Costs of Reducing Greenhouse Gas Emissions: A Case Study of India's Power Generation Sector

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Summary

If India were to participate in any international effort towards mitigating CO2 emissions, the power sector which is one of the largest emitters of CO2 in the country would be required to play a major role. In this context the study estimates the marginal abatement costs, which correspond to the costs incurred by the power plants to reduce one unit of CO2 from the current level. The study uses an output distance function approach and its duality with the revenue function to derive these costs for a sample of thermal plants in India. Two sets of exercises have been undertaken. The average shadow prices of CO2 for the sample of thermal plants for the period 1991-92 to 1999-2000 was estimated to be respectively Rs.3380.59 and Rs.2401.99 per ton for the two models. These shadow prices can be used for designing environmental policies and market-based instruments for controlling pollution in the power sector in India.

Keywords: Marginal Abatement Costs, Distance Function, CO2 Emissions, Shadow Prices, Power Generation Sector

JEL Classification: Q40

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1. Introduction

Issues concerning greenhouse gas (GHG) emission and global warming have received a great deal of attention in the 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 realization 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. Any commitment by India towards reducing emissions would mean that all the sectors in the economy would have to make efforts for reducing their respective GHG emissions so that the national emission targets are met.

Power sector in India is one of the largest emitters of carbon dioxide (CO_2) in the country accounting for about 35.53 percent of the total CO_2 emissions in the year 2001-02 (see Table 1). The main reason for such a high share is its heavy reliance upon coal. About 81.7 percent of the total power generation by the utilities in the country in the year 2000-01 was from coal (GOI, 2002). In addition, the coal burnt in the thermal power plants in the country is of inferior quality thereby resulting in an even higher level of emissions.[1] Thus, 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 corresponds 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

[1] Coal used in coal-fired power plants in India has a low calorific value (around 3,500 Kcal/kg) and a high ash content (as high as 45%).

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 recognized 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, 1988; Titenberg, 1985). Consequently, these estimates of marginal abatement cost could be used to predict the price level of emission permits to be introduced.

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

Year	Aggregate Emissions	Power Sector Emissions	Share of Power Sector in Total Emission (%)
80-81	244.71	68.06	27.81
85-86	342.22	105.09	30.71
90-91	481.70	170.42	35.38
95-96	632.08	237.98	37.65
96-97	676.80	250.49	37.01
97-98	704.05	269.81	38.32
98-99	632.41	185.33	29.31
99-00	682.78	219.98	32.22
00-01	736.49	242.98	32.99
01-02	698.76	248.24	35.53

Source: Derived from Energy Balance Table using TEDDY (various years) and IPCC (1995).

Theoretical framework of the study is based on production theory and in particular on the distance function approach. The distance function (also known as the gauge function, transformation function, or deflation function) identifies a boundary or a frontier technology, which contains all observation on one side of the frontier and minimises a suitable measure of the total distance of all 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, 1970), its application became popular only in the recent years by the works of Rolf Färe, Shawna Grosskopf and others. 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), 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., the production, cost, revenue and profit function is its computation requiring 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 abatement costs 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 organized 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 3 highlights the procedure for the empirical estimation of the model while Section 4 provides information on the data used and also discusses the estimation procedure. The estimated results are presented in Section 5. The final Section 6 concludes by summarizing the main results of the study.

2. 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 generalizes 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

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

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[2] on the output distance function some of which are as follows:

1. $D_o(0, y) = +\infty \; for \; y \geq 0,$ i.e., there is no free lunch. To produce outputs one requires inputs.
2. $D_o(x, 0) = 0 \; for \; all \; x \; in \; R_+^N$, i.e., inaction is possible. No output is possible from positive inputs.
3. $x' \geq x \; implies \; that \; D_o(x', y) \leq D_o(x, y),$ i.e., more the inputs the less efficient would the production be.
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*.

Of particular interest for our purpose is the disposability properties of the technology with respect to the 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 $v \leq y \in P(x) \; implies \; v \in P(x)$.

Let $r = (r_1, r_2, \ldots\ldots r_M)$ denote the output price vector. Using the output set concept we can now define the revenue function in the lines of Shephard (1970), and Färe and Primont (1995) as

$$(iii)\ldots\ldots \; R(x, r) = \max_y [ry : \; y \in P(x)]$$

The revenue function describes the maximum revenue that can be obtained from a given technology at the output price ***r.*** The revenue function, like the distance function, completely describes the production technology. Shephard (1970) showed that the revenue function and the output distance function are dual to one another. So,

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[2] For detailed descriptions of these properties refer to Färe (1988).

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

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

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 both the revenue and distance functions are differentiable. We follow the methodology used by Färe et al (1993) to derive the shadow price of the undesirable output. Let m' output be the undesirable output. In order to derive the shadow price of the undesirable output it is assumed that the price of at least one of the desirable output (say, the m^{th} output) is known and is equal to its shadow price, r_m^o. Then the absolute shadow price $r_{m'}$ of the m' output can be computed as

$$(vi)\ \ldots\ldots\quad r_{m'} = r_m^o * \frac{\partial D_o(x,y)\big/\partial y_{m'}}{\partial D_o(x,y)\big/\partial y_m}$$

As can be seen from equation *(vi)*, the shadow price of the m' output (the undesirable output) is given by the product of the market price of the m^{th} output (the desirable output) and the marginal rate of transformation. 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 between the outputs. 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 *(vi)* is based on the assumption that the production is occurring 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 one can 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 the output distance function is homogeneous of degree one in outputs and therefore its derivatives with respect to the outputs as shown in equation *(vi)* are homogeneous of degree zero. Thus, 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 of the inputs and outputs - both desirable and undesirable (Kwon and Yun, 1999).

3. The Empirical Model

The present study uses the deterministic parametric method[3] 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. Thus, the objective is to estimate the shadow price of reducing CO_2 emissions (the undesirable output) expressed in terms of the value of electricity generation (the desirable output) foregone for a sample of coal fired thermal power plants in India 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 $D_o(x, y)$ as a translog function, as has been followed in the literature (see studies by Althin, 1994; Färe et al, 1993). Thus,

$$(vii) \ldots\ldots \ln D_o(x,\ y) = \alpha_o + \sum_{n=1}^{N} \beta_n \ln x_n + \sum_{m=1}^{M} \alpha_m \ln y_m + 0.5 * \sum_{n=1}^{N} \sum_{n'=1}^{N} \beta_{nn'} \ln x_n \ln x_{n'}$$

$$+ 0.5 * \sum_{m=1}^{M} \sum_{m'=1}^{M} \alpha_{mm'} \ln y_m \ln y_{m'} + \sum_{n=1}^{N} \sum_{m=1}^{M} \gamma_{nm} \ln x_n \ln y_m$$

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

In the above equation *(vii)*, $x = (x_1, x_2, \ldots\ldots x_N)$ denotes the 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 $y = (y_{i+1} \ldots\ldots y_M)$ represent the undesirable outputs. In our empirical

[3] 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.

model fuel (F), capital (K) and labour (L) are the three inputs while the outputs consists of desirable output, electricity (Y) and undesirable output, CO_2 emitted by the power plants. We introduce a time variable t in the model to reflect technical change. In order to reduce the number of parameters to be estimated the terms of the products of time variable and logarithms of other variables are excluded by assuming a neutral technical change.

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

$$(viii)\ldots\ldots\ \ln D_o^k(x,y) \le 0 \qquad \forall\, k = 1,2,......,K.$$

where $k = (1,2,......,K)$ indexes individual observation. By adding a non-negative error term, one can write equation *(viii)* as

$$(ix)\ldots\ldots\ \ln D_o^k(x,y) + \varepsilon^k = 0$$

where ε, $(\varepsilon \ge 0)$ denotes the non-negative residual or the error term.[4] Next we choose the 'fitting' criterion to be the *minimum absolute error* (MAE), i.e., $\sum_{k=1}^{K} \left|\varepsilon^k\right|,\ \varepsilon^k \ge 0$. The MAE fits $\ln D_o(x,y)$ 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:

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

where $k = (1,2,......,K)$ indexes individual observation. $\ln D_o(x,y)$ has an explicit functional form as given by equation *(vii)*. We assume that the first i outputs are desirable while the remaining $(M-i)$ outputs are undesirable or bad outputs. The 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., $\ln D_o(x^k, y^k)$ will be less than or equal to zero and the expression $[\ln D_o(x^k, y^k) - \ln 1]$, which denotes the deviation from the frontier for observation k will be less than or equal to zero.

[4] It may be noted that in the literature the non-negative error term is interpreted as the reciprocal of Farrell output based technical efficiency index.

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

$$(xi) \ldots\ldots \ln D_o(x^k, y^k) \leq 0, \quad k = 1, \ldots\ldots, K$$

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

$$(xii) \ldots\ldots \frac{\partial \ln D_o(x^k, y^k)}{\partial \ln y_m^k} \geq 0, \quad m = 1, \ldots\ldots, i; \quad k = 1, \ldots\ldots, K$$

The constraint above ensures that the shadow prices of the desirable outputs are non-negative. In addition it is assumed that both the 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 *(xiv)* and the symmetry conditions represented by equation *(xv)* are being imposed. Therefore, one requires no additional constraints when the restrictions denoted by equations *(xiv)* and *(xv)* are imposed (Kwon and Yun, 1999).

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 the undesirable output:

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

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

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

$$(xv) \ldots\ldots \alpha_{mm'} = \alpha_{m'm}, \quad \beta_{nn'} = \beta_{n'n}, \quad \textit{for all } m, m', n \textit{ and } n'$$

Equations *(x)-(xv)* represent the model we shall use to derive the shadow prices of the undesirable output. The model is solved using the GAMS programming tool.

4. Data and Estimation Procedure

The empirical analysis is based on primary data collected from the coal fired thermal plants under the Calcutta 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.[5] We have collected detailed data on inputs and outputs for the years 1990-91 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, 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 on the other. Moreover, there are also plants that 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 inputs, outputs and prices of one of the desirable output is needed for our analysis.

Inputs: The main inputs needed for generation of electricity by the thermal plants are fuel, capital and labour. The major fuel input needed by the 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 stabilization 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 pertaining to coal and fuel oil consumed by the power plants are converted from their respective units to *tonnes of oil equivalent* (See Box 1 for conversion factors) 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: India, Ministry of Petroleum and Natural Gas (MPNG), (various years), *Indian Petroleum and Natural Gas Statistics,* (New Delhi: MPNG, various years).

The other important inputs in the generation of electricity are capital and labour. In the present study we have used the 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 plant is the desirable output and is measured in Megawatt hours (Mwh), CO_2 emission is the bad 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 the byproduct of electricity generation, and thus is considered as the undesirable output. The present study considers carbon dioxide as the only undesirable output. The 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 the consumption of coal and fuel oil or LDO, the emission factors of various fuels given by IPCC (1995) was used to derive plant wise total CO_2 emissions. We 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 the calorific values of different grades of coal consumed by the

[5] 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

power plants were incorporated and the CO_2 emission factors for coal provided by the IPCC were adjusted accordingly.[6]

The descriptive data on the inputs and outputs are given in Table 2 below. 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, in order 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 for their respective plants for the different years.

It should be noted here that as the data on CO_2 emission used in the present exercise is generated from the consumption of fossil fuels by the thermal plants it cannot be used for econometrically estimating the output distance function. Hence the present study uses the deterministic linear programming technique to derive the shadow prices of undesirable output.

As mentioned the sample consists of plants of different vintages, some are new and use 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

Titagarh TPS, Southern TPS and Budge-Budge TPS under the CESC.

[6] 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 the coal consumed by the plants under consideration. In order to capture the grade differential while

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[7] 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.[8] 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}	0.002092	0.001522
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.

estimating CO_2 emissions from the burning of coal the emission factors provided in the IPCC reference manual are adjusted accordingly.

[7] A Dummy Variable assuming values $D = 1$ for dirty plants and $D = 0$ for plants which are cleaner is incorporated in Model-2

[8] In Model-2, as per our formulation, Titagarh TPS, Bokaro TPS 'A', Durgapur TPS, and Chandrapura TPS fall under the category of dirty plants while the remaining thermal plants are considered as cleaner plants.

5. Results

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

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 unity, while the remaining 61 observations, for which the value of the output distance function is less than one, lie inside it. Similarly, in Model-2, 17 observations lie on the frontier of the output set and have value of the distance function as unity and the remaining 59 observations lie inside the frontier. On an average the mean value of the output distance function for the sample of thermal plants in Model-1 is estimated to be 0.9669 with standard deviation 0.0356. This means that the 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 estimated to be 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 estimated to be Rs. 3380.59 per tonne in case of Model-1 and Rs. 2401.99 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 their CO_2 emission by one tonne, they will have to forego electricity output worth Rs. 3380.59 in Model-1 and Rs. 2401.99 in Model-2. It should be noted here that these shadow prices or the marginal abatement costs of CO_2 are at constant 1990-91 prices. There is a wide variation in the mean values of the output distance function and the marginal abatement cost 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 is a considerable scope of increasing the 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 abatement costs of CO_2 across years as is seen in Table A3 in the appendix.

In both the models there is wide variation in the marginal abatement cost across plants. Even for a particular plant there are variations in the shadow prices across different years (Refer to Tables A4 and A5 in the Appendix). The wide variation in the marginal abatement costs or the shadow prices of CO_2 can be explained by the 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. The variations in the marginal abatement costs by plant have an important implication in evaluating the cost effectiveness of the current environmental policies in India. These differences in the marginal abatement costs across plants are important because of their policy implications. They suggest, per se, the current pollution control regulations in the country 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.

It would be meaningful to statistically test whether the equi-marginal principle is satisfied for power generation sector in the country. To secure a minimum number of observations for a statistical test, we divide the sample into two periods of 1990-91 to 1994-95 and 1995-96 to 1999-00. The hypothesis to be tested is that the marginal abatement costs for CO_2 are same within the sub-samples. For this end, after ordering the marginal abatement costs for CO_2, we separate each sub-sample into two groups of high and low marginal abatement costs. Using a *t*-test, we test whether the mean of high-cost group is different from that of low cost group. The results of the test are shown in Table 5. From Table 5 it is evident that for both the sub-samples, the hypothesis is rejected at 1 per cent level of significance, thereby implying that the equi-marginal principle does not hold for environmental regulations pertaining to CO_2 emission in the Indian power generation sector. Thus, the CO_2 emission reduction is not being achieved in the least cost way.

Table 5: Test results for cost-effectiveness

Period	*t*-value	
	Model-1	Model-2
1990-91 to 1994-95	4.280	4.017
1995-96 to 1999-00	6.339	7.030

We define the ratio of total CO_2 emissions to electricity generation as our index of efficiency. As per the definition an efficient plant is associated with a lower value of this ratio because it would emit less of CO_2 per unit of electricity output generated. In other words the higher the ratio the less efficient the plant is and vice-versa. On the basis of the index of efficiency and the estimated shadow prices, the present study gets the expected result that the higher efficiency is associated with a higher value of the shadow price of CO_2. This means that the marginal cost of abating CO_2 emissions is high for a clean and efficient plant while for a dirty and inefficient plant it is low. The estimated relation between the estimated shadow prices and the efficiency index is given in Table 6.

Table 6: Impact of Efficiency Index on Marginal Abatement Cost

Variable	Model-1	Model-2
Dependent Variable: *log(shadow price of CO_2)*		
Explanatory Variables:		
log(CO_2 emission/power generation)	-1.379 (-7.16)	-3.689 (-8.34)
constant	7.758 (80.78)	5.232 (17.58)
envt_dummy		3.942 (9.02)
R^2	0.748	0.668
Adjusted R^2	0.717	0.629
N	75	76

Note: Figures in parenthesis are t-values.
Plant dummies have been used in estimating both the regressions but are not reported while presenting the results.

From the estimated relationship between the marginal abatement costs and efficiency index one can infer that, for the sample of thermal plants, the marginal cost of abatement of CO_2 increases with the increase in the efficiency of the plant. That is, 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, the higher will be the cost of reducing an additional unit of the pollutant and vice-versa.

6. 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. These studies mainly relate to water pollutants like BOD (biological oxygen demand), COD (chemical oxygen demand), and SS (suspended solids) (Refer to studies by Murty and S. Kumar 2001, 2002). The present study is one of the few to use 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 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 technique 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 to derive the shadow prices of the pollutants using the output distance technique. Appendix Table A6 displays the results of some of the studies that use the output distance function 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, 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 etc. This type of information would be helpful for policy makers in designing or formulating policies to reduce carbon dioxide emissions.

Economic theory suggests that equalization of the marginal cost of abatement across the firms would minimise the total cost of abating the pollutants at an aggregate level. The results of the study reveal that the estimated shadow prices of CO_2 vary across plants. The estimated mean values of the 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 is Rs. 3380.59 per ton of CO_2 as per model-1 and Rs. 2401.99 per ton of CO_2 as per model-2. Considerable differences in the plant specific shadow prices point towards inefficient use of abatement technology by the thermal plants in the country. One can also infer from the study that the command and control measures are not successful in controlling pollution in this sector thereby building a case for consideration of various economic instruments like pollution taxes, input taxes or tradable pollution permits to control pollution. As the marginal abatement costs vary considerably across plants it implies that the current environmental regulations in India do not achieve cost minimisation condition. Therefore it would be expected that the introduction of environmental/pollution taxes, input taxes or tradable pollution permits which are highly market oriented and incentive-based would achieve reduction in social costs.[9]

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 the results of the study indicate that there exists a direct correlation between the two. This implies that a relatively efficient plant is associated with a higher marginal cost of abating CO_2. In other words, it becomes increasingly difficult for a plant, which emits less CO_2 per unit of its good output to reduce an additional unit of CO_2 vis-à-vis plants that are less efficient and hence emit more CO_2 per unit of good output. That is, the marginal abatement cost increases with the efficiency of the thermal plant.

[9] In order to predict the amount of cost savings by these market oriented policies, it would be necessary to analyse further the extent to which the costs related to reducing pollution emissions would be decreased compared to the current level due to the introduction of these policies.

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
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 out 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(1996)	1990-92	Coal Burning Utilities in Wisconsin	-	$175.7 - $326.7	-	-
Gollop and Roberts (1985)	1973-79	Fossil fueled electric generation in US	-	$141 - $1226	-	-
Kwon and Yun (1999)	1990-95	Bunker-C and coal power plants in Korea	$2.38	$194.1	$91.69	$ 9676.44
Kumar (1999)	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

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