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A State-Level Resource Allocation Model for Emission Reduction and Efficiency Improvement in Thermal Power Plants in India

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Abstract

This paper develops a framework for centralized allocation of resources and production targets among firms that produce a bad output side-by-side with a good output. The production technology is specifically defined for thermal power generation sector that produces one good output (electricity) and one bad output (stack emissions) with one polluting input (coal) and two neutral inputs (installed capacity of power plants and labor). The undesirable output is modeled as an incidental by-product resulting from use of the polluting input. We use a modified Directional Distance Function of Aparicio, Pastor, and Ray (2013), formulated with non-parametric Data Envelopment Analysis, to determine the extent by which good output can be increased in each region while minimizing the use of polluting inputs and the level of bad output, by increasing efficiency through reallocation.

For empirical illustration, we use data from major coal-fired power plants in India for fiscal year 2005-06 through 2014-15. Each state within India is treated as a regional jurisdiction within which inputs (only coal and labor) and outputs are reallocated under alternative structural assumptions. Our findings reveal that the thermal power sector is sub-optimal, leaving a scope for emission reduction and increase in power generation in different states of India.

JEL Codes: C61, L94, Q53

Keywords: By-production; Joint Disposability; Bad Outputs; Centralized Resource Allocation

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Introduction

India ranks behind China and the US as one of the top-3 sources of greenhouse gas (GHG) emission in the world. Within the country, more than 40% of air pollution comes from India's coal-fired power plants that account for 50% of the installed capacity and 70% of power generation. Even though there is a growing realization that GHG emissions must be drastically lowered to avoid potentially catastrophic consequences of climate change in the near future, with the manufacturing sector coming to the forefront in the country's growth strategy, the rate of increase in energy demand is expected to accelerate and this is will further aggravate the emission problem. To address this problem, use of renewable energy has been actively promoted. However, India's achievements towards renewable energy promotion, although significant, are still inadequate to cater its overall energy needs.[1] Given this setting, increasing power supply and clean energy promotion become conflicting goals, at least in the short run. In this study, we take an approach where the twin objectives of attaining higher power supply and mitigating pollution can be combined in a centralized resource allocation model. In particular, we evaluate the technical and environmental performance of thermal power plants across States in India using a Directional Distance Function (DDF), formulated within nonparametric data envelopment analysis (DEA) and examine if, and to what extent, reallocation of resources and generation across power plants within a state can enhance the overall environmental efficiency and productivity in the given state. In principle, it can be viewed as a problem of a regulatory authority that can reorganize total production in the state by redistributing the existing bundle of variable inputs across the units, thereby scaling down production in some units (or even closing down, if necessary) and expanding some others. At the same time we take explicit account of the fact that, at each unit there is some fixed input, which cannot be reallocated elsewhere.

To address the above question, we define the production technology for coal-fired plants considering one good output (power), one bad output (emission), a polluting input (calorific value of coal) and two neutral

[1] The installed capacity of renewables (excluding large hydro) as of March 2022 was about 110GW, accounting for about 27% of the total installed generating capacity in the country, In the fiscal year 2021-22, renewables constituted only 11.9% of the gross electricity generation in India (Central Electricity Authority, General Review 2023).

inputs (installed capacity and labour). The extant literature lends us three different ways of modelling undesirable outputs like emissions – (i) as a conventional input in the production process (Baumol and Oates (1988), Copper and Oates (1992)), (ii) as a joint product with the good output (Fare et al. (1989, 2005), Forsund (2009), etc.), and (iii) as incidental by-products resulting from the use of one or more inputs (Murty, Russel and Levkoff (2012) (MRL) and Ray, Mukherjee and Venkatesh (2017) (RMV). The by-production approach in MRL assumes two independent sub-technologies, one generating the marketable good output and the other producing the undesired output.[2] In RMV on the other hand, a common polluting input producing both the good and the bad output links the two sub-technologies together. We follow RMV and assume joint disposability between offending inputs and the unwanted output (Sueyoshi and Goto (2012) call it natural disposability).[3] Emissions, in this conceptualization of the technology, can be reduced only by reducing the use of polluting inputs like coal. This, in its turn, would imply a reduction in power generation. However, improvement in efficiency of power plants and redistribution of resources and generation away from less efficient plant could increase the overall power production despite restricted fuel use. The objective therefore, is to determine the potential for simultaneously increasing electricity generation and lowering pollution and fuel consumption in each region. Typically, this is explored through a DDF where the direction of projection of an inefficient unit on to the frontier is prespecified. Here we consider a non-radial DDF suggested by Aparicio, Pastor and Ray (2013) (APR) to determine the extent by which good output can be enhanced and bad output along with the polluting inputs can be reduced in a given region. In this approach the direction of for measuring the DDF is endogenously determined.

In the empirical application, we use Data from 65 major coal-fired power plants in India for the financial years 2005-06 to 2014-15.[4] Each state within India is treated as a regional jurisdiction within which inputs (only fuel and labor) and outputs can be reallocated across firms. Our findings reveal that the observed distribution of outputs and inputs across firms in several states is sub-optimal, leaving room for emission reduction and increase in power supply through optimal reallocation. The inefficiency in production of the good output ranges between 3% to 5% over the sample years, and environmental and fuel use inefficiency is slightly higher, varying between 3% to 8%. It is also found that the level of inefficiency in the industry started decreasing after 2008-09 but suddenly spiked again in the terminal year of our study period.

[2] Dapko (2016) criticizes this disjointed specification of the two production processes as being unrealistic and uses the materials-balance condition to link them.
[3]Sueyoshi and Goto (2012) also introduce a new concept called managerial disposability where more inputs are used to increase good outputs and at the same time reduce bad outputs by increasing managerial efforts.
[4] The data are reported by accounting year, which runs from April 1st to March 31st of the next year. Thus, the year 2009-10 refers to the period April 1, 2009 to March 31, 2010.

The rest of the paper is organized as follows – section 2 discusses the existing literature relating to efficiency in energy sector and summarizes the principal contributions of this paper. Section 3 provides the methodological background and describe relevant DEA models. Section 4 reports the empirical findings with some concluding remarks.

2. Brief Review of Literature

The existing literature relevant for this paper consists of three strands of papers addressing (a) measurement of productive efficiency in the presence of bad or undesirable outputs, (b) centralize models of resource allocation, and (c) environmental efficiency in power generation in India.

Efficiency in the Presence of Bad Outputs

There exists a rich and voluminous literature on measurement of efficiency in energy sector. Over the past years, on account of active participation of countries in the climates debate, efficiency measurement in presence of bad outputs has come into sharp focus. Several studies were dedicated towards devising techniques to incorporate pollution/emission variables as bad outputs within the electricity production function so as to estimate joint environmental and productive efficiency of the generating units. The initial treatment of bad outputs was introduced in Baumol and Oates (1975, 1988) and has been applied to numerous studies (Pittman (1981), Cropper and Oates (1992), Reinhard et al. (1999), Lee et al. (2002), Korhonen and Luptacik (2004), Yang and Pollitt (2009), Mahlberg and Sahoo (2011)). Their approach was fairly straightforward, in that emissions are treated as conventional production inputs satisfying free disposability.[5] The principal justification of the idea, as described in Cropper and Oates (1992) is that the undesirable outputs, like inputs are costly to the firms and because of that firms try to minimize both. The cost incurred from undesirable outputs is indirect in the sense that it implies diversion of other inputs towards abatement activities and reduces the amount of inputs available for production of the good output, rendering a positive relation between the good and bad outputs similar to a positive correlation between inputs and good outputs. The underlying assumptions of the input approach were questioned by several studies like Murty and Russell (2002), Fare and Grosskopf (2003), MRL (2012), Podinovski and Kuosmanen (2011), Murty (2015), and Murty and Russell (2016, 2018) for producing counter-intuitive implications about the production technology. The method has also been criticized for defying the materials balance principle of Ayres and Kneese (1969) (see for e.g. Forsund (1998), Coelli et al. (2007)). Later, RMV (2017) offered an economics-based definition of inputs to explain why bad outputs cannot be

[5] Free disposability of input implies that use of additional inputs do not lower the outputs. Analogously, free disposability of emissions imply that it is possible to have higher emissions without any associated reduction in power production.

regarded as inputs. The authors argue that an input is something which (i) exists in the system before any output is produced, (ii) is subject to some processing by the firms, and (iii) is consumed (and reduced in stock) in the production of the desired output. Bad outputs such as emissions clearly meet none of the three criteria.

The first alternative to the free disposability, input view of undesirable output was proposed in Fare et al. (1986). The authors treat undesirable outputs as weakly disposable, meaning that there is an opportunity cost associated with the disposal of bad outputs and the cost comes in the form of reduced production of the desirable output. In the view taken in Fare et al. (1986) and subsequently applied in Fare et al. (1989), the good and bad outputs are joint products such that more bad output will be produced if we increase the good output, and a reduction of the bad output is possible only simultaneously with a reduction in the good production. In their joint production approach, bad outputs are weakly disposable with the goods but, the good output and inputs are still freely disposable. Fare et al. (1994), and Fare and Grosskopf (2004a) extended their previous work on weak disposability to include null-jointness of the bad output. The null joint condition means that bad outputs cannot be eliminated as long as there is any good production.

An early critique of this widely popular weak disposability under joint-production approach came from Førsund (1998, 2009). The papers (Førsund (1998, 2009)) illustrate that the graph of the output set (with one good output, one bad output and a given input vector) when the undesirable outputs are weakly disposable has local regions of negative trade-offs between the good and the bad outputs, and though such segments are only weakly efficient, it is counter intuitive to believe that there are no opportunity costs of pollution reduction. The point was later reemphasized in Chen (2014), and Murty and Russell (2018). Some of the main criticisms of the above two methods of pollution modeling were related to violation of materials-balance condition, irrational trade-offs between good and bad outputs, and no explicit representation of abatement activities. In view of these shortfalls, Murty and Russell (2002) argued against the use of a single production relation to model an emission generating system and modeled the overall technology set (T) as an intersection of two sub-technologies, one generating the desirable outputs (T_1) and another producing undesirable outputs (T_2). The good and bad outputs, in the sense of Murty and Russell (2002) and MRL (2012), are no longer joint products; instead, the bad output is an unintended, inevitable by-product arising from the use of one or more inputs into the production process. Their method of addressing the bad production has come to be known as the "by-production" approach in the literature. Førsund (1998, 2009) has theoretically explained that standard the textbook representation of production possibilities are too general to accurately depict the production of unintended outputs and insists that (in agreement with materials-balance principle) any multi-output production representation must reflect the fact that residuals (bad outputs) are generated from the use of inputs and their correlation with the good outputs is only incidental. There are two distinct production functions separately capturing good and bad production, both with same set of inputs. Next, the inputs are categorized as “dirty, clean, green, pure purification, and integrated purification” and depending on the sign of marginal productivities of these inputs in each production function, one can identify its role as an abating input, or a polluting input or an ordinary production input. This was theoretically formalized as $T = T_1 \cap T_2$, and represented using DEA model by Murty and Russell (2002) and MRL (2012).[6] T satisfies free disposability with respect to the intended output and the non-pollution-causing input but not with respect to pollution-causing input, and pollution is treated as costly disposable. They also generalized the model to incorporate generation of an abating output in T_1, which is actually treated as an intermediate input to be used in the process of pollution abatement in T_2.[7] This was further developed in Murty and Russell (2018) to accommodate multiple emissions, which may be rival or joint in production.[8] They also model abatement and economic outputs as rival in nature. A problem exclusively incorporating end-of-pipe abatement within the by-production framework has been suggested in Førsund (2018). The overall technology in Førsund (2018) is an intersection of three separate production possibility sets (each estimated independently) – good production, bad production, and production of abatement. The by-production approach seems to be a promising approach for modeling the production of bad outputs (Dakpo et al. (2016)) and for joint environmental and production efficiency measurement of emission-causing industries. In MRL (2012) separate optimization problems are solved for sub-technologies T_1 and T_2, good output-oriented model for T_1 and bad oriented for T_2, and the overall efficiency is calculated as a simple average of the efficiency scores from the two models. A principle reservation raised by several researchers[9] with the DEA model from MRL (2012) is that the sub-problems of maximizing intended output (power) and minimizing the undesirable output (emission) are solved separately. Intuitively, the quantity of coal that produces power is what also causes pollution and it is not obvious that at the optimal solutions, the benchmark quantities of coal from the two sub-problems will be equal expect when there are no slacks in the input constraints of polluting input in

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[6] They define $T_1 = \{(x, y, z) \in R_+^{n+m+m'} \mid \lambda X \leq x \wedge \lambda Y \geq y \text{ for some } \lambda \in R_+^p\}$,
$T_2 = \left\{(x^1, x^2, y, z) \in R_+^{n_1+n_2+m+m'} \middle| \mu X^2 \geq x^2 \wedge \mu Z \leq z \text{ for some } \mu \in R_+^p\right\}$, and
$T = T_1 \cap T_2 =$
$\left\{(x^1, x^2, y, z) \in R_+^{n_1+n_2+m+m'} \middle| \lambda[X^1 X^2] \leq (x^1, x^2),\ \lambda Y \geq y, \mu X^2 \leq x^2, \mu Z \leq z, \text{ for some } (\lambda, \mu) \in R_+^{2p}\right\}$.

[7] Materials-balance is explained in this approach not as a mass–energy accounting identity, but rather as nature’s pollution-generating technology, which operates independently of a firm’s intended-production technology and relates emission generation to emission-causing inputs also used in production of the goods and abating output, and mitigation of emissions to abating output.

[8] Two outputs are joint in production when for a given vector of inputs, there is no trade-off in their production. On the other hand, they are rival if increase in the production of one output implies reduced production of the other (because more resources have been consumed in the production of the first output).

[9] For example, Dakpo et al. (2014), Lozano (2015), Dakpo (2016), Dakpo et al. (2016), and RMV (2017) among others.

either of the sub-problems at their optimal solutions. There is no reason that this will always be true.[10] Lozano (2015) interprets the by-production technology as a horizontal network of inter-dependent production units connected together through their use of a joint or public input and uses a "linking constraint" to enforce that the quantity of the polluting input is exactly the same in the reference input bundles in the two sub technologies. Dakpo (2016), by contrast, uses a mass-energy equation to link the two sub-problems. He also suggests various other dependence constraints, and/or estimation of a coupling relation between the good and bad outputs to link the two sub-technologies. The same was also recognized in Førsund (2018), unifying the independently estimated sub-technologies based on materials-balance condition. Another variant of a DEA model formulated under the by-production interpretation of unintended outputs is by RMV (2017). They treat the unwanted output and the offending input as 'jointly disposable' in the relevant sub-technology (T_2), in the sense that the emissions can be reduced only by limiting the use of polluting input like fuel. Unlike the previous works (MRL (2012), Lozano (2015), Dakpo (2016)), they integrate the two sub-technologies in a DDF (of Chambers et al. (1996)), estimated using DEA with common intensity vectors in constructing both the frontiers. The use of identical weights in constructing both the technologies ensure that each inefficient firm has same benchmark in both the problems and there is a unique amount of coal that simultaneously produces the good and the bad outputs. Murty and Nagpal (2019) offer a new interpretation to the joint production approach of RMV (2017) by tying together not just the polluting input and unintended output, but also the desired economic output. The authors state that a *ceteris paribus* reduction in polluting input/s to mitigate pollution will inevitably reduce the intended production. While this may be true along the frontier of the good output production set, there is no reason why this should hold for firms in the interior of the production set.[11] In the DEA formulation of their technology, only neutral inputs satisfy strong disposability. In this paper we implement joint disposability in the sense of RMV (2017) to set up an optimization problem for determining optimal distribution of resources within a region to simultaneously maximize the area's environmental and technical performance.

<u>Centralized Models for Efficiency Improvement</u>

Baumol (1977), Baumol and Fischer (1978), and Baumol, Panzar and Willig (1982) emphasized on the role of production technology in determining optimal industry structure. These studies employ the notion of cost-subadditivity, economies of scale, economies of scope, etc. to model gains from monopoly versus multiple firm production of a target output bundle (Evans and Heckman (1984), Maindiratta (1990) etc.). These concepts of have equivalently been applied in studying reorganization of production activities

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[10] See Dakpo et al. (2016) and Dakpo (2016) for a detailed critique of the approach.

[11] See Figure 2, RMV (2017, pp – 15) for detailed explanation.

through mergers or break-ups (examples include Fare (1986), Ray and Mukherjee (1998), Bogetoft and Wang (2005), Ray (2007), Blancard et al. (2016)). In all of the studies listed above, the question has been whether there is scope for improving efficiency or productivity by altering the industry structure given the existing resources of firms under evaluation. The primary consideration is the improvement in efficiency through optimal redistribution of productive resources, and scale down (or even shutdown) of relatively inefficient units while expanding the efficient ones.

In the past, several papers have emphasized the importance of optimal redistribution of inputs as a means of improved performance (Golany (1988), Golany and Tamir (1995)). Fare et al. (1992) for example, applied linear programming methods in analyzing industry efficiency with input reallocation.[12]Lozano and Villa (2004) formulated radial and non-radial input-oriented DEA problems for the municipal recycling system of Spain to minimize total resource consumption while meeting the total output target. In the context of energy and environment, Andersen and Bogetoft (2007) evaluated efficiency gains from the optimal distribution of fishing quotas across fishing vessels in the Danish fishing industry. Subsequent to the adoption of Kyoto Protocol for mitigation action on climate change, a host of studies have been conducted on optimal allocation of mitigation targets across different countries or industries or among different firms within an industry. In the context of Indian power sector, Sahoo et al. (2017) investigate the energy saving potential in the thermal power sector by maximizing the slacks in energy inputs, measured as heat content of coal and oil, for each power plant. They verify that the heat rate reduction targets under the PAT scheme are significantly lower than the true potential of the plants.

While the above studies have looked at the problem of central decision making, they have simply looked at attaining efficiency by altering the distribution of inputs and/or output targets or pollution permits/targets, in environmental context, of existing firms and have not optimized the industry structure by finding *the right number of firms* to produce the overall output with minimal input use in a more environment friendly manner. One of the first studies determining whether there are too many or too few firms in an industry, based on non-parametric representation of the technology is by Ray and Hu (1997). The principle idea of our study resembles closely with Ray and Hu (1997) where a nonparametric optimization model is developed for the technically optimal organization of an industry that would result in the maximum radial scaling down of the aggregate input bundle without reducing the industry output. Although related, a fundamental difference between Ray and Hu (1997) and the current study lies in the incorporation of bad outputs and a focus on improving joint environmental and technical efficiency in electricity generation

[12] Athanassopoulos (1998) addressed conflicting objectives of equity, efficiency, and effectiveness within a multi-level organization using a multi-objective goal programing framework that assigns specific targets to each objective and finds the best compromise solution in the form of optimal assignment of inputs/outputs that maximize the achievement of each of these goals.

within a region rather than input saving alone. Instead of an input-oriented model, ours is a directional model for simultaneous expansion in aggregate good output and contraction in total bad output and polluting input. We also have capacity constraint in the form of a fixed input for each firm and unlike in Ray and Hu (1997) the firms in the optimally restructured industry are not identical.[13] Lastly, our unit of analysis is not the entire power industry of the country. Instead, it is a state-wise analysis of power plants in India intending to improve regional performance, similar to Ray (2009) who determined the cost minimizing number of firms to optimally produce total manufacturing output in each state within India. Along similar lines, Ray (2016) applied a centralized resource allocation model to a large public sector bank in India, to optimize the number of branches within each postal district of a city that could provide the existing level of banking services to the customers in that area at the minimum cost.[14]

Efficiency Literature on Indian Power Generation Sector

Most studies on Indian power generation have used the standard input-oriented or output oriented radial DEA models, under conventional neo-classical assumptions of technology, to evaluate efficiency of different groups of power plants; grouped by either size or ownership or state of operation or even a time series analysis. A few papers have used DDF to analyze efficiency of Indian power plants. Most of these earlier works have also neglected emission generation in their technological specification. A directional output distance function based detailed technical and environmental efficiency assessment of some thermal power plants in Murty et al. (2006) is an early exception. Nevertheless, it is of a very limited coverage and examines only the state-owned plants from one Indian state only, the state of Andhra Pradesh. Some studies concentrating on environmental aspects of power plants focused on calculation of virtual or shadow price of emissions from parametrically estimated distance functions using linear programming methods. For example, Gupta (2006) estimated shadow price of CO2 emissions using an output distance function, Jain and Kumar (2018) estimate production efficiency and shadow prices of 56 coal-fired thermal power plants for the period of 2000 – 2013, using a parametric quadratic directional output distance function.

Murty and Nagpal (2018) was the first to adopt a by-production approach to measure efficiency of Indian thermal power plants. While their approach is quite similar to the present study, we employ the integrated model in RMV (2017) as opposed to the model in MRL (2012). Also, we evaluate efficiency of power plants aggregated at the state-level. Although we do compute individual plant level efficiencies, that is

[13] Also, we do not allow for duplication of firms; existing firms may be expanded, contracted or shut down but no new firms are added.

[14] A related problem was addressed in Ray, Chen and Mukherjee (2008), which involves a cost minimization problem of a multi-location firm facing heterogeneous technology and input prices across locations. The decision-making problem consists of selecting locations and the input bundle that would produce the target output (bundle) at the least cost, given the applicable prices of inputs.

treated only a base case with no reallocation of resources, and helps us to determine efficiency differential with scenarios where transfer of inputs across plants within a given state is permitted.

Another significant difference also lies in the data on emission used in the two studies. They use a linear formula based on the heat content of coal and oil to determine emission, owing to which, their frontier of the emission generating technology (with emission measure along the vertical axis and fuel input along the horizontal axis) is almost linear and all units happen to be nearly efficient in terms of emission generation. By contrast, we use data on stack emission, which is measured by suspended particulate matter (SPM) in one cubic meter of air per unit of generation and is not linearly related to the calorific values of coal and oil. Despite the differences in modeling and data, their results still serve as a close comparison for us.

Murty and Nagpal (2019) revised RMV's (2017) by-production model to set up a linear programing problem with good and bad outputs, and polluting inputs as jointly disposable and freely disposable non-polluting inputs and compared efficiency optimal efficiency improvements under 3 different technological specifications – the by-production approach of MRL (2012), weak disposability view of Fare et al. (1989) and the modified joint disposability as introduced in their paper. They prove theoretically and confirm based on their empirical findings that both weak and joint disposability based technologies have identical strongly efficient frontiers. They also find that the efficiency scores from all three technologies are highly correlated but the by-production model (due to MRL (2012)) is best at capturing the true data generating process. Their results suggest that when equal importance is given to the problem of emission reduction and generation expansion, it emerges that the better performing power plants should focus on curbing pollution by reducing their fuel consumption whereas, the less efficient plants should focus on expanding electricity generation with their existing inputs.

<u>Main Contributions of this paper</u>

The main contributions of this paper may be summarized as follows:

- To the best of our knowledge, this is the first paper that considers the potential for simultaneous increase in power generation and emission reduction through redistribution of inputs across existing plants within a state in a model of centralized resource allocation.
- Unlike earlier papers on centralized allocation, we explicitly recognize that capacity is not transferable across plants and after reallocation the output produced by a plant is limited by its existing capacity. As a result, unlike in the models of Baumol and Fischer (1986) or Ray and Hu (1997), all plants will not be identical.
- We measure the bad output (emission) directly from the stack emission data and do not construct an indirect measure obtained from heat content of fuels consumed.

- In our empirical analysis we explicitly consider how ownership type (central, state, or private) of the utilities affect efficiency.

3. Theoretical Background

3.1 The Production Technology

Consider an industry with a multiple input ($x, x \in R_+^n$) multiple output ($y, y \in R_+^m$) technology and suppose that the production possibility set, showing all possible technological choices facing the industry, is defined as:

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

An alternative definition of technology is through a production correspondence $F(x, y) = a$

$$T = \{(x, y): F(x, y) = a \leq 0\}.[15] \quad (2)$$

The frontier of the production possibility set, often described as the graph of the technology is the set:

$$G = \{(x, y): (x, y) \in T, \beta < 1 \Rightarrow (\beta x, y) \notin T; \alpha > 1 \Rightarrow (x, \alpha y) \notin T\}.[16] \quad (3)$$

These sets are assumed to be closed, convex and exhibit strong disposability in outputs and inputs. Free or strong disposability of inputs means that an increase in an input without a corresponding decrease in another input cannot reduce the output. Similarly, it is reasonable to assume that lower quantity of output can always be produced from a given input bundle.

Technical efficiency of a firm, with an input-output bundle (x_0, y_0) can be measured in different ways, using radial measures of output or input orientation that allow either a proportional expansion in outputs only with inputs held unchanged or a proportional reduction in inputs only with the level of all outputs remaining the same. By contrast, a variant of the directional distance function (DDF) introduced by Chambers et al. (1996), based on Luenberger's (1992) benefit function to measure technical efficiency, permits simultaneous increase in all outputs along with a reduction in all inputs in the same proportion. In general, it projects an inefficient input-output bundle on the frontier of the production set, in the direction chosen by the analyst. The DDF is:

$$\vec{D}(x_0, y_0; g^{x0}, g^{y0}) = \{max\, \beta: (x_0, y_0) + \beta(g^{x0}, g^{y0}) \in T\}. \quad (4)$$

Where, (g^{x0}, g^{y0}) is a direction prespecified by the analyst. The input-output bundle $(x_0 - \beta g^{x0}, y_0 + \beta g^{y0}) \in G$ is the resulting efficient projection. When $(g^{x0}, g^{y0}) = (-x_0, y_0)$, then the efficient projection

[15] In a single output case, T is often defined using a production function as: $T = \{(x, y), y \leq f(x)\}$.

[16] The graph of the technology in multiple outputs case is the set: $G = \{(x, y): F(x, y) = 0\}$, in a single output case the set is $G = \{(x, y): y = f(x)\}$.

becomes $(x_0\,(1-\beta), y_0\,(1+\beta))$. A β of say 0.05 would imply that output can be increased by 5% while lowering the input use by 5%.

The modified DDF, as introduced in APR (2013), allows the outputs to expand and inputs to contract in different proportions. Accordingly, the modified DDF is:

$$\overleftrightarrow{D}(x_0, y_0; g^{x0}, g^{y0}) = \{max\ (\beta_x + \beta_y): \left(x_0 + \beta_x\, g^{x0}, y_0 + \beta_y\, g^{y0}\right) \in T; \beta_x, \beta_y \geq 0\}. \tag{5}$$

Again, (g^{x0}, g^{y0}) is the pre-specified direction and $\left(x_0 + \beta_x\, g^{x0}, y_0 + \beta_y\, g^{y0}\right) \in G$ is the efficient projection.

The derivation of efficiency based on the aforementioned measure would necessitate a knowledge of the underlying production function. One could either estimate the function parametrically and measure efficiency using Stochastic Frontier Analysis (SFA), or, could resort to the non-parametric method of DEA. In nonparametric studies one empirically approximates a production possibility set as a free disposal convex hull of observed input–output vectors (x^j, y^j), $j = 1,2,..,N$, of N firms by making some fairly general assumptions about the technology (Banker et al. (1984)), and evaluates the technical efficiency of an individual firm with reference to this production possibility set. The underlying assumptions are:

(A1) Every observed input-output bundle is feasible. This implies, $(x^j, y^j) \in T, \forall\, j = 1\ to\ N$.

(A2) Inputs are freely disposable, that is, $(x, y) \in T: x' \geq x \Rightarrow (x', y) \in T$.

(A3) Outputs are freely disposable. Thus, $(x, y) \in T: y' \leq y \Rightarrow (x, y') \in T$.

(A4) The production possibility set is convex. Thus, $(x^1, y^1) \in T: (x^2, y^2)$ and $\lambda \in (0,1) \Rightarrow (\lambda(x^1, y^1) + (1-\lambda)(x^2, y^2)) \in T$.

We state the production possibility set in linear programming form, ignoring concerns of functional forms, satisfying these assumptions as:

$$S = \left\{(x, y): x \geq \sum_{j=1}^{N} \lambda_j\, x^j\ ; y \leq \sum_{j=1}^{N} \lambda_j\, y^j\ ; \sum_{j=1}^{N} \lambda_j = 1;\ \lambda_j \geq 0\ (j = 1,2,..,N)\right\}. \tag{6}$$

3.2 Production technology in presence of bad outputs

Next, we modify the standard assumptions routinely made about a conventional production technology, especially the ones pertaining to free disposability, to accommodate the production of unwanted outputs that arise incidentally while producing the economic outputs. As already noted, the four popular concepts of disposability in the presence of bad outputs are free output disposability, free input disposability, weak disposability and joint disposability. The present study assumes joint disposability of bad output and polluting input. As defined in RMV (2017), in the case of joint disposability, the feasibility of reducing the quantity of bad output is tied to the simultaneous reduction in one or more inputs. In the technology described in (1) to include bad outputs, we first partition the output vector y as $y = (y_g, y_b)$, where y_g and y_b are the sub-vectors of good and bad outputs respectively. Similarly, we partition the input vector x as $x = (x_1, x_2)$, where x_1 and x_2 are the sub-vectors representing 'neutral' and 'polluting' inputs respectively. The overall technology set can then be written as:

$T = T^1 \cap T^2 = \{(x_1, x_2; y_g, y_b): F^1(x_1, x_2; y_g) \leq 0$ and $F^2(x_2; y_b) \leq 0\}$, where,

$T^1 = \{(x_1, x_2; y_g): F^1(x_1, x_2; y_g) \leq 0\}$ and

$$T^2 = \{(x_2; y_b):\ F^2(x_2; y_b) \leq 0\}. \tag{7}$$

T^1 and T^2 can be viewed as two different sub-technologies, where strong disposability assumptions about inputs and outputs hold only for T^1. That is,

If $(x_1, x_2; y_g) \in T^1$, and $x_1' \geq x_1$ then $(x_1', x_2; y_g) \in T^1$.

Similarly, if $(x_1, x_2; y_g) \in T^1$, and $x_2' \geq x_2$ then $(x_1, x_2'; y_g) \in T^1$, and

if $(x_1, x_2; y_g) \in T^1$, and $y_g{}' \leq y_g$ then $(x_1, x_2; y_g{}') \in T^1$.

For T^2, the inputs and outputs are jointly disposable. The following disposability property holds for T^2:

If $(x_2; y_b) \in T^1$, and $0 \leq \theta \leq 1$ then $(\theta x_2, \theta y_b) \in T^2$.

Note that the same quantity of polluting inputs produce both good and bad outputs. The technological relation discussed in (3) is also consistent with the material-balance condition.

The modified directional efficiency measure in presence of bad outputs become:

$$\overleftrightarrow{D}(x_{10}, x_{20}\, ; y_{go}, y_{b0}; g^{10}, g^{20}) = \{ max\ (\beta_1 + \beta_2): (x_{10}, x_{20} - \beta_2\, g^{20}; y_{g0} +\ \beta_1\, g^{10}, y_{b0}\ - \beta_2\, g^{20}) \in T; \beta_1, \beta_2 \geq 0\ \}. \tag{8}$$

Here, $g^{10}$is the pre-defined direction in which bad outputs and polluting inputs are projected, and g^{20} is the direction in which good outputs are expanded. As in the APR (2013) paper, good outputs expand radially, and polluting inputs and the bad output contract radially in different proportions. The ((in)efficiency of any firm with input-output bundle $(x_{10}, x_{20}; y_{g0}, y_{b0})$ is measured as $(\beta_1 + \beta_2)$, with $(x_{10}, x_{20} - \beta_2\, g^{20}; y_{g0} +\ \beta_1\, g^{10}, y_{b0}\ - \beta_2\, g^{20})$ as the efficient projection.

The non-parametric construct of the production set under the assumption that the bad outputs are by-products of a subset of inputs and are technologically separable from the good outputs is:

$$S = \{(x_1, x_2; g, b): x_1 \geq \sum_{j=1}^{N} \lambda_j x_1^j, x_2 = \theta \sum_{j=1}^{N} \lambda_j x_2^j; g \leq \sum_{j=1}^{N} \lambda_j g^j, b = \theta \sum_{j=1}^{N} \lambda_j b^j, 0 \leq \theta \leq 1; \sum_{j=1}^{N} \lambda_j = 1; \lambda_j \geq 0; j = 1,2,..,N\}. \quad (9)$$

4. DEA Models for Efficiency Measurement

We next consider a power industry made up of N firms/power plants where each firm $j, j = 1,2,..,N$, uses one polluting input – fuel (c_j), and two neutral inputs – labor (l_j) and installed capacity (k_j) to produce one good output - electricity (y_{gj}) and one bad output – stack emission (y_{bj}). We now formulate the relevant DEA optimization problem for measuring modified directional efficiency of a power plant indexed 0, under the joint disposability and by-production assumption as:

$$\max_{\beta_1, \beta_2 \geq 0} \beta_1 + \beta_2$$

s.t.

$$\sum_{j=1}^{N} \lambda_j y_{gj} \geq (1 + \beta_1) y_{g0};$$

$$\sum_{j=1}^{N} \lambda_j y_{bj} = (1 - \beta_2) y_{b0};$$

$$\sum_{j=1}^{N} \lambda_j c_j = (1 - \beta_2) c_0;$$

$$\sum_{j=1}^{N} \lambda_j l_j \leq l_0;$$

$$\sum_{j=1}^{N} \lambda_j k_j \leq k_0;$$

$$\sum_{j=1}^{N} \lambda_j = B \in [0,1]; \lambda_j \geq 0; j = 1,2,..,N. \quad (10)$$

In the above problem, the equality constraints on the bad output and the polluting input portray joint disposability of the undesirable output and offending input. The condition that the same polluting input ($(1 - \beta_2) c_0$) in the optimal solution produces both good and bad output is what ties the two sub-technologies together. The above problem pertains to measurement of production efficiency with the unit of analysis being the individual firm. β_2 is proportional reduction in the observed level of polluting input and the bad output, which is emission, that could be achieved concomitantly while expanding the actual electricity production by β_1 percent for firm 0.

Next, assume that total electricity production in the country is distributed over S states. The total electricity produced across all regions taken together is Y_G which is explicitly broken up as $Y_G = \sum_{s=1}^{S} Y_G^s$ where Y_G^s is the output produced in state/region $s, s = 1,2,..,S$. Let the set n consist of the number of power plants located in the different states. Partition the set n into S subsets so that $n = \{n_1, n_2, .., n_S\}$. Also, $N = \sum_{s=1}^{S} n_s$ is the total number of power plants in the country. Plant $i \in n_s$ only if it is located in the state s.

Given this setting, let us focus on the problem of a state regulator who is trying to optimize the operations of the power plants under its ownership and jurisdiction. We assume that there is no transmission of power across states and each plant serves only the state in which it is located, so, $Y_G^s = \sum_{i=1}^{n_s} y_{gi}^s$ is the total output of all plants in region s. Similarly, the total emissions generated by these plants within the state is $Y_B^s = \sum_{i=1}^{n_s} y_{bi}^s$ and the aggregated quantity of fuel used by plants in state s is $C^s = \sum_{i=1}^{n_s} c_i^s$. Also, $L^s = \sum_{i=1}^{n_s} l_i$ and $K^s = \sum_{i=1}^{n_s} k_i^s$ gives the aggregate labor employed and installed capacity across all power plants in state s. The output bundle produced at plant i in state s, is (y_{gi}^s, y_{bi}^s), the input bundle used at that plant is (c_i^s, l_i^s, k_i^s). The efficient level of good and bad outputs produced at plant i is $y_{gi}^{s*} = y_{gi}^s(1 + \beta_{1i}^s)$ and $y_{bi}^{s*} = y_{bi}^s(1 - \beta_{2i}^s)$, and the optimal fuel consumption is given as $c_i^{s*} = c_i^s(1 - \beta_{2i}^s)$. A measure of combined technical and environmental efficiency for the plant i is $(\beta_{1i}^s + \beta_{2i}^s)$ (as obtained from the solution of (10) for plant i).

Define, $Y_G^{s*} = \sum_{i=1}^{n_s} y_{gi}^s(1 + \beta_{1i}^s)$, $Y_B^{s*} = \sum_{i=1}^{n_s} y_{bi}^s(1 - \beta_{2i}^s)$, and $C^{s*} = \sum_{i=1}^{n_s} c_i^s(1 - \beta_{2i}^s)$ as the efficient levels of good and bad outputs and fuel use in the state. A measure of total (in)efficiency for the state is $(\beta_1^s + \beta_2^s)$, where,

$$\beta_1^s = \frac{Y_G^{s*} - Y_G^s}{Y_G^s} = \frac{\sum_{i=1}^{n_s} y_{gi}^s(1+\beta_{1i}^s) - \sum_{i=1}^{n_s} y_{gi}^s}{Y_G^s} = \frac{\sum_{i=1}^{n_s} y_{gi}^s \beta_{1i}^s}{Y_G^s}, \text{ and}$$

$$\beta_2^s = -\left(\frac{Y_B^{s*} - Y_B^s}{Y_B^s}\right) = -\frac{\sum_{i=1}^{n_s} y_{bi}^s(1-\beta_{2i}^s) - \sum_{i=1}^{n_s} y_{bi}^s}{Y_B^s} = \frac{\sum_{i=1}^{n_s} y_{bi}^s \beta_{2i}^s}{Y_B^s}. \quad (11)$$

Notice that $\frac{y_{gi}^s \beta_{1i}^s}{Y_G^s}$ and $\frac{y_{bi}^s \beta_{2i}^s}{Y_B^s}$ are the shares of plant i in the total inefficiency of the state. That is, the overall efficiency of the state is a weighted average of the technical and environmental inefficiencies at the individual plants. Because β_{1i}^s and $\beta_{2i}^s \geq 0$, and y_{gi}^s, y_{bi}^s are always positive for all i, overall inefficiency for the state will be 0 only when each firm is efficient.

Full efficiency at each plant does not ensure, however, that the total good output in the state, Y_G^s, is being maximized and at the same time the bad production along with the polluting fuel usage being minimized if there is a different allocation of resources and, hence, output tasks across the existing plants that could lead to an better outcome in terms of good and bad production and fuel consumption. Any reduction in the total inefficiency that is achieved by optimal reallocation of inputs to the different plants is due to an improvement in what Ten Raa (2010) calls efficiency of industrial organization.

Ray (2016) formulated an optimization problem where a multi-location firm (a large public sector bank in his case) tries to meet the demand at a specific geographical location through optimal allocation of inputs within the units (branches) operated in that area only. He solves a separate problem for each region where the bank operates including an explicit constraint that the total output from all branches within that area is sufficient to meet the demand in that market. The problem of a state-regulator trying to optimize power production while minimizing environmental pollution within the state is somewhat similar to the case in Ray (2016), given that we assume away the possibility of inter-state transmission of electricity.[17] An important point of difference between the two studies is - unlike a bank trying to minimize the cost of producing a target output bundle demanded in the region as in Ray (2016), here, the regulator is trying to simultaneously maximize the good output and minimize the use of polluting input so as to minimize pollution in the region. This is achieved by transferring of inputs like fuel and/or labor, and hence, reallocating output within the power plants in the state. The reassignment of outputs and inputs across firms within the state is permissible so long as the total output in the region is not lower than the existing level of intended output. Similarly, the aggregate efficient fuel use and resulting emissions do not exceed existing levels of emission and coal/oil consumption in the state. In addition, the allotted output to each power plant must be producible from the existing installed capacity of that plant because installed capacity is not transferable across plants.

We now develop DEA model for measuring state level efficiency gains, allowing for reallocation of only production and fuel inputs across plants within a state while treating installed capacity and labor as plant specific.[18] For each state s we solve the following problem:

$$\beta_1^{s\prime} + \beta_2^{s\prime} = \max_{\beta_1,\beta_2 \geq 0} \beta_1^s + \beta_2^s$$

s. t.

$$\sum_{j=1}^{N} \lambda_{ij}^s \, y_{gj} = \widetilde{y_{gi}^s} \; ; (i \in n_s);$$

$$\sum_{i=1}^{n_s} \widetilde{y_{gi}^s} \geq (1 + \beta_1^s) Y_G^s;$$

$$\sum_{j=1}^{N} \lambda_{ij}^s \, y_{bj} = \widetilde{y_{bi}^s}; (i \in n_s);$$

[17] It is a reasonable assumption because often times there are transmission costs and constraints in terms of transmission capacity that restrict regional exchange of power.

[18] Transferring labor across plants located in different parts of the state is not always a viable option.

$\sum_{i=1}^{n_s} \widetilde{y_{bi}^s} = (1-\beta_2^s) Y_B^s;$

$\sum_{j=1}^{N} \lambda_{ij}^s c_j = \widetilde{c_i^s}; (i \in n_s);$

$\sum_{i=1}^{n_s} \widetilde{c_i^s} = (1-\beta_2^s) C^s;$

$\sum_{j=1}^{N} \lambda_{ij}^s l_j \leq l_i^s; (i \in n_s);$

$\sum_{j=1}^{N} \lambda_{ij}^s k_j \leq k_i^s; (i \in n_s);$

$$\sum_{j=1}^{N} \lambda_{ij}^s = B_i \in [0,1]; \lambda_{ij}^s \geq 0; (i \in n_s); j = 1,2,..,N. \quad (12)$$

An important point to note is that, if at the optimal solution of the problem, $B_i = 0$ for any plant i that would imply that every $\lambda_{ij}^s = 0$ for that i and the optimal output for that plant is 0. This implies that the state may choose to close down some plants. The optimal input-output bundle cannot be 0 for all plants because of the constraint that the actual output of the state has to be at least as much as its existing output. For a plant's contribution in state's input-output to be strictly positive, at least one λ_{ij}^s must be positive and convexity requires that B_i should be equal to 1 for those plants. Thus, there will be endogenously determined optimal number of power plants $n_s^* = \sum_{i=1}^{n_s} B_i$ in state s.[19] The optimal solution of this problem yields the input–output bundle $(\widetilde{c_i^s}, l_i^s, k_i^s; \ \widetilde{y_{gi}^s}, \widetilde{y_{bi}^s})$ for each existing plant i in the state s. It needs to be emphasized that the optimal bundle $(\widetilde{c_i^s}, l_i^s, k_i^s; \ \widetilde{y_{gi}^s}, \widetilde{y_{bi}^s})$ for plant i is a convex combination of the input–output bundles of all plants in country/industry and not merely of those in state s. As in the firm model (10), here also we construct technology from the data on all plants in the sample/industry because they all face the same technology but allow for reallocation of fuel and outputs only across plants located in state s. $(\widetilde{c_i^s}; \widetilde{y_{gi}^s}, \widetilde{y_{bi}^s})$ represents the fuel consumption, and good and bad output produced at plant i after reallocation. Since there is no reallocation of labor (l) and installed capacity (k), each plant i is constrained to operate with its available amount of the two resources, that is within (l_i^s, k_i^s). The allocation of outputs across power plants is an optimization problem and depends on how much spare generation capacity a plant has and also on the nature of local returns to scale at plant existing level of operation. The state can benefit by allocating resources to plants that are clean and efficient and operating in region of increasing returns to scale (IRS), but are not able to utilize their generation capacity to the full extent due to limited availability

[19] But unlike in Ray and Hu (1997), the plants will not have identical input-output bundles.

of fuel. In addition to surplus generation capacity, the plants also need to have surplus employees to be able to take advantage of IRS. [20]

For comparison, we also consider a more flexible model where not only fuel but also labor is allowed to move across power plants and only installed capacity is plant specific. Efficiency gains attained by allowing for reallocation of production, fuel and labor inputs across power plants within state s is empirically measured by solving the DEA problem:

$$\beta_1^{s''} + \beta_2^{s''} = \max_{\beta_1,\beta_2 \geq 0} \beta_1^s + \beta_2^s$$

s. t.

$$\sum_{j=1}^{N} \lambda_{ij}^s \, y_{gj} = \widetilde{y_{gi}^s} \, ; (i \in n_s);$$

$$\sum_{i=1}^{n_s} \widetilde{y_{gi}^s} \geq (1 + \beta_1^s) Y_G^s;$$

$$\sum_{j=1}^{N} \lambda_{ij}^s \, y_{bj} = \widetilde{y_{bi}^s}; (i \in n_s);$$

$$\sum_{i=1}^{n_s} \widetilde{y_{bi}^s} = (1 - \beta_2^s) Y_B^s;$$

$$\sum_{j=1}^{N} \lambda_{ij}^s \, c_j = \widetilde{c_i^s}; (i \in n_s);$$

$$\sum_{i=1}^{n_s} \widetilde{c_i^s} = (1 - \beta_2^s) C^s;$$

$$\sum_{j=1}^{N} \lambda_{ij}^s \, l_j = \widetilde{l_i^s}; (i \in n_s);$$

$$\sum_{i=1}^{n_s} \widetilde{l_i^s} \leq L^s;$$

$$\sum_{j=1}^{N} \lambda_{ij}^s \, k_j \leq k_i^s; (i \in n_s);$$

$$\sum_{j=1}^{N} \lambda_{ij}^s = B_i \in [0,1]; \lambda_{ij}^s \geq 0; (i \in n_s); j = 1,2,..,N. \tag{13}$$

The optimal solution of the mixed integer programming problem (13) yields the maximum good output producible and potential contraction in bad output and polluting input, along with the optimal number of power plants that should operate in state s. Model (13) is same as (12) except for the constraint on labor (l). Now that labor is allowed to move freely between plants, the optimal amount of workers at each plant

[20] A special situation arises in the cases of plants that are technically inefficient to begin with and the nature of returns to scale depends on the orientation of their projection to the frontier.

is determined endogenously (measured by $\widetilde{l_i^s}$) in a way such that the total number of employees at all plants taken together in state s are bounded above by L^s, the observed level of employees in the state's power generation facilities. As before the model redistributes transferable inputs, fuel and also labor, among power plants within the state in pursuit of maximum state-level efficiency. The model allows only those plants to operate in the state that can raise the total power supply in conjunction with improving the overall air quality, while collectively using no more labor than is currently employed in the state and with each plant operating within the existing installed capacity of its boiler. The spare resources due to shut down or reduced operation of a plant are transferred to the plants that are more efficient but not yet utilizing their full capacity due to factors such as fuel shortage.

We now have three measures of (in)efficiency for each power producing state in the industry under the following alternative structural assumptions:

(i) Determining potential efficiency gains for the state, by considering plant level optimization. No reallocation of either output or input is allowed, (we call this the Base Case)

$\beta_1^s = \frac{\sum_{i=1}^{n_s} y_{gi}^s \beta_{1i}^s}{Y_G^s}$, and $\beta_2^s = \frac{\sum_{i=1}^{n_s} y_{bi}^s \beta_{2i}^s}{Y_B^s}$.

(ii) Determining state-level efficiency gains by allowing for reallocation of only production and fuel inputs across plants within a state but treating installed capacity and labor as plant specific (Model 2)

$\beta_1^{s'} + \beta_2^{s'}$ as obtained from (12).

(iii) Determining state-level efficiency gains by allowing for reallocation of production, fuel and labor inputs across power plants within a state but treating only installed capacity as plant specific (Model 3).

$\beta_1^{s''} + \beta_2^{s''}$ as obtained from (13).

5. The Empirical Analysis

For empirical application of the models developed above, we use an unbalanced dataset on 83 major coal-based power plants from 16 states in India, for the years 2005-06 to 2014-15 (for the rest of this paper, we denote 2005-06 by 2005 and so on).[21] The main source of data for our analysis is the annual report on Review of Performance of Thermal Power Stations (RPTPP), published by Central Electricity Authority

[21] As noted earlier, the data are reported by accounting year, which runs from April 1st to March 31st of the next year. Thus, the year 2005-06 refers to the period April 1, 2005 to March 31, 2006. For the rest of this paper, we refer to the year 2005-06 as 2005, and so on till 2014-15 (denoted as 2014).

(CEA), Government of India. It may be noted that we have one year with missing data because the thermal performance review report was not published in 2011. The annual reviews provide data on the operating performance parameters (based on yearly generation) of major grid connected generating stations under the control of state governments, the central government, and private companies. The unit of observation is the generating station, plant-level data for each year.[22] There are 72 power plants in our sample with an installed capacity of 61,880 MW in 2005, which increased to 81 plants with productive capacity of 91,376 MW in 2014. The generation capacity and the number of power plants have increased over time for most states. The generating stations evaluated in the study together account for about 60-70% of the total thermal-generation capacity in the country, in each year.[23] Furthermore, the state-owned plants account for a dominant share in terms of number of plants and generating capacity. Typically the state-owned plants operate to serve local demand of the state in which it operates while the central and some private sector plants cater to a much broader customer base, from all regions combined. Also, the extent of fuel allocation and operations of state-owned and private plants are subjected to the control of the state utility or state electricity board (after seeking approval from the State Regulator). The state utilities do not directly exercise control over the central sector plants, but procure power from them to meet any un-catered demand in their states. This situation pertains to that of an independent regulator who has no authority over the operations of centrally owned plants and optimizes by reallocating inputs between the state-owned and private plants in their own state only. However, in scenarios with extreme power deficit or for clean energy promotion in the country the central regulator may (and is entitled to) specify and enforce standards to the state electricity regulatory authorities so that the coal and other inputs are allocated and utilized in the most efficient manner. So the problem can then be seen as that of a central planning authority that optimizes operations of power production facilities in each state individually by distributing productive to resources to the plants (irrespective of which sector it belongs to) that imply best outcomes in terms of electricity and emission generation in the state. We evaluate both these scenarios – first allowing reorganization of production across all plants in a given state, and then confining it merely to the state-owned and private plants in each state and treating each central sector company differently, permitting redistribution of resources and output tasks within their own plants only. The only distinction between these two scenarios is that the allocation

[22] In cases where data are available at the unit-level, we aggregate by taking a weighted average of unit-level data (weighted by the unit's installed capacity) to obtain plant-level information.

[23] A large number of power plants had to be dropped because of unavailability of complete information on all required variables for our models.

provided under the first case would also be more likely cost efficient as opposed to simply augmenting the state efficiency.[24]

The production technology is defined with one good output, one bad output and three inputs, of which two inputs (labor and capacity) are neutral and one (fuel) is polluting. The good output is annual megawatt hours of electricity generated (MWh or MUs) and the bad output is the average level of Suspended Particulate Matter (SPM) emissions at stack, measured in mg/NM^3.[25] The installed capacity of the power plant (measured in MW) and labor are the neutral inputs, and fuel, comprising kilocalories (kCal) of coal and oil is the polluting input. A detailed account of the construction of input and output variables merits discussion here. The good output is simply the total annual electricity generation at each plant, taken directly from the CEA RPTPP publication. Next, the data on SPM emissions can be viewed as a measure of air quality in the vicinity of the power plant. The CEA review reports for each power plant, annual estimates of maximum and minimum suspended particulates (in mg) generated in 1 NM^3 of air per kilowatt hour of energy produced. For an appropriate measure of a plant's normal emission rate we take an average of the reported upper and lower bounds. We then multiply the average emission rate by actual generation to obtain total emissions. As for the inputs, the installed capacities of the plants are adjusted for their operating unavailability due to planned maintenance or forced outages. In the past, several studies have talked about the importance of capacity utilization in measuring efficiency. Murty and Nagpal (2018) treats operating availability of a plant (in terms of percentage of a plant's capacity available for generation) as a proxy for capacity utilization and calls it a managerial input. They argue that low operating availability of a plant reflects managerial incompetency in a plant's maintenance. However, it is important to note that oftentimes, a power plant is operated at partial load (below capacity) at the discretion of the system operators due to low demand or transmission constraints, or even because of coal shortages. This has also been corroborated in the CEA thermal performance review reports.[26] Moreover, it may not be optimal for a generating station to be always loaded at 100% capacity – because that might lead to wear and tear and loss of generation in the future. Therefore, it is a ration decision to shut down the plant for planned maintenance from time to time. Therefore, factors such as planned maintenance, forced outage, part load operation, and other non-discretionary conditions like wet coal need to be controlled for while computing productivity instead of

[24] If one was to account for transportation costs in reallocating resources, it would be more economical and pragmatic to reallocate within a state than to, for example, ship coal and transfer labor from a NTPC plant in Western region of the country to another NTPC plant in Northern region.
[25] MUs = Million Units (One Unit is one kilowatt hour (kWh)).
[26] The 2014-15 CEA report explicitly mentions that "main reasons for low operating availability was increased forced shut down of thermal units due to coal shortage, Transmission constraints, Vintage units closed for operation and Reserve Shutdown."

attributing it to a plant's inefficiency. It reasonable to measure performance of power stations against the capacity that was actually available for production rather than the designed capacity of the plants.

Unfortunately, the unit- or plant-level data on employment is not reported for the power plants in India and almost all the studies on power generating utilities in India exclude labor from the analysis. In fact, some studies based on US power plants also take labor out of consideration (see, for example, Zhou and Huang (2016)).[27] For the labor input, in addition to the CEA data, we use another data set in this paper. We collect information on the number of employees from "Annual Report (2011-12 and 2013-14) on the working of State Power Utilities & Electricity Departments, Government of India". Data on labor are available only at the state level (separately reported for NTPC plants). They are reported in terms of number of employees per MWh of electricity sold. Therefore, we use this state-level labor data and allocate labor to power plant based on the electricity generation at each plant.[28]

<Insert Figure 1>

Lastly, the fuel input is computed using a plant's station heat rate (SHR) measured in kCal per kWh of energy generated.[29] It is possible that everything else remaining the same, two plants using the same volume of coal produce different levels of emission on account of differences in the type of coal used. As opposed to the routinely followed practice of measuring fuel use in terms of volume of coal/oil consumed (for example, Sueyoshi and Goto (2012)), we consider the total calories of fuel consumed at a plant (obtained by multiplying SHR with total generation) which takes into account varying calorific values of different grades of coal used in generation. Emissions are correlated with the heat input required by the plant and not physical amount of coal consumed *per se* (see Murty and Nagpal (2018) for an elaboration on heat input of fuel versus "mass input"). Accordingly, SHR multiplied by total generation gives us a more appropriate measure of the fuel input. It is important to note that direct data on SHR are not reported for several plants

[27] However, non- availability of data does not imply they are not relevant. Therefore, we recognize that ours' is a constructed labor data but it is better than ignoring it altogether. Also, the abovementioned annual report which is the source of this data is accessible only for three years – 2001, 2011, and 2013. The 2001 publication provides data from 1994 through 2001 and the remaining two issues cover the period from 2007 through 2013, leaving us with three years (2005, 2006 and 2014) of missing information. A simple time plot of the available data indicates a falling trend in labor usage in most states (see Figure 1) and the missing numbers for 2005 and 2006 could be easily interpolated. But, it would still leave for us to extrapolate 2014 and involve too much manipulation to an already constructed data. That being the case, we conduct our analyses without labor in these year

[28] In their application on evaluating the efficiency of various generating units in the US, Fare et al. (2005), rely on a similar mechanism to compute their labor data. They use aggregated utility-level data on employment and assign labor in proportion to the actual generation of each unit.

[29] SHR = (specific coal consumption (in kg/kWh) x Gross calorific value of coal (in kCal/kg)) + (specific oil consumption (in ml/kWh) x Gross calorific value of oil (in kCal/liter)).

included in our sample. The heat rates for such plants are derived based on the following formula obtained from CEA reports,

$$SHR = \left(\text{specific coal consumption } \left(\frac{kg}{kWh}\right) \times \text{Gross calorific value of coal } \left(\frac{kCal}{kg}\right)\right) + \left(\text{specific oil consumption } \left(\frac{ml}{kWh}\right) \times \text{ Gross calorific value of oil } \left(\frac{kCal}{liter}\right)\right). \tag{14}$$

We utilize available information on specific coal and oil consumption (SCC and SOC). Following the CEA reports, we assume gross calorific values (GCV) of oil to be 10000kCal/liter for all plants in all years. To compute GCV of coal, we follow two steps – (i) Use (14), data on SCC, SOC and GCV of oil to back-calculate GCV of coal for all plants with duly reported data on SHR, and then (ii) assume a GCV of coal for the plant with missing data to be a simple average of the GCVs of all other plants in the same state and under same ownership. We also double check the calculated GCV with the plant's actual GCV in preceding years. The underlying assumptions are that quality of coal is unlikely to be significantly different for plants in the same state and under same ownership, and neither does it vary considerably compared to a unit's own recent past. In other words, if a plant typically operates on domestic coal and is linked to a particular coal mine, in most cases it remains a continued practice for the plant to source its fuel from the same mine and quality of coal is expected to remain more or less consistent. We check for the sensitivity of our results to the SHR data and find that our optimization results remain stable within 10-15% deviation in the computed heat rates. Summary statistics of the inputs and outputs for selected sample years are provided in Table 1.

<Insert Table 1[30]>e

Several points may be noted from the statistics presented in the above table. First, there is evidence of capacity addition, and expansion of supply over years. The sample average air quality, though marked by fluctuations, largely worsened. There is a decline in the average heat and labor inputs, consumed per unit of electricity, over our study horizon. A rise in the level of mean SPM emission rate alongside reduced heat rates, by itself, suggests the worsening productivity and operational inefficiency at the power plants considered. Second, a great variability is observed in the plant sizes showing substantial diversity in terms of their inputs us and output generation. We find that barring the NTPC plants, maximum generation capacity is concentrated in the states of Uttar Pradesh (UP), Maharashtra and West Bengal, accounting for over 35% of the total installed capacity in each sample period. Third, the CEA in their Thermal Performance Review report prescribes norms for the level of SPM emissions at stack. The SPM emission level of greater

[30] For ease of presentation, all tables in the paper report results/data from selected years – 2005, 2010, and 2014. Results/data for other years can be provided upon request.

than 350mg/Nm3 has been identified as "very high". It is evident from the above table that the maximum SPM emission rate observed in each sample year is more than twice this permissible norm. Although the count of such plants is not alarmingly high (typically ranging between 3 to 7 every year), about 20% of the plants are observed to have particulate concentration in excess of 150mg/Nm3 in the ambient air (which is still considered high).

5.1 Results

<Insert Table 2>

The measured levels of technical and environmental inefficiency for individual power plants (without any reassignment of inputs and outputs) in each year are reported in Table 2. For each plant, the maximum possible increase in good output (measured by β_1) together with the maximum contraction in fuel use, and hence a cutback in polluting discharge (measured by β_2) that is concomitantly attainable are determined from the problem in (10) and the results are reported in Table 2. A beta value of 0% indicates full efficiency and implies that the plant operates on the frontier. The number of frontier plants increased from 14 in 2005 and 2006 to about 27 in the years 2007 through 2013 (barring a fleeting decline to 19 in 2010), reverting to 15 in 2014. Out of all the power plants analyzed, only Dahanu power station in Maharashtra and Talcher STPS in Orissa remain efficient through the sample years.[31] Ramagundem B and Ramagundem STPS in Andhra Pradesh, Korba STPS in Chhattisgarh and Obra in UP are also close o full efficiency throughout the sample period. It is interesting that three of these most efficient plants (Talcher, Ramagundem and Korba) are super thermal (exceeding 1000MW in capacity) and NTPC plants.

By contrast, the state owned generating facilities comprising I.P Station, Rajghat (Delhi); Faridabad (Haryana); Panki, Paricha (UP), Amar Kantak Extension (Madhya Pradesh); Ukai (Gujarat); Kothagudem (Andhra Pradesh); Ennore, Neyveli I (Tamil Nadu); Bokaro B, Tenughat (Jharkhand); and Bandel , D.P.L., Kolaghat and Santaldih (West Bangal) are consistently found to be highly inefficient in terms of both environmental and productive performance. We note at this point that our results are in agreement with those found by Murty and Nagpal (2018), namely that there is no major difference in overall efficiency and ranking of the plants. We also find that there is no significant difference in productive efficiency. In terms of environmental efficiency, we begin to find some differences.

5.1.1. Measuring State Inefficiency based on firm/power plant level optimization

[31] STPS: Super Thermal Power Station. Super thermal power plant is a power generating station with capacity of 1000MW and above

<Insert Table 3>

Table 3 contains more interesting, and for the present paper, more important results from this empirical analysis. For each state, the table reports actual fuel use, generation, emission, emission rate and heat rate, and the optimal percentage improvements (in generation (β_1^s), fuel saving (β_2^s)and air quality (β_2^s)) attainable through plant level optimization. Efficient levels of emission rate and heat rate, derived based on optimal quantities of power and emissions produced, and heat consumed in each state, are also shown. The state-level inefficiencies are derived as weighted average of individual plant level inefficiencies (in Table 2) based on the formulas in (11). It may be noted that while the same number β_2 represents percentage reduction in polluting input and also possible emission contraction in a plant-level optimization problem, when these are combined by state, the aggregation process might result in slightly differing fuel saving rate and rate of improvement in air quality. This is because, in order to obtain potential fuel saving in a state, the individual betas are weighted by each plant's share in state's total fuel use and for optimal emission reduction, the weights become plants' shares in total emissions in the state. The use of differing weights results in dissimilar β_2^ss; although the two numbers are not widely apart. The last row in each yearly sub-section of the Table 3 shows actual inputs and outputs and total possible improvement (in percentages) at an all India level.[32] Also shown in the table, are the total surplus labor and capital (installed capacity) remaining in each state after all efficiency improvements. These are simply the slacks in labor and capital constraints of (10), aggregated over all plants in each state. We call these our Base Case results.

Turning first to the yearly results for the sample as a whole, we find that the production inefficiency (β_1) hovered between 3%-5% each year. Environmental inefficiency (β_2) was marginally higher and ranged between 3%-6% most of the times.

Looking at the individual states, Jharkhand is continually highly inefficient. Gujarat, Karnataka, Punjab and Madhya Pradesh are among the other less efficient areas, with combined technical and environmental inefficiency exceeding 10%. On the other hand, Orissa is one of the better performing states; not to forget, two out of three of its generating stations are owned by NTPC. Tamil Nadu exhibits moderate performance. Rajasthan has worsened over time, while Bihar and Haryana have improved in the later years. Next, among the high capacity states, UP, Chhattisgarh and even Andhra Pradesh are the relatively more efficient whereas Maharashtra and West Bengal have remained consistently inefficient. An interesting point to note is that 5 of the 9 generating stations in Uttar Pradesh are under NTPC while Maharashtra had none and West Bengal has only one NTPC plant. Apparently, centrally-owned plants (especially the ones owned by NTPC) tend to raise the overall performance in states like Uttar Pradesh. In order to further examine how

[32] The potential improvements at the country level are computed using formulas similar to those in (11), by taking a ratio of the difference between aggregate actual and optimal levels of good output, bad output and polluting input to the observed levels of corresponding outputs and inputs.

the type of ownership of an electric utility impacts a state's efficiency, in Table 4 we report state-wise efficiency scores calculated with and without accounting for the central sector plants. The (in)efficiencies of center-run plants, aggregated by company, are also presented for comparison. The relevant figures reported in Table 4 reveal that the NTPC plants are comparatively the most efficient group but units under DVC and NLC are not particularly so. It also emerges that after omitting the central plants Delhi, UP, Madhya Pradesh, Chhattisgarh, Andhra Pradesh and also Orissa experienced a decline in overall efficiency. At this point it is important to bear in mind that while (in)efficiency scores may have increased for these states, in the present situation it is useful to evaluate improvements in absolute terms (comparing columns ΔG and ΔB in the columns including and excluding the Center-owned utilities). For example, in Chhattisgarh and Madhya Pradesh, despite an increase in (in)efficiency scores, the amount of increase in good output and reduction in bad output remain unchanged even after excluding the NTPC plants; suggesting that the NTPC plants operating in these states were actually fully efficient. On the other hand, for UP we see an increase in beta values but lower potential achievements in terms of increased generation and reduced emissions, which in turn implies that the central sector plants here were somewhat inefficient too. On a closer observation of the data in Table 4, the central sector plants in UP appear to be relatively efficient in production but dirtier than the state plants (total increase in state's generation is almost the same but reduction possibilities in emissions are much less after removing NTPC plants). Similar pattern is observed in West Bengal too. But, those in Tamil Nadu seem to be cleaner but technically less efficient.

On the whole, grouping or ungrouping the center-run power plants with state plants will have no impact on aggregate outcomes at the country level as long as efficiency is sought through individual plant level optimization. It is more interesting to see how these inefficiency scores and outcomes get altered after optimally reorganizing production through reassignment of inputs and outputs within each state. Furthermore, as can be seen from the last column in Table 4, many states have surplus capital and labor, implying that there might be opportunity for efficiency gains by utilizing spare resources and through appropriately reallocating resources towards the more efficient plants, meanwhile retiring or downsizing operations at less productive and dirtier stations.

<Insert Table 4>

5.1.2. Measuring Inefficiency at State-level (State-level Optimization)

We have discussed two ways in which activities may be reorganized in a state - (i) Restructuring production tasks across all plants in the state irrespective of their ownership, or (ii) Allowing reallocation only among the state-run and private entities within the state. As mentioned earlier, we explore both these alternatives and examine any implication that the choice of reorganization path may have for system strengthening. We first examine the case where reassignment of inputs and outputs takes place among all plants located within a particular state.

<Insert Tables 5 and 6>

As discussed in the previous section, we calculate two efficiency measures, based on equations (12) and (13), for each state in our sample. The results of these calculations are summarized in Tables 5 and 6 respectively. Our state-level (in)efficiency estimates ($\beta_1^{s\prime}$ and $\beta_2^{s\prime}$) after reallocating fuel while holding labor and installed capacity plant specific are presented in Table 5. We call these the *Model 1* results. The corresponding estimates ($\beta_1^{s\prime\prime}$ and $\beta_2^{s\prime\prime}$) when both fuel and labor are allowed to vary, and only installed capacity is fixed for each plant are provided in Table 6. These are the *Model 2* results. Unlike in the case of plant-level optimization, here we have a single β_2, representing both, percentage reduction in fuel use and improvement in air quality. In addition to the efficiency scores, we also show for each state, the actual and efficient number of power plants after restructuring.

Between the Base Case results in Table 3, and Models 1 and 2 (in Tables 5 and 6 respectively), we find that $(\beta_1^{s}+\beta_2^{s}) \leq (\beta_1^{s\prime}+\beta_2^{s\prime}) \leq (\beta_1^{s\prime\prime}+\beta_2^{s\prime\prime})$. This is intuitive because an option to redistribute inputs across generating facilities offers greater flexibility and hence, a greater potential for enhancing state's generation, and emission and fuel use performance. There are different ways in which a state could augment its good output production, and contain emission and fuel use at the same time. Any state has two kinds of plants to begin with – the efficient plants operating on the frontier and the off-frontier plants. Now, it must be reckoned that simultaneous increase in good output and a reduction in the bad is possible only as long as a plant is inefficient. Once it reaches the frontier, or if it is fully efficient from the beginning, any increase in generation would come at a cost of higher emission due to higher fuel use. Likewise, reducing pollution (by lowering fuel consumption) would imply a cutback in generation too. Therefore, in a centralized planning model, allotting more fuel to an efficient plant to increase generation will also imply higher emission. The decision to move a frontier plant in the direction of increasing good output or in the direction of further reducing bad output depends on the firm's position on the frontier and the associated opportunity costs of raising production versus reducing emission and the accompanying fuel use. Other possibilities along the frontier include fuel conservation to reduce emission but it may occasionally increase power generation. A possible explanation for this, as elucidated in RMV (2017), is that marginal productivity of the neutral inputs may be altered due to a change in the level of a polluting input. For example, lower emission from restricted fuel use could raise workers' productivity in a way that output increases despite lower fuel input. Sometimes it may also be optimal for the overall betterment of the state that a plant is moved from one point on the frontier to another point and that may involve scaling down its fuel use and hence lower generation by the plant, but may also reduce emission by a greater proportion. The surplus fuel is then allotted to another plant which when rendered efficient can increase total generation that more than compensates for the fall in output at the previous plant and similarly for the bad output.

On the other hand, an off-frontier plant can be inefficient in one of the three ways, (a) efficient in electricity generation but inefficient in environmental performance, that is, ($\beta_{1i}^s = 0, \beta_{2i}^s > 0$), or (b) efficient environmentally but technically inefficient, ($\beta_{1i}^s > 0, \beta_{2i}^s = 0$), or (c) inefficient in both aspects ($\beta_{1i}^s > 0, \beta_{2i}^s > 0$). Higher inefficiency means there is a greater potential for improvement. In the first case a state can increase output without increasing the use of fuel and without emitting more. In the second case, the plant could costlessly raise the good output production and lastly, emission reduction and fuel saving is concurrently possible with higher power production. Once any inefficiency is eliminated a plant may be scaled up or down in operation (in the interest of boosting state's overall functioning) depending on its opportunity cost of moving up or down along the frontier. Also, if the generation to fuel ratio (and, hence the good to bad output ratio) is very low, it may be optimal to retire it and employ the released resources (fuel and labor) elsewhere.

As previously mentioned, an important finding from our empirical analysis is that overall inefficiencies ($\beta_1 + \beta_2$) from Model 1 are at least as large as the ones in the Base Case, suggesting that there are gains to be realized from restructuring. Owing to a trade-off between β_1 and β_2 in the objective function, sometimes it may happen that β_1 in Model 1 is smaller than $\beta_1$from the Base Case but is compensated by a bigger β_2. For example, in the case of West Bengal in 2014 we see that the Base Case improvement is 5% increase in power production with 8% lower emissions. After reallocating fuel, the optimal generation expansion is only 2% but the bad output and polluting inputs are cut back to the extent of 11%. Reallocation improved state's generation performance in the former years but in the more recent years there is evidence of greater environmental improvements and fuel saving. Furthermore, the optimal number of plants in West Bengal is smaller than the actual in most years (2005, 2007, 2008, 2009, 2010, 2012, and 2013). The model regularly suggests that the Southern power plant be retired. A private sector plant New Cossipore plant is also recommended to be shut down in 2010, 2012, 2013. Interestingly, Calcutta Electric Supply Corporation Limited (CESC) had shut down the operations of this plant in 2004 because of economic unviability. When it resumed processes in 2010 we find that the effective capacity of the 160MW plant was only about 78MW, generating 363MUs at an implied load factor (PLF) of 25% and an operating heat rate of over 5000kCal/kWh, which is extremely high in comparison to the average heat rate of 2768kCal/kWh (see Table 2).[33] It is reassuring to see that findings from the model are not in an obvious conflict with actualities. Similarly for Maharashtra, there are mixed improvements – some years in terms of generation while other years with regards to air quality and fuel use. Paras Extension and Paras power plants are candidates for

[33] Plant load factor (PLF) = Generation (MWh) /Capacity (MW) x 8760 (hours). Moreover, Table 2 shows that generation at the plant was lowest in the sample with highest heat rate in 2010.

shut down in 2008 and 2009 respectively. Of these, Paras power station actually ceased production in late 2000s. Other states that saw alternating operational and environmental improvements after restructuring are Haryana and Rajasthan. The model recommends decommissioning of the Faridabad power plant in Haryana in 2008 and the plant was actually taken up for retirement in the same year. While a perfect correspondence between the DEA results and such ground realities is not expected, it is encouraging to have an independent validation of these optimization results. In Rajasthan, the existing number of power plants are optimal. Reorganization of operations have benefitted most states more in terms of fuel saving and less severe environmental consequences, comprising the states of UP, Andhra Pradesh, Orissa, Punjab, Chhattisgarh, Tamil Nadu, Madhya Pradesh, also Delhi to an extent. Along with reorganizing activities, the model also finds it optimal to discontinue production at Rajghat in Delhi, Panki in UP and Ramagundem B in Andhra Pradesh. This has steered recognizable improvements in average heat rates and emission rates in these states (see Table 5). The results between the Base Case and Model 1 do not change for Bihar and do not vary much for Karnataka because there was only one power plant in these states (the number increased to two in Karnataka from 2009 onwards). For Jharkhand and Gujarat however, there is no major change in overall efficiency because any increase in β_2 is offset by almost same corresponding percentage decline in β_1. The lignite based power station in Kutch, Gujarat is a candidate for shut down as per results in 2007 and 2014, and Dhuvaran in 2009. Overall, as shown in Table 5, if each existing plant could eliminate inefficiency but the present number of plants were retained, the generation would improve by an average of 4% each year and, fuel use and emissions would come down by only 5% on average. Thus, an extra fuel saving and increase in air quality standard by 5% and only 1% less increase in production could be attained by gaining full network (state) efficiency. Largely, Model 1 implies an increase in total generation by about 9000MUs (see Table 8) and reduction in mean national heat rate and emission rate to 2266kCal/kWh (compared to the actual of 2512kCal/kWh) and 109mg/Nm^3 (against the actual of 121mg/Nm^3) in 2014. Similar improvements are observed in other years too.

In Model 2 we allow the labor to be transferable across utilities and to be optimally assigned to plants along with coal and oil. Installed capacity is still plant specific. First thing we notice is that the optimal number of power plants in Model 2 are smaller than the number of plants optimal as per Model 1. When the plants are less constrained in terms of availability of variable inputs like fuel and labor, a more efficient utilization of the fixed input (installed capacity) prompts higher and cleaner power production at each existing facility, sometimes enabling an otherwise unproductive plant to be viable and at the same time, leaving greater flexibility to close down the relatively costlier plants. We see in the case of New Cossipore power station in West Bengal (in 2012 and 2013) that the plant was a candidate for shut down based on the Model 1 but reallocation of labor across the state enables it to operate effectively at a PLF of nearly 90%. A list of power plants identified for shut down by Models 1 and 2 is given in Table 7.

<Insert Table 8>

Next, between Model 1 and Model 2, the outcomes are identical in the years 2005, 2006, and 2014 for the reason that there is no labor data for these periods. In addition, Bihar, Chhattisgarh, Madhya Pradesh, Orissa, Punjab and Rajasthan also have exactly the same results in all years as in Model 1, indicating that the existing allocation of workers is already optimal or that there is over employment at each plant in which instance the possibility of reallocating labor becomes irrelevant. A detailed examination of the results in the relevant column of Table 6 reveals that labor is indeed surplus in each of these states throughout the sample years with an exception of Rajasthan in 2009, Bihar in 2008 and 2009, and Chhattisgarh from 2007 through 2009 when it is efficiently employed. The remaining states experienced some minor increase in generation compared to Model 1 as a result of a more efficient utilization of the neutral fixed input (installed capacity) when more workers are available. These states include Tamil Nadu (1% more good output in 2007 and 2008), Karnataka (9% more in 2012), Maharashtra (average 3% increase during 2007 to 2012), West Bengal (4% average increase from 2007-2012), Haryana (4% in 2007, 3% in 2012) and Gujarat (2% more in 2007 and 4% in 2009). While there was increase in generation (relative to Model 1), some of these places also faced slightly higher emission and fuel use during the same periods –Karnataka (8% increase in 2012), Maharashtra (4% average in 2007, 2008 and 2009), West Bengal (3% average increase from 2007-2012), Haryana (3% in 2012), and Gujarat (2% rise in 2007 and 2009 each). On the whole, total potential for improvement ($\beta_1^{s''} + \beta_2^{s''}$) either increased or remained unchanged for all of them. The states that gained in terms of β_2 alone are UP and Andhra Pradesh. Assessing at an all India level, we see an additional potential increase in generation, over and above Model 1, by 1% each year through 2007 to 2012. In 2012, there is also 1% extra fuel consumption and emission. To summarize, under Model 2 electricity output for the sample increases by 9136 MUs, mean station heat rate reduces to 2266 kCal/kWh and air quality improves from 121mg/Nm^3 to 109 mg/Nm^3 in 2014. Comparable improvements were found the past years as well. To put these numbers in perspective, the enhanced electricity production as a result of efficient allocation of factors is equivalent to about 25-30% of country's energy deficit on an average.[34]

5.1.3. State-level Optimization by Ownership

From the prior discussions, it emerges that while state-wide restructuring may be optimal, it may not be feasible owing to the differences in ownership of power plants and lack of states' control over the centrally-owned enterprises. A comparison of the efficient outcomes (measured as potential increase in power generation and decline in emissions and fuel use) when reallocation is considered across all power plants

[34] It is worthwhile to remember that our sample covers only about 60% of country's generation capacity. An optimization on a more complete dataset could entail greater potential increment in the good output. Also, the objective function simultaneously emphasizes on two contrasting policy objectives of more power and cleaner power, if maximizing generation alone constituted the focus of reallocation framework, further increases in the power production could be attainable.

in a state versus when it is limited only to the state and privately owned plants within the state leads to useful conclusions regarding the viability of alternate policy objectives for system strengthening. In Table 8 therefore, we report and evaluate the results from Model 1 under the two alternative scenarios, one which allows redistribution across all plants in a particular state (as already seen in Table 5) and another when we restrict the rearrangement of activities between state-owned and private sector plants but each central-enterprise is treated independently, with reallocation taking place within their own group of plants only. The results from Model 1 and 2 are not very different, although we do find slightly higher reduction in emission when all inputs allocated efficiently like in Model 2, opposed to Model 1 when only fuel is redistributed, Model 2 is more realistic as it might not be always possible to displace employees from one location to another. So, in Table 8 we only compare results from Model 1. Also, in order to evaluate which reorganization path is more value adding for the states, it is meaningful to compare in terms of actual energy increases, and fuel saving and emission reductions than in percentage terms. In the relevant columns, we present total change in the good and bad output from state-wide reallocation and the corresponding numbers when reassignment of inputs and outputs takes place separately for NTPC plants.

<Insert Table 8>

Punjab, Haryana, Rajasthan, Gujarat, and Maharashtra had no central sector plants and we have identical results between Table 5 and Table 8. For the rest of the states, UP, West Bengal, Andhra Pradesh, Tamil Nadu, Chhattisgarh and even Jharkhand show superior outcomes in terms of fuel usage and air quality, and also somewhat with regards to generation of power in all years when the central sector plants are included. For Orissa, omission of central sector plants leaves only one power plant and there is no scope for restructuring the state. Inclusion of central plants considerably improves the state's air quality and fuel use performance. Conversely, Madhya Pradesh exhibits augmented power generation and greater emission reduction when central sector plants are excluded from state's reallocation plan. A reasoning for this is that the state had only one central sector plant (Vindhyachal STPS) which was already functioning efficiently at 100% PLF even before any restructuring took place, meaning that state could not have benefitted from allocating higher fuel to that plant. For the sample as a whole, in 2010 and 2013, increase in generation and decline in emissions are both higher when reallocation encompasses centrally-owned plants. In 2007 alone we find that the outcomes for the sample is better overall when separate optimization of tasks is undertaken for the central sector power plants. In all other years an all-inclusive reallocation strategy works better in general. At this point it is crucial to note that the model assumes that restructuring a state's power sector and reallocation of production to plants is costless. For example, transportation costs associated with shipping coal between two NTPC plants located widely apart from each other versus a state plant and a NTPC plant may further reduce any gains from separately reallocating across central sector plants.

The main findings of the study can be summarized as below:

- The NTPC plants under the central sector are highly efficient. We find that these plants are fully efficient in regards to their production performance but environmentally (and thereby in fuel consumption) a bit inefficient. Centrally-owned plants operated by DVC and NLC are far more inefficient on both grounds. State sector plants on the contrary, particularly in the states of Madhya Pradesh, Delhi, Jharkhand, West Bengal and Gujarat lagged significantly.
- Standalone elimination of joint productive and environmental inefficiency among power plants could on an average result in 4% increase in total power production along with 5% reduction in fuel use and improvement in air quality for the entire sample each year. This translates into heat rate reduction from an actual of about 2600kCal/kWh to approximately 2300kCal/kWh, and SPM emission reduction to nearly 140mg/Nm^3 (actually observed emission rate ranged from 121 mg/Nm^3 to 177mg/Nm^3 during the analysis period).
- Another 5% increment could come from restructuring of the sector, primarily through optimal redistribution of fuel and closing down of the costlier plants (less productive, dirtier plants consuming more fuel) within the states. Power generation increases by only 3% on an average.
- Some nominal improvements (in the form of higher power supply) further arise for selected states in selected years owing to efficient utilization of plant's installed capacity when, in addition to fuel, labor is also optimally assigned. These states are Tamil Nadu, Karnataka, Maharashtra, West Bengal, Haryana and Gujarat.
- States particularly benefitting from restructuring include Tamil Nadu, West Bengal, Uttar Pradesh, Chhattisgarh, Delhi, Maharashtra and Madhya Pradesh. Each of these states experienced superior outcomes (5-10% over and above the Base Case attainments) either by way of furthering power production, or decline in emissions and the use of fuel, or both. Having said that, we find that restructuring primarily strengthened air quality and station heat rates for most states.
- We find that state-wide reallocation is slightly more effective in increasing country-wide electricity output and mitigating emissions compared to when rearrangement is limited to the respective state plants only. This is also more practical and economical if one were to factor in the cost of reallocating resources and tasks across distantly located NTPC plants. Higher potential improvements under this setting are seen for states that have high potential central sector plants located therein, like UP, West Bengal, Andhra Pradesh, Chhattisgarh, Tamil Nadu, Orissa and Jharkhand. On the counter side, Madhya Pradesh performs better after leaving out central plants.

Conclusion

A decade of tepid results for the state-owned plants clearly indicates that they have been unable to deliver the standards required for India's power sector and there is potential for improving a state's performance through optimal reorganization of processes. In light of this, we formulate a resource allocation model that redistributes transferable inputs like labor and/or fuel among power plants in pursuit of maximum state-level efficiency. The model would (hypothetically) allow only those plants to operate in a state that can raise the total power supply while keeping the fuel usage and emissions at its minimal and using no more labor than is currently employed in the state, and with each plant operating within the existing installed capacity of its boiler. The surplus resources due to shut down or reduced operation of a plant are transferred to the plants that are more efficient but not yet utilizing their full capacity due to factors such as fuel shortage. For modeling approach, we adopt the by-product interpretation assuming joint disposability of the bad output and the polluting input as in RMV (2017) and measure efficiency under alternate structural assumptions using a good output, and bad output and polluting inputs oriented modified DDF. We do find evidence of efficiency gains from reallocation.

A limitation of our model is that it does not consider the spatial distribution of the total output to be produced and also assumes that restructuring a state's power sector and reallocation of production to plants is costless. If the markets for the factor inputs (for example coal mines or ports in case of imported coal) are far from where the plants are located, a substantially higher transportation cost may easily overwhelm any output gains and/or environmental advantage enjoyed by a plant in some specific location. In addition, redistribution of output tasks based on efficiency considerations could reduce the average state-level pollution but may increase local pollution in the vicinity of the efficient power plant which would now be producing more power. It may be reasonable to allow a relatively dirtier plant located in a deserted area to operate than to allocate the generation to a more efficient plant which is closer to densely populated areas. For practical policy and real-life shutdown decisions, geographical factors may need to be accounted for before any major restructuring in production activities can take place.

An interesting extension to the above model could be to allow for inter-state transmission of electricity and performing a country level optimization. Other directions for future research could incorporation of abatement activities, conditional on the availability of the data.

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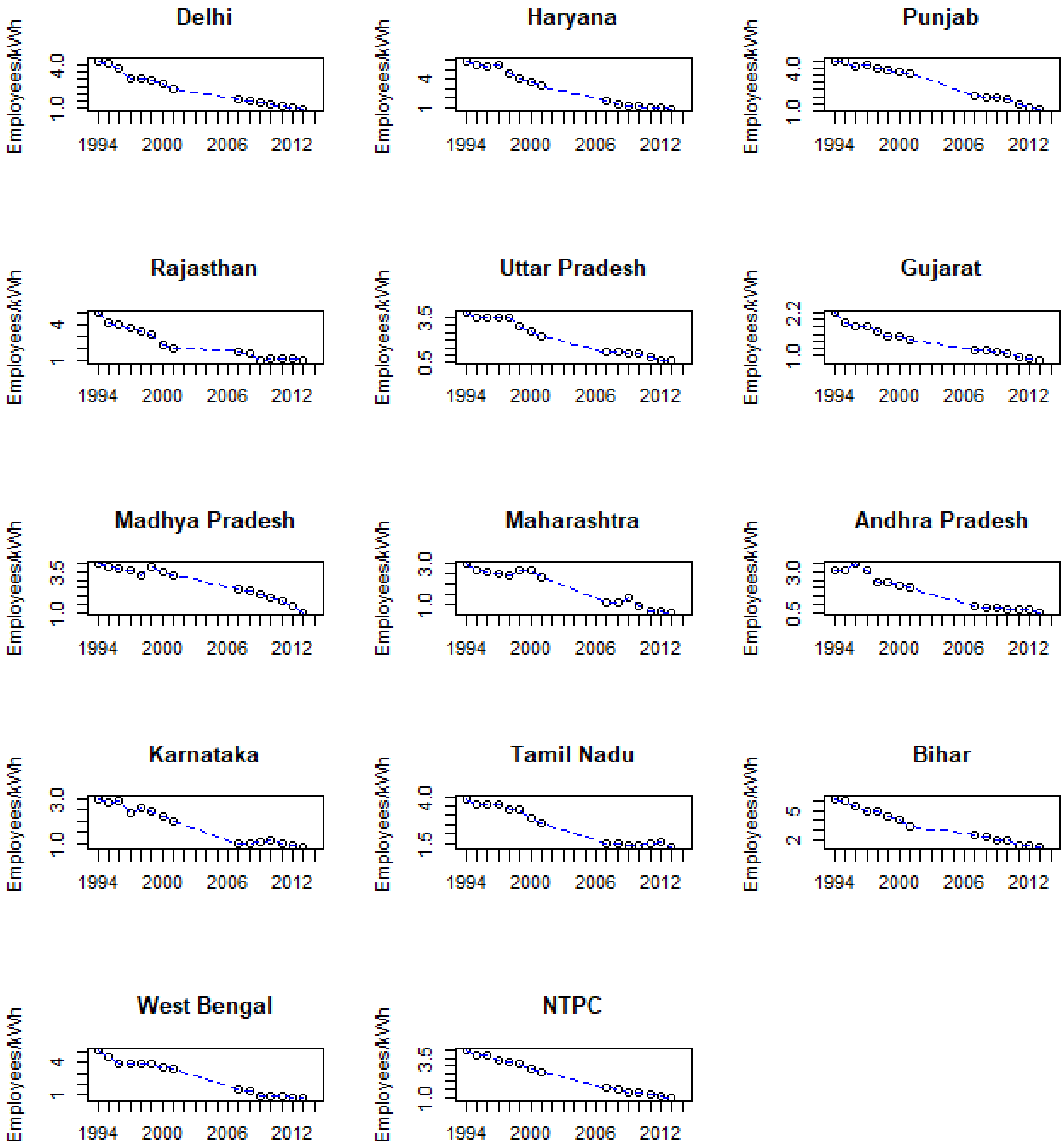

[1]The points in black represent observed data for different years and the blue line is a linear interpolation of the series.

List of Tables

Table 1: Descriptive Statistics of Inputs and Outputs (by year)

Year	Statistic	Unadjusted Capacity (MW)	Capacity Adjusted* (MW)	Fuel (kCal/kWh)	Labor (Employees/kWh)	Generation (MUs)	Emission (mg/Nm3)
2005	Mean	859	729	2,873	NA	5,776	178

Year	Statistic	Unadjusted Capacity (MW)	Capacity Adjusted* (MW)	Fuel (kCal/kWh)	Labor (Employees/kWh)	Generation (MUs)	Emission (mg/Nm3)
	Standard Deviation	626	556	527	NA	4,663	283
	Minimum	63	55	2,165	NA	397	29
	Maximum	3,000	2,659	4,972	NA	20,883	2,405
	Sum	61,880	52,506	206,879	NA	415,887	
	Count	72	72	72	NA	72	72
2010	Mean	943	806	2,768	1.10	6,304	156
	Standard Deviation	660	600	509	0.27	5,074	178
	Minimum	135	79	2,125	0.72	363	38
	Maximum	3,260	3,081	5,333	1.93	27,013	1,144
	Sum	70,748	60,474	207,606	82	472,803	
	Count	75	75	75	75	75	75
2014	Mean	1,128	906	2,692	NA	6,850	139
	Standard Deviation	810	752	632	NA	6,003	188
	Minimum	60	24	2,066	NA	69	32
	Maximum	4,260	3,781	7,470	NA	29,574	1,704
	Sum	91,376	73,410	218,012	NA	554,839	
	Count	81	81	81	NA	81	81

**Adjust for unavailability due to planned maintenance and forced outage*

Table 2: Technical (β_1) and Environmental (β_2) Inefficiency (by power plants)

Region	State	Name	2005		2006		2007		2008		2009		2010		2012		2013		2014	
			β1	β2	β1	β2	β1	β2	β1	β2	β1	β2	β1	β2	β1	β2	β1	β2	β1	β2
	Delhi	Badarpur[1]	0%	6%	4%	0%	5%	0%	5%	4%	5%	7%	9%	0%	0%	6%	0%	9%	6%	3%
	Delhi	I.P.Station	57%	0%	47%	0%	0%	0%	0%	0%	-	-	-	-	-	-	-	-	-	-
	Delhi	Rajghat	42%	0%	0%	0%	0%	0%	0%	0%	17%	18%	0%	0%	16%	15%	0%	0%	34%	0%
	Haryana	Faridabad	40%	18%	45%	0%	0%	0%	0%	0%	-	-	-	-	-	-	-	-	-	-
	Haryana	Mahatma Gandhi Stpp	-	-	-	-	-	-	-	-	-	-	-	-	0%	0%	0%	0%	0%	5%
	Haryana	Panipat	0%	25%	3%	10%	1%	16%	3%	19%	0%	0%	0%	0%	0%	15%	0%	13%	0%	12%
	Haryana	Rajiv Gandhi Tps	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0%	0%
	Haryana	Yamuna Nagar Tps	-	-	-	-	-	-	15%	0%	0%	13%	9%	0%	1%	19%	0%	0%	0%	7%
	Punjab	Ghtp (Leh Moh) II	-	-	-	-	-	-	8%	0%	0%	11%	-	-	-	-	-	-	-	-
	Punjab	Ghtp(Leh.Moh.)	1%	0%	5%	1%	2%	2%	2%	8%	0%	10%	1%	10%	0%	0%	0%	7%	0%	12%
	Punjab	Gndtp(Bhatinda)	5%	18%	19%	9%	16%	11%	20%	15%	17%	18%	10%	10%	13%	5%	2%	17%	0%	18%
NR	Punjab	Ropar	0%	9%	2%	14%	3%	9%	21%	1%	3%	14%	3%	14%	0%	9%	5%	10%	0%	18%
	Rajasthan	Kota	0%	8%	0%	11%	0%	11%	0%	14%	0%	0%	2%	10%	0%	6%	0%	10%	0%	10%
	Rajasthan	Suratgarh	0%	0%	0%	0%	0%	7%	0%	8%	0%	0%	0%	13%	0%	8%	7%	7%	2%	8%
	UP	Anpara	0%	7%	0%	1%	0%	0%	0%	5%	0%	8%	0%	8%	0%	1%	0%	0%	0%	0%
	UP	Dadri (Nctpp) [1]	0%	3%	1%	0%	0%	4%	0%	0%	4%	8%	0%	6%	0%	3%	0%	3%	0%	4%
	UP	Obra	0%	0%	-	-	0%	0%	0%	0%	0%	0%	-	-	0%	0%	0%	0%	0%	0%
	UP	Panki	35%	0%	31%	0%	0%	0%	5%	9%	22%	14%	17%	0%	2%	23%	7%	13%	-	-
	UP	Paricha	45%	14%	37%	0%	20%	26%	25%	27%	29%	26%	33%	16%	6%	33%	0%	5%	0%	21%
	UP	Rihand[1]	4%	4%	0%	4%	0%	1%	0%	0%	0%	0%	0%	3%	0%	8%	0%	2%	0%	1%
	UP	Singrauli Stps[1]	0%	0%	0%	2%	0%	6%	0%	9%	0%	7%	0%	0%	0%	0%	0%	0%	0%	3%
	UP	Tanda[1]	0%	12%	2%	8%	1%	10%	0%	9%	0%	7%	0%	3%	1%	15%	0%	1%	0%	6%
	UP	Unchahar[1]	0%	4%	5%	0%	0%	4%	0%	2%	0%	2%	0%	10%	0%	8%	0%	7%	0%	8%
	Chhattisgarh	Dr. Shyama Prasad Mukherjee Tps	-	-	-	-	-	-	-	-	0%	0%	0%	9%	5%	4%	0%	0%	6%	0%
WR	Chhattisgarh	Korba Stps[1]	0%	0%	0%	0%	0%	0%	0%	0%	0%	5%	0%	0%	0%	0%	0%	0%	0%	1%
	Chhattisgarh	Korba-II	0%	0%	0%	0%	0%	0%	0%	10%	0%	0%	2%	9%	6%	24%	0%	0%	44%	0%

Region	State	Name	2005		2006		2007		2008		2009		2010		2012		2013		2014	
			β1	β2	β1	β2	β1	β2	β1	β2	β1	β2	β1	β2	β1	β2	β1	β2	β1	β2
	Chhattisgarh	Korba-III	15%	12%	12%	4%	7%	2%	0%	16%	0%	6%	7%	12%	7%	23%	0%	0%	45%	0%
	Chhattisgarh	Korba-West	0%	17%	11%	8%	7%	9%	4%	13%	0%	0%	0%	13%	0%	15%	0%	0%	0%	14%
	Chhattisgarh	OP Jindal Stpp	-	-	-	-	-	-	-	-	-	-	0%	0%	0%	0%	0%	0%	0%	0%
	Chhattisgarh	Sipat[1]	-	-	-	-	-	-	-	-	-	-	-	-	0%	0%	0%	0%	0%	0%
	Gujarat	Dhuvaran	-	-	-	-	-	-	4%	1%	0%	0%	-	-	-	-	-	-	-	-
	Gujarat	Gandhi Nagar	15%	0%	32%	0%	12%	3%	9%	9%	10%	13%	21%	7%	17%	0%	15%	2%	16%	3%
	Gujarat	Kutch Lignite	0%	0%	0%	15%	0%	0%	0%	14%	33%	8%	36%	0%	16%	17%	5%	26%	0%	0%
	Gujarat	Sabarmati (C Station)	-	-	-	-	-	-	-	-	-	-	-	-	0%	0%	0%	0%	0%	0%
	Gujarat	Sabarmati (DF Station)	-	-	-	-	-	-	-	-	-	-	0%	0%	3%	3%	0%	8%	0%	8%
	Gujarat	Sikka Rep.	7%	14%	11%	10%	0%	11%	14%	4%	20%	9%	14%	0%	20%	3%	13%	9%	25%	3%
	Gujarat	Torr_Sabarmati	0%	13%	0%	0%	0%	0%	0%	0%	0%	0%	-	-	-	-	-	-	-	-
	Gujarat	Ukai	5%	16%	20%	0%	14%	4%	10%	12%	8%	14%	16%	12%	9%	10%	2%	17%	8%	15%
	Gujarat	Wanakbori	0%	10%	4%	7%	0%	0%	0%	10%	0%	16%	5%	11%	0%	14%	19%	2%	3%	15%
	MP	Amar Kantak Ext	65%	0%	39%	0%	27%	0%	46%	0%	38%	0%	-	-	-	-	15%	19%	29%	0%
	MP	Sanjay Gandhi	11%	13%	22%	3%	30%	0%	39%	1%	34%	10%	27%	4%	4%	20%	20%	4%	-	-
	MP	Satpura	11%	22%	14%	18%	8%	23%	17%	22%	30%	19%	40%	21%	39%	19%	63%	2%	13%	18%
	MP	Vindhyachal Stps[1]	0%	0%	0%	5%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Maharashtra	Bhusawal	0%	13%	13%	0%	4%	9%	15%	11%	19%	14%	22%	0%	4%	12%	0%	7%	25%	0%
	Maharashtra	Chandrapur	0%	16%	9%	3%	0%	0%	0%	0%	10%	14%	13%	6%	0%	0%	2%	15%	15%	0%
	Maharashtra	Dahanu	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Maharashtra	Kaperkheda II	0%	15%	5%	7%	0%	11%	6%	15%	12%	15%	15%	6%	4%	9%	15%	0%	9%	4%
	Maharashtra	Koradi	5%	22%	23%	5%	15%	10%	23%	11%	40%	5%	23%	12%	3%	13%	22%	2%	12%	14%
	Maharashtra	Nasik	0%	16%	13%	3%	0%	13%	12%	14%	20%	15%	18%	10%	1%	17%	14%	6%	0%	21%
	Maharashtra	New Parli	-	-	-	-	-	-	-	-	8%	23%	14%	0%	-	-	-	-	-	-
	Maharashtra	Paras	-	-	-	-	-	-	-	-	0%	0%	-	-	-	-	-	-	-	-
	Maharashtra	Paras Ext	-	-	-	-	-	-	0%	0%	25%	6%	17%	0%	0%	9%	6%	4%	12%	0%
	Maharashtra	Parli	0%	12%	8%	4%	7%	10%	21%	6%	26%	12%	29%	3%	4%	15%	19%	0%	9%	10%
	Maharashtra	Trombay	0%	0%	0%	0%	0%	0%	0%	0%	0%	2%	8%	5%	0%	3%	0%	7%	8%	0%
SR	AP	Dr. N. Tata Rao	0%	6%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	7%

Region	State	Name	2005		2006		2007		2008		2009		2010		2012		2013		2014	
			β1	β2	β1	β2	β1	β2	β1	β2	β1	β2	β1	β2	β1	β2	β1	β2	β1	β2
	AP	Kakatiya Tpp	-	-	-	-	-	-	-	-	-	-	-	-	0%	1%	0%	4%	0%	1%
	AP	Kothagudem	5%	51%	5%	11%	0%	13%	0%	0%	0%	0%	0%	13%	3%	19%	7%	21%	8%	19%
	AP	Kothagudem New	-	-	-	-	-	-	0%	0%	0%	0%	0%	0%	0%	5%	0%	5%	0%	3%
	AP	Ramagundem B	0%	0%	-	-	-	-	-	-	-	-	-	-	0%	0%	0%	0%	0%	0%
	AP	Ramagundem Stps[1]	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	-	-	0%	0%	0%	1%	0%	1%
	AP	Rayal Seema	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	4%	2%	5%
	AP	Simhadri[1]	0%	13%	1%	3%	0%	0%	0%	2%	0%	0%	0%	10%	0%	5%	0%	2%	0%	1%
	Karnataka	Bellary	-	-	-	-	-	-	-	-	0%	7%	-	-	15%	0%	4%	10%	9%	0%
	Karnataka	Raichur	0%	15%	4%	8%	0%	0%	0%	0%	0%	14%	19%	0%	0%	17%	18%	2%	1%	12%
	TN	Ennore	33%	0%	30%	0%	26%	8%	41%	0%	48%	0%	46%	0%	85%	0%	68%	0%	64%	0%
	TN	Mettur	0%	7%	1%	6%	0%	7%	3%	9%	8%	9%	7%	6%	0%	11%	3%	15%	0%	15%
	TN	Neyveli Fst Ext[3]	9%	9%	7%	8%	0%	0%	0%	0%	0%	10%	0%	0%	0%	0%	0%	0%	0%	0%
	TN	Neyveli I[3]	19%	31%	18%	29%	20%	0%	25%	25%	0%	0%	19%	28%	11%	27%	9%	37%	19%	23%
	TN	Neyveli II[3]	0%	18%	0%	8%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	17%
	TN	North Chennai	3%	4%	5%	2%	4%	2%	2%	8%	4%	9%	4%	10%	0%	8%	4%	10%	6%	5%
	TN	Tuticorin	0%	0%	0%	0%	0%	0%	0%	0%	0%	4%	0%	0%	0%	0%	0%	0%	0%	9%
	Bihar	Kahalgaon[1]	2%	30%	5%	25%	5%	0%	9%	0%	2%	9%	0%	5%	0%	10%	0%	3%	0%	3%
	Jharkhand	Bokaro B[2]	41%	0%	-	-	-	-	19%	10%	16%	11%	14%	10%	7%	15%	24%	0%	13%	11%
	Jharkhand	Chandrapura[2]	-	-	-	-	-	-	-	-	-	-	8%	17%	0%	9%	0%	12%	2%	15%
	Jharkhand	Tenughat	27%	3%	29%	1%	10%	6%	7%	0%	14%	13%	0%	0%	6%	17%	9%	12%	16%	9%
	Orissa	I.B.Valley	0%	6%	3%	0%	1%	0%	7%	0%	3%	9%	0%	7%	0%	5%	2%	9%	0%	6%
	Orissa	Talcher[1]	0%	4%	3%	0%	1%	0%	2%	4%	1%	10%	0%	5%	0%	3%	0%	0%	0%	4%
ER	Orissa	Talcher Stps[1]	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	WB	Bakreswar	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	3%	9%	0%	0%	0%	10%	0%	0%
	WB	Bandel	30%	0%	34%	0%	24%	0%	22%	0%	0%	16%	17%	10%	0%	27%	30%	0%	24%	9%
	WB	Budge Budge	0%	7%	2%	6%	2%	6%	1%	6%	0%	1%	4%	9%	0%	0%	0%	4%	2%	0%
	WB	D.P.L.	31%	7%	35%	10%	27%	5%	31%	14%	20%	20%	16%	23%	0%	0%	0%	0%	44%	0%
	WB	Durgapur[2]	15%	14%	25%	7%	21%	0%	11%	12%	6%	19%	0%	2%	0%	0%	0%	6%	0%	24%
	WB	Farakka Stps[1]	0%	21%	0%	0%	0%	9%	0%	8%	1%	10%	0%	7%	6%	5%	0%	4%	0%	4%

Region	State	Name	2005 β1	2005 β2	2006 β1	2006 β2	2007 β1	2007 β2	2008 β1	2008 β2	2009 β1	2009 β2	2010 β1	2010 β2	2012 β1	2012 β2	2013 β1	2013 β2	2014 β1	2014 β2
	WB	Kolaghat	22%	18%	28%	6%	24%	1%	27%	16%	11%	25%	18%	12%	0%	0%	14%	0%	13%	13%
	WB	Mejia[2]	3%	12%	7%	12%	17%	2%	1%	23%	7%	8%	0%	11%	0%	0%	0%	1%	0%	11%
	WB	New Cossipore	-	-	-	-	-	-	-	-	-	-	0%	0%	0%	0%	0%	0%	0%	0%
	WB	Sagardighi	-	-	-	-	-	-	-	-	0%	0%	7%	17%	0%	4%	12%	0%	-	-
	WB	Santaldih	31%	0%	38%	0%	23%	11%	40%	2%	11%	23%	0%	0%	0%	14%	0%	1%	17%	0%
	WB	Southern Repl.	2%	13%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	8%	12%
	WB	Titagarh	7%	14%	5%	7%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
All India Average (Simple Average)			**9%**	**9%**	**10%**	**4%**	**5%**	**4%**	**8%**	**6%**	**7%**	**8%**	**8%**	**6%**	**4%**	**7%**	**5%**	**5%**	**7%**	**6%**

NR: Northern Region, WR: Western Region, SR: Southern Region, ER: Eastern Region, UP: Uttar Pradesh, MP: Madhya Pradesh, AP: Andhra Pradesh, TN: Tamil Nadu, WB: West Bengal.
[1]NTPC plants, [2]DVC Plants, [3]NLC Plants.

Table 3: (Base Case Results) Potential efficiency gains for the State, by considering plant level optimization, no reallocation of either output or input is allowed

Year	Region	State	Actual Fuel Use (kCal)[1]	Actual Generation (MUs)	Actual Emission (mg/Nm3)[1]	Actual Emission Rate (mg/Nm3)	Actual Heat Rate (kCal/kWh)	Generation Expansion (β_1^s)	Air Quality Improvement (β_2^s)	Fuel Saving (β_2^s)	Optimal Emission Rate (mg/Nm3)	Optimal Heat Rate (kCal/kWh)	Surplus Capacity (MW)	Labor Surplus (No. of Employees)[1]
2005	NR	Delhi	18,644,841	6,940	856,880	123	2,687	12%	5%	4%	105	2306	6	-
		Haryana	26,545,009	8,704	1,315,020	151	3,050	4%	25%	25%	109	2221	0	-
		Punjab	38,137,748	14,834	1,870,727	126	2,571	1%	10%	9%	112	2327	0	-
		Rajasthan	46,508,396	18,245	1,463,461	80	2,549	0%	4%	4%	77	2451	0	-
		UP	155,127,948	61,398	21,462,190	350	2,527	2%	2%	4%	338	2391	2	-
	WR	Chhattisgarh	64,490,681	24,945	3,728,121	149	2,585	1%	5%	5%	141	2437	0	-
		Gujarat	59,543,434	22,311	4,071,326	182	2,669	4%	10%	10%	157	2303	31	-
		MP	89,743,524	31,698	5,645,555	178	2,831	6%	12%	8%	148	2447	0	-
		Maharashtra	137,210,133	52,625	8,643,306	164	2,607	1%	15%	13%	138	2257	0	-
	SR	AP	140,533,664	48,169	5,359,466	111	2,918	1%	15%	18%	93	2379	0	-
		Karnataka	23,863,313	9,185	932,932	102	2,598	0%	15%	15%	86	2212	0	-

Year	Region	State	Actual Fuel Use (kCal)[1]	Actual Generation (MUs)	Actual Emission (mg/Nm3) [1]	Actual Emission Rate (mg/Nm3)	Actual Heat Rate (kCal/kWh)	Generation Expansion (β_1^s)	Air Quality Improvement (β_2^s)	Fuel Saving (β_2^s)	Optimal Emission Rate (mg/Nm3)	Optimal Heat Rate (kCal/kWh)	Surplus Capacity (MW)	Labor Surplus (No. of Employees) [1]
		TN	98,403,950	35,057	7,541,420	215	2,807	4%	5%	12%	198	2368	5	-
	ER	Bihar	21,438,843	6,572	690,092	105	3,262	2%	30%	30%	72	2239	0	-
		Jharkhand	13,710,741	4,195	1,155,987	276	3,268	36%	0%	1%	201	2375	0	-
		Orissa	61,036,357	27,505	3,324,691	121	2,219	0%	1%	1%	119	2192	0	-
		WB	128,801,287	43,503	3,927,920	90	2,961	9%	14%	13%	71	2361	153	-
	All India		**1,123,739,869**	**415,887**	**71,989,094**	**173**	**2,702**	**3%**	**8%**	**10%**	**154**	**2346**	**197**	**-**
2010	NR	Delhi	13,439,252	5,331	608,217	114	2,521	8%	0%	0%	106	2334	2	1297
		Haryana	35,332,989	13,155	11,012,414	837	2,686	3%	0%	0%	815	2614	20	612
		Punjab	47,245,941	18,325	2,013,683	110	2,578	3%	12%	12%	94	2207	0	15808
		Rajasthan	48,128,589	19,301	1,750,539	91	2,494	1%	11%	11%	79	2185	137	4987
		UP	182,800,884	73,789	9,732,711	132	2,477	2%	5%	5%	123	2308	351	9418
	WR	Chhattisgarh	96,114,394	39,638	4,214,881	106	2,425	0%	5%	4%	101	2312	18	0
		Gujarat	71,832,985	25,940	3,900,516	150	2,769	12%	9%	8%	122	2265	111	836
		MP	110,718,589	40,791	5,970,325	146	2,714	11%	7%	5%	123	2315	0	9875
		Maharashtra	135,271,337	49,565	7,582,046	153	2,729	15%	7%	5%	125	2252	918	495
	SR	AP	83,863,109	35,350	3,971,313	112	2,372	0%	4%	5%	108	2265	45	3086
		Karnataka	23,078,963	8,804	949,530	108	2,622	19%	0%	0%	91	2211	51	127
		TN	104,038,552	36,699	10,996,354	300	2,835	5%	2%	6%	279	2525	15	5128
	ER	Bihar	33,647,885	14,029	1,387,841	99	2,399	0%	5%	5%	94	2285	427	2294
		Jharkhand	23,308,759	8,454	1,130,098	134	2,757	8%	9%	10%	113	2299	51	0
		Orissa	70,912,038	29,514	3,128,475	106	2,403	0%	2%	1%	104	2371	0	2497
		WB	145,284,758	54,118	5,434,294	100	2,685	5%	10%	10%	86	2311	604	2911
	All India		**1,225,019,025**	**472,803**	**73,783,240**	**156**	**2,591**	**5%**	**5%**	**6%**	**141**	**2315**	**2750**	**59372**
2014	NR	Delhi	9,301,039	3,705	384,844	104	2,511	10%	3%	3%	92	2224	0	-
		Haryana	45,980,835	20,154	2,453,119	122	2,281	0%	6%	6%	115	2149	87	-
		Punjab	30,169,411	11,672	1,476,056	126	2,585	0%	16%	16%	107	2174	0	-
		Rajasthan	48,602,161	19,000	1,373,375	72	2,558	1%	9%	9%	65	2307	0	-

Year	Region	State	Actual Fuel Use (kCal)[1]	Actual Generation (MUs)	Actual Emission (mg/Nm3) [1]	Actual Emission Rate (mg/Nm3)	Actual Heat Rate (kCal/kWh)	Generation Expansion (β_1^s)	Air Quality Improvement (β_2^s)	Fuel Saving (β_2^s)	Optimal Emission Rate (mg/Nm3)	Optimal Heat Rate (kCal/kWh)	Surplus Capacity (MW)	Labor Surplus (No. of Employees) [1]
		UP	192,118,194	79,361	15,156,980	191	2,421	0%	3%	4%	185	2317	30	-
	WR	Chhattisgarh	161,271,613	65,539	5,043,980	77	2,461	2%	3%	2%	73	2358	5	-
		Gujarat	62,796,428	23,087	2,597,936	113	2,720	7%	12%	11%	93	2281	0	-
		MP	95,993,794	37,999	4,946,183	130	2,526	4%	7%	3%	116	2349	13	-
		Maharashtra	128,396,208	49,565	6,665,593	134	2,590	11%	5%	4%	115	2237	398	-
	SR	AP	172,645,295	71,479	7,178,700	100	2,415	1%	4%	4%	95	2302	0	-
		Karnataka	43,151,988	16,786	1,459,580	87	2,571	3%	10%	8%	76	2283	36	-
		TN	126,018,966	45,526	6,580,211	145	2,768	4%	10%	12%	125	2347	45	-
	ER	Bihar	37,484,880	15,619	1,494,933	96	2,400	0%	3%	3%	93	2332	150	-
		Jharkhand	24,158,053	8,992	995,906	111	2,687	8%	13%	12%	90	2188	0	-
		Orissa	72,743,070	30,281	2,854,833	94	2,402	0%	1%	1%	93	2376	0	-
		WB	143,092,605	56,072	6,547,438	117	2,552	5%	8%	6%	103	2291	207	-
	All India		**1,393,924,540**	**554,839**	**67,209,666**	**121**	**2,512**	**3%**	**6%**	**6%**	**111**	**2303**	**971**	**-**

NR: Northern Region, WR: Western Region, SR: Southern Region, ER: Eastern Region, UP: Uttar Pradesh, MP: Madhya Pradesh, AP: Andhra Pradesh, TN: Tamil Nadu, WB: West Bengal.

[1]*The final numbers are in millions.*

Table 4: (Base Case Results) Potential efficiency gains for the State (with and without including Central sector plants), by considering plant level optimization, no reallocation of either output or input is allowed

Year	Region	State	Generation Expansion	Air Quality Improvement	Fuel Saving	ΔG	ΔB	Generation Expansion	Air Quality Improvement	Fuel Saving	ΔG	ΔB	Surplus Capital
			Inclusive of Central Sector Plants					*Excluding Central Sector Plants*					
2005	NR	Delhi	12%	5%	4%	803	-42,190	51%	0%	0%	803	0	6
		Haryana	4%	25%	25%	317	-327,498	4%	25%	25%	317	-327,498	0
		Punjab	1%	10%	9%	148	-193,246	1%	10%	9%	148	-193,246	0
		Rajasthan	0%	4%	4%	0	-63,460	0%	4%	4%	0	-63,460	0

Year	Region	State	Generation Expansion	Air Quality Improvement	Fuel Saving	ΔG	ΔB	Generation Expansion	Air Quality Improvement	Fuel Saving	ΔG	ΔB	Surplus Capital
		Uttar Pradesh	2%	2%	4%	1,065	-379,605	4%	1%	5%	676	-215,816	2
	WR	Chhattisgarh	1%	5%	5%	230	-183,943	**3%**	**11%**	**12%**	**230**	**-183,943**	0
		Gujarat	4%	10%	10%	914	-423,151	4%	10%	10%	914	-423,151	31
		Madhya Pradesh	6%	12%	8%	1,958	-678,765	**15%**	**20%**	**17%**	**1,958**	**-678,765**	0
		Maharashtra	1%	15%	13%	360	-1,325,894	1%	15%	13%	360	-1,325,894	0
	SR	Andhra Pradesh	1%	15%	18%	440	-821,570	2%	23%	31%	440	-743,275	0
		Karnataka	0%	15%	15%	21	-136,944	0%	15%	15%	21	-136,944	0
		Tamil Nadu	4%	5%	12%	1,369	-343,662	2%	2%	3%	322	-132,431	5
	ER	Bihar	2%	30%	30%	154	-205,329	-	-	-	0	0	0
		Jharkhand	36%	0%	1%	1,522	-3,992	27%	3%	3%	416	-3,992	0
		Orissa	0%	1%	1%	0	-45,371	0%	6%	6%	0	-26,302	0
		West Bengal	9%	14%	13%	3,949	-556,626	14%	12%	9%	3,477	-248,517	153
	Central Sector	NTPC	-	-	-	-	-	0%	4%	5%	542	-694,532	0
		DVC	-	-	-	-	-	15%	6%	9%	1,579	-122,249	0
		NLC	-	-	-	-	-	6%	20%	21%	1,047	-211,231	0
	All India		**3%**	**8%**	**10%**	**13,250**	**-5,731,247**	**3%**	**8%**	**10%**	**13,250**	**-5,731,247**	**197**
2010	NR	Delhi	8%	0%	0%	427	0	0%	0%	0%	0	0	0
		Haryana	3%	0%	0%	363	0	3%	0%	0%	363	0	20
		Punjab	3%	12%	12%	498	-239,629	3%	12%	12%	498	-239,629	0
		Rajasthan	1%	11%	11%	205	-200,205	1%	11%	11%	205	-200,205	137
		Uttar Pradesh	2%	5%	5%	1,268	-530,223	8%	9%	9%	1,268	-285,265	105
	WR	Chhattisgarh	0%	5%	4%	143	-206,969	**1%**	**10%**	**8%**	**143**	**-206,969**	18
		Gujarat	12%	9%	8%	3,109	-358,952	12%	9%	8%	3,109	-358,952	111
		Madhya Pradesh	11%	7%	5%	4,506	-416,952	**33%**	**15%**	**13%**	**4,506**	**-416,952**	0
		Maharashtra	15%	7%	5%	7,225	-498,459	15%	7%	5%	7,225	-498,459	918
	SR	Andhra Pradesh	0%	4%	5%	0	-140,579	0%	2%	3%	0	-68,989	45
		Karnataka	19%	0%	0%	1,635	0	19%	0%	0%	1,635	0	51
		Tamil Nadu	5%	2%	6%	1,965	-196,206	6%	1%	4%	1,219	-123,381	15

Year	Region	State	Generation Expansion	Air Quality Improvement	Fuel Saving	ΔG	ΔB	Generation Expansion	Air Quality Improvement	Fuel Saving	ΔG	ΔB	Surplus Capital
	ER	Bihar	0%	5%	5%	0	-65,761	-	-	-	0	0	0
		Jharkhand	8%	9%	10%	683	-101,335	0%	0%	0%	0	0	0
		Orissa	0%	2%	1%	0	-52,126	0%	7%	7%	0	-30,701	0
		West Bengal	5%	10%	10%	2,685	-545,329	8%	12%	10%	2,685	-395,818	251
	Central Sector	NTPC	-	-	-	-	-	0%	3%	3%	427	-470,520	873
		DVC	-	-	-	-	-	4%	9%	11%	683	-184,060	207
		NLC	-	-	-	-	-	4%	7%	8%	746	-72,825	0
		All India	**5%**	**5%**	**6%**	**24,713**	**-3,552,725**	**5%**	**5%**	**6%**	**24,713**	**-3,552,725**	**2,750**
2014	NR	Delhi	10%	3%	3%	359	-10,953	34%	0%	0%	146	0	0
		Haryana	0%	6%	6%	0	-138,641	0%	6%	6%	0	-138,641	87
		Punjab	0%	16%	16%	0	-232,801	0%	16%	16%	0	-232,801	0
		Rajasthan	1%	9%	9%	224	-123,078	1%	9%	9%	224	-123,078	0
		Uttar Pradesh	0%	3%	4%	0	-447,629	0%	3%	7%	0	-237,142	0
	WR	Chhattisgarh	2%	3%	2%	1,226	-173,135	5%	7%	6%	1,226	-159,050	5
		Gujarat	7%	12%	11%	1,549	-307,789	7%	12%	11%	1,549	-307,789	0
		Madhya Pradesh	4%	7%	3%	1,444	-361,439	**17%**	**16%**	**13%**	**1,444**	**-361,439**	13
		Maharashtra	11%	5%	4%	5,424	-348,720	11%	5%	4%	5,424	-348,720	398
	SR	Andhra Pradesh	1%	4%	4%	508	-321,850	1%	7%	7%	508	-286,475	0
		Karnataka	3%	10%	8%	572	-143,846	3%	10%	8%	572	-143,846	36
		Tamil Nadu	4%	10%	12%	1,646	-665,941	**4%**	**9%**	**9%**	963	-503,333	29
	ER	Bihar	0%	3%	3%	0	-42,601	-	-	-	0	0	0
		Jharkhand	8%	13%	12%	696	-124,657	**16%**	**9%**	**9%**	376	-18,818	0
		Orissa	0%	1%	1%	0	-40,524	0%	6%	6%	0	-24,806	0
		West Bengal	5%	8%	6%	2,549	-504,281	9%	7%	4%	2,549	-265,680	73
	Central Sector	NTPC	-	-	-	-	-	0%	2%	2%	213	-391,885	315
		DVC	-	-	-	-	-	2%	14%	13%	321	-281,772	0
		NLC	-	-	-	-	-	4%	16%	16%	684	-162,608	16
		All India	**3%**	**6%**	**6%**	**16,198**	**-3,987,884**	**3%**	**6%**	**6%**	**16,198**	**-3,987,884**	**971**

NR: Northern Region, WR: Western Region, SR: Southern Region, ER: Eastern Region
[1]*Colored rows represent the states whose inefficiency scores changed (either increased or decreased) after excluding the central sector plants.*
[2]*Non colored rows in bold (barring All India) represent the states whose inefficiency scores changed but optimal change in outputs (ΔG and ΔB) remain unaffected even after excluding the central sector plants.*

Table 5: (Model 1 Results) Measuring Inefficiency at the State level: Potential efficiency gains by allowing for reallocation of fuel input across power plants within a State but treating installed capacity and labor as plant specific

Year	Region	State	Model 1 (Reallocation of Fuel Only)								
			Labor Surplus[1]	**Actual Power Plants**	**Optimal Power Plants**	**Actual Emission Rate (mg/Nm3)**	**Actual Heat Rate (kCal/kWh)**	**Optimal Emission Rate (mg/Nm3)**	**Optimal Heat Rate (kCal/kWh)**	**Generation Expansion ($\beta_1^{s'}$)**	**Air Quality Improvement/ Fuel Saving ($\beta_2^{s'}$)**
2005	NR	Delhi	-	3	3	123	2,687	104	2268	7%	10%
		Haryana	-	2	2	151	3,050	110	2215	3%	25%
		Punjab	-	3	3	126	2,571	111	2261	0%	12%
		Rajasthan	-	2	2	80	2,549	77	2449	0%	4%
		Uttar Pradesh	-	9	9	350	2,527	320	2312	0%	8%
	WR	Chhattisgarh	-	4	4	149	2,585	134	2324	0%	10%
		Gujarat	-	6	6	182	2,669	153	2239	0%	16%
		Madhya Pradesh	-	4	4	178	2,831	139	2215	0%	22%
		Maharashtra	-	8	8	164	2,607	139	2207	0%	15%
	SR	Andhra Pradesh	-	6	6	111	2,918	86	2266	0%	22%
		Karnataka	-	1	1	102	2,598	86	2212	0%	15%
		Tamil Nadu	-	7	7	215	2,807	173	2262	0%	19%
	ER	Bihar	-	1	1	105	3,262	72	2239	2%	30%
		Jharkhand	-	2	2	276	3,268	201	2380	37%	0%
		Orissa	-	3	3	121	2,219	119	2192	0%	1%
		West Bengal	-	11	10	90	2,961	72	2370	17%	7%
		All India	**-**	**72**	**71**	**173**	**2,702**	**147**	**2277**	**2%**	**13%**
2010	NR	Delhi	1297	2	2	114	2,521	106	2334	8%	0%
		Haryana	0	2	2	837	2,686	796	2554	0%	5%

			Model 1 (Reallocation of Fuel Only)								
Year	**Region**	**State**	**Labor Surplus**[1]	**Actual Power Plants**	**Optimal Power Plants**	**Actual Emission Rate (mg/Nm3)**	**Actual Heat Rate (kCal/kWh)**	**Optimal Emission Rate (mg/Nm3)**	**Optimal Heat Rate (kCal/kWh)**	**Generation Expansion ($\beta_1^{s\prime}$)**	**Air Quality Improvement/ Fuel Saving ($\beta_2^{s\prime}$)**
		Punjab	15876	3	3	110	2,578	94	2207	2%	13%
		Rajasthan	3563	2	2	91	2,494	80	2205	6%	6%
		Uttar Pradesh	11889	8	7	132	2,477	122	2283	0%	8%
	WR	Chhattisgarh	2095	6	6	106	2,425	100	2276	0%	6%
		Gujarat	616	6	6	150	2,769	123	2263	15%	6%
		Madhya Pradesh	9966	3	3	146	2,714	125	2316	10%	6%
		Maharashtra	194	10	10	153	2,729	126	2247	20%	1%
	SR	Andhra Pradesh	3270	5	5	112	2,372	107	2259	0%	5%
		Karnataka	76	1	1	108	2,622	91	2216	18%	0%
		Tamil Nadu	11630	7	7	300	2,835	240	2274	8%	13%
	ER	Bihar	2217	1	1	99	2,399	94	2289	0%	5%
		Jharkhand	0	3	3	134	2,757	111	2283	11%	8%
		Orissa	3381	3	3	106	2,403	103	2344	0%	2%
		West Bengal	1503	13	11	100	2,685	84	2254	7%	10%
		All India	**67574**	**75**	**72**	**156**	**2,591**	**137**	**2278**	**6%**	**7%**
2014	NR	Delhi	-	2	2	104	2,511	92	2213	10%	3%
		Haryana	-	4	4	122	2,281	113	2123	0%	7%
		Punjab	-	3	3	126	2,585	106	2173	0%	16%
		Rajasthan	-	2	2	72	2,558	65	2299	0%	10%
		Uttar Pradesh	-	8	8	191	2,421	181	2296	0%	5%
	WR	Chhattisgarh	-	7	7	77	2,461	73	2339	0%	5%
		Gujarat	-	7	6	113	2,720	92	2217	0%	18%
		Madhya Pradesh	-	3	3	130	2,526	121	2340	3%	4%
		Maharashtra	-	9	9	134	2,590	113	2179	10%	7%
	SR	Andhra Pradesh	-	8	8	100	2,415	95	2284	0%	5%
		Karnataka	-	2	2	87	2,571	76	2250	3%	10%
		Tamil Nadu	-	7	7	145	2,768	116	2225	0%	20%

Year	Region	State	Model 1 (Reallocation of Fuel Only)								
			Labor Surplus[1]	Actual Power Plants	Optimal Power Plants	Actual Emission Rate (mg/Nm3)	Actual Heat Rate (kCal/kWh)	Optimal Emission Rate (mg/Nm3)	Optimal Heat Rate (kCal/kWh)	Generation Expansion ($\beta_1^{s\prime}$)	Air Quality Improvement/ Fuel Saving ($\beta_2^{s\prime}$)
	ER	Bihar	-	1	1	96	2,400	93	2332	0%	3%
		Jharkhand	-	3	3	111	2,687	90	2187	8%	12%
		Orissa	-	3	3	94	2,402	93	2376	0%	1%
		West Bengal	-	12	12	117	2,552	101	2210	2%	11%
	All India		**-**	**81**	**80**	**121**	**2,512**	**109**	**2266**	**2%**	**8%**

NR: Northern Region, WR: Western Region, SR: Southern Region, ER: Eastern Region
[1]*The final numbers are in millions.*

Table 6: (Model 2 Results) Measuring Inefficiency at the State level: Potential efficiency gains by allowing for reallocation of fuel and labor across power plants within a State, treating only installed capacity as plant specific

Year	Region	State	Model 2 (Reallocation of Fuel and Labor)								
			Labor Surplus[1]	Actual Power Plants	Optimal Power Plants	Actual Emission Rate (mg/Nm3)	Actual Heat Rate (kCal/kWh)	Optimal Emission Rate (mg/Nm3)	Optimal Heat Rate (kCal/kWh)	Generation Expansion ($\beta_1^{s\prime\prime}$)	Air Quality Improvement/ Fuel Saving ($\beta_2^{s\prime\prime}$)
2005	NR	Delhi	-	3	3	123	2,687	104	2268	7%	10%
		Haryana	-	2	2	151	3,050	110	2215	3%	25%
		Punjab	-	3	3	126	2,571	111	2261	0%	12%
		Rajasthan	-	2	2	80	2,549	77	2449	0%	4%
		Uttar Pradesh	-	9	9	350	2,527	320	2312	0%	8%
	WR	Chhattisgarh	-	4	4	149	2,585	134	2324	0%	10%
		Gujarat	-	6	6	182	2,669	153	2239	0%	16%
		Madhya Pradesh	-	4	4	178	2,831	139	2215	0%	22%
		Maharashtra	-	8	8	164	2,607	139	2207	0%	15%
	SR	Andhra Pradesh	-	6	6	111	2,918	86	2266	0%	22%
		Karnataka	-	1	1	102	2,598	86	2212	0%	15%
		Tamil Nadu	-	7	7	215	2,807	173	2262	0%	19%

Year	Region	State	Model 2 (Reallocation of Fuel and Labor)								
			Labor Surplus[1]	Actual Power Plants	Optimal Power Plants	Actual Emission Rate (mg/Nm3)	Actual Heat Rate (kCal/kWh)	Optimal Emission Rate (mg/Nm3)	Optimal Heat Rate (kCal/kWh)	Generation Expansion ($\beta_1^{s''}$)	Air Quality Improvement/ Fuel Saving ($\beta_2^{s''}$)
	ER	Bihar	-	1	1	105	3,262	72	2239	2%	30%
		Jharkhand	-	2	2	276	3,268	201	2380	37%	0%
		Orissa	-	3	3	121	2,219	119	2192	0%	1%
		West Bengal	-	11	10	90	2,961	72	2370	17%	7%
		All India	**-**	**72**	**71**	**173**	**2,702**	**147**	**2277**	**2%**	**13%**
2010	NR	Delhi	1297	2	2	114	2,521	106	2334	8%	0%
		Haryana	0	2	2	837	2,686	795	2550	0%	5%
		Punjab	15876	3	3	110	2,578	94	2207	2%	13%
		Rajasthan	3563	2	2	91	2,494	80	2205	6%	6%
		Uttar Pradesh	11889	8	7	132	2,477	122	2283	0%	8%
	WR	Chhattisgarh	1169	6	6	106	2,425	100	2277	0%	6%
		Gujarat	0	6	6	150	2,769	122	2256	15%	6%
		Madhya Pradesh	9966	3	3	146	2,714	125	2316	10%	6%
		Maharashtra	0	10	10	153	2,729	125	2228	21%	1%
	SR	Andhra Pradesh	0	5	5	112	2,372	105	2207	0%	7%
		Karnataka	76	1	1	108	2,622	91	2216	18%	0%
		Tamil Nadu	11572	7	7	300	2,835	240	2272	8%	14%
	ER	Bihar	2217	1	1	99	2,399	94	2289	0%	5%
		Jharkhand	0	3	3	134	2,757	111	2297	15%	4%
		Orissa	3381	3	3	106	2,403	103	2344	0%	2%
		West Bengal	0	13	11	100	2,685	84	2233	12%	7%
		All India	**61006**	**75**	**72**	**156**	**2,591**	**136**	**2269**	**7%**	**7%**
2014	NR	Delhi	-	2	2	104	2,511	92	2213	10%	3%
		Haryana	-	4	4	122	2,281	113	2123	0%	7%
		Punjab	-	3	3	126	2,585	106	2173	0%	16%
		Rajasthan	-	2	2	72	2,558	65	2299	0%	10%
		Uttar Pradesh	-	8	8	191	2,421	181	2296	0%	5%

Year	Region	State	Model 2 (Reallocation of Fuel and Labor)								
			Labor Surplus[1]	**Actual Power Plants**	**Optimal Power Plants**	**Actual Emission Rate (mg/Nm3)**	**Actual Heat Rate (kCal/kWh)**	**Optimal Emission Rate (mg/Nm3)**	**Optimal Heat Rate (kCal/kWh)**	**Generation Expansion ($\beta_1^{s''}$)**	**Air Quality Improvement/ Fuel Saving ($\beta_2^{s''}$)**
	WR	Chhattisgarh	-	7	7	77	2,461	73	2339	0%	5%
		Gujarat	-	7	6	113	2,720	92	2217	0%	18%
		Madhya Pradesh	-	3	3	130	2,526	121	2340	3%	4%
		Maharashtra	-	9	9	134	2,590	113	2179	10%	7%
	SR	Andhra Pradesh	-	8	8	100	2,415	95	2284	0%	5%
		Karnataka	-	2	2	87	2,571	76	2250	3%	10%
		Tamil Nadu	-	7	7	145	2,768	116	2225	0%	20%
	ER	Bihar	-	1	1	96	2,400	93	2332	0%	3%
		Jharkhand	-	3	3	111	2,687	90	2187	8%	12%
		Orissa	-	3	3	94	2,402	93	2376	0%	1%
		West Bengal	-	12	12	117	2,552	101	2210	2%	11%
		All India	**-**	**81**	**80**	**121**	**2,512**	**109**	**2266**	**2%**	**8%**

NR: Northern Region, WR: Western Region, SR: Southern Region, ER: Eastern Region

[1]*The final numbers are in millions.*

Table 7: Candidate Power Plants for Shut Down as per Model 1 and Model 2

Year	Region	State (Model 1)	Plant (Model 1)	State (Model 2)	Plant (Model 2)
2005	ER	West Bengal	SOUTHERN REPL.	West Bengal	SOUTHERN REPL.
2006	NR	Delhi	RAJGHAT	Delhi	RAJGHAT
		Uttar Pradesh	PANKI	Uttar Pradesh	PANKI
2007	NR	-	-	Delhi	RAJGHAT
	WR	Gujarat	KUTCH LIGNITE	Gujarat	KUTCH LIGNITE
	ER	West Bengal	SOUTHERN REPL.	West Bengal	SOUTHERN REPL.
2008	NR	-	-	Delhi	RAJGHAT
		Haryana	FARIDABAD	Haryana	FARIDABAD
		-	-	Uttar Pradesh	PANKI
	WR	-	-	Gujarat	KUTCH LIGNITE
		Maharashtra	PARAS EXT	Maharashtra	PARAS EXT
	ER	West Bengal	SOUTHERN REPL.	West Bengal	SOUTHERN REPL.
2009	NR	-	-	Uttar Pradesh	PANKI
	WR	Gujarat	DHUVARAN	-	-
		Maharashtra	PARAS	Maharashtra	PARAS
	ER	-	-	West Bengal	SOUTHERN REPL.
2010	NR	Uttar Pradesh	PANKI	Uttar Pradesh	PANKI
	ER	West Bengal	SOUTHERN REPL.	West Bengal	SOUTHERN REPL.
		West Bengal	NEW COSSIPORE	West Bengal	NEW COSSIPORE
2012	ER	West Bengal	NEW COSSIPORE	-	-
2013	NR	Delhi	RAJGHAT	Delhi	RAJGHAT
	SR	Andhra Pradesh	RAMAGUNDEM B	Andhra Pradesh	RAMAGUNDEM B
	ER	West Bengal	NEW COSSIPORE	-	-
2014	WR	Gujarat	KUTCH LIGNITE	Gujarat	KUTCH LIGNITE

Table 8: (Model 1 Results) Potential gains for the State (with and without including Central sector plants), reallocation of only fuel is allowed

Year	Region	State	All Plants		State-owned and Central sector Plants considered Separately	
			ΔG (MUs)	ΔB (mg)	ΔG (MUs)	ΔB (mg)
2005	Northern Region	Delhi	494	-81,909	810	0
		Haryana	252	-332,300	252	-332,300
		Punjab	0	-225,260	0	-225,260
		Rajasthan	0	-57,750	0	-57,750
		Uttar Pradesh	0	-1,822,866	299	-1,340,230
	Western Region	Chhattisgarh	0	-377,037	0	-322,130
		Gujarat	24	-651,759	24	-651,759

Year	Region	State	All Plants		State-owned and Central sector Plants considered Separately	
			ΔG (MUs)	ΔB (mg)	ΔG (MUs)	ΔB (mg)
		Madhya Pradesh	0	-1,229,328	2,485	-461,926
		Maharashtra	0	-1,328,341	0	-1,328,341
	Southern Region	Andhra Pradesh	0	-1,196,264	496	-1,057,379
		Karnataka	21	-136,944	21	-923,726
		Tamil Nadu	0	-1,465,294	0	-379,745
	Eastern Region	Bihar	154	-205,329	-	-
		Jharkhand	1,565	0	416	-3,992
		Orissa	0	-41,062	0	-26,302
		West Bengal	7,212	-262,107	5,338	-144,484
	Central Sector	NTPC	0	0	0	-1,555,898
		DVC	0	0	850	-324,035
		NLC	0	0	821	-230,951
	All India		**9,721**	**-9,413,552**	**11,812**	**-9,366,207**
2010	Northern Region	Delhi	427	0	0	0
		Haryana	0	-542,261	0	-542,261
		Punjab	325	-259,089	325	-259,089
		Rajasthan	1,108	-113,686	1,108	-113,686
		Uttar Pradesh	0	-763,801	2,041	-168,763
	Western Region	Chhattisgarh	0	-257,884	0	-175,269
		Gujarat	3,870	-237,860	3,870	-237,860
		Madhya Pradesh	4,251	-345,174	4,314	-376,336
		Maharashtra	10,013	-77,862	10,013	-77,862
	Southern Region	Andhra Pradesh	0	-189,630	0	-90,893
		Karnataka	1,612	0	1,612	0
		Tamil Nadu	2,952	-1,467,819	1,428	-366,987
	Eastern Region	Bihar	0	-63,561	-	-
		Jharkhand	948	-89,416	0	0
		Orissa	0	-76,414	0	-30,701
		West Bengal	3,596	-569,392	1,731	-545,172
	Central Sector	NTPC	0	0	0	-702,644
		DVC	0	0	1,478	-148,670
		NLC	0	0	0	-172,362
	All India		**29,103**	**-5,053,851**	**27,920**	**-4,008,556**
2014	Northern Region	Delhi	362	-12,520	117	-3,532
		Haryana	0	-169,899	0	-169,899
		Punjab	0	-234,930	0	-234,930
		Rajasthan	0	-138,884	0	-138,884

Year	Region	State	All Plants		State-owned and Central sector Plants considered Separately	
			ΔG (MUs)	ΔB (mg)	ΔG (MUs)	ΔB (mg)
		Uttar Pradesh	0	-784,087	0	-678,980
	Western Region	Chhattisgarh	0	-249,001	0	-274,602
		Gujarat	0	-480,569	0	-480,569
		Madhya Pradesh	1,193	-220,070	1,207	-391,290
		Maharashtra	5,112	-480,930	5,112	-480,930
	Southern Region	Andhra Pradesh	0	-390,812	0	-385,464
		Karnataka	430	-149,255	430	-149,255
		Tamil Nadu	0	-1,289,966	543	-702,661
	Eastern Region	Bihar	0	-42,601	-	-
		Jharkhand	696	-122,318	376	-18,818
		Orissa	0	-31,549	0	-24,806
		West Bengal	1,343	-740,233	1,306	-485,886
	Central Sector	NTPC	0	0	0	-962,052
		DVC	0	0	16	-304,206
		NLC	0	0	685	-199,409
	All India		**9,136**	**-5,537,625**	**9,792**	**-6,086,174**

[1]*Colored rows represent the states whose outcomes changed (either improved or worsened) after excluding the central sector plants.*