Estimation of Marginal Abatement Costs for Undesirable Outputs in India's Power Generation Sector: An Output Distance Function Approach

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Abstract

Many production activities generate undesirable byproducts in conjunction with the desirable outputs they produce. The present study uses an output distance function approach and its duality with the revenue function to estimate the marginal abatement cost of CO_2 emissions from a sample of thermal plants in India. Two sets of exercises have been undertaken. The marginal abatement cost is first estimated without considering the distinction between the clean and the dirty plants (model-1) and then by differentiating between the two (model-2). The shadow prices of CO_2 for the coal fired thermal plants in India for the period 1991-92 to 1999-2000 was found to be Rs. 3,380.59 per ton of CO_2 as per model-1 and Rs. 2401.99 per ton of CO_2 as per model-2. The wide variation noticed in the marginal abatement costs across plants is explained by the ratio of CO_2 emissions to electricity generation, the different vintages of capital used by different plants in the generation of electricity and provisions for abatement of pollution. The relationship between firm specific shadow prices of CO_2 and the index of efficiency (ratio of CO_2 emission and electricity generation) points to the fact that the marginal cost of abating CO_2 emissions increases with the efficiency of the thermal plant.

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Acknowledgements

This forms a part of my Ph.D. work carried out at the Centre for Economic Studies and Planning, School of Social Sciences, Jawaharlal Nehru University, New Delhi under the supervision of Prof. Ramprasad Sengupta. I would like to thank Prof. M.N. Murty for his encouragement, suggestions and comments. Thanks are also due to Prof. Gopinath Pradhan for his suggestions on an earlier version of the paper. However, the usual disclaimers apply.

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Introduction

Power sector in India is one of the largest emitters of carbon dioxide in the country accounting for about 38.61 percent of the total CO_2 emissions in the year 1997-98 (refer to Table 1 below). The main reason for such a high share is its heavy reliance upon coal, which is the largest source of CO_2 emissions in the world. About 79.9 percent of the total power generation by the utilities in the country in the year 1997-98 was from coal (GoI, 1998). In addition, the coal burnt in the thermal power plants in the country is of inferior quality, which is responsible for an even higher level of pollution.

Table 1: Carbon Dioxide Emissions in India (mn t CO_2)

Year	Aggregate Emissions	Power Sector Emissions	Share of Power Sector in Total Emission (%)
1980-81	251.726	70.583	28.04
1985-86	351.911	108.986	30.97
1990-91	494.926	176.398	35.64
1991-92	525.067	193.461	36.84
1995-96	649.210	246.308	37.94
1996-97	695.211	259.255	37.29
1997-98	723.069	279.192	38.61

***Source*:** Derived from Energy Balance Table using TERI Energy Data Directory and Yearbook (various years) and IPCC Greenhouse Gas Inventory Reference Manual.

Issues concerning greenhouse gas (GHG) emission and global warming have received a great deal of attention in recent years. As per the Kyoto Protocol signed in 1997, the industrialised countries, which have historically been mostly responsible for increase in GHG concentration, agreed to reduce the flow of their GHG emission by 5.2 percent below the level prevailing in 1990. While the developing countries do not yet have any binding commitment, there is a realisation that large developing countries such as China and India need to take some action in this regard since they are among the large contributors to incremental emissions. Such a course of action, however, would adversely affect their economic growth prospects. Hence, if India were to sign any agreement on GHG emissions reduction, it must know the costs and benefits of such an agreement. In near future if India were to participate in any international effort towards mitigating CO_2 emissions, the power sector, which is one of the largest emitter of carbon dioxide in the country, would be required to play a major role.

In this context the present study analyses the potential costs imposed on the coal fired thermal power plants, one of the main sources of CO_2 emissions in India, by the implementation of environmental regulation. More specifically the study aims to estimate the marginal abatement costs, which correspond to the costs incurred by the power plants to reduce one unit of carbon dioxide from the current level. The present exercise, therefore, seeks to derive the 'shadow prices' of reducing carbon dioxide emissions generated by the thermal plants in India. It, thus, attempts to provide an answer to the question: how much does it cost the thermal plants in India to reduce CO_2 emission in terms of foregone output or revenue? These estimates are expected to help in formulating environmental policies. The marginal abatement costs thus obtained would provide guidance on whether the current regulation on pollution satisfies the cost-effectiveness criterion which is based on the principle of marginal abatement costs be equal across individual power plants (Baumol and Oates, 1988). It is being recognised by the developed world that the marketable emission permit system is a more efficient way of regulating pollution. The unit price of a marketable emission permit would be equivalent to the derived marginal abatement costs (Baumol and Oates, 1998; Titenberg 1985). Consequently, these estimates of marginal cost of abatement could be used to predict the price of emission permits to be introduced.

Theoretical framework of the present study is based on the production theory and in particular on the distance function approach. The distance function (also known as the gauge function, transformation function, or deflation function) approach identifies a boundary or a frontier technology, which contains all observation on one side of the frontier and minimises a suitable measure of total distance of all the observations from the frontier. Although the basic ingredients of the theoretical framework on which the distance function is based was known long ago owing to the works of Debreu (1951), Malmquist (1953), and Shephard (1953, and 1970), its application became popular by the works of Rolf Färe, Shawna Grosskopf and others only in recent years. The methodology based on distance function framework was first developed by Färe *et., al.* (1993) and applied by Coggins and Swinton (1996) to the US coal burning utilities. Hetemäki (1996); Kumar (1999); Kwon and Yun (1999); Murty and Kumar (2002) etc., have also used the technique to derive the shadow prices of reducing the undesirable outputs. The main advantage of using the distance function approach over the conventional ones i.e., production, cost, revenue, and profit function is that its computation requires only quantity data. This feature is of particular importance in the field of environment economics since price data related to environmental compliance costs are often not available or are unreliable.

The present study uses the output distance function and its duality with the revenue function to derive the marginal cost of abatement or the shadow prices of reducing CO_2 emissions for a sample of coal fired thermal power plants in India. The remainder of the paper is organised as follows: the next section provides a theoretical model for estimating the marginal abatement costs. It also describes the methodology for deriving marginal abatement costs using an output distance function approach. Section III highlights the procedure for the empirical estimation of the model, while section IV provides information about the data used and also discusses the estimation procedure. The estimated results are presented in section V. The final section VI concludes by summarising the main results of the study.

II. Theoretical Model

The conventional production function is defined as the maximum output that can be produced from a given vector of inputs. The distance function generalises this concept to a multi-output case and describes how far an output vector is from the boundary of the representative output set. We can define the output distance function in terms of the output set $P(x)$**.** Suppose that a producer employs the vector of inputs $x \in R_{+}^{N}$ to produce the vector of outputs $y \in R_{+}^{M}$, where R_{+}^{N}, R_{+}^{M} are non-negative *N* and *M* dimensional Euclidean spaces, respectively. The plant technology captures the relationship between the inputs and outputs and is described by the output set $P(x)$. The output set $P(x)$ denotes all output vectors that are technically feasible for any given input vector ***x,*** i.e.,

$$(i)\ldots\ldots\ P(x) = \{y \in R_{+}^{M} : x \ can\ produce\ \ y\}$$

The output set is assumed to satisfy certain axioms, the details of which can be seen in Färe (1988). The output distance function is defined on the output set $P(x)$ as

$$(ii)\ldots\ldots\ D_0(x, y) = \min_{\theta}\{\theta > 0 : (y/\theta) \in P(x)\}\ \forall\, x \in R_{+}^{N}$$

The above equation measures the largest radial expansion of the output vector ***y***, for a given input vector ***x***, that is consistent with ***y*** belonging to $P(x)$. The value of the output distance function must be less than or equal to one for any feasible output. The axioms regarding the output set $P(x)$ impose a set of properties[1] on the output distance function which are as follows:

1. $D_0(0, y) = +\infty \ for\ y \geq 0,$ i.e., there is no free lunch. To produce outputs one requires inputs.

2. $D_0(x,0)=0$ *for all* x *in* R_+^N, i.e., inaction is possible. No output is possible from positive inputs.
3. $x' \geq x$ *implies that* $D_0(x',y) \leq D_0(x,y)$, i.e., more the inputs the less efficient would the production be.
4. $D_0(x,\mu y)=\mu D_0(x,y)$ *for* $\mu > 0$, i.e.,positive linear homogeneity.
5. $D_0(x,y)$ is convex in *y*.

Of particular interest for our purpose is the disposability properties of the technology with respect to output, especially the undesirable outputs. We assume that such outputs are *weakly disposable* i.e., a reduction in the undesirable outputs can only be achieved by simultaneously reducing some of the desirable outputs. We also assume that the desirable outputs are *strongly disposable* i.e., it is possible to reduce the desirable outputs without actually reducing the undesirable outputs. In other words the outputs are weakly disposable if $y \in P(x)$ *and* $\theta \in [0,1]$, *then* $\theta y \in P(x)$; and strongly disposable if we have $\nu \leq y \in P(x)$ *implies* $\nu \in P(x)$.

Let $r = (r_1, r_2, \ldots\ldots r_M)$ denote the output price vector. From the producer's perspective, shadow prices of pollutants or the undesirable outputs are negative in general, and can thus be interpreted as the negative values of the marginal abatement cost. The revenue function can now be defined in the lines of Shephard (1970) and Färe and Primont (1995) as

$$(iii)\ldots\ldots\ R(x,r)=\max_{y}[ry:\ y\in P(x)]$$

Shephard (1970) showed that the revenue function and the output distance function are dual to one another. So,

$$(iv)\ldots\ldots\ R(x,r)=\max_{y}[ry:\ D_0(x,y)\leq 1]$$

$$(v)\ldots\ldots\ D_0(x,y)=\max_{r}[ry:\ R(x,r)\leq 1]$$

Thus the revenue function can be derived from the output distance function by maximising revenue over output quantities and the output distance function can be derived by maximising the revenue function over output prices. This duality between the output distance function and the revenue function can be used to derive the shadow prices of the outputs. These are relative output shadow prices and in order to obtain absolute shadow prices additional information regarding the revenue is required (Färe *et., al*. 1993). In order to derive the shadow prices of outputs we assume that the revenue and distance functions are differentiable. We follow the methodology used by Färe *et., al*. (1993) and write the Lagrangian function as

$$(vi)\ldots\ldots \max \Lambda = ry + \lambda(D_0(x,y)-1)$$

The first order conditions with respect to outputs are

$$(vii)\ldots\ldots r = -\lambda \nabla_y D_0(x,y)$$

where *r* and the gradient vector $\nabla_y D_0(x,y)$ are of dimension (Mx1) and λ is a scalar. Following Färe *et., al*. (1993) and with a distance function which is homogeneous of degree +1 in output ***y*** it can be shown that

$$(viii)\ldots\ldots -\lambda = \Lambda$$

Thus at the optimum, we have

$$(ix)\ldots\ldots -\lambda = \Lambda = R(x,r)$$

and equation *(vii)* can be written as

$$(x)\ldots\ldots r = R(x,r) * \nabla_y D_0(x,y)$$

In order to establish the relation between the gradient vector $\nabla_y D_0(x,y)$ and the shadow prices, we make use of the Shephard's duality theorem *(v)*, namely,

$$(xi)\ldots\ldots\ D_0(x,y) = r^*(x,y) * y$$

where, $r^*(x,y)$ is the revenue maximising output price vector. Differentiating both sides of equation *(xi)* with respect to ***y*** we get

$$(xii)\ldots\ldots\ \nabla_y D_0(x,y) = r^*(x,y)$$

Substituting *(xii)* in *(x)* we get

$$(xiii)\ldots\ldots\ r = R(x,r) * r^*(x,y)$$

Here $r^*(x,y)$ derived from Shephard's dual lemma can be interpreted as a vector of normalised or deflated output shadow prices. The formulation of equation *(xiii)* shows that the undeflated shadow prices ***r*** can be computed when the maximum revenue $R(x,r)$ is known. However, $R(x,r)$ depends on ***r***, which is the vector of shadow prices. In order to obtain $R(x,r)$ we assume that the market price or the observed price of one of the output equals its absolute shadow price. Suppose the observed price of the m^{th} output r_m^o equals its absolute shadow price r_m. Then, whenever ***x*** and ***y*** are known we can compute the revenue from equation *(xiii)* as

$$(xiv)\ldots\ldots\ R = r_m^o \big/ r_m^*(x,y)$$

In reality one can use the market price (or the observed price) of the desirable output as the normalising price, since the prices of the desirable output are market determined and therefore observable. For all $m' \neq m$, the absolute shadow prices $r_{m'}$ are given by

$$(xv) \ldots\ldots \quad r_{m'} = R * r_{m'}^{*}(x, y) = R * \left[\frac{\partial D_0(x, y)}{\partial y_{m'}} \right]$$

$$= r_m^o * \frac{\partial D_0(x, y) / \partial y_{m'}}{\partial D_0(x, y) / \partial y_m}$$

As shown in equation *(xv)*, the shadow price of m' output is given by the product of the marginal rate of transformation and the market price of the m^{th} output. If one considers the m' output to be the undesirable output (i.e., the pollutant) and the m^{th} output as the desirable output then, from equation *(xv)* the shadow price of the undesirable output is given by the product of the marginal rate of transformation and the market price of the desirable output. This, in turn, is equivalent to the value of the foregone desirable output associated with the reduction in one unit of the undesirable output. In the above equation the ratio of the output shadow prices reflects the relative opportunity cost of the output in terms of the revenue foregone. In other words, it is equivalent to the marginal rate of transformation. Thus the shadow prices reflect the trade-off between the desirable and undesirable outputs at the actual mix of outputs. Derivation of the shadow prices of undesirable output as given by equation *(xv)* is based on the assumption that the production is occuring at the frontier of the output set. But if the production firms lie within the output set and not on the frontier (i.e., for such firms the value of the output distance function is less than one), then there might be some problem in estimating the shadow prices. To resolve the problem of estimating the shadow prices for such inefficient firms, we proportionately increase all the outputs so that they are on the frontier. Such proportionate scaling of the outputs will have no affect on the shadow prices as we have assumed that the output distance function is homogeneous of degree one in outputs and therefore its derivatives with respect to the outputs as shown in equation *(xv)* are homogeneous of degree zero. To put it differently, regardless of the location of the observed production combinations, the shadow prices can be derived through an estimated output distance function by using the actual data on the inputs and outputs–both desirable and undesirable (Kwon and Yun, 1999).

III. The Empirical Model

The present study uses the deterministic parametric method[2] for estimating the output distance function. The objective of such an exercise is to analyse the potential cost, if any, imposed on the coal fired thermal power plants in India by the implementation of environmental regulation. In other words, the shadow prices of reducing carbon dioxide (i.e., the undesirable output) expressed in terms of electricity generation (i.e. the desirable output) foregone for the coal fired thermal power plants in India are obtained by using the output distance function and its duality with the revenue function.

In order to derive the shadow prices by estimating the deterministic parametric output distance function we have to initially define its functional form. We choose to parameterise the output distance function $D_0(x, y)$ as a translog function, which has been followed in the literature (e.g., Althin, 1994; Färe *et., al.* 1993 etc.). Thus,

$$(xvi) \ldots\ldots \ln D_0(x,\ y) = \alpha_o + \sum_{n=1}^{N} \beta_n \ln x_n + \sum_{m=1}^{M} \alpha_m \ln y_m$$

$$+ 0.5 * \sum_{n=1}^{N} \sum_{n'=1}^{N} \beta_{nn'} \ln x_n \ln x_{n'}$$

$$+ 0.5 * \sum_{m=1}^{M} \sum_{m'=1}^{M} \alpha_{mm'} \ln y_m \ln y_{m'}$$

$$+ \sum_{n=1}^{N} \sum_{m=1}^{M} \gamma_{nm} \ln x_n \ln y_m$$

$$+ \gamma_t t \; + \; 0.5 * \gamma_{tt} t^2$$

In equation *(xvi)*, $x = (x_1, x_2, \ldots\ldots x_N)$ denotes inputs, and $y = (y_1, y_2, \ldots\ldots y_M)$ corresponds to both the desirable and undesirable outputs. In the model $y = (y_1, y_2, \ldots\ldots y_i)$ are the desirable outputs while $y = (y_{i+1} \ldots\ldots\ldots y_M)$ represent the undesirable outputs. In our model fuel (F), capital (K) and labour (L) are the three inputs while the output consists of desirable output, electricity (Y) and undesirable output, CO_2 emission (P) generated by the power plants. A time variable *t* is introduced to reflect technical change. In order to reduce the number of parameters to be estimated the terms corresponding to the product of time variable (*t*) and logarithms of other variables are excluded by assuming a neutral technical change.

The parameters of the equation *(xvi)* are computed by using the linear programming technique as suggested by Aigner and Chu (1968). Theoretically the value of the output distance function $D_0(x, y)$ cannot exceed unity and it must be less than or equal to unity (assuming there are no measurement errors). Formally,

$$(xvii) \ldots\ldots \ln D_0^k(x, y) \leq 0 \qquad\qquad \forall k = 1, 2, \ldots\ldots, K.$$

where $k = (1, 2, \ldots\ldots, K)$ indexes individual observation. Now if we add a non-negative error term to equation *(xvii)*, it can be rewritten as:

$$(xviii) \ldots\ldots \ln D_0^k(x, y) + \varepsilon^k = 0$$

where ε, $(\varepsilon \geq 0)$ denotes the non-negative residual or the error term. Next we choose the 'fitting' criterion to be the *minimum absolute error* (MAE), i.e., $\sum_{k=1}^{K} \left| \varepsilon^k \right|, \;\; \varepsilon^k \geq 0$. The MAE fits $\ln D_0(x, y)$ so that the sum of errors is as small as possible (Hetemäki, 1996). The parameters of the translog output distance function can be obtained by solving the following problem:

$$(xix)\ldots\ldots \max \sum_{k=1}^{K}\left[\ln D_0(x^k, y^k) - \ln 1\right]$$

where $k = (1, 2, ..., K)$ indexes individual observation. $\ln D_0(x, y)$ has an explicit functional form as given in equation *(xvi)*. We assume that the first i outputs are desirable while the remaining $(M - i)$ outputs are undesirable or bad outputs. Our objective function minimises the sum of deviations of individual observations from the frontier of the technology. We know that the distance function takes a value less than equal to unity, therefore the natural logarithm of it, i.e., $\ln D_0(x^k, y^k)$ will be less than, or equal to zero and the expression $[\ln D_0(x^k, y^k) - \ln 1]$, which denotes the deviation from the frontier for observation *k* will be less than or equal to zero.

Our objective is to maximise the expression in equation *(xix)* subject to the following constraints:

$$(xx)\ldots\ldots \ln D_0(x^k, y^k) \le 0, \quad k = 1, ..., K$$

This constraint restricts the individual observations to be either on or below the frontier of technology i.e., there are no outputs outside the frontier of technology, given the set of inputs.

Desirable outputs are assumed to be strongly disposable, which implies that the output distance function should be increasing in desirable outputs. The strong disposability condition can be represented by the following inequality:

$$(xxi)\ldots\ldots \frac{\partial \ln D_0(x^k, y^k)}{\partial \ln y_m^k} \ge 0, \quad m = 1, ..., i; \quad k = 1, ..., K$$

The constraint above ensures that the shadow prices of the desirable outputs are non-negative. In addition it is assumed that undesirable outputs are weakly disposable. This weak disposability is always satisfied for the output distance function specified as the translog form when linear homogeneity condition represented by equation *(xxii)* and the symmetry conditions represented by equation *(xxiii)* are being imposed.

The weak disposability of undesirable outputs implies that the desirable output decreases when the emission of the pollutants or the undesirable outputs is reduced. The following assumption satisfies the criterion of weak disposability of undesirable outputs:

$$(xxii)\ldots\ldots \partial \ln D_0(x^k, y^k) \Big/ \partial \ln y_m^k \leq 0, \quad m = i+1, \ldots\ldots, M; \quad k = 1, \ldots\ldots, K$$

In addition to the above constraints we also impose the homogeneity and symmetry constraints into the model which can be represented as

$$(xxiii)\ \ldots\ldots \sum_{m=1}^{M} \alpha_m = 1, \quad \sum_{m=1}^{M} \gamma_{nm} = \sum_{m'=1}^{M} \alpha_{mm'} = 0, \quad for\ all\ \ m, n$$

and

$$(xxiv)\ \ldots\ldots \alpha_{mm'} = \alpha_{m'm}, \quad \beta_{nn'} = \beta_{n'n}, \quad forall\ m, m', n\ and\ n'$$

Equations *(xix) - (xxiv)* represent the model we shall use to derive the shadow prices of the undesirable output. The model is solved using the GAMS programming tool developed by Brooke *et., al*. (1992).

IV. Data and Estimation Procedure

The empirical analysis is based on primary data collected from the coal fired thermal plants under the Calcutta State Electricity Supply Corporation (CESC), West Bengal Power Development Corporation Limited (WBPDCL), and Damodar Valley Corporation (DVC) in the eastern region of India. These coal fired thermal plants are a part of the Eastern Grid.[3] We have collected detailed time series data on the inputs and outputs for the years 1991-92 to 1999-2000 for all the thermal plants listed above. However, the data for the Mejia TPS and Budge-Budge TPS were available for the years 1997-98 to 1999-2000 as these thermal plants were commissioned in the year 1997 and had started commercial production only from the year 1997-98. A detailed table listing the various thermal power stations along with the year of commissioning of their respective units is presented in Table A1 in the appendix. An interesting feature worth mentioning about our sample of thermal plants is that these plants are of different vintages. On the one hand we have plants like Bokaro TPS'A' which was commissioned in the decade of fifties, on the other there are newer plants like Mejia TPS and Budge-Budge TPS which are still under construction and only some of their units have started commercial operations. The sample also includes plants which were commissioned in the decades of eighties and nineties. So we have a whole spectrum of thermal plants in the analysis representing technologies of different vintages. The primary data pertaining to inputs and outputs were collected from the WBSEB, DVC, and CESC for their respective thermal plants. Only plant level data on the different inputs, outputs, and prices of one of the desirable output is needed for our analysis.

Inputs: The main inputs required for the generation of electricity by the thermal plants are fuel, capital, and labour. The major fuel input needed by the thermal power plants considered in the present study is coal. In addition, the coal fired thermal plants also require fuel oil or light diesel oil (LDO), as a secondary fuel to provide the necessary heat input as and when required to start-up the boiler or for stabilisation of flame at low load. Coal consumption figures are given in metric tonnes while the fuel oil (or LDO) consumption is recorded in kilolitres. The data on coal and fuel oil consumed are converted into tonnes of oil equivalent (*see*, Box 1) and are then aggregated to get the total fuel consumption figure for the individual plants.

Box 1: Conversion Factors		
1 kilolitre of LDO	=	0.863 metric tonnes of LDO
1 metric tonne of LDO	=	1.035 tonne of oil equivalent
1 metric tonne of coal	=	0.67 tonnes of oil equivalent

***Source*:** Indian Petroleum and Natural Gas Statistics 1995-96 and 1996-97

The other important input in the generation of electricity is capital. In the present study we have used plant capacity in megawatt

(MW) as the capital variable following Kwon and Yun (1999). The data on labour input cover both production and non-production (white-collar) workers employed in the plant.

Outputs: The output variable consists of both desirable and undesirable outputs. While electricity generated by the thermal plants is the desirable output and is measured in megawatt hours (Mwh), CO_2 emission is the bad or undesirable output. We have used for the desirable output the plant-wise electricity generation data which was made available by the WBSEB, DVC and CESC for their respective thermal plants for the period 1990-91 to 1999-2000.

Coal is burnt to generate electricity in the thermal plants. Since in coal, carbon is bundled with ash, carbon, sulfur etc., its burning results in the emission of carbon dioxide, particulate matters, NO_x, etc., in the atmosphere as pollutants. The emission of these pollutants in the atmosphere can be regarded as a byproduct of electricity generation, and thus is considered by us as undesirable outputs. The present study considers carbon dioxide (CO_2) as the only undesirable output. Data relating to the emission of CO_2 are not readily available, as most of the thermal plants in India still do not measure the emissions of CO_2. As a result we have used the data on fuel consumption for generating the data on CO_2 emissions. Having obtained the plant wise data on consumption of coal and fuel oil or LDO, we use fuel specific emission factors given by the IPCC reference manual to derive plant wise total CO_2 emissions. We have also collected data on the calorific value of coal consumed by the thermal plants in the sample and found that the coal supplied to these thermal plants is of a higher grade and has a higher calorific value *vis-à-vis* those used in most thermal plants in India. In the present study while calculating plant-wise CO_2 emissions from burning of coal, we have incorporated the calorific value of different grades of coal consumed by the power plants over the years and have adjusted the CO_2 emission factors provided by the IPCC reference manual accordingly.[4]

The descriptive data on the inputs and outputs are given in Table 2. The standard deviations for all the variables are less than their mean values, indicating that the plants are a relatively homogeneous group (Hetemäki, 1996).

Table 2: Descriptive Statistics

Variables	Unit	Mean	Std. Dev	Min	Max
Electricity (Y)	Mwh	1874281	1541744	141000	6686101
Capital (K)	MW	469.64	341.52	67.50	1260
Labour (L)	Number	1308	792.48	104	2946
Fuel (F)	Toe	887848.20	735710.10	68720.71	3197387
CO_2 (P)	TCO_2	2413491	2182987	139013.60	9169197

***Note*:** Sample size is 76; toe = tonnes of oil equivalent; t CO_2 = tonnes of carbon dioxide; Mwh = Megawatt hour; MW = Megawatt; Fuel comprises both coal and oil consumption.

Electricity Prices: In order to derive the shadow prices of the outputs, market price of at least one of the output is necessary. As there exists no market for the undesirable outputs, we do not get the prices for these. Therefore, to derive the shadow prices of the undesirable outputs we need to know the price of the desirable output, which in the present case is electricity. The data on electricity tariffs i.e., the sale price of electricity is taken as the price of electricity and is obtained from CESC, DVC, and WBPDCL separately for the different years under consideration.

It should be noted here that the data on CO_2 emission is generated from the consumption of fossil fuels by the thermal plants. As the data on CO_2 emissions is related to the consumption of fossil fuels, one cannot use these for econometrically estimating the output distance function. The unavailability of consistent and reliable plant-wise data on CO_2 emissions for the years under consideration does not permit us to estimate the stochastic output distance function by the econometric method. Hence only deterministic linear programming technique is used in the present study to derive the shadow prices of undesirable output.

The study considers carbon dioxide, which is one of the important greenhouse gases, as the only undesirable output in the analysis while electricity (or power) generated is the desirable output. As mentioned the sample consists of plants of various vintages, some plants are new and are constructed with relatively better and efficient technologies and thus emit less CO_2 than the plants which are very old and pollute more per unit of output. In order to differentiate plants that are old and have not installed any equipment to control their emissions i.e., the dirty plants, from the plants that use new technology which is less polluting and plants which have old technology but have installed equipment or have taken additional measure to restrict emissions and hence pollute less i.e., the cleaner plants, a dummy variable[5] is introduced in the model. The output distance function is initially estimated without making any distinction between the dirty and cleaner plants. This is our Model-1. The estimation of the output distance function is again carried out, now by incorporating the dummy variable to distinguish the dirty plants from the cleaner ones. This is called Model-2. The estimated parameters of both the models are presented in Table 3.

Table 3: Estimated Parameters

Parameter	Value		Parameter	Value	
	Model-1	Model-2		Model-1	Model-2
α_o	5.713907	8.265383	α_{YY}	-0.073590	-0.069163
β_L	-0.756283	-0.168085	α_{YP}	0.073590	0.069163
β_K	0.526069	0.947600	α_{PP}	-0.073590	-0.069163
β_F	-1.875104	-2.727518	γ_{LY}	-0.253212	-0.306170
α_Y	-0.892840	-0.409482	γ_{LP}	0.253212	0.306170
α_P	1.892840	1.409482	γ_{KY}	-0.103620	-0.017939
β_{LL}	-0.005172	-0.100494	γ_{KP}	0.103620	0.017939
β_{LK}	0.148123	0.205437	γ_{FY}	0.261308	0.220088
β_{LF}	-0.013652	-0.036834	γ_{FP}	-0.261308	-0.220088
β_{KK}	0.126568	0.060381	γ_t	-0.010469	-0.007900
β_{KF}	-0.181760	-0.210416	γ_{tt}	0.001046	0.000761
β_{FF}	0.163526	0.250791	Dummy	-	0.051274

Note: In Model 2 we have used Dummy *D = 1* for plants which are dirty and used dated technology and *D = 0* for plants which are clean.

V. Results

Having estimated the parameters of the distance function, we now substitute their values in equation *(xvi)* to get the estimated output distance function. Substituting the estimated output distance function in equation *(xv)* and simplifying we get the marginal cost of abating CO_2 emissions expressed in terms of the electricity output foregone.

The results of the study indicate that out of a total 76 observations in Model-1, 15 observations are located on the frontier of the output set as the value of the output distance function for these observations is one. The remaining 61 observations, for which the value of the output distance function is less than one, lie inside the output set. Similarly, in Model-2, we find that 17 observations lie on the frontier of the output set and have value of the distance function as unity and 59 observations lie inside the output set as their output distance function have value less than one. On an average the mean value of the output distance function for the sample of thermal plants in Model-1 is 0.9669 with standard deviation 0.0356. This means that electricity generation can be increased by 3.31 percent (with CO_2 emissions increasing in the same proportion) on an average by the thermal plants if they produce efficiently i.e. if they operate on the frontier of the output set. On the other hand, for Model-2, the mean value of the distance function is 0.9722 with a standard deviation of 0.0275 implying that the electricity generation can be increased by 2.78 percent if the plants operate efficiently. But such increase in output will be accompanied by a proportionate increase in the emission of the pollutants. The mean value of the shadow price or the marginal cost of abatement of CO_2 for the power plants in the study is Rs. 3,380.59 per tonne in case of Model-1, and Rs. 2,401.99 per tonne in case of Model-2. These shadow prices reflect the trade-off between the desirable and undesirable outputs at the actual mix of outputs. This means that if the plants were to reduce the emission of CO_2 by one tonne, they will have to forego electricity output worth Rs. 3,380.59 in Model-1, and Rs. 2,401.99 in Model-2. It should be noted here that the shadow prices or the marginal abatement costs of

CO_2 are at constant 1990-91 prices. There is a wide variation in the mean value of the output distance function and the mean value of the marginal cost of abating CO_2 emissions across plants as is shown in Table A2 in the appendix. The mean value of the distance function varies, in case of Model-1, between 0.896814 (for Titagarh TPS) and 0.998510 (for Mejia TPS) and between 0.937319 (for Bokaro 'B' TPS) and 0.997814 (for Mejia TPS) in case of Model-2. Thus there exists considerable scope for increasing electricity output if these plants were to operate efficiently. Similarly, there is a wide variation in the mean value of the output distance function and the mean value of the marginal costs of abating CO_2 emission across the years as is evident from Table A3 in the appendix.

Tables A4 and A5 in the appendix display plant wise shadow prices or marginal cost of abatement for CO_2 for the years between 1990-91 and 1999-2000. As is noted above, these shadow prices are expressed at constant 1990-91 prices. Table A5 illustrates the results of Model-2 where a dummy variable was used to distinguish the dirty plants from the cleaner ones, while the results for Model-1 are represented in the Table A4. We see there exists wide variation in the marginal abatement cost across plants in both the models. Even for a particular plant there are variations in the shadow prices across the years. The wide variation in the marginal abatement costs or the shadow prices of CO_2 can be explained by variation in the ratio of CO_2 emissions to electricity generation, the different vintages of capital used by the different plants for generation of power and the different measures adopted for abating or controlling pollution.

We consider the ratio of total CO_2 emissions to electricity generation to be our index of efficiency (or inefficiency). The higher the ratio, the less efficient the plant is and *vice versa*. In other words, an efficient plant is associated with a lower value of this ratio because it would emit less CO_2 per unit of output generated. On the basis of the index of efficiency, the study finds, for the sample of thermal plants under consideration, higher efficiency is associated with a higher shadow price of CO_2. This implies that for a cleaner and efficient plant the marginal cost of abating CO_2 emissions is high while for a dirty and inefficient plant, it is low. The estimated relation between the shadow prices and the efficiency index is given below.

Model-1 Dependent Variable: ***ln (shadow price of CO_2)***

Variables	***Coefficient***	***t-statistic***	***Probability***
C	8.2629	28.32	0.000
Ln (CO_2 emission/power generation)	- 0.54729	-2.04	0.045
R^2 = 0.0918			

Model-2 Dependent Variable: ***ln (shadow price of CO_2)***

Variables	***Coefficient***	***t-statistic***	***Probability***
C	7.8737	26.21	0.000
Ln (CO_2 emission/power generation)	- 0.57931	- 2.10	0.039
R^2 = 0.1057			

Note**:** Year dummies have been used in estimating both the regressions but are not reported while presenting the results.

While carrying out the regression analysis we have considered the natural logarithm *(ln)* of the shadow prices as the dependent variable and the natural logarithm of the efficiency index i.e., the ratio of CO_2 emissions and electricity generation as the independent variable. Year dummies have been incorporated while regressing the logarithm of shadow prices on the logarithm of the index of efficiency, but have not been reported in the results presented above. From the above results, one can infer that the shadow price of CO_2 or the marginal cost of abating CO_2 emissions increases with the increase in efficiency of the power plants. In other words it becomes increasingly difficult or expensive for a plant, which has invested in pollution abating technology or equipment and is emitting less of CO_2 per unit of output to reduce an additional unit of the pollutant *vis-à-vis* plants that emit more CO_2 per unit of electricity generation. Thus, for a given level of output the less one pollutes per unit of output, the higher will be the cost of reducing an additional unit of the pollutant and *vice versa*.

V. Conclusion

There have been a number of studies for India, which have applied the output distance function approach to calculate the shadow prices of the undesirable outputs. They mainly relate to water pollutants like BOD (biological oxygen demand), COD (chemical oxygen demand), and SS (suspended solids). These include studies by Murty and Kumar (2002; 2001); Kumar and Rao (2002). The present study is one of the very few studies that uses the output distance function technique for the coal fired thermal plants in India and, perhaps the only one to calculate the shadow price of CO_2 emissions for the power sector in India. The only other study that uses the output distance technique to calculate the shadow prices of the pollutants emitted by the power plants in India, is Kumar (1999) which uses both deterministic and stochastic output distance function to derive the shadow price of PM_{10} for the power plants in India. Apart from the studies relating to India, numerous other studies have also been carried out worldwide using the output distance technique.[6] A number of studies have also been conducted worldwide to derive the shadow prices of pollutants for the power sector. Appendix Table A6 displays the results of some of the studies that use the output distance technique to derive the shadow price(s) of pollutant(s) for the power sector.

The present study uses the output distance function approach and its duality with the revenue function to calculate the plant specific shadow prices of CO_2, which is the undesirable output for the coal fired thermal power plants in India. A distinguishing feature of this framework is that it provides a measure of productive efficiency for each producer. The output distance function technique, since it allows shadow prices to vary across producers, can reveal a pattern of variation by production techniques, by other plant characteristics like the age of the plant, volume of pollution. This type of information would be helpful for policymakers in designing or formulating policies to reduce carbon dioxide emissions.

Economic theory suggests that equalisation of the marginal cost of abatement across firms would minimise the total cost of abating pollutants at an aggregate level. In the present exercise the estimated shadow prices of the pollutant CO_2 vary across plants. The average shadow price or the marginal abatement cost of CO_2 for the coal fired thermal plants in India for the period 1991-92 to 1999-2000 being Rs. 3,380.59 per ton of CO_2 as per Model-1 and Rs. 2,401.99 per ton of CO_2 as per Model-2. Considerable differences in the plant specific shadow prices points towards inefficient use of abatement technology by the thermal plants in India thereby building a case for using economic instruments like pollution taxes or marketable pollution permits to regulate/control pollution by the power plants instead of currently used command and control instruments.

As regards the relationship between efficiency of the power plants defined in terms of CO_2 emissions per unit of electricity output generated and marginal cost of abating CO_2 is concerned, there exists a direct correlation between the two. This implies that an efficient plant is associated with a higher marginal cost of abating CO_2 and an inefficient plant with a lower marginal cost of abatement. In other words, it becomes increasingly difficult for a plant which emits less CO_2 per unit of its good output to reduce one unit of its CO_2 emissions *vis-à-vis* plants that are less efficient and hence emit more CO_2 per unit of good output. That is, the marginal cost of abatement or the shadow price of the undesirable output increases with the efficiency of the thermal plant.

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Appendix

Table A1: Details of the Various Thermal Power Stations (TPS)

Thermal Power Stations	Units	Year of Commissioning	Thermal Power Stations	Units	Year of Commissioning
Calcutta Electric Supply Corporation			**Damodar Valley Corporation**		
			Bokaro TPS "A"	Unit 1	February 1953
Titagarh TPS	Unit 1	1983		Unit 2	August 1953
	Unit 2	1983		Unit 3	October 1953
	Unit 3	1984		Unit 4	1 April 1960
	Unit 4	1985			
			Bokaro TPS "B"	Unit 1	12 March 1987
Southern TPS	Unit 1	1990		Unit 2	15 December 1991
	Unit 2	1991		Unit 3	1 April 1968
Budge-Budge TPS	Unit 1	1997	Chandrapura TPS	Unit 1	November 1968
	Unit 2	1999		Unit 2	April 1965
				Unit 3	1 August 1968
				Unit 4	31 March 1975

Table A1: Details of the Various Thermal Power Stations (TPS) (contd.)

Thermal Power Stations	Units	Year of Commissioning	Thermal Power Stations	Units	Year of Commissioning
West Bengal Power Development Corporation Ltd.				Unit 5	1 April 1976
				Unit 6	1 April 1980
Kolaghat TPS	Unit 1	9 September 1990			
	Unit 2	9 March 1986	Durgapur TPS	Unit 1	December 1960
	Unit 3	12 October 1984		Unit 2 *	February 1961
	Unit 4	1 April 1995		Unit 3 *	1 April 1967
	Unit 5	14 May 1991		Unit 4	1 December 1982
	Unit 6	1 January 1994			
			Mejia TPS	Unit 1	1 December 1997
				Unit 2	15 March 1999
				Unit 3	28 September 1999

Note**:** * Decommissioned due to fire since 23 October, 1985.

Table A2: Mean Values of Output Distance Function and Shadow Prices Across Plants

Thermal Plants	Model-1		Model-2	
	Distance Function	**Shadow Price (Rs./ tonne)**	**Distance Function**	**Shadow Price (Rs./ tonne)**
Titagarh TPS	0.896814	3086.94	0.966136	2436.48
Southern TPS	0.964838	3709.37	0.965143	2715.56
Bokaro TPS 'A'	0.965746	939.31	0.976638	673.47
Bokaro TPS 'B'	0.977155	3418.66	0.937319	2453.95
Chandrapura TPS	0.984893	4760.05	0.984939	2679.60
Durgapur TPS	0.981496	7595.67	0.988897	5726.76
Kolaghat TPS	0.986287	1312.70	0.982368	909.74
Mejia TPS	0.998510	2587.78	0.997814	1567.78
Budge-Budge TPS	0.972593	1716.42	0.960523	630.81
Overall	***0.966916***	***3380.59***	***0.972229***	***2401.99***

Note: The values of the shadow price or marginal abatement costs of CO_2 abatement are at 1990-91 prices; TPS = Thermal Power Station.

Table A3: Mean Values of Output Distance Function and Shadow Prices Across Years

Year	Model-1		Model-2	
	Distance Function	**Shadow Price (Rs./tonne)**	**Distance Function**	**Shadow Price (Rs./tonne)**
1990-91	0.961592	4492.213	0.973064	2788.97
1991-92	0.961590	4768.077	0.972118	2746.79
1992-93	0.961934	3357.720	0.973692	3679.13
1993-94	0.967121	2445.274	0.972898	1922.71
1994-95	0.971794	3091.220	0.976806	2213.27
1995-96	0.969427	3124.218	0.971137	2327.37
1996-97	0.959193	3714.176	0.961707	2535.19
1997-98	0.979707	3074.603	0.981455	2041.24
1998-99	0.968473	3313.584	0.971292	2187.87
1999-00	0.964824	2717.520	0.967193	1888.36
Overall	***0.966916***	***3380.59***	***0.972229***	***2401.99***

Note: The values of the shadow price or marginal abatement costs of CO_2 abatement are at 1990-91 prices; The numbers of plants in our study which were seven till 1996-97 increased to nine from the year 1997-98 with the commissioning of two new plants.

Table A4: Shadow Price of CO_2 (Rs. / tonne)

(Model-1)

Year	Titagarh	Southern	Bokaro 'A'	Bokaro 'B'	Chandrapura	Durgapur	Kolaghat	Mejia	Budge-Budge
1990-91	3004.55	9788.45	720.96	2399.59	5329.14	7985.58	2217.22	-	-
1991-92	3580.52	3069.24	866.61	3594.23	4945.82	15652.64	1667.48	-	-
1992-93	3470.91	3087.15	675.99	6199.12	4757.24	-	1955.90	-	-
1993-94	2742.66	2727.92	826.29	3277.56	2740.97	3140.97	1660.54	-	-
1994-95	2926.60	2990.87	855.24	3565.90	5649.30	4372.71	1277.93	-	-
1995-96	3535.08	2912.66	872.74	4875.58	3858.90	4926.40	888.17	-	-
1996-97	2498.35	3316.50	947.68	3897.56	2987.34	11564.53	787.27	-	-
1997-98	2622.94	2443.97	627.65	2301.21	5400.80	6380.25	962.00	4120.71	2811.91
1998-99	2869.59	3152.50	1539.58	1995.88	6619.60	9302.76	901.01	2035.36	1405.98
1999-00	3618.20	3604.45	1460.34	2079.96	5311.41	5035.23	809.47	1607.27	931.36

***Note*:** The shadow prices or the marginal abatement costs are at 1990-91 prices.

Table A5: Shadow Price of CO_2 (Rs. / tonne)

(Model-2)

Year	Titagarh	Southern	Bokaro 'A'	Bokaro 'B'	Chandrapura	Durgapur	Kolaghat	Mejia	Budge-Budge
1990-91	2369.08	5415.70	558.19	1979.47	2883.03	4806.78	1510.57	-	-
1991-92	2733.01	2256.15	656.19	2428.11	2823.26	7148.74	1182.07	-	-
1992-93	2719.09	2397.26	534.72	4002.66	2741.40	12058.91	1299.88	-	-
1993-94	2161.01	2208.95	575.29	2961.04	1860.65	2599.88	1092.12	-	-
1994-95	2306.98	2431.92	615.41	2605.58	2780.10	3877.56	875.37	-	-
1995-96	2796.70	2414.38	563.99	3535.65	2241.55	4098.96	640.34	-	-
1996-97	2048.91	2666.44	562.14	2587.65	2047.18	7264.05	569.95	-	-
1997-98	2115.83	2037.96	440.12	1651.34	2991.31	4965.66	686.01	2413.82	1069.13
1998-99	2320.92	2516.58	1124.43	1398.27	3478.73	6422.47	653.19	1298.90	477.35
1999-00	2793.23	2810.25	1104.22	1389.69	2948.78	4024.56	587.94	990.61	345.96

***Note*:** The shadow prices or the marginal abatement costs are at 1990-91 prices.

Table A6: The Marginal Abatement Costs for Air-borne Pollutants from various Studies

Study	Period	Sample	CO_2	SO_X	NO_X	TSP
Coggins and Swinton	1990-92	Coal Burning Utilities in Wisconsin	-	$175.7 - $326.7	-	-
Gollop and Roberts	1973-79	Fossil fueled electric generation in US	-	$141 - $1226	-	-
Kwon & Yun	1990-95	Bunker-C and coal power plants in Korea	$2.38	$194.1	$91.69	$9676.44
Kumar	1992-93	Coal burning utilities in India	-	-	-	Rs.326.18*
Our Study	1990-2000	Thermal power plants in eastern India	Rs.3380.59 # Rs.2401.99 @	-	-	-

Note: * this shadow price value is for PM_{10} and the unit is Rs. per kg.
This pertains to Model-1 and @ for Model-2
Kwon and Yun's estimates assume the exchange rate to be 1600 won per dollar.

Endnotes

1 For a detailed description of these properties refer to Färe (1988).

2 The advantage of using the deterministic parametric method for estimating the output distance function is that it is easy to use and allows computation of a large number of parameters even with a small number of observations (Hetemäki, 1996).

3 The thermal plants included in the empirical model are Kolaghat Thermal Power Station (KTPS) under the WBPDCL, Bokaro TPS 'A', Bokaro TPS 'B', Chandrapura TPS, Durgapur TPS, Mejia TPS under the DVC and Titagarh TPS, Southern TPS, and Budge-Budge TPS, under the CESC.

4 In India most of the coal that is consumed in the thermal plants is of a lower grade and has low calorific value in comparison to the coal consumed by the plants under consideration. In order to capture the grade differential while estimating CO_2 emissions from the burning of coal the emission factors provided in the IPCC reference manual are adjusted accordingly.

5 A dummy variable assuming values $D = 1$ for dirty plants and $D = 0$ for plants which are cleaner is incorporated in Model-2.

6 *See* among others studies by Färe *et., al.* (1993), Hetemäki (1994; 1996); Althin (1994); Swinton (1998); and Yaisawarng and Klein (1994).