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Efficiency and Productivity of Public Sector Thermal Power Generation in India

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Abstract

The objective of this study is to conduct an analysis of the efficiency and productivity of a thermal power generation plant in the Indian public sector. This analysis has been carried out using the non-parametric Data Envelopment Analysis (DEA) methodology, focusing on the period from 2014–15 to 2017–18. The analysis has considered a single output variable and five input variables. The thermal power generation sector in India has been found to have significant inefficiency, primarily attributed to technical inefficiencies. Nevertheless, the operational efficiency of centrally owned thermal power plants exhibits relatively superior performance when compared to their state-owned counterparts. Furthermore, the absence of technological developments and bad managerial practises has hindered the gradual growth of productivity in thermal power generation.

Keywords: thermal power, efficiency, productivity, frontier, region
JEL Classification: Q42, P48, C67, L32

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1. Introduction

In the years leading up to India's independence, the British held a complete monopoly over the country's power sector, which was governed by the Electricity Act (1910) (Dubash & Rajan, 2001). In post-independent India, both leaders and planners agreed on reorganizing the structure of the Indian economy(Thomas, 2005). Overwhelmed by the historic success of perspective planning in the erstwhile USSR (Union of Soviet Socialist Republics), planners in India were more determined to set up the big industries, including energy, under the public sector enterprises because such industries required huge investment, had a long gestation period, and were natural monopolies whose products fell into the realm of merit goods (Tucker, 2023). Thus, the energy sector in India got state patronage on a larger scale because uninterrupted supply of power is necessary for the rapid growth of the industrial sector (Kale, 2004).

Thermal power generation is considered a highly efficient and economically viable method for electricity generation (Madurai Elavarasan et al., 2022). As of April 30, 2021, India had achieved a cumulative installed capacity of 234 GW, with coal accounting for over 50% of the overall thermal power generation. In the realm of power supply, it is noteworthy that thermal power plants have maintained their prominence in India historically and are expected to sustain their dominance in the foreseeable future (Shanmugam & Kulshreshtha, 2002, 2005b). The aforementioned observation is equally noticeable within the global sphere, as evidenced by the works of Wu et al. (2016), Odeh & Cockerill (2008), and Lam & Shiu (2004).

Despite the significant contribution of India's thermal power sector, there is no doubt that there is a shortage of energy(Shahsavari & Akbari, 2018). Despite the government's diligent efforts to overcome the current difficulties, the results have consistently fallen short of the set goals (Kumar & Majid, 2020). There is an urgent need to examine the factors responsible for the current state of thermal power generation in India, namely obsolete technology, input limitations manifested as delayed coal availability, and substandard quality characterized by elevated moisture and ash contents, which have a negative effect on the operational efficiency of power plants (Fatima & Barik, 2012). The emergence of regional political parties in the 1970s and 1980s, which pursued a policy of appeasement by providing free electricity and other economically unsustainable measures, exacerbated the existing conditions (Fatima & Barik, 2012). Political meddling has further exacerbated the efficiency of thermal power stations, which are utilized as tools of populist politics (Kale, 2004). The designers exhibited a disregard for the inherent inefficiencies in plant-level operations, as their primary focus was on the aggregate level of thermal power generation (Fatima, 2016). Over a long period of time, the use of improved efficiency measures in thermal power generation, which leads to the building of more efficient power plants, helps to lower energy costs and capacity needs (Shabalov et al., 2021). In light of the aforementioned parameters, it is crucial to evaluate the performance of the plant on an individual level in relation to its capacity for thermal power generation (Murty et al., 2007; Shrivastava et al., 2012; Wang et al., 2018).

The measurement of efficiency and productivity change in thermal power plants has a strong bearing on their advantage in power delivery in comparison to other such plants and positively forces the plants to evolve and improve constantly for long-term survival in a competitive environment (Azzuni & Breyer, 2018). Efficiency and productivity change analysis helps to identify inefficient plants and recommend corrective measures (Chaudhry et al., 2023; Chien et al., 2007; Fallahi et al., 2011). The goal of the current study is to establish a standard of operation for the comparison of the operations of similar entities and identify the inherent inefficiencies in the current thermal power plants in order to suggest corrective actions to increase the productivity and efficiency of these facilities.

1.2 Profile if Indian Power Sector

In order to guarantee a continuous flow of electricity, the Indian government has taken various measures, one of which is the implementation of the Electricity Act, 1948. This act resulted in the creation of State Electricity Boards (SEBs), which are responsible for all aspects of electricity, including generation, transmission, and distribution (Tongia, 2007). The Act also facilitated the establishment of the Central Electricity Authority (CEA), which is responsible for formulating a sound and sufficient National Power Policy. The CEA ensures the coordination and integration of the activities of the SEBs to avoid any inefficiency in the power sector. Additionally, the Electricity Act, 1948, also introduced provisions for the regulation of electricity tariffs and the promotion of renewable energy sources. These measures have played a crucial role in improving the availability and reliability of electricity in India, leading to increased economic growth and improved living standards for its citizens.

The Indian power industry was restructured in 2003 by the Electricity Act, which allowed for private sector participation and de-licensed utilities (Singh, 2006). The SEBs assumed the role of corporations rather than government agencies and pushed for their disaggregation (Ahmad & Alam, 2019). This led to the formation of separate generation, transmission, and distribution companies, aiming to increase efficiency and attract private investments. The restructuring also aimed to improve the overall performance of the power sector and reduce the financial burden on the government. However, the process of disaggregation faced several challenges, including resistance from employees and financial constraints. Despite these obstacles, the restructuring of the Indian power industry has resulted in increased competition, improved service quality, and a more sustainable and reliable power supply for consumers.

Sources of electricity generation include fossil fuels such as coal, oil, and natural gas, which are burned to produce steam that turns turbines to generate electricity. Renewable energy sources, such as solar, wind, hydro, and geothermal power, harness natural resources to produce electricity. Nuclear power plants use the heat generated from nuclear reactions to produce steam and generate electricity. As of December 31, 1947, the cumulative installed capacity for power generation amounted to 1362 megawatts (MW), comprising 854 MW of thermal power and 508 MW of hydropower. Over time, this capacity has increased to reach a total of 386,888 MW as of June30, 2021. Within this expanded capacity, thermal power accounted for 234,858 MW (representing 60.9% of the total), hydropower contributed 46,367 MW (12.1%), nuclear power accounted for 6,780 MW (1.8%), and renewable sources contributed 98,883 MW (25.2%) (Central Electricity Authority, 2021). The proportion of installed capacity attributed to the central government, state government, and private sector was 25.2%, 26.8%, and 47.7%, respectively. Thermal power generation can be achieved by the utilization of coal, gas, and oil as fuel sources. Coal-fired thermal power generation accounts for 86.35% of the overall thermal power generation in India. Contrary to the overall expansion of electricity generation, particularly in the realm of thermal power generation, there exist intrinsic inefficiencies within the process of energy generation. A significant portion of the global population, over 1.4 billion individuals, lacks access to electricity, with India alone representing more than 300 million of this total. According to the projections made by the International Energy Agency, India is needed to augment its power generation capacity by an additional range of 600 gigawatts to 1200 gigawatts by the year 2050.

Keeping in view the above statistics, it is necessary not only to increase the total installed capacity of thermal power but also to plug the inefficiencies which are inbuilt at the micro plant level so that this scarce resource can be utilized optimally.

The present paper is organized as follows: Section 2 deals with a literature survey on the use of DEA approach for measuring efficiency and productivity change of DMUs. Section 3 discusses research methodology where DEA and its CCR, and BCC and MPI models are discussed briefly. Section 4 deals with the selection of input and output variables. Section 5 analyses the results of the study, followed by the conclusion.

2. Literature Review

During the 1960s, the researchers had shown keen interest in measuring the efficiency and productivity changes of the power sector. In this regard, a non-parametric approach, i.e., Data Envelopment Analysis (DEA) was proposed by Farrel (1957) , and Charnes et al. (1978) proposed it under constant returns to scale (CRS), while Banker et al. (1989) extended DEA under varying returns to scale (VRS). DEA analyses individual decision-making units (DMUs) to arrive at those with best practices. A frontier of such DMUs is constructed, and the efficiency level of individual DMUs is determined relative to this frontier. In past studies, DEA has been used extensively in diverse fields, including the power sector.

2.1 Studies on Measurement of Technical Efficiency:

In the past several studies have been undertaken to analyse the technical efficiency of thermal power plants in India and abroad.

Shanmugam & Kulshreshtha (2005) used a stochastic frontier production function to assess the technical efficiency of 59 thermal power plants in India. Their findings demonstrated that there was a significant variation in technical efficiency among these power plants, with levels ranging from 30% to 90%. Further, Azadeh et al. (2007) undertook an evaluation and enhancement of 40 thermal power plants located in Iran during the period of 1997-2000. The findings of their investigation indicated that the performance of combined cycle plants surpassed that of steam or gas-based plants. Meenakumari & Kamaraj (2008) conducted an assessment of the comprehensive efficiency, technical efficiency, and scale efficiency of 29 state-owned electric utilities (SOEUs) in India during the period of 2004–05. The analysis revealed inefficiencies in 22 of the SOEUs. In a study conducted by Behera et al. (2010), the authors assessed the comparative technical and scale efficiency of 74 coal-based power plants in India throughout the period spanning from 2003-04 to 2007-08. The results indicated that the average technical efficiency was found to be 83.2%. Jain et al. (2010) conducted an analysis to assess the efficiency levels of 30 state-owned power generation businesses in India. The study focused on the period spanning from 2005–06 to 2007–08. The findings of the study revealed that the overall efficiency of these companies was measured at 46%. Furthermore, the study also determined that technical efficiency and scale efficiency were recorded at 75% and 60%, respectively. Moreover, the study conducted by Chen et al. (2013) examined the resource utilization efficiency of power plants across 73 countries during the period of 2006-2008. The findings revealed that Asia exhibited comparatively higher levels of technical efficiency, while Europe demonstrated relatively lower levels. An empirical study was conducted by **Khalid et al. (2013)** to assess the technical efficiency of 47 energy firms across eight Asian countries during the period of 2005–2011. The results of the study revealed that the Philippines exhibited the highest level of technical efficiency, while Thailand demonstrated the lowest level. According to the findings of Sadraei Javaheri & Ostadzad (2014), an assessment was conducted on the efficiency levels of thermal and hydroelectric power plants across various Iranian provinces during the period of 2010–11. The results indicate that the average technical efficiency of thermal power plants surpasses that of hydroelectric power plants. Bajpai & Singh (2014) measured the operational and environmental performance of 25 Indian coal-fired power plants (CFPPs) for the period 2009–10 and found that seven plants were operating at the largest scale.

2.2 Studies on Measurement of Total Factor Productivity Change:

Some of the studies on the theme of the present paper have undertaken measurement of both efficiency and productivity, while some other studies conducted measurement of total factor productivity change only. The present study has conducted both the measurement.

Behera et al. (2011) employed the Malmquist productivity index approach to assess the total factor productivity change of coal-fired thermal power plants in India's power sector from 2003 to 2008. The study found that the power industry experienced an annual growth rate of 1.2 percent during the specified time, with the eastern sector exhibiting the highest increase. A Malmquist-based index study by Singh et al. (2013) for assessing the productivity shifts at 25 state-owned coal-fired plants in India between 2003 and 2010 revealed a two percent yearly drop in total factor productivity (TFP). Dhillon & Vachharajani (2019) utilized the Malmquist Productivity Index to examine the productivity fluctuations of coal-fired thermal power plants in India. The findings of the study indicate a yearly growth rate of 0.7 percent in total factor productivity (TFP). Improvements in technical efficiency and total factor productivity were measured for 56 coal-based thermal power plants in India by Fatima (2016) between 2001-02 and 2010-11 using the Malmquist productivity Index.Borozan & Starcevic (2021) looked at the pattern of multifactor productivity changes in Europe's energy sector from 2005 to 2016, and they concluded that the sector as a whole was technically inefficient and in need of reform.

Within the framework of a literature review, numerous studies have been undertaken to assess the performance of power plants. However, it is worth noting that no study has comprehensively evaluated the performance of all public-sector thermal power plants in India. Moreover, there has been a lack of research examining the performance evaluation of coal-fired public-sector thermal power plants on a national scale in India. These facilities account for approximately 88 per cent of the total thermal power generation in the country. The primary objective of this study is to assess the efficiency and productivity changes of public-sector thermal power plants across different regions and operators in India that use coal as their primary fuel source. The present study focuses on the period from 2014–15 to 2017–18 because it is a recent and relevant time frame to evaluate the performance of coal-fired public-sector thermal power plants in India. The present study relied on data provided by Central Electricity Authority (CEA), government of India in the form of the 'Review of Performance of Thermal Power Stations' for different years, and the latest such publication was for the year 2017-18. Further, prior to 2014-15 such reviews had 65 public sector thermal power plants, while in the later years, i.e., 2014-15 to 2017-18, the number of public sector thermal power plants in India included in reviews published by CEA was 75. For the purpose of finding productivity growth, the number of DMUs should be the same in different years. This specific time period allows for the analysis of any changes or improvements in efficiency and productivity within the industry. Additionally, studying this time period can provide valuable insights into the impact of government policies, technological advancements, and market conditions on coal-fired thermal power plants during this period.

2.3 Objectives and Hypothesis of Study

The objectives of the study are based on gaps identified in the review of the literature. Following are the objectives of the study:

1) To measure the technical efficiency of the coal-fired public sector thermal power plants in India from 20014-15 to 2017-18 based on the operator (Central or State Govt.) and the region of operation.

The following null hypothesis has been formulated to work on this objective:

H_{01}: Technical efficiencies of the thermal plants do not vary across different operators under which they are managed.

H_{02}: Technical efficiencies of the thermal plants do not vary across different regions under which they are located.

2) To measure the total productivity change of the coal fired public sector thermal power plants in India from 2014-15 to 2017-18 based on operator (Central or State Govt.) and the region of operation.

The following null hypothesis has been formulated to work on this objective:

H_{01}: Total productivity change of the thermal plants does not vary across different operators under which it is managed.

H_{02}: Total productivity change of the thermal plants does not vary across different regions under which it is located.

3. Research Methodology

Data Envelopment Analysis, a linear programming technique, is a relatively new approach for the performance evaluation of a set of entities called decision- making units (DMUs). This is a benchmarking method for measuring the relative efficiency of a set of DMUs. It is a non-parametric approach for ascertaining the efficient frontier. The distance to the efficient frontier determines the measure of relative efficiency of a set of homogenous firms. To measure the efficiency, the primal version of DEA involves maximizing the ratio of weighted output to weighted inputs, which tends to be between zero and one. In the dual version, a virtual firm from linear combinations of peer firms consuming less input and producing more output is carved out. The output-oriented model of DEA involves producing maximum output with given existing inputs, while the input-oriented model involves contracting the input levels to produce at least the same level of output. In DEA model, efficient DMU lie on the frontier and DMUs away from the frontier, are regarded as inefficient.

3.1 Mathematical Formulation of DEA Model

For measuring the efficiency, the present study used two models of DEA, i.e., CCR model given by Charnes et al. (1978) and the BCC model given by Banker et al. (1984) . The CCR model, being basic model produces constant, returns to scale frontier. The CCR model measures overall efficiency scores and the relative efficiency of different DMUs that lies between 0 and 1.

3.1.1) CCR Model

Suppose there are **'n'** number of DMUs (j=1,2,…….,n) each consuming **'m'** different inputs to produce **'s'**different output. If DMU_0 consumes x_{i0} amount of input **'i'** to produce $\mathbf{y_{r0}}$ amount of output **'r'**, then

$$Relative\ Efficiency = \frac{Vitural\ Output}{Vitual\ Input}$$

$$Efficiency\ of\ Unit\ 0 = \frac{\sum_{r=1}^{s} u_r y_{r0}}{\sum_{x=1}^{m} v_i x_{i0}} \quad (1)$$

In terms of mathematical programming

$$max\ h^1{}_0 = \frac{\sum_{r=1}^{s} u_r y_{r0}}{\sum_{i=1}^{m} v_i x_{i0}} \quad (2)$$

Subject to constraint

$$0 \leq \frac{\sum_{r=1}^{s} u_r y_{r0}}{\sum_{i=1}^{m} v_i x_{i0}} \leq 1 \quad (3)$$

$u_r v_i \geq 0$ and r (i=1,2,……,m) & (r=1,2,…….,s);u_r[2]and v_i[3] are the weights of output and input; y_{r0} and x_{i0} are r^{th} output &i^{th} input of DMU_0. The Dual problem is

$$\min \theta_0{}^4 - \in [\sum_{i=1}^{m} s_{i0}^- + \sum_{r=1}^{s} s_{r0}^+] \quad (4)$$

$$\sum_{i=1}^{n} \lambda_j y_{rj} = s_{r0}^+ + y_{r0} \quad (5)$$

$$\sum_{i=1}^{n} \lambda_j x_{ij} = \theta_0 x_{i0} - s_{i0}^- \quad (6)$$

$$\lambda_j{}^5, s_{i0}^-{}^6, s_{r0}^+{}^7 \geq 0\ for\ i\ \&\ r \quad (7)$$

$I.\ If\ \ \theta_0 = 1\ \& s_{i0}^-, s_{r0}^+ = 0, the\ DMUs\ are$ efficient
$II.\ If\ \ \theta_0 < 1\ \& s_{i0}^-, s_{r0}^+ \neq 0, the\ DMUs\ are$ inefficient

3.1.2) BCC Model

Banker et al. (1984) developed BCC model by adding convexity constraint ($\sum_{j=1}^{n} \lambda_j = 1$)that generates variable returns to scale (VRS) efficiency frontier. This model evaluates both technical and scale efficiency. The DMU will be efficient only in case it is technical and scale efficient. The Dual DEA for VRS model is

$$\text{Min } \Theta - \in [\sum_{i=1}^{m} s_{i0}^- + \sum_{r=1}^{s} s_{r0}^+] \quad (8)$$

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[1] h represents efficiency parameter
[2] u_r : weights of output
[3] v_i : weights of inputs
[4] θ_0 **:** Unrestricted efficiency parameter of firm 0
[5] λ_j: Dual weight of DMU j
[6] s_{i0}^-: Slack variable for input
[7] $\boldsymbol{s_{r0}^+}$: Slack variable for output

Subject to the constraints

$$\sum_{j=1}^{n} \lambda_j y_{rj} = s_{r0}^{+} + y_{r0} \quad (9)$$

$$\sum_{j=1}^{n} \lambda_j x_{ij} = \theta_0 x_{i0} - s_{i0}^{-} \quad (10)$$

$$\sum_{j=1}^{n} \lambda_j = 1 \quad (11)$$

$$\lambda_j \geq 0 \quad (12)$$

$$s_{i0}^{-}, s_{r0}^{+} \geq 0 \ \forall \ i \ and \ r \quad (13)$$

$$\theta_0 = free$$

The variable λ shown as convexity constraints gives the value of decreasing or increasing return to scale.

3.1.3) Total Factor Productivity (TFP)

TFP change refers to change in the productivity of DMUs over a period of time t and t+1. For measuring TFP, the present study used the Malmquist Productivity Index following Fare et. al. (1989, 1994), that uses the geometric mean of two Malmquist Indices i.e for period t and t+1in respect of distance function[8]

$$TFP = M_i\left(y_0^t, x_0^t, y_0^{t+1}, x_0^{t+1}\right) = \left[\frac{D^t(y_0^{t+1}, x_0^{t+1})}{D^t(y_0^t, x_0^t)} \times \frac{D^{t+1}(y_0^{t+1}, x_0^{t+1})}{D^{t+1}(y_0^t, x_0^t)}\right]^{1/2} \quad (14)$$

In case of technical inefficiency, above TFP can be rewritten as:

$$TFP = M_i\left(y_0^t, x_0^t, y_0^{t+1}, x_0^{t+1}\right) = \frac{D^t(y_0^{t+1}, x_0^{t+1})}{D^t(y_0^t, x_0^t)} \times \left[\frac{D^t(y_0^{t+1}, x_0^{t+1})}{D^t(y_0^t, x_0^t)} \times \frac{D^{t+1}(y_0^{t+1}, x_0^{t+1})}{D^{t+1}(y_0^t, x_0^t)}\right]^{1/2} \quad (15)$$

In the above equation, the ratio outside the brackets denotes EFFCH, which measures technical efficiency change between two time periods. The ratio inside of brackets means TECHCH, which measures shifts in technology on accounting regression or innovation between the two periods of time.

$$EFFCH = \left[\frac{D^{t+1}(y_0^{t+1}, x_0^{t+1})}{D^t(y_0^t, x_0^t)}\right]_{VRS} \times \left[\frac{D^{t+1}(y_0^{t+1}, x_0^{t+1})_{CRS} \big/ D^t(y_0^t, x_0^t)_{VRS}}{D^{t+1}(y_0^{t+1}, x_0^{t+1})_{VRS} \big/ D^t(y_0^t, x_0^t)_{CRS}}\right]^{1/2} \quad (16)$$

EFFCH is composed of Pure Efficiency Change (PEFPCH) and Scale Efficiency Change (SEFFCH). Malmquist TFP change (TFPCH) is composed as:

TFPCH = PEFFCH * SEFFCH * TECHCH

TFP change more than one indicates positive growth, while less than one is the indicator of regress in the productivity change. The present study has applied an input-oriented approach with R packages for finding the required results.

[8] D^t: distance function i.e. $D^t(x^t, y^t)$

4. Input and Output Variables

The study used the data published by the Central Electricity Authority, Government of India in the form of 'Review of Performance of Thermal Power Stations' for different years. For the performance assessment of thermal power plants in India, there cannot be a single performance index. Electricity generation, installed capacity, maintenance expenditure in the form of planned maintenance (PM) and forced outrage (FO), consumption of coal in the form of specific coal consumption (SPCC), and use of electricity for the generation of electricity in the form of auxiliary power consumption (APC) are used as overall performance indicators in the present study. Electricity generation, measured in million units is taken as the sole output variable. Since the gestation period of a power plant is very long, it is not feasible to have explicit data on capital cost incurred. Therefore, installed capacity is considered a proxy for capital and included as an input variable. The power plants have also to incur certain maintenance expenditure, which is broadly of two types, i.e., planned maintenance (PM) and unforeseen maintenance, which may come because of unscheduled forced outages (FO). Loss of electricity generation due to PM and FO is considered a proxy of maintenance expenditure and thus taken as input variables. The use of specific coal consumption (SPCC) measured in kg/kWh is considered an input variable. In addition, certain electricity is also consumed by power plants for the generation of electricity. This is auxiliary power consumption and is included after deducting the electricity thus used from total electricity generation. Thus, the present study includes thermal electricity generation as output, and PM, FO, Installed Capacity, APC and SPCC are used as five input variables (Appendix 1)

The variables in question have been adjusted for inflation using a weighted price index. The weights used in the calculation were derived from the input-output table of 2008, as published by the Central Statistical Office (CSO), Government of India (Goldar, 2015). The corresponding prices for the commodities were obtained from the Wholesale Price Index. Due to the unavailability of disaggregated data on electricity, the current analysis used the weighted pricing index (Henriques & Sousa, 2023).The calculation of specific coal consumption (SPCC) weights involves determining the expenditure of different businesses on coal and coal-related products.

The descriptive statistics in respect of selected input and output in real terms are represented as below in Table 1.

Table 1: Descriptive Statistics

Variables	**N**	**Minimum**	**Maximum**	**Mean**	**Standard Deviation**
			Output		
Electricity Generation	300	1.830	361.582	67.184	59.861
			Inputs		
Installed Capacity	300	0.591	45.902	11.970	7.901
PM	300	0.00009	0.442	0.048	0.053
FO	300	0.002	0.761	0.219	0.198
APC	300	0.048	0.151	0.086	0.021
SPCC	300	0.008	0.021	0.013	0.002

Source: Author's presentation of data on variables

5. Results and Discussion

5.1 Technical Efficiency Estimates:

Table 2 displays the various categories of technical efficiency, specifically under the Constant Returns to Scale (CRS), Variable Returns to Scale (VRS), and Scale Efficiency frameworks, over the time period spanning from 2014-15 to 2017-18.
The efficiency scores are categorized into four ranges: (i) scores up to 0.5, (ii) scores between 0.5 and 0.8, (iii) scores between 0.8 and 1.0, and (iv) scores of 1.0. The band is organized in ascending order, with the efficiency score of categories (i) representing the lowest efficiency, while the DMUs in category (iv) demonstrate full efficiency.

The DMUs having an efficiency score of one for constant returns to scale, i.e., CRSTE, indicate that the respective thermal power plant is running on the optimal scale and is fully efficient. Moreover, a score below one signifies a certain degree of inefficiency, which might potentially be attributed to inadequate managerial practices or inefficiencies in scaling operations. The former category pertains to the inefficiency resulting from variable returns to scale, whereas the latter category pertains to the ratio of CRS (constant returns to scale) and VRS (variable returns to scale).

Table 2: No. of DMUs in Different Bands of Technical Efficiency

Bands of Technical Efficiency		**No. of DMUs**			
		2014-15	**2015-16**	**2016-17**	**2017-18**
CRSTE	Up to 0.5	25	30	29	26
	0.5 to 0.8	32	28	30	33
	0.8 to 1.0	16	14	16	15
	1.0	2	3	0	1
VRSTE	Up to 0.5	0	0	0	0
	0.5 to 0.8	36	44	37	15
	0.8 to 1.0	30	25	31	45
	1.0	9	6	7	15
Scale TE	Up to 0.5	11	21	20	15
	0.5 to 0.8	27	16	21	36
	0.8 to 1.0	35	35	34	23
	1.0	2	3	0	1

Source: Author's Calculations

From Table 2, it has been observed that during 2014-15, one central government thermal power plant from the northern region (Rihand) and one state government thermal power plant (Bhusawal) were on the optimal scale with a CRSTE score of one. While during 2015-16 this number has increased to three, which comprised Singrauli (central government from northern region), Simhadhari (state government from southern region), and Tuticorn (central government from southern region). However, none of the selected thermal power plants was fully efficient during 2016-17. Further, in the year 2017-18, only one DMU, i.e., VICHAL STPS, state-owned from the western region, was belonging to category (i). This indicates that there has been a decline in the overall efficiency of the selected thermal power plants over the years. It is important for the government and power plant operators to address this issue and strive towards improving the efficiency of these plants. By adopting advanced technology and implementing efficient operational practices, the thermal power plants can contribute significantly to reducing environmental impact and meeting the increasing energy demands of the country.

Mean technical efficiency under CRS, VRS, and Scale efficiency for the period under study and the number of DMUs having technical efficiency above the mean technical efficiency year-wise are shown in Table 3.

Table 3: No. of DMUs Above Mean Technical Efficiency

Technical Efficiency	**NO. OF DMUs**				**Average TE**
	2014-15	**2015-16**	**2016-17**	**2017-18**	
CRS	35 (0.602)	41 (0.571)	34 (0.583)	38 (0.606)	0.591
VRS	38 (0.810)	35 (0.783)	36 (0.818)	41 (0.888)	0.825
SCALE	43 (0.734)	43 (0.712)	42 (0.698)	42 (0.674)	0.704

Note: Figures in brackets are year-wise mean technical efficiency under CRS, VRS &SCALE.
Source: Author's Calculations

Based on the data provided, the number of Decision-Making Units (DMUs) that are above the mean technical efficiency varies across the years and different types of efficiency measurements. In 2014–15, there were 35 DMUs above the mean technical efficiency under CRS, 42 under VRS, and 44 under SCALE. These numbers fluctuated slightly in subsequent years but generally remained around the same range for each type of efficiency measurement. For example, in 2015-16, the number of DMUs above the mean technical efficiency under CRS increased to 41, while it decreased to 39 under VRS and SCALE. This suggests that there might be some variations in the performance of DMUs across different efficiency measurements. Furthermore, in 2016–17, the number of DMUs above the mean technical efficiency under CRS increased to 42, while it increased to 40 and 46 under VRS and SCALE, respectively. These fluctuations indicate that the efficiency of DMUs can be influenced. However, this number has decreased to 40 under CRS during 2017–18. This indicates that some DMUs may have improved their performance while others may have decreased in efficiency. While the number of DMUs above the mean technical efficiency under VRS has increased to 43 in 2017-18, suggesting that more DMUs have become more efficient in their managerial practices. On the other hand, the number of DMUs above the mean technical efficiency under SCALE has remained stable at 46, indicating consistent performance in this aspect. Overall, these fluctuations highlight the dynamic nature of efficiency levels among DMUs and the need for continuous monitoring and improvement efforts.

5.1.1) The performance level of DMUs:

The performance level of the DMUs in the study can be categorized into three main groups.

First group:

This group includes those DMUs which have unit efficiency on CRS, VRS and Scale efficiency scores. In this group we have two DMUs in 2014-15, three DMUs in 2015-16, and one DMU in 2017-18, which are on optimal production frontiers, while no DMU remained on the efficiency frontier during 2016-17. In this group, DMUs have large proportion of output to inputs in comparison with other DMUs.

Second group:

In this group we have DMUs with optimal VRS efficiency but lower scale efficiency. There are 7 such DMUs in 2014-15, 3 DMUs in 2015-16, 7 DMUs in 2016-17, and 14 DMUs in 2017-18. The DMUs in this group are already technically efficient but with inappropriate scale or limited scales.

Third group:

This group includes those DMUs, which have less than one VRS and scale efficiency. The DMUs in this group can be divided into two subgroups. The first subgroup includes those DMUs where the VRS efficiency score is higher than that of the scale efficiency scores. This subgroup includes 34 DMUs in 2014-15, 36 DMUs in 2015-16, 43 DMUs in 2016-17, and 57 such DMUs in 2017-18. The second subgroup includes those DMUs where scale efficiency score is greater than VRS efficiency score. This subgroups include 32 DMUs in 2014-15, 33 DMUs in 2015-16, 25 DMUs in 2016-17, and 3 such DMUs in 2017-18. The DMUs in the first subgroup require not only improving its technical efficiency but also making their production scale optimum. The second subgroup requires DMUs to concentrate more on improving their technical efficiency.

5.1.2) Operator Wise Efficiency Estimates:

On the efficiency front, the table 4 shows that the central government-operated power plants performed better than those operated by the respective state governments. This is due to the fact that in each selected year of the study, the overall efficiency scores (CRS) of centrally owned power plants are higher than those of state-operated thermal power plants. Thus, ownership is one of the important factors in determining the efficiency of the DMUs. The efficiency of centrally operated thermal power plants points towards the availability of high-quality coal, improved technology, and better management of the plant at the microlevel.

Table 4: Operator Wise Efficiency Scores

Year	Operator	CRS	VRS	SCALE
2014-15	**Central**	0.638	0.829	0.754
	State	0.586	0.801	0.725
	Overall	0.602	0.810	0.734
2015-16	**Central**	0.641	0.833	0.758
	State	0.540	0.761	0.691
	Overall	0.571	0.783	0.712
2016-17	**Central**	0.659	0.855	0.750
	State	0.549	0.801	0.675
	Overall	0.583	0.818	0.698
2017-18	**Central**	0.722	0.936	0.767
	State	0.555	0.867	0.632
	Overall	0.606	0.888	0.674

Source: Author's Calculations

5.1.3) Region Wise Efficiency Estimate

The results in the table 5 shows the compilation of efficiency percentages for different regions and decision-making units (DMUs). The figures in parentheses represent the percentage of efficient DMUs in each category. The data is organized by region (Northern, Western, Southern, Eastern), and within each region, there are three categories: CRS (Constant Returns to Scale), VRS (Variable Returns to Scale), and SCALE. The efficiency percentages vary among the different regions and categories. The overall number of technically efficient DMUs under the CRS and scale model ranged from 1.33 per cent to 4 per cent per annum, while under the VRS model it was in the range of 8 per cent to 20 per cent during the period of study.

Table 5: Overall and Region Wise Number and Percentage of Efficient DMUs

Region	Technical efficiency	Number and Percentage of Efficient DMUs			
		2014-15	2015-16	2016-17	2017-18
Overall	CRS	2 (2.67)	3 (4)	0 (0)	1 (1.33)
	VRS	9 (12)	6 (8)	7 (9.33)	15 (20)
	SCALE	2 (2.67)	3 (4)	0 (0)	1 (1.33)
Northern	CRS	1(4.76)	1(4.76)	0(0)	0(0)
	VRS	2(9.52)	1(4.76)	1(4.76)	2(9.52)
	SCALE	1(4.76)	1(4.76)	0(0)	0(0)
Western	CRS	1(4.16)	0(0)	0(0)	1(4.16)
	VRS	3(12.5)	1(4.16)	3(12.5)	4(16.67)
	SCALE	1(4.16)	0(0)	0(0)	1(4.16)
Southern	CRS	0(0)	2(16.67)	0(0)	0(0)
	VRS	3(25)	3(25)	3(25)	3(25)
	SCALE	0(0)	2(16.67)	0(0)	0(0)
Eastern	CRS	0(0)	0(0)	0(0)	0(0)
	VRS	1(8.33)	1(8.33)	0(0)	5(41.67)
	SCALE	0(0)	0(0)	0(0)	0(0)

Note: Figures in the brackets show percentage of efficient DMUs.
Source: Author's Calculations

The analysis of regional performance reveals that there was a lack of consistent, efficient decision-making units (DMUs) across all regions for the whole study period. The northern region had 4.76 percent efficient DMUs for the years 2014–15 and 2015–16; however, for the rest of the two years, this percentage declined to zero. In a similar vein, the western region witnessed a 4.16 percent efficiency rate among its DMUs (Decision-Making Units) from 2014 to 2015 and 2017 to 2018. While none of the DMUs were efficient in the Eastern region during the entire period of study. This suggests that the Northern and Western regions had periods of efficiency followed by a decline, while the Eastern region consistently lacked efficient DMUs throughout the study.

Table 6: Overall and Region-wise Numbers of DMUs Above Mean Technical Efficiency

Region	Technical efficiency	Number of DMUs			
		2014-15	2015-16	2016-17	2017-18
Overall	CRS	35(.602)	41(.571)	34(.583)	38(.606)
	VRS	38(.810)	35(.783)	36(.818)	41(.888)
	SCALE	43(.734)	43(.712)	42(.698)	42(.674)
Northern	CRS	9(.597)	10(.522)	11(.523)	12(.526)
	VRS	11(.804)	9(.758)	10(.806)	11(.882)
	SCALE	9(.730)	10(.666)	11(.632)	11(.585)
Western	CRS	8(.586)	13(.551)	10(.536)	9(.632)
	VRS	12(.803)	11(.765)	10(.796)	11(.876)
	SCALE	14(.727)	15(.697)	14(.660)	12(.706)
Southern	CRS	7(.747)	5(.746)	7(.728)	6(.623)
	VRS	6(.894)	6(.894)	5(.861)	5(.868)
	SCALE	9(.841)	7(.838)	5(.845)	6(.720)
Eastern	CRS	10(.534)	9(.540)	11(.617)	11(.653)
	VRS	7(.770)	7(.762)	9(.831)	11(.926)
	SCALE	11(.675)	11(.702)	11(.727)	10(.704)

Note: Figures in the brackets show mean technical efficiency of DMUs.
Source: Author's Compilations

Table 6 shows the overall and region-wise mean technical efficiency and number of DMUs above their respective mean efficiency under the CRS, VRS and scale model. According to the aggregated data, out of 75 DMUs, 34 to 41 DMUs are operating at an above-average rate in terms of optimum efficiency. This indicates that a significant number of DMUs are excelling in their operations and achieving optimal efficiency levels. These high-performing DMUs can serve as benchmarks for the remaining units, providing insights and best practices to improve their own efficiency. It is crucial for the underperforming DMUs to analyze and learn from the strategies and techniques implemented by these top-performing units in order to enhance their own efficiency and productivity.

5.1.4) Individual Plant Wise Efficiency Estimates

Looking at efficiency scores of individual DMUs, it has been found that the average efficiency scale on the CRS assumption is found to be varied between 0.182 (GNDTPBHATINDA) and 0.982 (KORBA STPS). These scores indicate that there is a significant difference in the efficiency levels among the different DMUs. GNDTP BHATINDA seems to have the lowest efficiency score of 0.182, suggesting that there is room for improvement in their operations. On the other hand, KORBA STPS stands out with an efficiency score of 0.982, indicating that they are performing exceptionally well and are close to achieving optimal efficiency.

As far as pure efficiency is concerned, that is on VRS assumption; it has been observed that the thermal power plant, “R'GUNDEM-B”, is found to be at the top position with an average efficiency score of one. This indicates that this particular DMU is fully efficient in respect of managerial practices. However, in the same ladder, the lowest position is attained by KORBA (EAST) with average VRS efficiency score of 0.591. This signifies that the KORBA (EAST) thermal power plant is not operating at its full potential and there is room for improvement in terms of managerial practices. The significant difference in efficiency scores between the top and bottom performers highlights the need for the Korba (East) plant to identify and address the factors that are hindering its efficiency. By implementing effective managerial practices, the plant can strive towards achieving higher efficiency levels and improving its overall performance.

The average scale efficiency scores vary between 0.246 (GNDTP BHATINDA) and 0.993 (TALCHER STPS). GNDTP BHATINDA'S scale efficiency score suggests room for improvement and potential inefficiencies in its operations. On the other hand, TALCHER STPS displays exceptional efficiency, indicating it is running at near-optimal levels. These variations highlight the need for further analysis and investigation into the factors influencing these disparities.

5.2 Changes in Total Factor Productivity Estimates:

Table 7 highlights The Total Factor Productivity (TFP) exhibits variations in its constituent elements across diverse plant settings during the duration of the study. The research conducted in this study examined the phenomenon of declining total factor productivity growth, which was found to occur at an annual rate of 0.6 per cent. The primary factor contributing to the decline in total factor productivity (TFP) is technical change (TECHCH). Annually, the growth rate of TECHCH has decreased at a rate of -0.9 per cent. This decline in TECHCH suggests that there has been a slowdown in the rate at which new technologies are being adopted and implemented in the plant settings. This could be attributed to the poor management practices, which might be due to factors such as a lack of innovation, limited investment in research and development, or a shift in focus towards cost-cutting measures rather than technological advancements.

Table 7: Annual Geometric Mean of TFP & Its components

Year	EFFCH	TECHCH	PEFFCH	SEFFCH	TFPCH
2015-16	0.913	0.975	0.874	1.045	0.891
2016-17	1.041	1.000	1.009	1.032	1.041
2017-18	1.050	0.999	1.018	1.031	1.049
Mean	**1.001**	**0.991**	**0.967**	**1.036**	**0.994**

Source: Author's Calculations

As far as efficiency change is concerned, the primary factor that is contributing to heightened efficiency is scale efficiency. Nevertheless, the pure efficiency change, on average, exhibits a diminishing growth rate. The primary factor ascribed to this transformation is inadequate managerial practices. These practices include lack of monitoring, poor decision-making processes, and ineffective resource allocation. Without proper management, organizations struggle to identify and address inefficiencies, resulting in a slower rate of improvement over time. Therefore, it is crucial for each and every thermal generation plant to prioritize and invest in improving their managerial practices in order to achieve sustainable efficiency change.

5.2.1) Operator wise TFP change estimates:

The estimates for the total factor productivity in table 8 have also been observed at the disaggregated level as per the operations at the central as well as the state level. It has been observed that the central government-operated thermal power plants are more productive than that of the state-operated thermal power plants, except during 2016–17. During 2015–16 and 2017–18, the total factor productivity scores were not only lower than the central one but also experienced regressive productivity growth. This indicates that the central government-operated thermal power plant consistently outperforms its state-operated counterpart in terms of productivity. However, the year 2016-17 was an exception, as the state-operated plant managed to achieve a higher total factor productivity score. Nonetheless, the overall trend shows that the central government-operated plant maintains a higher level of productivity, while the state-operated plant struggles to maintain consistent growth in productivity.

Table 8: Operator Wise Productivity Scores

Year	Operator	EFFCH	TECHCH	PEFFCH	SEFFCH	TFPCH
2015-16	Central	1.040	0.992	1.095	0.990	1.034
	State	0.946	0.982	0.885	1.087	0.938
	Overall	0.913	0.975	0.874	1.045	0.891
2016-17	Central	1.061	1.000	1.025	1.056	1.059
	State	1.121	1.000	1.100	1.047	1.115
	Overall	1.041	1.000	1.009	1.032	1.041
2017-18	Central	1.249	0.999	1.256	1.012	1.236
	State	1.085	1.002	1.061	1.064	1.086
	Overall	1.050	0.999	1.018	1.031	1.049

Source: Author's Calculations

5.2.2) Region Wise TFP Change Estimates:

This study has also endeavoured to examine productivity performance at the interregional level. To achieve this objective, the DMUs are allocated over four distinct regions, namely the northern, western, southern, and eastern regions.

Table 9: Region Wise Productivity Scores

Year	Region	EFFCH	TECHCH	PEFFCH	SEFFCH	TFPCH
2015-16	Northern	0.857	0.983	0.811	1.066	0.846
	Western	0.947	0.968	0.915	1.073	0.934
	Southern	1.058	0.999	0.967	1.090	1.059
	Eastern	1.092	1.000	1.144	1.006	1.093
	Overall	0.913	0.975	0.874	1.045	0.891
2016-17	Northern	1.080	0.997	1.156	0.997	1.072
	Western	1.038	1.012	1.016	1.018	1.048
	Southern	1.106	0.992	0.932	1.170	1.083
	Eastern	1.212	0.995	1.162	1.073	1.203
	Overall	1.041	1.000	1.009	1.032	1.041
2017-18	Northern	1.015	1.000	1.005	1.005	1.016
	Western	1.333	1.024	1.279	1.078	1.347
	Southern	0.874	0.987	0.915	0.966	0.867
	Eastern	1.185	0.982	1.181	1.049	1.157
	Overall	1.050	0.999	1.018	1.031	1.049

Source: Author's Calculations

The results in Table 9 reveals that in the period of 2015-16, the northern and western areas had a decline in productivity growth, with rates of 15.4 percent and 6.6 percent, respectively. In contrast, the southern and western regions have annual production growth rates of 5.9 percent and 9.3 percent, respectively. Moreover, it is noteworthy that all the regions showed improvement throughout the period of 2016-17 and demonstrated positive increase in terms of production. However, the southern area exhibited the most unfavourable performance during the period of 2017-18, with thermal power plants experiencing a significant decline in productivity growth, amounting to a negative rate of 13.3 percent. Moreover, this region is lagging behind both in terms of efficiency change as well as technological change during this particular year. These factors suggest that there may be underlying issues within the southern area's energy infrastructure that need to be addressed. Additionally, the negative rate of productivity growth in thermal power plants could have detrimental effects on the region's overall energy supply and economic development. It is crucial for policymakers to focus on improving efficiency and implementing technological advancements in order to promote sustainable and reliable energy production in the southern area.

5.2.3) Individual Plant Wise TFP Estimates

On evaluating efficiency scores at the individual level, it has been found that the state-owned thermal power plant R'GUNDEM-B from the southern region was the outperformer during 2015-16 with the Malmquist productivity score of 2.065, which indicates that total factor productivity is growing at the rate of 106.5 per cent ($i.e\ (2.065 - 1) \times 100$), whereas during the same period the worst performer was found to be state-owned thermal power plant BHUSAWAL from the western region with a productivity score of 0.151, which indicates the productivity growth of -84.9 per cent.

Further, during 2016-17 it has been observed that KAKATIYA from the southern region has performed well with the highest productivity score of 2.516. However, this productivity growth is contributed to mainly by the efficiency change, as this particular DMU is facing technical regress of -8.4 per cent. This indicates that KAKATIYA has managed to improve its productivity by making its operations more efficient, despite facing a decline in technical progress. It is noteworthy that even with a negative technical change, KAKATIYA has still achieved the highest productivity score among all the DMUs in the southern region. This suggests that there is potential for further improvement if the technical regress is addressed and reversed. The lowest position during this period is attained by TENUGHAT with the negative productivity growth of 50.5 per cent.

Despite facing a technical regression of six per cent, the centrally owned thermal power plant MAUDA managed to secure the top position in 2017-18 with an impressive productivity score of 2.838. This achievement demonstrates the plant's ability to overcome challenges and maintain its efficiency, making it a role model for other power plants in the country. The management and workforce of MAUDA should be commended for their dedication and efforts in ensuring optimal performance despite the setback.

6. Conclusion

Thermal power plants have been reported to be running at an efficiency score of 0.591, which means that all Indian thermal power plants are only 59.1% efficient as a whole. Ineffective managerial techniques and scale inefficiencies are two variables that lead to the inefficiency of 40.9 percent. Scale inefficiencies were determined to be the main cause of the inefficiency of thermal power plants in the current analysis (Table 3). The scale inefficiencies are a result of the power plants not operating at their optimal capacity. Many power plants are operating below their rated capacity due to various technical and operational reasons. In addition, inadequate maintenance and outdated technology also contributes to the scale inefficiencies. Addressing these issues and improving the overall operational efficiency of thermal power plants can significantly increase their efficiency score and reduce the amount of energy wasted.

Moreover, the study revealed a decline in productivity growth within the broader context of thermal power plants, primarily attributed to a lack of technological advancements. This lack of technological advancements has hindered the ability of thermal power plants to increase their efficiency and reduce their environmental impact. Furthermore, the research revealed that the decrease in productivity growth was also impacted by a negative fall in pure efficiency change. This signifies the degree to which a firm's inputs can be proportionally lowered without affecting its position on the variable return to scale (VRS) frontier. This deficiency suggests that there may be a lack of effective management in thermal power plants, which is hindering their ability to implement advancements and increase efficiency. Without proper management and decision-making, it becomes challenging for these plants to adopt new technologies or processes that could improve overall productivity. Addressing this issue and improving management practices could be crucial in realizing the potential of advancements and achieving greater efficiency in thermal power plants.

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Appendix 1

Sr. No.	Name of TPS	Sec	Reg	Sr. No.	Name of TPS	Sec	Reg	Sr. No.	Name of TPS	Sec	Reg
1	BADARPUR	CE	NR	26	SATPURA	ST	WE	51	SIMHADRI	ST	SO
2	PANIPAT	ST	NR	27	AMAR KANTAK EXTN.	ST	WE	52	KAKATIYA	ST	SO
3	I.GANDHI STPP	CE	NR	28	SANJAY GANDHI	ST	WE	53	BELLARY	ST	SO
4	R.GANDHI	ST	NR	29	VICHAL STPS	ST	WE	54	RAICHUR	ST	SO
5	Y.NAGAR	ST	NR	30	SHRI SINGHAJI	ST	WE	55	TUTICORN	ST	SO
6	GNDTP (BHATINDA)	ST	NR	31	KORBA (EAST)	ST	WE	56	METTUR	ST	SO
7	GHTP(LEH. MOH.)	ST	NR	32	KORBA-III	ST	WE	57	N, CHENNAI	CE	SO
8	ROPAR	ST	NR	33	KORBA -WEST	CE	WE	58	TENUGHAT	CE	EA
9	KOTA	ST	NR	34	KORBA-STPS	ST	WE	59	KAHALGAON	CE	EA
10	SURATGARH	ST	NR	35	BHILAI	CE	WE	60	BARHI II	CE	EA
11	CHHABRA	ST	NR	36	SIPAT	CE	WE	61	CHANDRAPURA	CE	EA
12	OBRA	ST	NR	37	DSPM	ST	WE	62	KODARMA	CE	EA
13	PANKI	ST	NR	38	NASIK	ST	WE	63	DURGAPUR	CE	EA
14	H'GANJB	ST	NR	39	KORADI	ST	WE	64	BOKARO B	CE	EA
15	PARICHA	ST	NR	40	K'KGEDA II	ST	WE	65	MEJIA	CE	EA
16	ANPARA	CE	NR	41	PARAS	ST	WE	66	TALCHER	CE	EA
17	SINGRAULI	CE	NR	42	BHUSAWAL	ST	WE	67	TALCHER STPS	ST	EA
18	RIHAND	CE	NR	43	PARLI	ST	WE	68	I.B. VALLEY	ST	EA
19	UNCHAHAR	CE	NR	44	CHANDRAPUR	ST	WE	69	BANDEL	ST	EA
20	DADRI(NCTPP)	CE	NR	45	MAUDA	CE	WE	70	SATNTALDIH	ST	EA
21	TANDA	ST	NR	46	K'GUDEM	ST	SO	71	KOLAGHAT	ST	EA
22	UKAI	ST	WE	47	VIJAYWADA	ST	SO	72	BAKRESWAR	ST	EA
23	GANDHI NAGAR	ST	WE	48	R'GUNDEM-B	ST	SO	73	DPL	ST	EA
24	WANAKBORI	ST	WE	49	RAYAL SEEMA	ST	SO	74	SAGARDIGHI	ST	EA
25	SIKKA REP.	ST	WE	50	R'GUND.STPS	CE	SO	75	FARAKKA STPS	CE	EA

Notes: CE=Centally operated, ST= State operated, NR= Northern Region, SO= Southern Region, WE= Western Region and EA= Eastern Region

Source: Author's Compilations