 1$, the plant can be regarded as 100 percent efficient. For $D_o \leq 1$, the plant produces in the interior and could be characterized as $100*D_o$percent efficient. The output distance function has, among others, the following properties (for a detailed description, see Fare 1988):

1. $D_o (0, y) = +$ ¥for $y \geq 0$, i.e., no free lunch.
2. $D_o (x, 0) = 0$ for all x in $Â^N_+$ i.e., inaction is possible
3. $X' \geq x$ implies that $D_o (x', y) \leq D_o (x, y)$, i.e., the more input the less efficient.
4. $D_o (x, \mu y) = \mu D_o (x, y)$ for $\mu > 0$, i.e. positive linear homogeneity.
5. $D_o (x, y)$ is convex in y.

The assumptions about the disposability of outputs become very important in the context of a plant producing both good and bad outputs. The normal assumption of strong or free disposability about the technology implies,

if (y_1, y_2) Î$P (x)$ *and* 0 £$y_1{}^*$ £y_1, 0 £$y_2{}^*$ £y_2 Þ$(y_1{}^*, y^*{}_2)$ Î$P (x)$.

That means, we can reduce some outputs given the other outputs or without incurring any cost. This assumption may exclude important production processes, such as undesirable outputs. For example, in the case of air pollution, Suspended Particulate Matter (SPM), Sulfur Dioxide (SO_2) and Nitrogen Oxides (NO_X) are regulated and the plant cannot freely dispose of them. The assumption of weak disposability is relevant to describe such production processes. The assumption of weak disposability implies,

if y Î$P(x)$ *and* 0 £θ £1 Þ θy Î$P(x)$.

That means a firm can reduce the bad output only by incurring some positive costs. Using the output set, we can analogously, define the revenue function as (Fare et al. 1993, Fare and Primont 1995)

$$R(x, r) = max\{ry: y\hat{I}P(x)\} \tag{3}$$

Where r denotes the vector of output prices. The revenue function describes the maximum revenue that can be obtained from the given technology at output prices r, and it also completely describes the production technology. Shephard (1970) and Fare (1988) showed that the revenue function and output distance function are dual to each other. Consequently, we can define the revenue function in terms of the distance function and vice-versa.

$$R(x, r) = max\{ry: D_o(x, y) \le 1\} \quad (4a)$$

$$D_o(x, y) = max\{ry: R(x, r) \le 1\} \quad (4b)$$

This duality between technology and revenue permits one to estimate the actual shadow prices of outputs. The optimality condition, in a multi-output model in which all outputs are desirable, is that for any of two outputs the slope of the production possibility frontier should equal the ratio of the corresponding output prices. The same logic can be applied to the present problem, except that the prices of undesirable outputs can be negative.

Here the problem is to seek the shadow prices for undesirable output r_i, with $i \ne 1$. In order to have these prices, it is necessary to assume the price of y_1, the desirable output, is known to equal its own undeflated shadow price, r_i^o. Thus for each output $i \ne 1$ the shadow prices are

$$r_i = \{r_1^o \, \partial D_o(x, y)/\partial yi\}/\{\partial D_o(x, y)/\partial y_1\} \quad (5)$$

(For detailed description see Fare et al. (1993)).

In equation (5) the ratio of output shadow prices reflects the marginal rate of transformation between outputs, i.e. the relative opportunity costs of the outputs. Fare et al. (1993) observes that the advantage of such a derivation is that it does not require information about regulatory controls. This is important because often data about regulations is not available and even if data is available plants rarely operate exactly at the level of the constraints. Thus "shadow prices reflect the trade-off between desirable and undesirable outputs at the actual mix of outputs, which may or may not be consistent with the maximum allowable under regulations" (Fare et al. 1993, p.376). The output distance function is homogenous of degree +1 in outputs, the derivatives, which give the shadow prices, are homogenous of degree zero with respect to the proportional scaling of outputs. Since the output distance function in such scaling of outputs, the shadow prices are independent of whether the observations are on the frontier, i.e. shadow prices do not require that the plants operate on the production frontier (Hetemaki, 1996). Our aim is to estimate the marginal abatement costs of SPM for a collection of thermal power plants in India. This purpose requires parameterization and calculation of the parameters of an output distance function, which is the subject of discussion in the following section.

DATA, ESTIMATION PROCEDURE AND RESULTS

Data

For the present study the data requirement is of the quantities of the different inputs and outputs, and the price of one output (desirable) at the plant level. Since the study deals with the thermal power sector in India, the required data is collected from two sources – the Performance Review of Thermal Power Stations 1991-92 (CEA, 1993) and the Annual Report on the Working of State Electricity Boards and Electricity Departments (Planning Commission, 1994). The former source provides information about input and output quantities while the statistics for output prices are taken from the latter publication.

The process of fossil-fueled electricity generation typically uses three conventional inputs, namely, labor, capital and fuel to produce the desired output. This study also requires environmental variables. Plants in our sample use coal as their primary fuel. Coal is bundled with ash, sulfur and carbon; these plants produce SO_2, NO_x, and Particulate matters (SPM) as a byproduct of their electricity generation through the coal burning process. Meanwhile, the plants have to comply with regulating limits on these emissions. Plants have to invest in pollution abatement equipment. As a result these byproducts are classified as undesirable outputs. But it is unfortunate that statistics about these variables are not published in India. There are some engineering relationships between the consumption of coal and the amounts of these emissions produced. The data on these byproducts has been constructed using such engineering relationships. This makes them collinear and hence only one of them is really independent. Then, certainly, there is some relationship between these pollutants and it would be enough to take only one for further analysis. In India, coal has low sulfur content but it has a very high content of ash, therefore, SPM has been considered more important for environmental management in India, and shadow prices of only SPM are calculated.

SPM emitted from coal combustion consists primarily of carbon, silica, alumina and iron oxide in flyash. The quantity of SPM emissions is dependent upon the type of combustion unit in which the coal is burned, the ash content of the coal and the type of control equipment used. Marshall (1975) gives the range of collection efficiency for common types of fly ash control equipment and emission factors before control for various coal fired furnaces. According to him, to calculate the SPM, the relation between the flyash and coal-burnt for general pulverized furnaces is 8A Kg./MT coal burned (A is the ash content of coal) and the range of collection efficiency of electrostatic precipitators (ESP) for pulverized units is 80 to 99.5 percent. In the present study, it is assumed that the ESP efficiency is 90 percent in the Indian thermal power sector (Krishnan, 1993). In India, thermal power plants receive coal of various grades simultaneously, i.e., 75 percent of the coal is grade 'E', 'F', and 'G'. The CEA also publishes the average annual heat value of coal for every plant. Therefore, for every plant the ash content is calculated on the basis of these heat values of coal and it is assumed that the content of moisture is on average 5 percent (the moisture content in Indian bituminous coal ranges from 4 to 6 percent). Capital input in a power station has been calculated in almost the same manner as adopted by Dhryms and Kurz (1964)

$$K = SFT/10^3 \qquad (6)$$

Where K = *capital input,* 10^6 *kWh,*
S = *station size, MW,*
F = *availability factor ratio of the station*
T = *number of hours in a year.*

The central electricity authority, keeping in view the fact that a power plant may consist of sets of different sizes, defines the availability factor of a plant in the following way:

$$F = å_j Z_j E_j / T å_j Z_j \quad (j=1,2, \ldots\ldots, w) \qquad (7)$$

Where: Z_j = *size, MW, of the jth set in the station,*
E_j = *number of hours jth set was available for generating electricity during a year,*
W = *number of sets in the station.*

In India, the State Electricity Boards, (SEBs) and Electricity Departments (EDs) make these SEBs and EDs take the supply of electricity to the consumers, and the power generated by the thermal power plants. Therefore, plant level data on prices of electricity is not available in India. Moreover, presently there is a monopoly of these SEBs and EDs in the supply of power in their respective regions and electricity is made available to different categories of consumers at different rates where agricultural and domestic users are heavily subsidized. It is assumed that prices for the commercial use of electricity are competitive since the commercial use of electricity in India is not subsidized very much. In the study a total of 33 plants are considered for analysis for which all the above-mentioned statistics are available and described in table1.

Estimation Procedure

We adopt the parametric linear programming approach to estimate the parameters of the output distance function. The deterministic linear programming method has so far been the commonly used method in the estimation of distance functions. The advantages of the deterministic linear programming approach are that it does not require any distributional assumptions (Nishimizu and Page, 1982). It is relatively easy to use, and in principle, allows for the computation of a large number of parameters even with a small number of observations (Hetemaki, 1996). The major weakness of this approach is that it does not allow for random disturbances and provides no statistical criterion for the consistency of results (Lovell and Schmidt 1988, and Ramaswamy 1994). Thus in order to justify the approach it becomes necessary to assume that measurement errors can be neglected or, that they are all of the same (negative) sign. Observed data on pollution in the thermal power sector in India is not available and stochastic estimation cannot be implemented with derived data on pollution. With the computed statistics on pollutants, the covariance matrix becomes singular since the coal and pollutants are related to each other in a fixed proportion and the stochastic estimation is not feasible.

The distance function approach has been used to derive the shadow prices for inputs and outputs in recent years. Most of these applications are based on a translog linear programming model, which uses the Aigner and Chu (1968) method for the estimation of parameters of the objective function. (e.g. Fare et al. 1993, Althin 1994, Grosskopf et al. 1995, Coggins and Swinton 1996, Hetemaki 1996, Kumar 1999 etc.). The translog distance function is:

$$\begin{aligned} ln\ Do(x, y) &= \alpha_0 + \Sigma_i\ \alpha_i\ ln\ y_i + \Sigma_j \beta \\ & ln\ xj + 1/2 \Sigma_i \Sigma_{i'} \alpha_{ii'} (lny_i)(lny_{i'}) + 1/2 \Sigma_j \Sigma_{j'} \beta_{jj'} (lnx_j)(lnx_{j'}) \\ & + \Sigma_i \Sigma_j \gamma_{ij} (lny_i)(lnx_j) \end{aligned} \tag{8}$$

In (8), y_1 denotes desirable electricity output, the remaining are bad outputs, and $x=(x_1,x_2,...x_n)$ inputs. The following symmetry (S) and homogeneity (H) restrictions are imposed.

$$\text{(S)}\ \alpha_{ii'} = \alpha_{i'i}\quad \beta_{jj'} = \beta_{j'j'}$$
$$\text{(H)}\ \Sigma_i \alpha_i = 1,\ \Sigma_{i'} \alpha_{ii'} = \Sigma_i \gamma_{ij} = 0$$

Aigner and Chu (1968) provide the linear programming formulation to compute the parameters of equation (8). The theory of output distance function states that its value should be equal to less than one, i.e. $D_o(x, y) £1$ or in logarithm it should be less than or equal to zero. Formally

$$ln\ D^k_o(x, y) £0, \quad \forall k=1,2,....,K. \tag{9}$$

(Assuming that there is no measurement error) where k stands for the number of observations. By adding a non-negative error term

$$ln\ D^k_o(x, y) + \varepsilon^k = 0 \tag{10}$$

where $\varepsilon^3 0$, is an error term. In the literature of output distance function it is customary to interpret this non-negative error term as the reciprocal of Farrell output based on technical efficiency indexes. The complete linear programming model, with restrictions, can be expressed as

$$Max\ \ å_k[ln\ D_o(x^k, y^k) - ln\ 1] \tag{11}$$

(i) $\ln D_o(x^k, y^k) \leq 0,$

(ii) $\partial \ln D_o(x^k, y^k)/\partial \ln y_1 \geq 0$

(ii $\partial \ln D_o(x^k, y^k)/\partial \ln y_i \leq 0 \quad i=2,3, \ldots M$

In addition to the above restrictions, the symmetry and homogeneity restrictions are also imposed. The homogeneity constraint imposes proportionality of output, which ensures that the technology satisfies weak disposability of outputs. The first condition labeled (i) restricts individual observations to be on or below the frontier of the technology i.e. this is a frontier approach. The constraint (ii) ensures that the desirable output shadow prices are greater than or equal to zero whereas the restrictions in (iii) impose that the price of non-desirable products are non-positive. This model is computed using the *GAMS* program.

Results

Equation (8) was solved as a linear programming problem using the 33 observations subject to the collection of constraints from earlier sub-section. The resulting parameter estimates appear in table 2. These estimates were used to calculate the value of the output distance function for each observation. At the estimated parameter values, the output distance function of the form of full translog obeyed all the properties expected of them. The average $D_o(x, y)$ across the plants is 0.948. This indicates that in the thermal power sector in India there is a 5 percent scope for increasing productive efficiency, i.e. more electricity could be generated with the given bundle of inputs by moving towards the output distance function frontier.

It should be noted that the above results are in line with the findings of Singh (1991) for Indian thermal power sector. His observations are also based on plant level cross section data from the same source and indicate that there is a large difference between the technical efficiency levels of the least and most efficient plants. There is a great difference between the average technical efficiency scores of two studies. He calculated it to be equal to 0.73. But there is a difference in the methodologies of the two studies. Singh used the production function estimation approach and the labor variable was absent in his study.

The fourth column of table 3 presents the shadow prices of SPM emissions for each plant. Our results show that the overall shadow price or marginal abatement cost of SPM is Rs. 144.99 per kilogram. This is perhaps our principal finding. If India were to opt for MBI for SPM of our sample of plants in 1991-92, the average value of an allowance or tax should equal approximately Rs. 145 per kilogram of SPM. This table also presents the average SPM emissions rates by plants expressed in kilograms of SPM per megawatt of electricity generation. Note that firms with relatively high SPM shadow prices have the lower emission rates, while the dirty plants have lower shadow prices. It becomes more obvious by regressing the absolute value of shadow prices on emissions per megawatt of electricity, i.e.,

$$\text{Log (Marginal abatement cost)} = 5.256 - 0.05 \text{ Emissions per megawatt}$$
$$\text{(t-statistics)} \quad (6.35) \quad (-1.304)$$
$$R^2 = 0.052 \qquad \text{F-statistics} = 1.701$$

This regression line shows that the investment or operating decision that causes a fall in a plant's emission rate leads to an increase in the marginal abatement cost.

These cost differences across plants, which are significant, are important because of their policy implications. They suggest, per se, the current pollution control regulations cause an inefficient allocation of abatement resources across plants, and a market oriented system would potentially result in transfer of such resources across plants and this would lead to cost effectiveness. The SPM shadow prices vary across plants. Plant wide any number of factors might help to explain this variation, including the vintage of plants, and coal sources and their properties. Were they present, the emission collection efficiency of ESPs would also contribute to the variation in SPM shadow prices. The emissions of SPM by a plant are affected by the ash content of the coal used and the vintage of the plant. The coal prices rise as the ash content falls, holding other characteristics of the fuel constant. The coal market is not perfect. Firms have to buy coal with high ash content even if the vintage of their plant permits reduction of SPM by using coal with lower ash content. Indian thermal power plants are owned by the respective State Governments and they operate under totally regulated environments. Then the question arises as to how the shadow prices we have calculated reflect the actual cost of reducing SPM emission by purchasing such coal. The answer to this complicated question depends in many ways upon the properties of the boiler and on the various properties of different types of coal grades (qualities). Our data sources are insufficiently detailed to permit a comprehensive examination of this question. But for illustrative purposes, we provide for one particular coal grade a calculation of the hypothetical cost to our average plant of reducing SPM emissions by one kilogram solely through the purchase of better quality coal.

The example is based upon 1991-92 coal prices contained in the Gazette Notification of Government of India of December 28, 1991. Suppose the plant in question purchases coal of grade 'A', that has approximately the ash content of 12 percent excluding the moisture content, while the ash content in the coal used in practice is more that 35 percent. The pithead price of grade 'A' coal was Rs. 519 per ton, whereas the average price of grade 'E', 'F', and 'G' coal was Rs. 207 per ton. These prices exclude the premium charges, local taxes and transportation charges. Using these figures and assuming the efficiency of emission collection equipment to be 90 percent and constant, the cost of reducing SPM emissions by one kilogram through low ash coal purchase is Rs. 17. This is quite low in comparison to the average shadow prices we have calculated for the Indian thermal power plants. These numbers indicate that the plants in our data set would achieve reduction in their SPM emissions at relatively low cost simply through purchasing coal of lower ash content. Indeed, switching to lower ash coal has more comparative advantage for reducing the SPM emissions, but the availability of low ash content coal in India is very limited.

CONCLUSION

Thermal power plants in India have been asked to make compliance decisions to meet environmental standards that can involve investments of millions of rupees. Their decisions, in an essential way, should depend upon the marginal abatement costs of emissions. In this paper we employed a distance function framework to extract the marginal abatement cost of SPM emissions from a data set containing production information for a collection of 33 coal burning thermal power plants and this sector accounts for approximately one third of the total pollution in the country. The empirical approach uses the output distance function to capture the technological relationship, and the corresponding dual information contained in a revenue function. The main advantage of this approach lies in its modest data requirements. It needs no information about an individual plant's production function. From the estimated output distance function parameters for the Indian thermal power plants in our data set we found the average shadow price of SPM emissions to be Rs. 145 per ton. This figure can be used for opting MBI as a baseline argument for controlling pollution in the thermal power sector in India since there is wide variation in the shadow prices across the plants. Moreover, this study also finds that switching to lower ash content coal has more cost advantage for controlling pollution in the Indian thermal power sector. Here it should be kept in mind that the shadow prices calculated for SPM are not the virtual shadow prices of SPM, but they are the scaled value of the marginal productivity of coal, i.e. switching to lower ash coal has higher heat value and higher marginal productivity which can reduce the pollution of this sector. Perhaps more importantly, by this Fare et al model one could study the relative effect of such different abatement choices as pollution prevention through fuel switching or process changes and pollution control methods.

The result of the study promises to prove useful for ongoing compliance planning in the Indian thermal power sector, as one would anticipate the future regulations. This analysis is conducted under the following assumptions: potential application of MBI is not impeded by institutional or such other costs; all firms participate to the extent warranted by the economics; there is a low or non-existent transactions cost, and there is no monopolistic behavior. Moreover, here it should be noted that our analysis is more specific to the thermal power sector in India, its implications for other sectors cannot be generalized, although the differentials in the abatement costs of pollutants across firms advocates the application of market based instruments in general.

TABLE 1

Descriptive Statistics of the Data Used in Estimation

Variable	Mean	Standard Deviation	Maximum	Minimum
Coal ('000 tons)	2360.24	2247.11	9181.00	199.00
Labor (No.)	2065.79	1038.65	5074.00	363.00
Capital (10^6kWh)	4594.44	4194.85	15970.07	400.61
Electricity (Gwh)	3471.22	3452.27	14054.51	309.67
SPM ('000 Kgs.)	71010.72	72804.03	299773.70	5799.93
Price of electricity (Rs./1000 Kwh)	1434.76	333.41	2088.00	1008.00

TABLE 2

Linear Programming Parameter Estimates of Output-Distance Function

Parameter	Value	Parameter	Value
α_0	-1.998	β_{13}	0.217
α_1	1.225	β_{22}	0.055
α_2	-0.225	β_{23}	-0.192
α_{11}	0.024	β_{33}	0.233
α_{22}	0.015	γ_{11}	0.050
α_{12}	-0.039	γ_{12}	0.236
β_1	0.800	γ_{13}	-0.334
β_2	0.544	γ_{21}	0.046
β_3	-1.639	γ_{22}	0.018
β_{11}	-0.157	γ_{23}	-0.017
β_{12}	-0.222		

Table 3: SPM Emission per Megawatt, and Shadow prices

Sr. No.	Name of the Plant	SPM/MW (Kg.)	Shadow Prices Rs.)
1	Badarpur	22.585155	-29.39131
2	I.P.Stn	20.321202	-59.2753
3	Panipat	23.726117	-15.83853
4	Bhatinda	21.827319	-36.47464
5	Kota	20.434695	-84.53707
6	Panki Ext.	17.287924	-59.56235
7	Singrauli	18.583615	-1089.188
8	Ghandhinagar	19.470078	-130.0073
9	Ukai	18.946714	-97.67324
10	Wanakbari	19.429268	-159.2237
11	Korba STPC	22.582517	-1209.398
12	Bhusawal	21.86097	-104.4701
13	Chandrapur	20.208819	-16.72922
14	Koradi	22.757227	-28.2385
15	K.Kheda	23.333832	-180.9838
16	Parli	20.583056	-91.34025
17	Paras	20.137026	-89.95021
18	Trombey	1.006264	-57.516
19	R.Gundam	25.668655	-120.2477
20	R.GundamSTPC	22.167708	-34.47
21	Raichur	28.475267	-167.0952
22	Ennore	27.88748	-29.3865
23	Mettur	24.716475	-9.809255
24	Tuticorin	21.086025	-76.01345
25	Muzaffarpur	23.403414	-47.58979
26	Patratu	23.03655	-3.682634
27	Bokaro	26.102165	-33.29763
28	Bandel	15.973971	-90.43874
29	Titagarh	15.221816	-158.5152
30	SouthGenStn	9.9842533	-199.7921
31	DurgapurDPL	20.328859	-66.13952
32	Farakka	28.724391	-34.0025
33	Bondiagoan	24.236752	-62.80141
Mean		20.81	-144.99

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