Measurement of Operational and Environmental Performance of the Coal-Fired Power Plants in India by Using Data Envelopment Analysis

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***Abstract*—**In this study, the performance analyses of the twenty five Coal-Fired Power Plants (CFPPs) used for electricity generation are carried out through various Data Envelopment Analysis (DEA) models. Three efficiency indices are defined and pursued. During the calculation of the operational performance, energy and non-energy variables are used as input, and net electricity produced is used as desired output (Model-1). CO_2 emitted to the environment is used as the undesired output (Model-2) in the computation of the pure environmental performance while in Model-3 CO_2 emissions is considered as detrimental input in the calculation of operational and environmental performance. Empirical results show that most of the plants are operating in increasing returns to scale region and Mettur plant is efficient one with regards to energy use and environment. The result also indicates that the undesirable output effect is insignificant in the research sample. The present study will provide clues to plant operators towards raising the operational and environmental performance of CFPPs.

***Keywords*—**Coal fired power plants, environmental performance, data envelopment analysis, operational performance.

I. Introduction

ELECTRICITY, a preferred form for energy consumption since independence in India, has registered a higher growth rate in comparison with the other forms of energy. Various estimates indicate that India would have to increase its electricity generation capacity by five to six times of the 2003-2004 levels by 2031 [16]. Being a developing country with over a billion of populations, increased consumption of an electric power is more intimately bound up with economic development on the one hand and the increased emission of pollutants on the other hand. The electricity in India is mostly generated by CFPPs. Moreover, sixty-seven percent of the total power is generated by CFPPs [3]. It is widely known that CFPPs are a major source of coal consumption and carbon dioxide emissions. Three-fourths of the in-house coal production is consumed in power generation [31]. But Indian coal has high ash content and low gross calorific value against the international average. Consequently, CO_2 emissions from Indian CFPPs are very high. In absolute terms, India is the world's sixth largest emitter of CO_2 energy, contributing 3.3% of the world CO_2 emissions [17]. Carbon dioxide released into the atmosphere from the burning of fossil fuels is the single most important greenhouse gas contributing to the climate change. In the context of climate change, it is necessary to consider not only traditional inputs and outputs but also to consider the effects of undesirable outputs in evaluating the performance of CFPPs.

As far as the world wide sustainable development on energy and environmental issues are concerned, energy efficiency and environmental performance evaluation play a crucial role. While reviewing the existing studies on CFPPs, we found that the studies have access to the operational performance of power plant skipping the effect of the undesirable output on environment. Therefore, the present study would embed the undesirable along with desirable variables to achieve the performance of power plant keeping in view the effect of the undesirable output on environment. To the best of our knowledge, none of the CFPPs studies in India has examined the operational and environmental issues in the present mode. Motivated by the aforesaid information, the present study is an attempt to investigate both the operational and environmental performance of CFPPs.

In this empirical study, we applied DEA approach in different settings 'i.e. Constant Return to Scale (CRS) and Variable Returns to Scale (VRS) settings' to assess the operational and environmental performance of CFPPs. The use of the DEA provides better insight into the issues related to resource utilization and emission of pollutants. In Model 1, the main production indicators are taken as inputs and net electricity produced is taken as desired output. In Model 2, CO_2 emissions of power plant are taken as undesirable output in conjunction with desirable output. In Model 3, CO_2 emissions of power plant are taken as environmentally detrimental input in combination with the main inputs.

This study complements the existing research in three different ways:

1) There is a dearth of DEA based research on the assessment of the operational and environmental performance of CFPPs. The findings of the research underline the need for state-owned CFPPs to be operationally as well as environmentally efficient.
2) It further identifies the nature of returns to scale, scale size and benchmark the power plant in operational and environmental mode.
3) The study also examines whether or not the difference between operational (Model 1) and pure environmental performance (Model 2) or operational and environmental

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Model 3 is significantly important.

The remainder of this study is organized as follows. Literature pertinent to the study has been presented in Section II. Variables and data used in this study have been discussed in Section III. Methodology of the research has been explained in Section IV. The results and discussions have been presented in Section V. Concluding remarks have been given with the directions of future research in the last section.

II. Literature Review

A. Operational Performance

Several studies have been performed to analyze the operational efficiency of power generation sector. Reference [5] determined the inefficiencies in generating units of National Thermal Power Corporation (NTPC) using the DEA approach. The most important result was not only the measurement of the inefficiencies of units but also the identification of the causing factors of those inefficiencies in different generating units. Reference [23] analyzed and compared the efficiency of thermal, hydro and wind powered plants in Turkey. They concluded that the operational performance of the public sector thermal plants was significantly lower than their private counterparts. Reference [24] examined the efficiency of coal-based power plants during the period of 1994-1995 and 2001-2002 using the stochastic frontier function method. The results indicated that the highest efficiency was attained by the Dhanu plant. They also suggested that the inefficient plants should adopt the best practices of the efficient plants. Reference [25] assessed the efficiency of Thermal Power Plants (TPPs) using the DEA method and compared the results with respect to size and ownership. The results reflected that the efficiency of smaller plants was lower in comparison with medium and large plants. The performance of state-owned power plants was comparatively lower than centrally and privately owned plants. Reference [14] measured the technical efficiency of China's thermal power generation based on cross-sectional data. The analysis demonstrated that the fuel efficiency and capacity factors significantly affect the technical efficiency. Reference [15] evaluated the power generation efficiency of major TPPs in Taiwan during 2004-2006. Based on their stability test, the heating value of total fuels and installed capacity were the important variables for the efficiency evaluation of steam turbine power plants. Reference [20] empirically explained the performance of heat plants in Poland. The study determined the factors that could influence the technical efficiency of heat plants. Reference [19] analyzed the impact of number of potentially influenced exogenous factors and the other variables on operating inefficiency in the CFPPs in US. The results showed that allocative inefficiency was highly influenced by heat rates, vintage and technology.

B. Environmental Performance

A number of studies have used the different approaches to explain the environmental performance of the CFPPs. Reference [36] proposed the models to distinguish weak and strong disposability features among various undesirable outputs and measured the environmental performance of China's coal based power plants with these models. Authors' result suggested that taking CO_2 emissions in account the weak disposability assumption was more appropriate but it was inappropriate for SO_2 emissions. Reference [33] assessed the environmental performance of Greek fossil fuel-fired power stations by means of DEA-bootstrap modeling taking into account the undesirable outputs (CO_2 emissions).The result suggested that the non-lignite-fired stations were on average more efficient than the lignite-fired stations. Reference [10] examined the effect of air quality regulations on the efficiency of US power plant. Authors demonstrated that more stringent sulphur dioxide (SO_2) regulations have a negative effect on coal plant efficiency. Reference [28] applied DEA for measuring the efficiency of power plants in Turkey. The authors compared and analyzed the results for offering the suggestions to reveal the redundancies in the input variables and for reduction of environmental effects. Reference [30] used the DEA to analyze the performance of US CFPPs. Their results suggested that the plant operators needed to balance between their environmental performance and operational efficiency. Reference [8] measured the traditional productivity of US CFPPs during 1985–1995 under regulated and unregulated bad output production using the joint production model. They concluded that traditional productivity and technical change associated with abatement activities declined and it was not statistically significant. Reference [29] proposed a non-radial DEA approach to measure the unified efficiency of power plants. They separated the outputs into desirable and undesirable outputs, and then they applied DEA to measure the operational efficiency on desirable outputs and environmental efficiency on undesirable outputs. Reference [16] measured environmental efficiency of the Indian cement industry within joint production framework. Their results demonstrated that cement industry had the potential to expand good output and reduced the bad output at the given input levels. Reference [21] investigated the CO_2 emissions from the coal based power generation in India. They suggested the number of strategies to reduce the CO_2 emissions from power plants. Reference [13] proposed two different approaches to estimate the ecological efficiency. The approaches were applied to evaluate the eco-efficiency and the emission reduction program of 24 power plants in an European country. Reference [35] adopted three different DEA models to assess the environmental performance of 48 fossil fuel power plants in the USA and observed an important discrepancy in the ranking of the results. Reference [34] provided a comprehensive survey of literature on environmental performance measurement. Reference [39] summarized more than 100 DEA applications in energy and environment policy. Reference [7] introduced an environmental performance indicator based on the decomposition of overall factor productivity into a pollution index and an input-output efficiency index. This indicator was compared with [12].

There are a few published studies on performance measurement which measure the operational performance of CFPPs in Indian context. These few studies [23], [25] and [15] measured the operational performance of power plants but left unexamined the environmental performance which is the most important in case of CFPPs. Moreover, [28] assessed the environmental performance of power plants but considered only undesirable outputs which did not represent true production structure. This study intends to fulfill the gap that currently exists in the assessment of the environmental performance of CFPP.

III. Variables and Data

Frontier models require the identification of inputs (resources) and outputs (transformation of resources). No universal rule is available for the selection of variables. The choice of variables in the present study is based on three parameters as suggested by [2], availability of data within which important features of the operations of CFPPs can be modeled, our previous discussion on current literature and expert opinions of relevant professionals.

The operational activity of the power plant is conceptualized by five inputs, a single desirable and undesirable output. The desirable output is measured by net electricity generated (MUs). The undesirable output is measured by the total amount of CO_2 emission per year in tones. CO_2 emission is a major factor for depletion of ozone layer and resulting into climatic changes. The five inputs are separated into non-energy input and energy input. Installed capacity and operational availability are the non energy inputs. The installed capacity is a fundamental input variable that differentiates plant productivity and is measured by the name plate capacity of the plant. Operational availability is measured by the amount of time that the power plants are in operation in a year. Energy inputs are coal, oil and auxiliary power consumption. Coal is the primary fuel for boilers in CFPPs and is measured in thousand of tones. Oil is measured by the kilo liters and is the secondary fuel for the boiler that is used at the time of starting, plant tripping and for stand-by purposes. Auxiliary power consumption (MUs) represents the electricity consumed to operate the electrical equipment within the plant such as the feed pumps and fans. Table I descriptively and statistically summarizes a set of data based on Indian state-owned CFPPs in 2009- 2010.

The DEA requires that the set of Decision Making Units (DMUs) being analyzed should be comparable to utilize the same input from each DMU, which would result into the same type of outputs [18]. The study is confined to CFPPs because they are the key players in electricity generation. Based on the ownership structure, state-owned power plants have the highest installed capacity and higher CO_2 emissions in comparison with central and private sectors [11]. The other reasons for selecting state-owned power plant for the study are explained in the paper [26], [27]. Physical data used in this study consists of a cross section of 25 CFPPs from the various geographical regions of India. Data for selected variables except CO_2 were extracted from the report "Review of performance of thermal power stations" annually published by the Central Electricity Authority (CEA). Data for the CO_2 emissions was derived from the CO_2 baseline data base [6]. For a meaningful DEA analysis, the DMU sample size should be greater than the product of the number of inputs and outputs or three times the sum of the inputs and outputs [22]. In our study, 25 plants are more than three times the sum of the input and output variables.

IV. Methodology

The present study applies a DEA methodology to assess the operational and environmental performance of CFPPs. This technique is Linear Programming (LP) principles oriented where the mathematical form of the production function is not required. The DEA has major advantages over all other similar efficiency measurements because its methodology is directed to the frontiers rather than central tendencies [28]. The DEA technique using a frontier analysis was described by [9] but the mathematical formulation to handle the frontier analysis was provided by [4] and it was further extended by [1]. The two most frequently applied models used in DEA are the CRS and the VRS. The basic difference between these two models is the Returns to Scale (RTS). The VRS model takes into account the effect of variable RTS while the CRS model restricts DMUs to operate with constant RTS.

TABLE I
SAMPLE SUMMARY STATISTICS OF THE VARIABLES: 2009-2010

Variables			Mean	Median	Maximum	Minimum	SD
Output	Desirable output	Net electricity produced (MUs)	4455.9	3830.9	13390.3	308.9	3481.8
	Undesirable output	Total CO_2 emission (Tonnes)	5263812	4920484	15308206	509206	3752976
Input	Energy input	Coal (thousand ton)	3774.2	3412.6	12722	385.2	2885.6
		Oil (thousand liter)	13022.8	11355.2	57966.9	1538.9	11776.8
		Auxiliary power consumption (MUs)	467.6	442.6	1232.7	69.2	320.3
	Non-energy input	Installed capacity (MW)	792.3	730	2340	110	513.42
		Operational time (h)	7064.98	7597.55	8152.06	2998.55	1222.69

Though the efficiency measurements have different orientations yet the present study has adopted input-oriented CRS and VRS models to assess the operational efficiency ignoring the negative output. Undesirable output oriented models are used in different environmental technology to determine the pure environmental performance and the last one model measures the unified efficiency (operational and environmental) under VRS of CFPPs. The appropriate DEA models are described in the following subsections:

A. Operational Performance Model

The traditional CRS model is constructed based on certain assumptions of production possibility sets (PPS) [32]. The boundary of the PPS is referred as efficient frontier. This model measures the efficiency of the DMUs with reference to CRS frontier which reflects the efficiency relative to the best-practice power plant in the sample. The traditional CRS model is as given below:

$$\min \theta_o$$

Subject to

$$\sum_{j=1}^{n} \lambda_j x_{ij} \leq \theta_o x_{io} \qquad i = 1,...,m \tag{1}$$

$$\sum_{j=1}^{n} \lambda_j y_{rj}^d \geq y_{ro}^d \qquad r = 1,...,s \tag{2}$$

$$\lambda_j \geq 0 \qquad j = 1,...,n \tag{3}$$

Following the concept of [37], the conventional inputs used in traditional model separated into its energy $(x_{pj}^E : p = 1,..., P)$ and non energy inputs $(x_{ij}^N : i = 1,..., m)$. Basically, energy inputs play an important role in the operation of power plant. It is also environmentally oriented. The CRS traditional model is reformulated as illustrated below:

$$\min \theta_o$$

Subject to

$$\sum_{j=1}^{n} \lambda_j x_{ij}^N \leq x_{io}^N \qquad i = 1,...,m \tag{4}$$

$$\sum_{j=1}^{n} \lambda_j x_{pj}^E \leq \theta_o x_{po}^E \qquad p = 1,...,P \tag{5}$$

$$\sum_{j=1}^{n} \lambda_j y_{rj}^d \geq y_{ro}^d \qquad r = 1,...,s \tag{6}$$

$$\lambda_j \geq 0 \qquad j = 1,...,n \tag{7}$$

The referred aforesaid model is energy efficiency model (Model 1C). This model radially measures the maximum reduction in all the energy inputs without reducing the non energy inputs and the desirable output. The efficiency score obtained from the above CRS model is mainly determined by the energy inputs. The optimal solution of the model yields dual possibilities: (i) If $\theta_o = 1$, the plants are efficient and will be on the CRS frontier; and (ii) If $\theta_o < 1$, the plants are inefficient and will be below the CRS frontier. If the objective value of Model 1C is one and the set of indices corresponding to positive λ_j is called the reference set to DMU_o.

When CRS assumption is relaxed or invalid then a VRS assumption is in effect. The VRS demonstrates that the power plant operation follows either an increasing return to scale (IRS) or a decreasing return to scale (DRS) for the ranges of different outputs. To handle VRS property Banker et al. [1] developed a new model by adding a convexity constraint ($\sum_{j=1}^{n} \lambda_j = 1$) in the CRS model which referred as VRS model (Model 1 V). To further investigate the type of RTS holding at the location of a DMU_o, VRS model is modified with non increasing return to scale (NIRS) condition $\sum_{j=1}^{n} \lambda_j \leq 1$ imposed on it. The nature of the scale inefficiency for a particular DMU can be determined by comparing the NIRS efficiency score with VRS efficiency score. If they are unequal, then IRS exists for the DMU and if they are equal, then DMU exhibit DRS. If the CRS score is equal to the VRS score, the reference DMU is expected to reveal the CRS. In order to examine whether the power plant is most productive scale size (MPSS) or not, the concept given in the [32] (pp. 147) is applied. If a DMU is efficient under CRS model then plant operates at MPSS.

B. Environmental Performance Model

Modeling undesirable outputs is necessary in evaluating the performance of CFPPs as discussed in Section I. The usual approach to measure environmental performance is based on relative distance to the DEA environmental technology frontier. Various methods are available to measure the distance from frontier. In this study, we assess the environmental performance of the power plant by considering the two orientations- pure environment and input-environment. The specific treatment of negative output as either input or output has considerable debate in literature. Some authors [34], [13] consider undesirable outputs as input while other group of authors has argued that waste is technically an output. The production technology T of the power plant defines that emission of substance (CO_2, SO_2 and NO_x) to air is undesirable side products and side effect of production. Integrating waste in the production theory, we define the production possibility set as:

$$T^{Env}=\{x,y^d,y^u | \text{ inputs x can produce outputs } y^d \text{ and } y^u\}$$

1. Pure Environmental Performance (Model 2)

When undesirable outputs are treated as output (Model 2), an undesirable output orientation model is particularly attractive one because it provides a pure environmental performance measure for plants i.e. PEI. Here PEI, is referred as a pure EPI because only the undesirable outputs are reduced as much as possible, keeping the inputs and a desirable output at the given level. For PEI model, we adopt the undesirable output oriented models with different RTS proposed by [37], [38]. Before we describe the details of the model, we would like to focus the joint production technology as assumed by [38] to illustrate the following properties:

1) Outputs are weakly disposable. It implies that a proportional reduction in desirable and undesirable output is feasible. The weak disposability is exposed by using the equalities sign in the set of constraints.
2) Desirable and undesirable outputs are null-joint. It means that desirable outputs cannot be produced without producing undesirable outputs.

The CRS environmental performance index model (Model 2 C) is shown below:

$$\text{PEIndex (CRS)} = \min \theta_o$$

Subject to (4), (5), (6), (7), and

$$\sum_{j=1}^{n} \lambda_j y_{cj}^{u} = \theta_o y_{co}^{u} \qquad c = 1,\ldots,C \tag{8}$$

PEindex (CRS) is an aggregated and standardized environmental performance index which lies in the interval (0, 1). If a specific DMU has a larger performance index (CRS), it has a better environmental performance under the CRS environmental DEA technology.

In case of NIRS environmental performance index, PEindex is formulated by imposing the restriction of intensity variables $\left(\sum_{j=1}^{n} \lambda_j \le 1\right)$ on the CRS environmental performance index. In case of power generation, VRS assumption is more appropriate than CRS assumption [14]. The VRS demonstrates that the power plant operation follows either IRS or DRS for the ranges of different outputs. The pure environmental performance index under VRS environmental DEA technology (Model 2V) is as shown below:

$$\text{PEIndex (VRS)} = \min \theta_o$$

Subject to (6) and (8)

$$\sum_{j=1}^{n} \lambda_j x_{ij}^{N} \le \beta_o x_{io}^{N} \qquad i = 1,\ldots,m \tag{9}$$

$$\sum_{j=1}^{n} \lambda_j x_{pj}^{E} \le \beta_o x_{po}^{E} \qquad p = 1,\ldots,P \tag{10}$$

$$\sum_{j=1}^{n} \lambda_j = \beta_o \qquad j = 1,\ldots,n \tag{11}$$

$$0 \le \beta_o \le 1,\ \lambda_j \ge 0 \tag{12}$$

PEindex (VRS) is also an aggregated and standardized EPI which lie between (0, 1). Note that CRS, NIRS and VRS DEA technologies satisfy the properties of joint production technology.

The concept given in [22] and [40] is used to investigate the RTS properties of a DMU with respect to the production of desirable outputs and undesirable outputs. The following sets of conditions are defined for the nature of the scale: if PEI (CRS) =PEI (VRS), the reference DMU is expected to reveal the CRS, PEI (NIRS) < PEI (VRS), the DMU is expected to reveal the IRS; PEI (NIRS) =PEI (VRS), the reference DMU is expected to reveal the DRS. In order to investigate the environmental scale size, a mixed environmental performance model (MEIndex) is used which measures the production scale of desirable output to undesirable outputs. The equivalent linear programming suggested by [40] is given below:

$$\text{MEIndex} = \min \theta_o$$

Subject to (6), (7), (8), (9), (10), and (11).

If the optimal objective value of MEIndex model is one the plant operates at most environmental scale size (MESS). If the above model value is less than one then the plant does not operate at its MESS.

2. Input–Environmental Orientation Model (Model 3)

In the study, the energy inputs are valuable resources from an environment view point. The most conventional approach is to model CO_2 emissions as input because both inputs and undesirable outputs incur pollution to environment. Hence the plant operator tries to avoid the excessive consumption of energy inputs and excessive CO_2 emissions from the plant. In this model, the power plant simultaneously reduces the inputs and undesirable outputs, keeping the desirable output constant. The VRS model for measuring the unified (operational and environmental) efficiency is given as:

$$\min \theta_o$$

Subject to (4), (5), (6), (7), (8)

$$\sum_{j=1}^{n} \lambda_j = 1 \qquad j = 1,\ldots,n \tag{13}$$

V. Results and Discussion

A. Operational Performance

The result of the Model 1C, as listed in Table II, shows the CRS, VRS efficiency scores and RTS. The CRS efficiency scores vary across the plants ranging from 0.520 to 1. The optimized result of CRS Model 1C shows that the Ropar, Ukai, Chandrapur, Raichur and the Mettur plants are efficient irrespective of their sizes. The inefficiency score of the remaining power plants indicates that they should reduce their existing energy input levels by maintaining the input mix to produce the current level of power generation. For example, the Panki plant has an efficiency score of 73.6%, which indicates that its current energy input level should be reduced by 26.4% to be an efficient plant.

The VRS Model 1V is applied to determine the sources of inefficiencies present in the CRS efficiency. The inefficiencies in the CRS may be either due to inadequate scale of operation or due to an inefficient operation of the plants themselves. A number of plants that appeared inefficient in the CRS assumption are now surprisingly found to be efficient using the VRS assumption. VRS efficient power plants, such as the Indraprasth, Rajghat, Faridabad, North Chennai and Santaldih plants increased to an efficiency of one. This depicts that the inefficiencies assigned to these five plants, with respect to CRS assumption, are purely scale based inefficiencies. In order to make the non-efficient power plants efficient the inputs of the power plants have to be reduced in accordance with their efficiency scores (Table II) obtained as a result of VRS analyses. The efficiency of Ropar, Ukai, Chandrapur, Raichur and Mettur power plants remain the same under both the assumptions. This consistency shows that the operation of these plants is at the MPSS and has efficient operations. Consequently, the efficient operations may be due to proper preventive and routine maintenance of the plant, better management and attitude of the employees towards energy saving. The Karodi, Parli and Ennore plants have a lower VRS efficiency whereas their scale efficiency values are approximately one. This result shows that these plants are at an optimal production scale but they are inefficient in operation. The scale efficiency of the plants demonstrates that 8 % of the plants are operating at optimal scale (CRS), 64 % are operating at a suboptimal scale (IRS) and 28 % of the plants are operating above the optimal scale (DRS). The lowest scale efficiency is calculated for the Faridabad plant. Plants operating under the IRS (DRS) must increase (downsize) their scale of operation to be an efficient plant.

Table II presents the reference power plants number. The set of indices corresponding to positive λ_j is called the reference set to DMUo. The Mettur plant is shown to have maximum frequency as a peer for 15 inefficient plants. Therefore, it plays a better role model for the inefficient plants because this peer is genuinely efficient. VRS results show that the Koradi plant is the most inefficient plant in the catalog, and its peers are the Indraprasth (with the weight 0.18), Santaldih (with the weight 0.098) and Mettur (with the weight 0.722) plants. This implies that the operating practices and the environment of Indraprasth, Santaldih and Mettur plants are quite similar to the structure of Ennore plant. The peers can serve for a policymaker as benchmarks to be used for a possible improvement of operational performance in power plants. However we explored that out of these ten VRS efficient plants North- Chennai and Raichur plants have not appeared as a peer for any inefficient plants to monitor their efficiency; the efficiency of such plants must be viewed cautiously.

B. Environmental Performance

A number of plants that appeared inefficient in the CRS environmental DEA technology assumption shift to efficient category while using the VRS technology assumption. VRS efficient power plants, such as Indraprasth, Rajghat, Faridabad, Tuticorin, North Chennai and Santaldih plants increased to an index of one. This reflects that the inefficiencies assigned to these six plants, with respect to CRS assumption, are purely due to wrong selection of environmental DEA reference technology.

TABLE II
OPERATIONAL PERFORMANCE OF POWER PLANTS UNDER CRS AND VRS MODEL

Plant No.	Plant Name	CRS Score	VRS Score	Scale Efficiency	NIRS Score	RTS	Peers(VRS)	Scale Size
1	Indraprasth	0.692	1.000	0.692	0.692	IRS	1	NMPSS
2	Rajghat	0.611	1.000	0.611	0.611	IRS	2	NMPSS
3	Faridabad	0.520	1.000	0.520	0.520	IRS	3	NMPSS
4	Panipat	0.935	0.937	0.999	0.935	DRS	6,19,25	NMPSS
5	GNDTP	0.868	0.892	0.973	0.868	IRS	1,3,22	NMPSS
6	Ropar	1.000	1.000	1.000	1.000	CRS	6	MPSS
7	Kota	0.960	0.992	0.967	0.992	DRS	6,22,25	NMPSS
8	Suratgarh	0.956	0.956	1.000	0.956	DRS	19,6,21,22,25	NMPSS
9	Panki	0.736	0.877	0.839	0.736	IRS	3,22,1	NMPSS
10	Parichha	0.806	0.799	1.008	0.780	IRS	22,1	NMPSS
11	Ukai	1.000	1.000	1.000	1.000	CRS	11	MPSS
12	Sikka Rep	0.715	0.983	0.728	0.715	IRS	2,11,22	NMPSS
13	Nasik	0.837	0.781	1.071	0.771	IRS	21,22,25,24	NMPSS
14	Koradi	0.666	0.670	0.995	0.666	IRS	22,1,25	NMPSS
15	Bhusawal	0.699	0.792	0.882	0.739	IRS	2,22,21,11,1	NMPSS
16	Parli	0.684	0.680	1.006	0.681	DRS	24,22,21	NMPSS
17	Chandrapur	1.000	1.000	1.000	1.000	CRS	17	MPSS
18	RayalSeema	0.894	0.901	0.993	0.894	IRS	22,6,3,25	NMPSS
19	Raichur	1.000	1.000	1.000	1.000	CRS	19	NMPSS
20	Ennore	0.597	0.678	0.881	0.597	IRS	1,25,22	NMPSS
21	Tuticorin	0.971	0.972	0.999	0.972	DRS	11,6,22,17	NMPSS
22	Mettur	1.000	1.000	1.000	1.000	CRS	22	MPSS
23	North Chennai	0.916	1.000	0.916	0.916	IRS	23	NMPSS
24	Bandel	0.929	0.997	0.932	0.929	IRS	1,22,25	NMPSS
25	Santaldih	0.810	1.000	0.810	0.810	IRS	25	NMPSS
	Average	0.832	0.916					
	Efficient	5.000	10.000					

Note: RTS, return to scale; IRS, increasing returns to scale; DRS, decreasing return to scale; CRS, constant returns to scale; VRS, variable returns to scale; NIRS, non increasing returns to scale; MPSS, most productive scale size; NMPSS, not most productive scale size.

In order to make the inefficient power plants efficient the CO_2 emissions of the power plants have to be reduced in accordance with their performance indexes (Table III) obtained as a result of VRS analyses. The performance of the seven power plants remains the same under both the assumptions. The Karodi and Parli plants have a lower VRS performance index. The RTS properties of the plants demonstrate that 36 % of the plants are operating at environment optimal scale (CRS), 64 % are operating at a suboptimal scale (IRS) and none of the plants are operating above the optimal scale (DRS). Here, IRS meaning is completely opposite to IRS as defined in operational performance. IRS result indicates if a plant increases its operational size, the plant produces more pollutions than before the size increase. For this reason, it is recommended that the plant should decrease the operational size in order to improve its environmental performance in short term. As an alternative strategy for long term, plant should adopt technology innovation to enhance the environmental performance. The result obtained from the MEIndex Model 2 exhibits that Indraprasth, Rajghat, Faridabad, RayalSeema, Tuticrion, Mettur and Santaldih are at MESS and the remaining plants do not operate at MESS. According to the VRS results, the Rayal- Seema plant became a reference for 11 power plants. Hence, it is a peer for these inefficient plants because this peer is genuinely efficient. The Parli plant is the most inefficient plant in the list, and its peers are the Indraprasth (with the weight 0.44), Tuticorin (with the weight 0.32) and Rayal-Seema (with the weight 0.17) plants. These are the points with efficient performances that are used to evaluate power plants' performance since their mixing of inputs and outputs are similar to that of inefficient plants. However, we have explored that out of these fourteen VRS efficient plants Chandrapur and Raichur plants have not appeared as a peer for any inefficient plants; the performance of such plants must be viewed cautiously.

The unified efficiency measures obtained from the Model 3 are based on the assumption that CO_2 emission is input in the electricity generation and results are presented in Fig. 1. The efficiency varies across the plants. The efficiency had a mean of 0.937, and the majority of the plants lie above the mean score. Fifteen plants demonstrate 100% unified efficiency while Koradi and Parli plants have the lowest level of efficiency in the sample. The unified efficiency of Ennore plant has the score of 76.5% which indicates that its current energy input level would be possible to reduce all the energy inputs, including carbon dioxide, proportionately by 24.5% and still produces the given level of output.

TABLE III
PERFORMANCE OF POWER PLANTS UNDER DIFFERENT ENVIRONMENTAL DEA TECHNOLOGIES

Plant No.	Plant Name	PEI (CRS)	PEI (VRS)	PEI (NIRS)	RTS	Peers (VRS)	MEI (VRS)	Scale size
1	Indraprasth	0.706	1.000	0.706	IRS	1	1.000	MESS
2	Rajghat	0.582	1.000	0.582	IRS	2	1.000	MESS
3	Faridabad	0.448	1.000	0.448	IRS	3	1.000	MESS
4	Panipat	0.938	0.951	0.938	IRS	6,8,17,25	0.865	NMESS
5	GNDTP	0.735	0.781	0.735	IRS	18,1,3	0.772	NMESS
6	Ropar	1.000	1.000	1.000	CRS	6	0.880	NMESS
7	Kota	1.000	1.000	1.000	CRS	7	0.992	NMESS
8	Suratgarh	1.000	1.000	1.000	CRS	8	0.961	NMESS
9	Panki	0.659	0.864	0.659	IRS	3,2,18	0.863	NMESS
10	Parichha	0.741	0.754	0.741	IRS	18,1	0.754	NMESS
11	Ukai	1.000	1.000	1.000	CRS	11	0.888	NMESS
12	Sikka Rep	0.726	0.949	0.726	IRS	2,1,22,18	0.915	NMESS
13	Nasik	0.738	0.807	0.738	IRS	18,1	0.741	NMESS
14	Koradi	0.658	0.667	0.658	IRS	18,1,25	0.665	NMESS
15	Bhusawal	0.744	0.859	0.744	IRS	2,21,1,18	0.850	NMESS
16	Parli	0.627	0.636	0.627	IRS	1,21,18	0.685	NMESS
17	Chandrapur	1.000	1.000	1.000	CRS	17	0.886	NMESS
18	RayalSeema	1.000	1.000	1.000	CRS	18	1.000	MESS
19	Raichur	1.000	1.000	1.000	CRS	19	0.875	NMESS
20	Ennore	0.639	0.756	0.639	IRS	1,25,18	0.756	NMESS
21	Tuticorin	0.999	1.000	1.000	DRS	21	1.000	MESS
22	Mettur	1.000	1.000	1.000	CRS	22	1.000	MESS
23	North Chennai	0.958	1.000	0.958	IRS	23	0.943	NMESS
24	Bandel	0.707	0.790	0.707	IRS	1,22,25,18	0.734	NMESS
25	Santaldih	0.602	1.000	0.602	IRS	25	1.000	MESS
	Average	0.808	0.913				0.881	
	Efficient	7	14					

Note: PEI, pure environmental index, RTS, return to scale; IRS, increasing returns to scale; DRS, decreasing return to scale; CRS, constant returns to scale; VRS, variable returns to scale; NIRS, non increasing returns to scale; MEI, mixed environment index; MESS, most environment scale size; NMESS, not most environment scale size.

This is possible under two modes - using high quality of coal and oil which results into reduction of the amount of coal, oil with less CO_2 emissions. It implies that natural reduction in the inputs automatically enhance the operational as well as environmental performance. Secondly, by applying the managerial efforts such as training the employees about the environmental issues and introduction of new technology to improve environmental performance.

C. Overall Assessment

Overall assessment of the power plants based on VRS analysis of all the models is given in Fig. 1 and Table IV. Ten power plants are the efficient power plant as it is determined efficient one for all of the VRS models. Koradi power plant shows the worst performance for all VRS models followed by Parli. Mettur plant is at its MPSS and MESS. In other words, Mettur plant is efficient one with regards to energy use (operational) and environment.

D. Rank-Sum Test

While comparing the VRS efficiency scores as presented in Tables II and III, it can be seen that average efficiency gauged by Model 3 based on both desirable and undesirable output is higher than that of the obtained from the Model 1 that considers only desirable output. In order to validate whether omitting undesirable output results into biased estimates of efficiency scores, the Mann-Whiteny rank sum test has been carried out. The null hypothesis is that efficiency scores obtained from the two models contain the identical population of relative frequency distribution whereas alternative hypothesis is that the mean efficiency score obtained from undesirable model is significantly different from the one obtained without considering undesirable output. The value of Mann-Whiteny statistic (Z_U) is - 1.04 and the value of two tailed 'Z' statistic is -1.64 at 5% of the significance level. Therefore, the null hypothesis can be accepted at 10% level, implying that there is no major difference between the two groups in their performance on efficiency in exclusion of undesirable output.

TABLE IV
COMPARISON OF MODEL 1 AND MODEL 2 UNDER VRS MODE

Performance	Efficient	Benchmark	Scale Size	Nature of RTS		
				IRS	CRS	DRS
Operational	10	Mettur	MPSS(5)	15	5	5
Environmental	14	Rayal Seema	MESS(7)	16	9	NA

Note: RTS, return to scale; IRS, increasing returns to scale; DRS, decreasing return to scale; CRS, constant returns to scale; MPSS, most productive scale size; MESS, most environmental scale size.

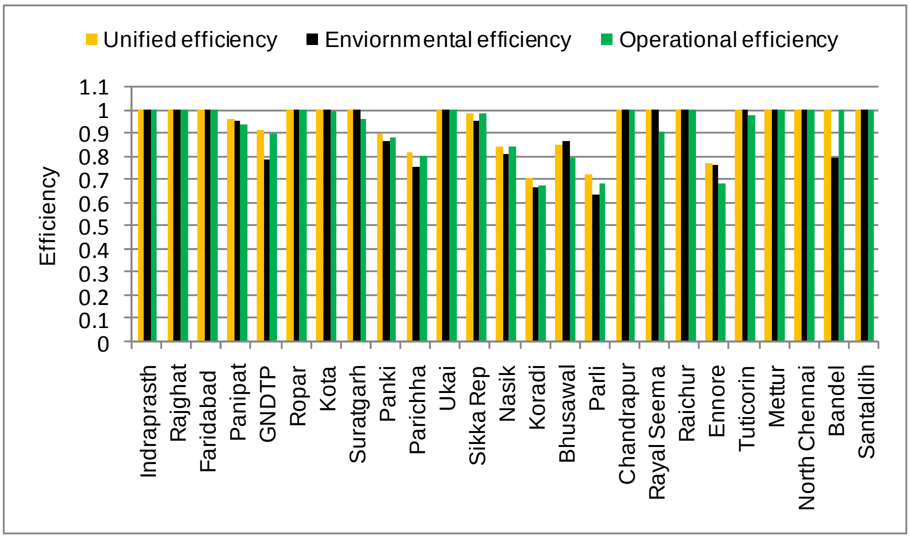

Fig. 1 Comparison of all VRS Models

VI. CONCLUSIONS

In this study, Data Envelopment Analysis (DEA) is applied to the Indian CFPPs with multiple inputs and outputs in order to measure their relative performances in terms of operational and environmental modes. Since CFPPs are the major producer of environmentally detrimental carbon dioxide gas that is an undesirable by-product, a special emphasis is given to that undesirable output while evaluating performance. Efficiency analyses of 25 coal-fired state-owned power plants are conducted with the DEA technique. In the analysis, efficiency values are obtained by the use of CRS model and VRS models. Three different models have been developed by changing efficiency input and output variables of the power plants. Therefore, power plants' electricity generated (Model 1) and their environmental effect performances (Model 2 and Model 3) are relatively analyzed.

The number of efficient plants varies according to the different models. Inefficient plants become efficient by reducing the energy inputs or by introducing advance technology in its operations. The findings of scale size indicate that seven plants are operating at MESS whereas five plants operate at MPSS. The analysis reveals that Mettur plant is the benchmark for most of the inefficient plants from operational point of view whereas Rayal-Seema is benchmark plant in environmental perspective.

Overall assessment under VRS analyses demonstrates that Koradi power plant has the worst performance. On the contrary, Mettur plant is efficient one with regards to energy use and environment. The majority of power plants are operating in IRS region in both the modes. Furthermore, this study also employs Mann-Whitney statistical test to validate the effect of undesirable output. Results show that undesirable effect is not significant in the research sample which states that any model stands in good making consequently it is impossible to classify a universally best model. However, the result of insignificant effect of undesirable output should be used very cautiously and it needs for future projection. We are positively hopeful that this study would be beneficiary to the policy makers and the plant operators who are trying to improve the performance in both the modes i.e. operational and environmental. Moreover, similar research can be repeated with more number of undesirable outputs and power plant data.

NOMENCLATURE

x_{ij} amount of input i consumed by j^{th} plant

x_{ij}^{N} amount of non-energy input i utilized by j^{th} plant

x_{pj}^{E} amount of energy input p consumed by j^{th} plant

y_{rj}^{d} amount of desirable output r produced by j^{th} plant

y_{cj}^{u} amount of undesirable output c produced by the DMU_j

θ_o relative efficiency score of o^{th} power plant

β_o sum of the optimized value of lambdas

λ_j dual weight assigned to the DMU_j

λ_j^* optimized value of lambda of j^{th} power plant

Subscripts

o power plant under observation
m number of non-energy inputs
p number of energy inputs
s number of desirable outputs
C number of undesirable output
n number of DMUs

Superscripts

E Energy inputs
D Desirable output
N Non-energy inputs
U Undesirable output

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