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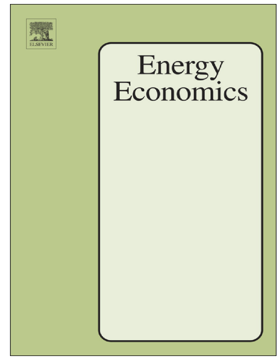

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CO_2 Mitigation Policy for Indian Thermal Power Sector: Potential Gains from Emission Trading

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Abstract
This study shows potential cost savings by adoption of emission trading in India. At the Paris Agreement, India pledged to reduce CO_2 emissions intensity by about 30-35 percent by 2030 relative to 2005. Applying joint production function of electricity and CO_2 emissions, we find that India could have saved about US$ 5 to 8 billion, if she had constituted an emission trading system, with the provision of banking and borrowing over the study period of 5 years. To our knowledge, this is the first study measuring foregone gains due to absence of a nationwide carbon emission-trading program in coal fired thermal power sector, using an ex-post analysis.

JEL Classification: Q54; Q56; O13

Key Words: CO_2 Emission trading; India; Technical Efficiency

1. Introduction

At the Paris Agreement in 2015, India pledged to reduce CO_2 emissions intensity[1] by about 30-35 percent by 2030 relative to 2005. Coal based electricity generation sector, with an installed capacity of 222 GW, accounts for about three-fourth of total electricity generation (Central Electricity Authority [CEA], 2018) and will remain dominant source of power generation in India. This sector contributes to about half of the total CO_2 emissions generated in the country (CEA, 2013). Therefore, if India is to achieve the targets announced at the Paris agreement, it is imperative to find cost effective measures of reducing CO_2 emissions in this sector. Carbon pricing is economically the most efficient strategy for reducing the emissions (Aldy and Pizer, 2015; Managi, 2015; Schmalensee and Stavins, 2017). The Paris Agreement offers avenues for new market-based approaches such as emission trading, to countries for realizing their Nationally Determined Contributions (NDCs).

Emission trading, popularly known as cap-and-trade program, is one of the ways of putting price on pollution, the other being taxation. Given the heterogeneity in abatement costs, market-based instruments, such as emission trading, accomplish the targeted emission levels cost effectively, by equalizing marginal abatement cost across the polluters (Carlson et al., 2000). An emission-trading program offers an opportunity to thermal power plants to realize regulatory compliance at lower costs, as compared to CAC regulatory mechanism, by purchasing rights to emit CO_2 emissions from the plants facing lower abatement costs. Moreover, inter-temporal trading of emissions equalizes marginal abatement costs, not only spatially but also inter-temporally, and thus, further reduces the abatement costs. Note that given the flexibility in regulatory compliance with least cost, investments in technology or procedures flow to the plants having low abatement costs (Chan et al., 2012; Goulder and Schein, 2013).

The first full-fledged successful application of emission trading program was undertaken in the form of US Clean Air Act of 1990 to limit sulfur dioxide emissions. During the period of 1990 to 2007, the US electricity plants could reduce sulfur dioxide emissions by 79 percent, while increasing electricity production by 26 percent, with about 15 to 90 percent savings in abatement costs relative to other policy options (Schmalensee and Stavins, 2013). Moreover, trading brought down the abatement costs over time, through incentivizing innovations (Popp, 2003; Kumar and Managi, 2010; Bellas and Lange, 2011). European Union - Emission Trading Scheme (EU-ETS), covering CO_2 emissions from different industries including power sector across 27 countries, and many smaller programs have sprung up across the world (Grubb, 2012).[2] China has also announced launching of a nationwide cap-and-trade program by 2020, covering about 5 Gt of CO_2 emissions, to harness the benefits of markets in realizing the environmental goals.

Formulation of cost-effective environmental policy and pricing pollution mechanism require estimates of opportunity abatement costs of reducing emissions. Earlier attempts, measuring cost savings from emission trading in comparison to CAC

[1] CO_2 intensity is measured as CO_2 emissions per unit of gross domestic product (GDP)
[2] According to the recent World Bank's Report on 'State and Trends of Carbon Pricing 2018' there are 51 implemented or scheduled carbon pricing initiatives worldwide, covering about 15 percent of the global CO_2 emissions.

strategies, include Atkinson and Tietenber (1991), Kerr and Maŕe (1998), Carlson et al. (2000), Newell and Stavins (2003) among others. These studies conclude that emission-trading programs resulted in substantial savings in abatement costs relative to CAC regulatory mechanism. We note that the actual costs of compliance under trading were higher than the efficient cost of compliance due to presence of significant transaction costs.

Previous ex-post analysis, for estimating unrealized gains of foregone trading, use joint production framework, with the assumption of weak disposability of bad outputs. Färe et al. (2013, 2014) employ the framework to calculate the maximum production of electricity for the US coal burning power plants for the period 1995 – 2005, with observed level of bad outputs, under three different policy scenarios i.e., CAC, spatial trading, and spatial and temporal trading, to demonstrate the unrealized gains from foregone trading under the existing regulatory trading system.[3] Following Färe et al. (2013, 2014), recent studies have attempted to estimate the gains of foregone emission trading in China (e.g., Wang et al., 2016; Wang et al., 2016; Xian et al., 2019)

Studies, estimating opportunity cost of carbon mitigation in India, are limited. To our knowledge, only two studies have estimated the shadow prices of CO_2 emissions (Gupta, 2006; Jain and Kumar, 2018). Gupta (2006) estimates the shadow price of CO_2 emissions using output distance function, a radial measure of efficiency. Jain and Kumar (2018) estimate the shadow prices for the period of 2000 – 2013 using directional output distance function. Both the studies use parametric linear programming approach for estimating output distance function and directional output distance function respectively.

We estimate potential gains of emission trading using a sample of 45 coal fired thermal power plants for the period 2008 – 2012. The required information for estimating the abatement costs is gathered soliciting the Right to Information (RTI) Act 2005[4] and the publications of Central Electricity Authority (CEA) and Central Electricity Regulatory Commission (CERC).

We apply joint production of electricity and CO_2 emissions framework for estimating technical efficiency of power plants under different nested and non-nested models. Non-nested estimates of technical efficiency provide an idea about potential increase in electricity production if the power plants were not required to reduce carbon emissions. The nested models under different policy scenarios such as CAC, spatial trading of emissions and spatial and temporal trading of emissions determine potential to increase electricity production while maintaining observed aggregate levels of emissions. Comparison of potential increase in electricity production under nested and non-nested models reflects the abatement costs of reducing carbon emissions under different policy scenarios. Differences in potential to increase electricity production, under trading programs relative to CAC mechanism for a given level of aggregate emissions, demonstrate the unrealized gains of foregone emission trading relative to existing or CAC system.

[3] Färe et al. (2013, 2014) consider the existing trading system as CAC and compare it with an efficient trading systems.
[4] Right to Information (RTI) Act 2005 mandates time bound reply to citizen appeals for government information. (http://righttoinformation.gov.in/).

We find that the sample thermal power plants in India had to incur an abatement cost of US$ 3.23 billion to reduce CO_2 intensity, under business-as-usual scenario (CAC), which is about 3 percent in this study period. However, the plants could have accomplished the business-as-usual level of the intensity at an abatement cost of US$ 1.05 billion and US$ 0.55 billion, if they were allowed to trade the emissions spatially and spatially and temporally, respectively among themselves. Interpolation of abatement costs for the entire thermal power sector shows that India could have saved more than US$ 5 billion if she had constituted an emission trading system with the provision of banking and borrowing over the study period of 5 years.[5] To our knowledge, this is the first study measuring foregone gains due to lack of a nationwide carbon emission-trading program in Indian coal fired thermal power sector using an ex-post analysis.

The rest of this paper is structured as follows: Section 2 provides a brief introduction of the coal fired electricity generation and carbon mitigation policy followed in the country. Section 3 describes the framework followed for estimating opportunity abatement cost. In Section 4, we present and discuss the data and results. Section 5 concludes the paper.

2. Coal Fired Electricity Generation and Carbon Mitigation Policy in India

There are about 309 billion tons of coal reserves (mostly sub-bituminous) in India[6]. The share of coal-based electricity generation capacity has consistently been around 55 percent during this period. The share of coal-based sector in total electricity generation has increased from around 42 in 1947 to 75 percent in 2017. Domestic coal, although cheaper than imported coal and natural gas, has low fixed carbon and high ash contents. Indian thermal power plants rely more on domestic coal.

Coal-fired electricity generation and the associated CO_2 emissions increased by 71 and 55 percent, respectively during 2005 - 2013 in India (Table 1).[7] This reflects a declining trend in CO_2 intensity of electricity generation by about 10 percent over the period, though there is no formal policy for reducing the emissions in the sector. The reduction in emissions involves costs in terms of changing fuel-mix or/and changing production processes.

India's emission reduction policies are largely based on command and control (CAC) mechanism. Ministry of Environment, Forests and Climate Change is the nodal agency for control of pollution and setting up of standards for emissions from thermal power sector in India. While no standards have been set for CO_2 emissions, rigid emission standards for emission of SO_2, NO_x and particulate matter exist in India. These norms are comparable with emission norms in USA, European Union and

[5] The sample plants constitute about 50 percent of the thermal electricity generation in the country during 2008 – 2012.
[6] Statistical Yearbook 2018, Ministry of Statistics and Programme Implementation, accessed from mospi.gov.in
[7] Information on thermal power plants is available on financial year basis in India, starting April of a year and closing in the March of following year. Therefore, 2005 refers to April 2005–March 2006 and 2013 refers to April 2013–March 2014.

China. Besides, there are norms for ash content in the coal used in coal-based thermal power stations. CO_2 and local pollutants may be related to each other (Kumar and Managi, 2011; Färe et.al. 2012).[8]

A National Action Plan on Climate Change (NAPCC) was prepared by India in 2008 to make policies for climate mitigation and adaptation. As a part of implementation of the plan, the country has put forward a very ambitious targets to increase carbon efficiency and the share of renewable in the energy production All the coal fired thermal power plants are making efforts to increase energy efficiency so as to reduce coal consumption, thereby resulting in reduction in the emissions per unit of electricity. This has been achieved by addition of units of higher capacity, which are lower in carbon intensity as compared to units of lower generation capacity (Jain and Kumar 2018).

India was not required to reduce carbon emissions under the Kyoto Protocol, but at the Paris Agreement the country has pledged to reduce CO_2 intensity of GDP. Reduction in the proposed level of the intensity under business-as-usual scenario requires taking some regulatory measures. Use of market-based instruments, such as carbon emissions trading program, can be cost-effective measures for achieving the targets pledged at the Paris Agreement. The Government of India has taken some initiatives to discourage the generation of CO_2 emissions. A sort of carbon tax known as Clean Energy Cess of Indian Rupees (INR) 50 (about US$ 0.75) per ton on consumption of coal and lignite was introduced in 2010-11. This tax was further increased to INR 400 (more than US$ 6) per ton in 2016-17.[9] Further, Perform, Achieve and Trade (PAT) program of energy efficiency and renewable energy certificates (REC) are market based regulatory steps to price the carbon emissions.

We consider that the prevailing CO_2 emission reduction policy, though formally absent, follows a command and control (CAC) regulatory framework. We intend to provide estimates of potential or unrealized gains from emission trading in terms of mitigation cost saving, if the plants were regulated under spatial or/and temporal emission-trading programs in place of CAC mechanism. These estimates are useful for formulating a policy of carbon pricing in the coal fired thermal power sector in India.

3. Opportunity Abatement Cost Estimation

Assume that a coal-fired electricity generating plant produces a vector of good outputs $y = (y_1, \dots \dots, y_M) \in \Re_+^M$ and bad outputs (emissions) $b = (b_1, \dots \dots, b_J) \in \Re_+^J$ using a vector of inputs $x = (x_1, \dots \dots, x_N) \in \Re_+^N$. An output set represents the environmental production technology; and the output set is defined as:

$$P(x) = \{(y, b): x \; can \; produce \; (y, b)\}, x \in \Re_+^N \tag{1}$$

[8] Year-wise plant level data for local pollutants was not available for the study period.
[9] With effect from July 01, 2017, the Clean Energy Cess has been replaced by a GST Compensation Cess at the rate of INR 400 per metric ton of coal and lignite consumption. (http://www.cercind.gov.in/2018/orders/13SM.pdf as accessed on July 22, 2019)

The output set defines that a given vector of inputs produce combinations of good and bad outputs and the output set satisfies the standard axioms of compactness[10] and free disposability of inputs (Färe et al., 2005). Moreover, as the output set consists of both good output (electricity) and bad output (emissions), it satisfies the axioms of *null-jointness* between good and bad outputs, and good and bad outputs are jointly weakly disposable.[11]

The axiom of *null-jointness* indicates that a coal fired thermal power plant, while generating electricity, certainly produces CO_2 emissions, i.e., $if\ (y, b) \in P(x)\ and\ b = 0, then\ y = 0$. Similarly, the axiom of weak-disposability of CO_2 emissions suggests that reduction in CO_2 emissions involves simultaneous proportional reduction in generation of electricity: $if\ (y, b) \in P(x)\ and\ 0 \leq \alpha \leq 1, then\ (\alpha y, \alpha b) \in P(x)$. However, production of less electricity without reducing bad outputs is possible: $if\ (y, b) \in P(x), then\ for\ y_0 \leq y, (y_0, b) \in P(x)$.

Using conventional production function, we assume that a thermal power plant produces only one good output. In view of $y \in \mathfrak{R}_+^M$, an environmental production function is defined as:

$$F(x; b) = \max\{y: (y, b) \in P(x)\} \quad (2)$$

The function $F(x; b)$ exists as $P(x)$ is non-empty and compact. $F(x; b)$ is non-decreasing in inputs. The axioms of weak disposability of emissions and *null-jointness* suggest that an environmental production function satisfies the following conditions:

$$if\ y \leq F(x; b)\ and\ 0 \leq \alpha \leq 1, then\ \alpha y \leq F(x; \alpha b) \quad (3)$$

and

$$F(x; 0) = 0 \quad (4)$$

Equation (3) implies a proportional reduction in good and bad outputs and equation (4) infers essentiality of carbon emissions in production of electricity, given the *null-jointness* axiom.

Since electricity is freely disposable, $y \leq F(x; b);\ y$ is feasible and the output set can be recovered by defining:

$$P(x) = \{(y, b): y \leq F(x; b)\} \quad (5)$$

This shows that an environmental production function completely characterizes a single good output environmental production technology and is considered a special case of environmental directional distance functions (Färe et al., 2007). However, note that this production function does not directly credit a producer for reduction in emissions but an environmental directional distance function does. An environmental

[10] A closed and bounded set is known as a compact set.
[11] Forsund (2009) and Murty et al. (2012) show that such kind of technology which assume weak disposability of bad outputs fails to account for material balance conditions.

production function maximizes the production of good output only for an observed level of inputs and bad outputs.

Using data envelopment analysis (DEA), we assume a common production technology followed by each of the thermal power plant that maximizes production of electricity. Consider there are $k = 1,2, \ldots\ldots, K$ thermal power plants producing good output and bad outputs using a vector of inputs, i.e. (y^k, b^k, x^k), $k = 1, 2, \ldots\ldots, K$, is a production vector. Considering weak disposability of emissions, we assume a regulated production function for observation k' as:

$$\max_{\tilde{y}^t, z^t} \tilde{y}_k^t, \; for\ each\ t = 1, 2, \ldots\ldots, T \qquad (6)$$

Subject to

$$\sum_{k=1}^{K} z_k^t y_k^t \geq \tilde{y}_k^t,$$
$$\sum_{k=1}^{K} z_k^t b_{kj}^t = b_{kj}^t, \quad j = 1,2, \ldots, J$$
$$\sum_{k=1}^{K} z_k^t x_{kn}^t \leq x_{kn}^t, \quad n = 1,2, \ldots, N$$
$$z_k^t \geq 0 \qquad k = 1,2, \ldots\ldots, K$$

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Deleted: .¶ .¶ Power Plant K $\sum_{k=1}^{K} z_k^{Kt} y_k^t \geq \tilde{y}_K^t$,¶ $\sum_{k=1}^{K} z_k^{Kt} b_{kj}^t = b_{Kj}^t$, $j = 1,2, \ldots, J$¶ $\sum_{k=1}^{K} z_k^{Kt} x_{kn}^t \leq x_{Kn}^t$, $n = 1, 2, \ldots, N$¶ $z_k^{Kt} \geq 0$ k = 1, 2,….., K¶

where z_k $(k = 1,2, \ldots, K)$ are the intensity variables or the weights assigned to each observation in construction of production possibility frontier. Moreover, we assume constant returns to scale.[12] Maximization occurs over z_k^t and $\tilde{y}^t$ for the observed levels of bad output and inputs.[13]

To ensure *null-jointness* in good and bad outputs, we impose following conditions:

(a) $\sum_{j=1}^{J} b_{kj} > 0, \quad k = 1,2, \ldots, K$

(b) $\sum_{k=1}^{K} b_{kj} > 0, \quad j = 1,2, \ldots, J$

i.e., each row and column have at least one positive element which is confirmed by the data.

Contrary to a regulated production technology, in an unregulated technology, bad outputs are freely disposable. In a case of free disposability of bad outputs, the equality constraint on bad outputs in equation (6) is replaced by an inequality constraint of greater than equal to (≥) sign.[14]

The weak disposability condition implies that reduction in CO_2 emissions requires reduction in the production of electricity. Abatement cost of reducing the emissions can be defined as a ratio of maximum good output produced under regulated to unregulated production conditions. If this ratio is equal to one, it implies that

[12] Variable returns to scale can be imposed by restriction $\sum_{k=1}^{K} z_k = 1$, and non-increasing returns to scale by restriction the condition to $\sum_{k=1}^{K} z_k \leq 1$, along with the non-negativity of z_k.
[13] The tilde (~) over the y and b indicates that these are choice variables.
[14] It is a well known fact that technologically there is a positive relation between the production of good and bad outputs, irrespective of the state of regulation. Under regulation, to internalize the emissions effect, the good output is reduced for reducing emissions and in an unregulated situation more of good output is produced simultaneously producing more of bad outputs. We thank one of the reviewers for pointing out this important concern. However, we use free disposability condition (a counter-intutive case), following Färe et al. (2016), to estimate absolute cost of emission reduction under CAC regime.

regulation of emissions is not affecting the production possibility of marketed output, and if it is less than one it indicates that emission reduction is costly (Färe et al., 2016). Alternatively, cost of emission reduction is computed as a difference in maximum production of good output under unregulated and regulated conditions. While computing the abatement cost in this manner it is assumed that each of the thermal power plant meets its emission reduction target by abating its emissions. This kind of emission abatement framework is described in the literature as a command and control (CAC) environmental policy and difference in maximum good output produced under unregulated and regulated conditions is termed as the cost of abatement under CAC regime.

Emission trading equalizes marginal abatement cost across polluters, while maintaining the aggregate limit. Intra-temporal or spatial trading warrants that in each of the time-period aggregate observed emissions do not exceed an allowed aggregate emissions limit. Similarly, inter-temporal trading ensures that the sum of observed emissions over a defined period does not exceed the allowed emission quota over that period. Following Färe et al., (2013, 2014), we compute maximum output of electricity under the scenarios of spatial and inter-temporal industry-wide emission trading. Comparisons of maximum good output produced under unregulated to spatial and inter-temporal trading scenarios provide estimates of pollution abatement costs under these scenarios. Differences in abatement costs under different regulation regimes indicate the benefits of concerned regulatory systems.

In spatial emission trading, an aggregate allowed pollution level is introduced, which is equal to or less than an observed aggregate pollution level in a particular year, i.e., $\sum_{k=1}^{K} b_{kj}^{t} \leq B_j^t$, where B_j^t is an aggregate allowed pollution level. To estimate maximum possible production of electricity in a scenario of spatial trading, the linear program described by equation (6) is solved subject to an additional constraint in the form of allowable aggregate emissions, i.e.,

$$\max_{\tilde{y}^t, z^t, \tilde{b}^t} \sum_{k=1}^{K} \tilde{y}^t \quad for\ each\ t = 1, 2, \ldots\ldots, T \qquad (7)$$

Subject to

Power Plant 1

$$\begin{aligned}
&\sum_{k=1}^{K} z_k^{1t} y_k^t \geq \tilde{y}_1^y, \\
&\sum_{k=1}^{K} z_k^{1t} b_{kj}^t = \tilde{b}_{1j}^t, \quad j = 1,2, \ldots, J \\
&\sum_{k=1}^{K} z_k^{1t} x_{kn}^t \leq x_{1n}^t, \quad n = 1, 2, \ldots, N \\
&z_k^{1t} \geq 0 \qquad \text{k = 1, 2, ….,K} \\
&. \\
&.
\end{aligned}$$

Power Plant K

$$\begin{aligned}
&\sum_{k=1}^{K} z_k^{Kt} y_k^t \geq \tilde{y}_K^y, \\
&\sum_{k=1}^{K} z_k^{Kt} b_{kj}^t = \tilde{b}_{Kj}^t, \quad j = 1,2, \ldots, J \\
&\sum_{k=1}^{K} z_k^{Kt} x_{kn}^t \leq x_{Kn}^t, \quad n = 1, 2, \ldots, N \\
&z_k^{Kt} \geq 0 \qquad \text{k = 1,2, …,K} \\
& \\
&\sum_{k=1}^{K} \tilde{b}_{kj}^t \leq B_j^t, \qquad \text{t = 1, 2, ……,T}
\end{aligned}$$

The solution of linear program (7) yields maximum production of electricity by all of the plants and an optimal allocation of emissions among the plants in the year subject to the maximum permissible emission limit. The maximization occurs over intensity variables, good output and emissions. The difference in the levels of emissions produced by a plant under the optimal allocation of emission permits and observed levels identifies buyers or sellers of emission permits. Difference of maximum possible production of electricity under unregulated and regulated framework, when spatial emission trading is allowed, indicates total abatement cost, and the difference between maximum electricity produced under spatial trading and CAC quantifies the advantages of spatial trading over CAC.

Abatement cost of given limit is further reduced if banking of unused emission permits and borrowing of the permits from future is allowed. The unused permits of one period are saved and used in another period, i.e., reallocation of permits not only takes place between the polluters but also over time. As a result, under inter-temporal trading of emissions, the constraint of aggregate allowable emissions in linear program (7) changes to $\sum_{k=1}^{K}\sum_{t=1}^{T} b_{kj}^{t} \leq \sum_{t=1}^{T} B_{j}^{t}$ i.e. an aggregate allowed pollution level is introduced, which is equal to or less than an aggregate observed pollution level in a particular period. The linear program for an inter-temporal program is:

$$\max_{\tilde{y}^t, z^t, \tilde{b}^t} \sum_{t=1}^{T}\sum_{k=1}^{K} \tilde{y}^{t} \quad (8)$$

Subject to

Power Plant 1
$$\sum_{k=1}^{K} z_k^{1t} y_k^t \geq \tilde{y}_1^t, \quad t = 1, 2, \ldots, T$$
$$\sum_{k=1}^{K} z_k^{1t} b_{kj}^t = \tilde{b}_{1j}^t, \quad j = 1,2,\ldots,J;\ t = 1,\ldots,T$$
$$\sum_{k=1}^{K} z_k^{1t} x_{kn}^t \leq x_{1n}^t, \quad n = 1,2,\ldots,N;\ t = 1,\ldots,T$$
$$z_k^{1t} \geq 0 \quad k = 1,2,\ldots,K$$

.

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Power Plant K
$$\sum_{k=1}^{K} z_k^{Kt} y_k^t \geq \tilde{y}_K^t, \quad t = 1, 2, \ldots, T$$
$$\sum_{k=1}^{K} z_k^{Kt} b_{kj}^t = \tilde{b}_{Kj}^t, \quad j = 1,2,\ldots,J;\ t = 1,\ldots,T$$
$$\sum_{k=1}^{K} z_k^{Kt} x_{kn}^t \leq x_{Kn}^t, \quad n = 1,2,\ldots,N;\ t = 1,\ldots,T$$
$$z_k^{Kt} \geq 0 \quad k = 1,2,\ldots,K$$

$$\sum_{k=1}^{K}\sum_{t=1}^{T} \tilde{b}_{kj}^{t} \leq \sum_{t=1}^{T} B_{j}^{t}$$

The solution of linear program given in equation (8) yields maximum electricity production under the inter-spatial and inter-temporal trading of emissions. It also yields levels of emissions generated by each of the plants when they are allowed, not only spatial trading of emissions but also banking and borrowing over the regulation period. Difference between maximum electricity produced under intra-temporal (spatial) and inter-temporal trading quantifies the advantages of inter-temporal trading over intra-temporal trading of emissions.

4. Data and Results

For estimating the costs of abating CO_2 emissions by the Indian thermal power plants, we need information on the production of electricity and CO_2 emissions along with various inputs such as coal, labour among others. To obtain the information on these outputs and inputs, we utilize Right to Information (RTI) Act and various publications of the Central Electricity Authority (CEA) and the Central Electricity Regulatory Commission (CERC).

We were able to get the required information on an unbalanced panel of 56 coal fired thermal power stations for the period of 1999 – 2013 by invoking the RTI Act. However, we could get the information on a balanced panel of only 45 plants for the period of 2008 – 2012. Out of these 45 plants, 18 plants are owned and operated by the Central government (including 13 by one corporation, National Thermal Power Corporation (NTPC) and the remaining 27 plants are run by various state governments.[15]

To estimate opportunity cost of CO_2 emission mitigation, we employ plant-level information on three inputs: capital, labour and coal, and two outputs: electricity and CO_2 emissions. We measure net electricity generation in gigawatt hours (GWh) and CO_2 emissions in tons. The CEA has been collecting the baseline data in order to facilitate the Clean Development Mechanism (CDM) projects since 2001. Details of CO_2 emissions estimation in the coal fired thermal power sector are given in the User Guide of Baseline Data, published by CEA.[16]

Coal is the primary fuel in electricity generation process in the sample plants and its consumption is measured in tons. We measure labour in terms of wage bill paid during a year; wage bill information is available at current prices and is converted into constant prices using the labour wage index published by the Labour Bureau, Government of India. Capital input is computed following Dhrymes and Kurz (1964).

Table 2 provides the descriptive statistics of the variables for the years 2008 and 2012. We observe that between 2008 and 2012, the average electricity production and CO_2 emissions of sample plants have increased by about 12 and 9 percent. Declining CO_2 intensity of coal fired electricity generation in the country shows that Indian thermal power plants are making efforts for reducing CO_2 emissions.

We solve the above-described linear programs using GAMS program under different policy scenarios to obtain estimates of maximum electricity production in the absence of technical inefficiency.[17] We compute the opportunity costs of emission reductions under two scenarios: aggregate emissions generated each year or over the period of 2008-12 remain constant, and the aggregate emissions are reduced by 10 percent for the given level of electricity generation. Table 3 provides the estimates of opportunity cost of the emissions reduction in terms of reduction in electricity production or revenue foregone. To compute the revenue foregone we use electricity prices observed by the respective thermal power plants at 2004-2005 prices and convert into US$ at an exchange rate of Indian Rupees 70 for one US$.

Table 3 shows that over the period of 2008 – 2012, the sample plants have to forego about 73 billion units of electricity production for reducing CO_2 intensity of electricity generation by about 3 percentage points under CAC regulatory framework.

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[15] For details on the data collection and collation process and variable measurement, see Jain and Kumar (2018).

[16] CO_2 Baseline Database for the Indian Power Sector, User Guide, Version 11.0, April 2016, CEA.

[17] We are very grateful to Carl Pasurka for providing us access to the GAMS program code used in their studies Färe et al. (2013, 2014).

The electricity output foregone increases to about 166 billion units if these plants were required to reduce the emissions further by 10 percentage points. The simulated results show that India spent more than US$ 6 billion for producing the given level of CO_2 emission for the entire coal fired thermal power sector under CAC regulations as we interpolated the estimates of sample plants for the entire coal fired electricity sector. However, the given level of emission intensity could have been achieved if the plants were allowed to trade emission permits within a year among themselves (spatial trading) at an opportunity cost of about US$ 2 billion and this cost could have been further reduced to only US$ one billion, if banking and borrowing of the emission permits were allowed over the study period. The country could have saved about US$ 8 billion under the spatial and temporal trading of emissions in comparison to CAC regulatory framework by further reducing 10 percent CO_2 emissions in entire coal-fired sector. It is worth to note that further reduction in CO_2 emissions is more costly irrespective of the policy scenario; this implies that marginal cost of abatement is increasing at an increasing rate.

We also observe that under spatial-temporal trading, the thermal power plants were not mitigating emissions in the first two years, and they borrowed from the future years expecting some innovations. Similarly, in the last year of study they did very small mitigation and used the banked emissions to comply the targets (Table 3).

Table 4 presents the opportunity cost of emission reduction in terms of electricity output foregone as a percentage of electricity generation for the plants owned by state and central governments separately. Over these five years, average potential abatement costs for obtaining the observed level of emissions are about 4.15, 1.35 and 0.71 percent of electricity generation under the CAC, spatial-trading and spatial and temporal trading of emissions, respectively. It is also observed that the average opportunity cost of abatement was higher for the state sector plants in comparison to the central sector thermal power plants in all these cases. Central sector owned plants get benefited more than the state sector owned plants under trading in the absence of inter-temporal borrowing and banking of emission permits, though the average opportunity cost of abatement is marginally different under inter-temporal borrowing and banking system of emission trading. Under spatial trading of emissions, the state sector abates more than its limit and sells the emission permits to the central sector, but if inter-temporal borrowing and banking of emission permits is allowed, then the state sector pollutes more and complies the regulatory requirements by purchasing emission permits from the central sector (Appendix Table A1). Appendix Table A1 presents the yearly observed and potential levels of electricity and CO_2 emissions at sectoral level under different policy scenarios. If the plants were required to reduce 10 percent more emissions, the state sector would have benefited slightly more from trading in comparison to central sector. Plant size and vintage could be the reasons of differences in the abatement costs between state and central sectors. Generally, the state-owned plants are of small size and old vintages. Note that further reduction in CO_2 emissions does not change the position of the sectors, i.e., state sector remains seller under spatial trading but becomes buyer when the trading is combined with inter-temporal banking and borrowing of emission permits.

Figure 1 presents the temporal pattern of potential abatement costs under different policy scenarios; for the given level of emissions (Panel A) and with 10 percent reduction in CO_2 emissions (Panel B). From the figure, it is evident that the opportunity cost of reducing emissions is consistently higher under CAC regime in comparison to spatial or spatial and inter-temporal trading of emissions (Panel A). Under CAC and spatial trading regimes the opportunity cost was lowest in 2010, but it is highest in 2010 when the plants were required to maintain the observed aggregate level of emissions under inter-temporal trading program.

Figure 2 provides the graphical representation of potential annual increase in electricity generation in the sample plants for the three simulations. For the observed levels of emissions, technical inefficiency attained a minimum in 2009, but in the remaining years, it was about 10 percent. However, technical inefficiency and inefficiency due to sub-optimal allocation of CO_2 emissions attained a minimum in 2009 and the combined inefficiency was highest in 2011 under spatial trading of the emissions. Combined efficiency is lowest in 2010 and then shows increasing trend, when spatial trading is coupled with inter-temporal borrowing and banking of emissions (Panel A). Note that potential to increase electricity production under CAC is lowest in all the three policy simulations, implying that emission-trading programs are beneficial.

Panel B of Figure 2 depicts the presence of inefficiencies under three policy simulations for additional 10 percent reduction in the emissions. Combined inefficiency (technical inefficiency and inefficiency due to sub-optimal allocation of emissions) is higher under spatial-temporal trading of emissions in comparison to spatial and CAC regulatory regimes in the first four years. In 2009, not only technical inefficiency under CAC gets eliminated but also the plants have to give up about two thousand GWh of electricity production if required to remove 10 percent more emissions and it is highest in 2010, and in the years 2011 and 2012 it is about 5 percent. On average, the presence of yearly inefficiency under the three regimes was 3.84, 7.94 and 10.16 percent respectively. This shows that the Indian coal-fired plants can increase electricity production by more than 10 percent by eliminating technical and CO_2 emission allocation inefficiencies even in a scenario when they produce 10 percent less emissions than the observed level. This finding supports Porter hypothesis that properly designed environmental policy can lead to a win-win situation (Porter and van-der Linde, 1995; Murty and Kumar, 2003).

The realization of gains from emission trading during 2008 – 2012 can be explained by reallocation of emission reduction burden of the plants with high environmental inefficiencies and high abatement costs to the plants with low environmental efficiency and low abatement costs. Table 5 reports the five-year average abatement costs estimates at the plant level under different policy scenarios. Among the state sector plants, Bhusawal thermal power plant sacrifices about 23 percent of its electricity generation towards abatement costs under the CAC regulatory regime, but it can comply with the regulatory requirements by doing less abatement on its own and purchasing the right to emit emissions from other plants. Similarly in the central sector, we observe that the thermal power plants of Farakka, Kahalgoan and Chandrapur have to lose more than 10 percent of their electricity generation as abatement costs at the existing level of emissions under the CAC but these plants will be better-off under trading as they can fulfill their obligation under the emission trading program by purchasing the permits from the thermal power plants such as Amarkantak, Rihand, R-Gundam, which are meeting their regulatory requirements at low abatement costs, but they would like to abate more emissions if the trading of emission permits is allowed. Appendix Table A2 reports observed and potential level of electricity and CO_2 emissions at the plant level that help in identifying the buyers and sellers of emissions under the spatial and spatial-temporal trading of CO_2 emissions.

Table 5 also shows that if the plants were asked to remove additional 10 percent emissions, about 25 percent of the plants had to forego more than 10 percent of their electricity generation towards abatement costs under CAC regulations, but if these plants get involved in the purchase of emitting rights from the plants that can abate at low abatement cost, only three plants will be required to forego more than 10 percent under spatial trading and only one plant will be required to forego more than 10 percent under spatial–temporal form of trading. Note that, generally old and small size plants are less efficient and have to incur high abatement cost relative to newer and bigger size plants. For example, Suratgarh is only 10 years old and is of 1450 MW capacity and at the current level of emissions it has zero abatement cost. Similarly, Rihand, which is 15 years old and is of 2000 MW capacity, meets its regulatory requirement at a minimal cost. On the other hand plants such as R-Gundam (62.5 MW), Ennore (450 MW), Neyvell ST1 (600 MW) are about 40 years old and are made of small units and have to incur higher costs for complying with the regulatory requirements.

Above analysis shows the potential and importance of CO_2 emission trading in Indian thermal power sector, i.e., the coal fired power plants can achieve the stated emissions targets at lower costs under trading regime in comparison to each plant facing individual carbon emission reduction burden. The power plants that face relatively high abatement costs could purchase additional emitting rights from low abatement costs plants, thus providing an incentive to each power plant in identifying cost minimizing abatement opportunities.

5. Conclusions

India pledged to reduce CO_2 emissions intensity by about 30-35 percent by 2030 relative to 2005 at the Paris Agreement. Emission trading and emission taxation can accomplish the targeted emission levels cost effectively by equalizing marginal abatement costs across the polluters. This study estimated potential gains of emission trading, using a sample of 45 coal fired thermal power plants for the period 2008 – 2012. The required information was gathered invoking the Right to Information Act and from the Central Electricity Authority and Central Electricity Regulatory Commission.

We use data envelopment analysis (DEA) based linear programming approach to estimate technical efficiency of power plants under different nested models. These models under different policy scenarios such as CAC, spatial trading of emissions and spatial and temporal trading of emissions provide estimates of potential economic gains. Applying joint production of electricity and CO_2 emissions framework for estimating technical efficiency of power plants under different models, we find that India could have saved about US$ 5 to 8 billion, if she had constituted an emission trading system, with the provision of banking and borrowing over the study period of 5 years. Moreover, we find that there is huge potential in Indian thermal power sector to increase electricity production and reduce CO_2 emissions by eliminating technical and allocative inefficiencies, implying presence of win-win potential.

Given the potential benefits of equalizing marginal cost of abatement among emitters, India needs to constitute a system of pricing carbon emissions in the country either through emission taxation or cap and trade system. In a recent paper Robert Stavins provides a comparison of emission taxation and trading approaches to internalize the externalities (Stavins, 2019). In the absence of additional market and government failures and uncertainty in the estimates of marginal abatement costs and benefits, theoretically, both emission trading and taxation schemes have equivalent potential in terms of efficiency and cost effectiveness (Goulder and Schein, 2013). However, in a recent paper Sim and Lin (2018) show that emission trading outperforms emission taxation in an open economy with spatial implications of emission generation in terms of global and domestic welfare. Choice between emission taxation and cap and trade system is generally an issue of choice of design elements along a policy continuum (Stavins, 2019).

To our knowledge, this is the first study measuring foregone gains due to absence of a nationwide carbon emission-trading program in Indian coal fired thermal power sector using an ex-post analysis. This study shows the need for designing an effective carbon market. Our estimates of potential economic gains should be considered as lower bound as these are based on cost saving potential effect of carbon emissions trading within the thermal power sector and do not consider the potential for emission trading among other industries. It should be noted that these estimates of potential gains have not included transaction costs; transaction costs do decrease the potential gains of trading and depend on the designing of carbon trading markets. There is another approach in the literature, known as by-production approach, for estimating the mitigation costs of CO_2 emissions that does not assume null-jointness and jointly weak disposability of good and bad outputs. Future studies can compare the potential gains of emission trading obtained in this study with the gains acquired using the by-production approach.

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Table 1: Trend in electricity generation and CO_2 Emissions from power sector in India

Year	CO_2 (million tons)	Electricity (Billion Units)	CO_2 intensity	CO_2 intensity relative to 2005-06
2005-06	469.7	435.10	1.080	1
2006-07	494.7	461.34	1.072	0.993
2007-08	520.5	486.76	1.069	0.991
2008-09	548.6	512.53	1.070	0.992
2009-10	580.1	539.98	1.074	0.995
2010-11	598.4	561.76	1.065	0.987
2011-12	637.8	612.88	1.041	0.964
2012-13	696.5	691.56	1.007	0.933
2013-14	727.4	746.09	0.975	0.903

Source: Compendium of Environment Statistics-2016

Table 2: Descriptive statistics

Variable	Unit	Obs	Mean	Std. Dev.	Min	Max
2008						
Electricity	Thousand GW	45	6.457	5.463	0.422	24.964
CO_2	Thousand tons	45	6950	5151	470	23965
Coal	Thousand tons	45	5252	3974	334	18045
Labour	INR (millions)	45	5236	3462	76	13199
Capital	Thousand GW	45	7.003	5.260	0.430	24.041
Carbon Productivity	Electricity/CO_2	45	0.87	0.15	0.53	1.15
2012						
Electricity (GW)	Thousan GW	45	7.241	5.983	0.397	24.467
CO_2	Thousand tons	45	7578	5550	448	23467
Coal	Thousand tons	45	5910	4607	359	18920
Labour	INR (millions)	45	5522	3125	260	11329
Capital (GW)	Thousand GW	45	8.400	6.328	0.426	27.361
Carbon Productivity	Electricity/CO_2	45	0.88	0.18	0.46	1.43

Table 3: Potential abatement costs of CO_2 emission reduction for sample plants

Year	Policy-option	No change in aggregate observed emissions		Additional 10% reduction in CO_2 emissions	
		Electricity Units (billions)	2011US$ (billions)	Electricity Units (billions)	2011US$ (billions)
2008	CAC	13.82	0.56	38.26	1.55
	Spatial	6.81	0.28	31.65	1.28
	Spatial-temporal	0.00	0.00	1.29	0.05
2009	CAC	16.11	0.75	41.58	1.93
	Spatial	2.99	0.14	31.97	1.48
	Spatial-temporal	0.06	0.00	0.89	0.04
2010	CAC	8.37	0.38	20.99	0.95
	Spatial	1.79	0.08	8.85	0.40
	Spatial-temporal	6.73	0.30	21.44	0.97
2011	CAC	15.17	0.68	29.19	1.31
	Spatial	2.29	0.10	8.81	0.40
	Spatial-temporal	5.54	0.25	8.43	0.38
2012	CAC	19.13	0.86	35.76	1.61
	Spatial	9.81	0.44	21.31	0.96
	Spatial-temporal	0.07	0.00	39.87	1.80
Overall	CAC	72.60	3.23	165.78	7.36
	Spatial	23.69	1.05	102.59	4.56
	Spatial-temporal	12.4	0.55	71.92	3.20

Note: CAC: command and control; Spatial: intra-temporal emission trading between plants; Spatial-temporal: inter-temporal emission trading between plants. Exchange rate: 1US$=INR70

Table 4: Yearly Potential Abatement Cost (% of electricity generation at frontier) for sample plants

		No change in aggregate observed emissions				Additional 10% reduction in CO_2 emissions			
Sector	Year	CAC	Spatial trade	Spatial-temporal trade	Trade	CAC	Spatial trade	Spatial-temporal trade	Trade
State	2008	3.83	3.18	0.00	S, P	9.58	10.17	0.52	S, P
Centre		4.36	1.07	0.00	P, P	12.93	8.83	0.27	P, P
Combined		4.12	2.03	0.00	N, P	11.41	9.44	0.38	N, P
State	2009	5.30	1.86	0.01	S, P	12.20	14.15	0.52	S, P
Centre		4.35	0.08	0.02	P, P	12.46	5.62	0.05	P, P
Combined		4.78	0.89	0.02	N, P	12.34	9.49	0.26	N, P
State	2010	1.93	0.70	1.79	P, P	6.37	2.80	5.84	P, S
Centre		2.89	0.40	2.14	S, S	6.07	2.47	6.72	S, S
Combined		2.47	0.53	1.99	N, S	6.20	2.61	6.33	N, S
State	2011	4.12	0.94	1.93	P, S	8.16	2.49	2.45	P, P
Centre		4.29	0.39	1.23	S, S	8.07	2.41	2.25	S, P
Combined		4.22	0.64	1.54	N, S	8.11	2.45	2.34	N, P
State	2012	6.01	3.53	0.02	P, P	10.34	5.62	9.26	P, S
Centre		4.30	1.87	0.02	S, P	8.71	5.59	11.40	S, S
Combined		5.03	2.58	0.02	N, P	9.40	5.60	10.48	N, S
State	Average	4.27	2.06	0.75	S, P	9.35	7.01	3.76	S, P
Centre		4.05	0.79	0.68	P, S	9.56	4.95	4.38	P, S
Combined		4.15	1.35	0.71		9.47	5.86	4.11	

Note: CAC: command and control; Spatial: intra-temporal emission trading between plants; Spatial-temporal: inter-temporal emission trading between plants; S: Sell; P: Purchase, and N: no trade. The first digit in column 'trade' is trade under spatial trading and the second digit is for trade under spatial-inter-temporal trading.

Table 5: Plant-level Potential Abatement Cost (% of electricity generation at frontier)

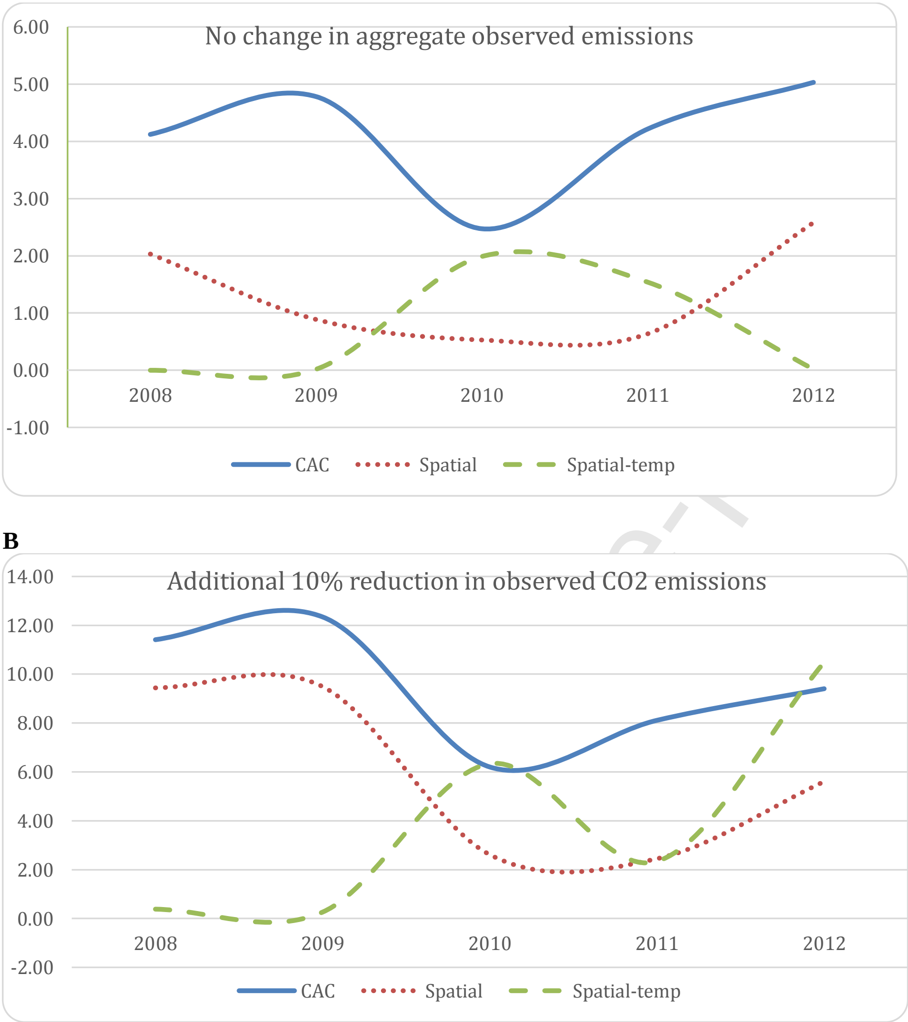
	No change in aggregate observed emissions				Additional 10% reduction in CO_2 emissions			
	CAC	Spatial	Spatial-temporal	Trade	CAC	Spatial	Spatial-temporal	Trade
Rajghat	2.21	0.88	1.99	S, S	6.40	5.74	4.19	S, S
Rayalseema	4.21	1.85	0.88	P, P	8.45	8.79	4.29	S, P
Vijaywada/N Tata Rao	8.91	6.29	1.86	P, P	17.91	8.59	4.29	P, P
Suratgarh	0.00	0.00	0.00	N, N	8.63	5.12	0.00	P, P
Kota	2.51	0.84	0.00	S, S	5.70	9.66	4.13	S, S
Nasik	3.35	1.37	1.21	P, P	8.42	4.97	3.19	, P
K-Kheda II	8.12	1.51	0.03	P, P	12.84	7.84	4.74	P, P
Paras	5.73	2.61	0.58	P, P	9.43	3.70	4.42	P, P
Bhusawal	23.14	1.79	0.41	P, P	28.39	3.17	2.56	P, P
Parli	3.02	1.47	0.84	P, P	5.02	5.86	3.43	P, P
Chandarpur STPS	6.12	2.31	0.72	P, P	11.82	6.16	4.20	P, P
R_GUNDEM – B	0.81	2.99	2.14	S, S	3.42	6.41	4.27	S, S
K_gudem	5.01	0.48	0.73	P, P	9.37	5.12	4.68	P, S
Panipat	1.60	1.07	0.21	S, S	6.36	1.95	4.40	S, S
Ukai	0.93	2.03	1.28	S, S	3.42	6.27	3.85	S, S
Gandhinagar	5.21	1.62	0.71	P, P	8.38	6.05	2.62	S, S
Wanakbori	0.40	1.11	0.00	S, P	8.62	17.97	0.00	S, P
Sikka REPL	0.72	1.44	1.15	S, S	4.31	6.75	3.02	S, S
Kutch Lignite	2.12	0.56	0.56	S, S	6.93	4.58	4.58	S, S
Akrimota Lignite	2.56	0.57	0.28	P, P	8.25	6.26	4.69	P, P
Bandel	1.72	2.50	0.78	S, S	6.79	8.50	3.59	S, S
Ennore	5.16	3.21	1.26	P, P	10.02	6.61	3.21	P, P
Korba-west	1.12	2.99	1.03	S, S	2.50	5.30	3.87	S, S
Korba-East	2.00	1.86	2.02	S, S	6.44	4.84	3.99	S, S
Amarkantak	0.00	14.78	0.00	S, N	7.80	16.90	29.20	S, S
Bhatinda	0.90	1.06	0.65	S, S	3.76	6.45	2.70	S, S
DPL	2.20	3.73	1.26	S, S	6.79	9.45	3.06	S, S
State	4.27	2.06	0.75	P, S	9.35	7.01	3.76	S, P
Tanda	0.84	0.00	2.03	S, S	4.49	4.96	4.07	S, S
Singrauli STPS	1.38	0.18	1.92	P, S	5.66	5.29	4.09	S, S
Rihand STPS	0.01	0.05	0.05	S, S	6.06	4.73	5.04	P, S
Unchahar	0.44	3.13	1.72	S, S	4.35	6.73	3.84	S, S
DADRI (NCTPP)	0.85	1.54	0.30	S, P	4.48	6.19	4.52	S, S
Korba STPS	1.34	0.86	1.65	P, S	6.26	3.32	4.95	P, S
Vindhyachal STPS	1.73	0.39	0.00	P, P	8.29	5.37	4.52	P, P
R-Gundem STPS	0.02	1.32	0.02	S, N	4.91	6.04	4.10	S, S
Kahalgaon STPS	13.75	0.15	0.11	P, P	20.10	3.25	5.24	P, P
Talcher	1.07	0.54	1.93	S, S	5.25	4.87	4.12	S, S
Farakka STPS	11.12	1.98	0.61	P, P	16.26	4.27	3.55	P, P
Sipat STPS	7.17	0.38	0.53	P, P	13.95	4.00	3.96	P, P
SIMHADRI	5.96	0.00	0.00	P, P	12.45	3.43	4.84	P, P
Neyveli ST1	9.04	0.52	1.91	S, S	25.07	4.04	4.04	S, S

Neyveli ST2 (M Cut)	5.19	0.53	0.81	S, S	9.40	4.17	4.10	S, S
Neyveli FST EXT	2.38	1.07	0.56	S, S	7.39	5.83	4.64	S, S
Chandrapura(DVC)	17.53	2.31	0.71	P, P	21.69	10.91	3.15	P, P
Durgapur	1.76	0.28	0.74	S, S	5.38	8.53	3.99	S, S
Centre	4.05	0.79	0.68	P, S	9.56	4.95	4.38	P, S
Overall	4.15	1.35	0.71		9.47	5.86	4.11	

Note: CAC: command and control; Spatial: intra-temporal emission trading between plants; Spatial-temporal: inter-temporal emission trading between plants; S: Sell; P: Purchase, and N: no trade. The first digit in column ‘trade’ is trade under spatial trading and the second digit is for trade under spatial-inter-temporal trading.

Figure 1: Potential Abatement Cost (% electricity lost)

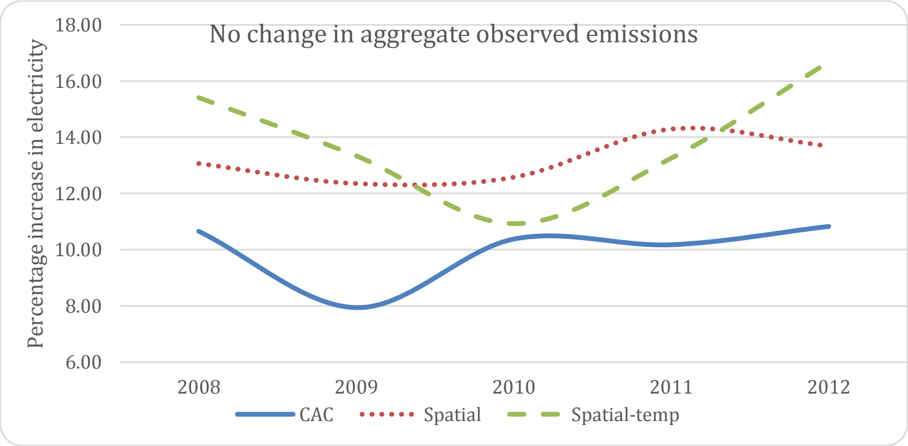
A



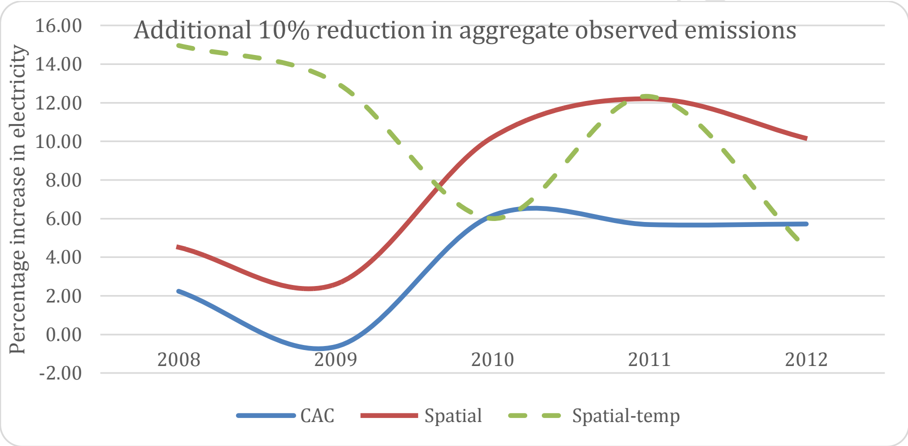
Note: CAC: command and control; Spatial: intra-temporal emission trading between plants; Spatial-temp: inter-temporal emission trading between plants.

Figure 2: Increase in electricity production with elimination of inefficiency

A



B



Note: CAC: command and control; Spatial: intra-temporal emission trading between plants; Spatial-temp: inter-temporal emission trading between plants.

Table A1: Yearly Observed and Potential levels of Electricity (thousand GW) and CO_2 Emissions (thousand tons) for sample plants

		Observed		Potential under no change in aggregate observed emissions						Potential for additional 10% reduction in CO_2 emissions				
Sector	Year	Electricity	CO_2 emissions	Electricity (No policy)	Electricity (CAC)	Electricity (spatial trade)	CO_2 emissions (spatial trade)	Electricity (spatial & temporal trade)	CO_2 emissions (spatial & temporal trade)	Electricity (CAC)	Electricity (spatial trade)	CO_2 emissions (spatial trade)	Electricity (spatial & temporal trade)	CO_2 emissions (spatial & temporal trade)
State	2008	127	146446	152	147	148	141458	152	149019	138	137	128116	152	147463
Centre		163	166307	183	175	181	171295	183	174309	159	167	153362	182	173405
Total		291	312753	335	322	329	312753	335	323327	297	304	281478	334	320869
State	2009	126	145375	153	145	150	144888	153	149519	134	131	123954	152	147755
Centre		171	174755	184	176	184	175242	184	175502	161	174	164162	184	175317
Total		297	320130	337	321	334	320130	337	325022	295	305	288117	336	323072
State	2010	123	135993	148	145	147	138518	145	130829	139	144	124346	139	108911
Centre		176	180535	191	185	190	178010	186	163290	179	186	160529	178	135511
Total		299	316528	338	330	337	316528	332	294119	317	330	284875	317	244422
State	2011	131	142230	161	154	159	142527	158	132422	148	157	130069	157	130171
Centre		182	184889	199	190	198	184592	196	170442	183	194	164338	194	164896
Total		313	327118	360	345	358	327118	354	302864	331	351	294407	351	295067
State	2012	129	141704	163	153	157	142232	162	160490	146	153	132002	147	120537
Centre		197	199296	218	208	214	198768	218	211707	199	206	174897	193	151809
Total		326	341000	380	361	370	341000	380	372197	345	359	306900	340	272346
State	Total	636	711747	777	744	761	709623	771	722279	704	722	638487	748	654837
Centre		890	905783	974	935	966	907906	967	895250	881	926	817289	931	800939
Total		1526	1617529	1751	1678	1727	1617529	1738	1617529	1585	1648	1455776	1679	1455776

Note: No Policy: No concern for CO_2 emission reduction; CAC: command and control; Spatial: intra-temporal emission trading between plants; Spatial-temp: inter-temporal emission trading between plants.

Table A2: Plant level Observed and Potential levels of Electricity (thousand GW) and CO_2 Emissions (thousand tons)

	Observed		Potential under no change in aggregate observed emissions						Potential for additional 10% reduction in CO_2 emissions				
	Electricity	CO_2 emissions	Electricity (No policy)	Electricity (CAC)	Electricity (spatial trade)	CO_2 emissions (spatial trade)	Electricity (spatial & temporal trade)	CO_2 emissions (spatial & temporal trade)	Electricity (CAC)	Electricity (spatial trade)	CO_2 emissions (spatial trade)	Electricity (spatial & temporal trade)	CO_2 emissions (spatial & temporal trade)
Rajghat	3.41	4885	4.53	4.43	4.49	4024	4.44	3784	4.24	4.27	3377	4.34	3473
Rayalseema	31.77	30280	35.16	33.68	34.51	31569	34.85	31536	32.19	32.07	27163	33.65	28090
Vijaywada	55.11	42878	60.91	55.48	57.08	44510	59.78	51059	50	55.68	43070	58.3	46221
Suratgarh	45.09	47139	45.09	45.09	45.09	47139	45.09	47139	41.2	42.78	44314	45.09	47139
Kota	42.5	44890	45.05	43.92	44.67	43596	45.05	44180	42.48	40.7	38639	43.19	40322
Nasik	22.02	27330	31.37	30.32	30.94	28942	30.99	28233	28.73	29.81	25984	30.37	26028
K-Kheda II	28.57	32734	39.03	35.86	38.44	37403	39.02	38265	34.02	35.97	32490	37.18	33232
Paras	9.99	11646	13.79	13	13.43	12236	13.71	12810	12.49	13.28	11533	13.18	10946
Bhusawal	12.4	16129	24.59	18.9	24.15	23297	24.49	23846	17.61	23.81	21661	23.96	21886
Parli	22.34	28652	32.08	31.11	31.61	29472	31.81	29365	30.47	30.2	26585	30.98	26323
Chandarpur STPS	61.89	69729	83.64	78.52	81.71	76388	83.04	76948	73.75	78.49	70433	80.13	69700
R_GUNDEM – B	2.11	2321	2.34	2.321	2.27	1922	2.29	1945	2.26	2.19	1735	2.24	1793
K_gudem	44.41	45656	54.54	51.81	54.28	49234	54.14	48340	49.43	51.75	41291	51.99	40953
Panipat	42.9	49977	48.61	47.83	48.09	45436	48.51	45238	45.52	47.66	43732	46.47	40404
Ukai	23.66	27378	28.08	27.82	27.51	24557	27.72	24490	27.12	26.32	21833	27	22005
Gandhinagar	24.05	27433	30.92	29.31	30.42	28935	30.7	28785	28.33	29.05	26313	30.11	26575
Wanakbori	46.8	50960	47.7	47.51	47.17	50460	47.7	51245	43.59	39.13	40865	47.7	51245
Sikka REPL	5.03	6653	6.96	6.91	6.86	6170	6.88	6108	6.66	6.49	5510	6.75	5660

Kutch Lignite	6.04	10165	8.95	8.76	8.9	7993	8.9	7993	8.33	8.54	6742	8.54	6742
Akrimota Lignite	4.57	6329	7.03	6.85	6.99	6732	7.01	6715	6.45	6.59	5975	6.7	5951
Bandel	9.14	13877	12.82	12.6	12.5	11462	12.72	11685	11.95	11.73	10092	12.36	10388
Ennore	5.47	8774	10.28	9.75	9.95	8790	10.15	8962	9.25	9.6	8012	9.95	8242
Korba-west	29.47	32102	32.06	31.7	31.1	25753	31.73	27801	31.26	30.36	23922	30.82	24554
Korba-East	29.21	34691	35.56	34.85	34.9	30408	34.84	29600	33.27	33.84	26951	34.14	27384
Amarkantak	8.46	11791	8.46	8.46	7.21	9211	8.46	11791	7.8	7.03	8992	5.99	7039
Bhatinda	9.5	12183	12.24	12.13	12.11	11212	12.16	11163	11.78	11.45	10081	11.91	10233
DPL	9.78	15164	15.02	14.69	14.46	12771	14.83	13252	14	13.6	11194	14.56	12309
State	635.69	711747	776.81	743.611	760.84	709623	771.01	722279	704.18	722.39	638487	747.6	654837
Tanda	15.19	17883	16.72	16.58	16.72	15908	16.38	13868	15.97	15.89	12610	16.04	12829
Singrauli STPS	75.06	73337	77.67	76.6	77.53	73430	76.18	65327	73.27	73.56	58886	74.49	60146
Rihand STPS	77.29	73715	77.35	77.34	77.31	73476	77.31	73476	72.66	73.69	68814	73.45	65394
Unchahar	39.43	39071	41.18	41	39.89	33720	40.47	34484	39.39	38.41	30357	39.6	31600
DADRI (NCTPP)	50.68	49460	53.13	52.68	52.31	48372	52.97	49977	50.75	49.84	43270	50.73	42414
Korba STPS	85.92	82495	90.39	89.18	89.61	82496	88.9	77594	84.73	87.39	74345	85.92	71435
Vindhyachal STPS	124.96	119805	128.06	125.85	127.56	123299	128.06	124203	117.44	121.18	115040	122.27	112585
R-Gundem STPS	99.53	95050	99.55	99.53	98.24	93187	99.53	95050	94.66	93.54	84919	95.47	82539
Kahalgaon STPS	57.99	56418	75.14	64.81	75.03	71777	75.06	71225	60.04	72.7	68153	71.2	63337
Talcher	16.85	20317	18.68	18.48	18.58	16739	18.32	15576	17.7	17.77	14108	17.91	14320
Farakka STPS	50.38	48780	63.67	56.59	62.41	57613	63.28	59269	53.32	60.95	53983	61.41	52582
Sipat STPS	48.4	43840	52.46	48.7	52.26	50919	52.18	50523	45.14	50.36	46129	50.38	45638
SIMHADRI	45.86	43301	49.8	46.83	49.8	48483	49.8	48483	43.6	48.09	45468	47.39	42783

Neyveli ST1	17.25	32363	23.02	20.94	22.9	20673	22.58	19287	17.25	22.09	17796	22.09	17796
Neyveli ST2	47.59	64145	56.61	53.67	56.31	50774	56.15	50088	51.29	54.25	43529	54.29	43587
Neyveli FST EXT	14.17	17823	15.96	15.58	15.79	15042	15.87	14417	14.78	15.03	12857	15.22	12652
Chandrapura (DVC)	14.84	17417	23.84	19.66	23.29	22036	23.67	22726	18.67	21.24	18776	23.09	20829
Durgapur	8.47	10564	10.79	10.6	10.76	9963	10.71	9677	10.21	9.87	8248	10.36	8475
Centre	889.86	905783	974.02	934.62	966.3	907906	967.42	895250	880.87	925.85	817289	931.31	800939
Overall total	1525.55	1617529	1750.83	1678.231	1727.14	1617529	1738.43	1617529	1585.05	1648.24	1455776	1678.91	1455776

Note: CAC: command and control; Spatial: intra-temporal emission trading between plants; Spatial-temp: inter-temporal emission trading between plants.

Authors Contribution:
Analysis: SK, SM, RJ
Manuscript writing: SK, SM, RJ
Reviewing manuscript: SK, SM, RJ

Highlights

- This study shows potential cost savings by adoption of emission trading in India.
- India could save about US$ 5 to 8 billion by an emission trading system.
- Measuring foregone gains due to absence of a carbon emission-trading program.
- Pricing carbon emissions in India through emission taxation and trade system.