Evaluating Efficiency and Productivity Trends of Indian Electricity Distribution Utilities: DEA-Malmquist Analysis

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Abstract—**This study evaluates the Technical Efficiency (TE) and Total Factor Productivity (TFP) of 54 Indian Electricity Distribution Utilities (IEDUs) from 2020 to 2023 using Data Envelopment Analysis (DEA) and the Malmquist Productivity Index (MPI). The Charnes-Cooper-Rhodes (CCR) model revealed that only 35.18% of DMUs (19 out of 54) were technically efficient, with average efficiency improving marginally from 0.84 to 0.88. Slack-based inefficiencies resulted in an estimated input overutilization of Rs. 63,270.12 crore, highlighting significant operational inefficiencies. Further examined the Total Productivity (TFP) of IEDUs, revealing a 2.5% improvement in operational efficiency (efficiency change = 1.025), driven by gains in pure efficiency (1.036). Although a 7.6% decline in Technological Change (TECHCH = 0.924), due to outdated infrastructure and regulatory delays, offset these gains. Persistent Aggregate Technical & Commercial (AT&C) losses averaged 17.71%, leading to a 5.3% decrease in TFP. Efficient Decision-Making Units (DMUs) incurred lower costs per million units sold (Rs. 0.776 crores) than inefficient units (Rs. 0.924 crores), underscoring the importance of operational optimization. This study employs a DEA–Malmquist framework on 54 IEDUs during 2020–2023 a reform-critical period encompassing post-UDAY, RDSS, and COVID-19 to quantify inefficiency costs, benchmark peer utilities, and provide strategic direction for enhancing operational performance, financial sustainability, and sector-wide reforms.**

Index Terms—**Aggregate Technical & Commercial (AT&C) losses, Charnes-Cooper-Rhodes (CCR) model, Data Envelopment Analysis (DEA), electricity distribution utilities, Malmquist DEA, Total Factor Productivity (TFP)**

NOMENCLATURE

DMU No.	Full name of utility
1 _NBPDCL	North Bihar Power Distribution Company Limited
2 _SBPDCL	South Bihar Power Distribution Company Limited
3 _JBVNL	Jharkhand Bijli Vitran Nigam Limited
4 _CESU	Central Electricity Supply Utility of Odisha
5_ NESCO	Northeastern Electricity Supply Company of Odisha Limited
6 _SOUTHCO	Southern Electricity Supply Company of Odisha Limited
7 _WESCO	Western Electricity Supply Company of Odisha Limited
8 _WBSEDCL	West Bengal State Electricity Distribution Company Limited
9 _Sikkim PD	Sikkim Power Department
10 _APDCL	Assam Power Distribution Company Limited
11 _MSPDCL	Manipur State Power Distribution Company Limited
12 _TSECL	Tripura State Electricity Corporation Limited
13 _Arunachal PD	Arunachal Pradesh Power Department
14 _Mizoram PD	Mizoram Power Department
15_Nagaland PD	Nagaland Power Department
16 _BRPL	BSES Rajdhani Power Limited (Delhi)
17 _BYPL	BSES Yamuna Power Limited (Delhi)
18 _TPDDL	Tata Power Delhi Distribution Limited
19 _DHBVNL	Dakshin Haryana Bijli Vitran Nigam Limited
20 _UHBVNL	Uttar Haryana Bijli Vitran Nigam Limited
21 _AVVNL	Ajmer Vidyut Vitran Nigam Limited (Rajasthan)
22 _JdVVNL	Jodhpur Vidyut Vitran Nigam Limited (Rajasthan)
23 _JVVNL	Jaipur Vidyut Vitran Nigam Limited (Rajasthan)
24 _DVVNL	Dakshinanchal Vidyut Vitran Nigam Limited (Uttar Pradesh)
25 _KESCO	Kanpur Electricity Supply Company Limited
26 _MVVNL	Madhyanchal Vidyut Vitran Nigam Limited (Uttar Pradesh)
27 _PaVVNL	Paschimanchal Vidyut Vitran Nigam Limited (Uttar Pradesh)
28 _PuVVNL	Purvanchal Vidyut Vitran Nigam Limited (Uttar Pradesh)
29 _UPCL	Uttarakhand Power Corporation Limited
30 _HPSEBL	Himachal Pradesh State Electricity Board Limited
31 _PSPCL	Punjab State Power Corporation Limited
32_ APCPDCL	Andhra Pradesh Central Power Distribution Company Limited
33_APEPDCL	Andhra Pradesh Eastern Power Distribution Company Limited
34_APSPDCL	Andhra Pradesh Southern Power Distribution Company Limited
35_BESCOM	Bangalore Electricity Supply Company Limited
36_CHESCOM	Chamundeshwari Electricity Supply Corporation Limited
37_GESCOM	Gulbarga Electricity Supply Company Limited
38_HESCOM	Hubli Electricity Supply Company Limited
39_MESCOM	Mangalore Electricity Supply Company Limited
40_TSNPDCL	Telangana Northern Power Distribution Company Limited
41_TSSPDCL	Telangana Southern Power Distribution Company Limited
42_KSEBL	Kerala State Electricity Board Limited
43_TANGEDCO	Tamil Nadu Generation and Distribution Corporation
44_Puducherry PD	Puducherry Electricity Department
45 _CSPDCL	Chhattisgarh State Power Distribution Company Limited
46_DGVCL	Dakshin Gujarat Vij Company Limited

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47_MGVCL	Madhya Gujarat Vij Company Limited
48_PGVCL	Paschim Gujarat Vij Company Limited
49_UGVCL	Uttar Gujarat Vij Company Limited
50_MPMaKVVCL	Madhya Pradesh Madhya Kshetra Vidyut Vitaran Company Limited
51_MPPaKVVCL	Madhya Pradesh Paschim Kshetra Vidyut Vitaran Company Limited
52_MPPoKVVCL	Madhya Pradesh Poorva Kshetra Vidyut Vitaran Company Limited
53_MSEDCL	Maharashtra State Electricity Distribution Company Limited
54_Goa PD	Goa Power Department

I. Introduction

India's electricity sector is undergoing a rapid and multifaceted transformation in last three decades, driven by its robust economic, population growth, international climate commitments and critical national priorities, including universal energy access, and enhanced energy security [1, 2]. The efficiency and productivity of the electricity sector are critical determinants of a nation's economic vitality, directly influencing industrial output and supporting the sustainable growth of all economic sectors [3–5]. Sustainable, affordable, reliable, and high-quality electricity is essential for advancing technological innovation, driving industrial expansion, and promoting inclusive economic growth in India [6, 7]. In the past decade, India's electricity generation mix has undergone a notable transformation, with renewable energy sources becoming increasingly prominent in the sector [5, 8–10]. India is among the most rapidly expanding economies and targets upper middle-income status by 2047 [11].

India's electricity sector is fundamental to sustaining rapid economic growth and achieving the Viksit Bharat 2047 (developed India 2047) vision, with projected aggregate demand of 708 GW highlighting critical distribution efficiency imperatives. The sector's resilience is demonstrated by the successful management of a 250 GW peak load in 2024, while a 45.8% increase in per capita electricity consumption over the past decade, reaching 1,395 kWh, indicates substantial generation capacity expansion [12]. Indian electricity sector has witnessed exponential increase during the last three decades, led by strategic reforms and policy initiatives [13–16]. This has resulted in a significant addition in established generating capacity, rising from 1,362 MW in 1947 to approximately 476 GW by June 2025. This rapid economic expansion, positioning India as the world's 3rd biggest economy by 2030, is consistent with the nation's bold target of securing 500 GW of non-conventional energy by the same year. As of 2025, India's power sector serves a second largest consumer base of 275.44 million, reflecting its critical role in supporting the world's fourth-largest economy [17, 18]. Achieving this goal necessitates a resilient electricity sector value chain, wherein distribution utilities play a pivotal role in procuring electricity from generators, facilitating its transmission, and supplying diverse consumer segments—domestic, agricultural, commercial, and industrial—each subject to distinct tariff structures based on consumption patterns [17, 19, 20].

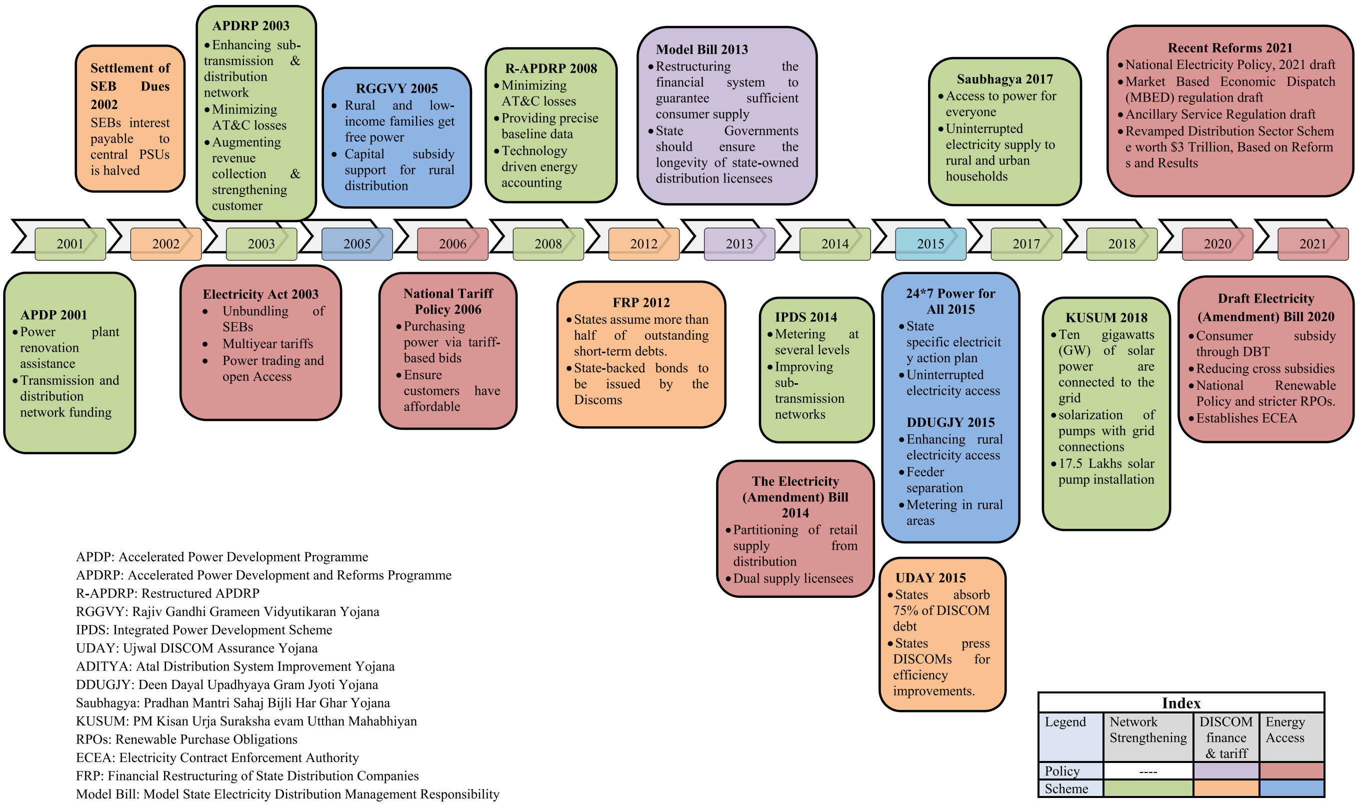

Fig. 1. Power sector policy and reform trajectory in India (2001–2021) [4].

The major evolution of Indian electricity industry reforms led to a significant transformation since the early 2000s, driven by a series of legislations, laws, acts policy interventions which is shown Fig. 1 [4, 14, 21, 22]. The key initiatives include the Accelerated Power Development Program (APDP-2001), aimed at boosting generation capacity, and the landmark Electricity Act of 2003, which established competition and facilitated private sector participation [13, 21]. A potential focus on rural electrification emerged with programs like RGGVY-2005 (Rajiv Gandhi Grameen Vidyutikaran Yojana) and DDUGJY-2015 (Deendayal Upadhyaya Gram Jyoti Yojana). Recognizing the financial distress of IEDUs (Indian Electricity Distribution Utilities), the UDAY-2015 (Ujwal DISCOM Assurance Yojana-2025) initiative was launched to address debt burdens and improve operational efficiency. Focus has shifted towards renewable energy integration with initiatives like Sahaj Bijli Har Ghar Yojana (Saubhagya), Pradhan Mantri Kisan Urja Suraksha evam Utthan Mahabhiyan (PM-KUSUM) and Revamped Distribution Sector Scheme (RDSS) is to improve operational efficiencies and financial sustainability by reducing AT&C losses and ACS-ARR gap during 2017, 2018 and 2021 respectively [5].

During FY 2023–24, With a total generation of 1,949 terawatt-hours (TWh), India has risen to the standing among the top three global power producers. The rising electricity consumption dependency can further escalate as the transport industry transitions to electric vehicles, replacing internal combustion engines [17].

This has led to electricity restructuring measures and policy interventions in last two decades energy shortages plummeted from 4.2% in FY 2013–14 to mere 0.1% in FY 2024–25 and India is no longer a power-deficit country [23], which is shown in Fig. 2.

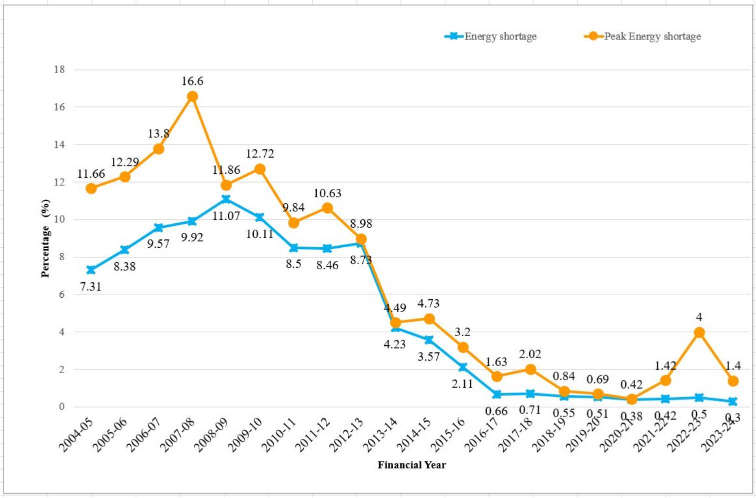

Fig. 2. All India power supply position during 2004-2024.

Fig. 3 shows that India's per capita electricity consumption has risen steadily from 348 kWh in 1991–92 to 1,395 kWh in 2023–24, yet it remains significantly lower than that of major economies [4]. This growth trajectory was temporarily disrupted during the COVID-19 lockdown period [24].

The nation's power infrastructure has undergone major modernization and expansion to support rising energy demand [5, 14, 17]. The distribution sector is the weakest and most vulnerable segment of the overall electricity sector [1, 4, 25]. Ensuring the financial sustainability of distribution utilities is crucial to the Indian power sector's overall performance, as they are key revenue generators [4, 26–28].

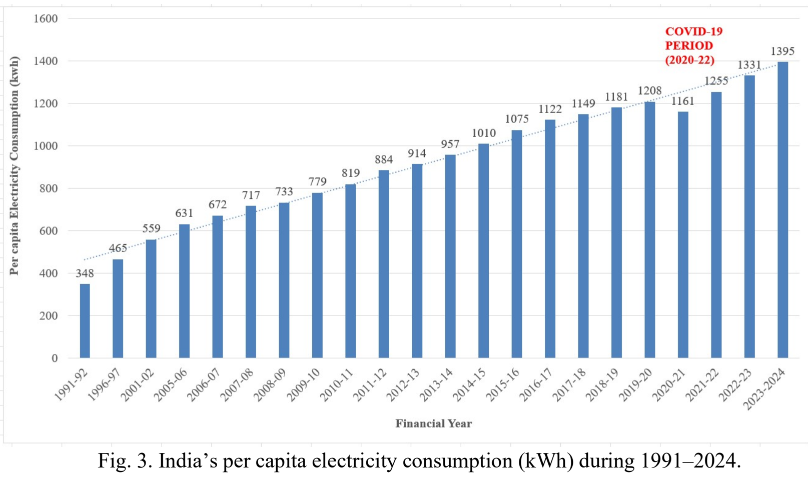

Fig. 3. India's per capita electricity consumption (kWh) during 1991–2024.

Despite of thirty years of reforms, the Indian electricity supply industry continues to grapple with substantial

Transmission and Distribution (T&D) losses [25]. As depicted in Fig. 4, a considerable disparity in T&D losses persists across various countries, with India and Brazil reporting the highest figures, both exceeding 20%. India's and Brazil's T&D losses of 20.46% and 20.56% significantly exceed the world average of 8.81%, indicating substantial inefficiencies in its power delivery system.

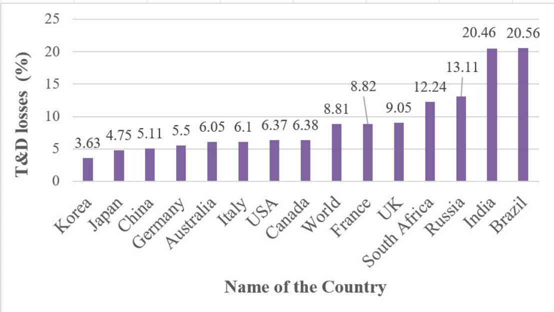

Fig. 4. Transmission and Distribution (T&D) losses across selected countries (%).

In contrast, nations like South Korea, Japan, China, Germany, Australia, Italy, and the USA exhibit significantly lower T&D losses, typically below 8.81%, the world average. This disparity highlights the impact of infrastructure investment, technological advancements, and regulatory frameworks on minimizing energy loss during transmission and distribution. The world average T&D loss of 8.81% provides a benchmark against which individual country's performance can be assessed. The wide disparity in losses, with a world average of 8.81%, underscores the considerable potential for strengthening grid efficiency and lowering energy losses in numerous countries, including India, Brazil, South Africa, the UK, and France [29].

According to Grid controller of India [Grid-India, 2025], all-India transmission losses constitute only 3% to 4% of total T&D losses, with the majority occurring within the distribution sector [30]. IEDUs faces multiple challenges that threaten national economic growth, energy security, and the transition to a sustainable power system [1, 28, 31]. The Indian power sector identifies AT&C losses and the Average Cost of Supply–Average Revenue Realized (ACS-ARR) gap as critical Key Performance Indicators (KPIs) for distribution utilities [1, 28, 32–34]. These metrics are detailed comprehensively in Table I.

These KPIs directly impact cash flow and financial health, potentially necessitating higher electricity prices. These include persistent mismanagement of the IEDUs due to high power procurement costs, excessive manpower expenditures, delayed subsidy disbursements, government arrears, poor revenue collection, tariff order delays, and non-cost reflective. A pressing issue is the high AT&C losses (24.53%) from 2015–16 to 2023–24 (19.42%) which is presented in Table I [18]. These losses significantly surpass the global benchmark of 6% to 8% and harm the financial performance of IEDUs [29].

The IEDUs have failed to meet key operational targets outlined in power sector initiative UDAY Memorandums of Understanding (MoU), such as mandatory metering, Covid-19 demand reduction, smart meter implementation, consumer indexing, GIS mapping, and transformer or meter upgrades. This noncompliance has resulted in consistently high AT&C losses and an increasing ACS-ARR gap, gross debts thereby limiting operational efficiency and self-sufficiency [32].

TABLE I: THE AT & C LOSSES TREND IN INDIA (%) AND ACS-ARR GAP FROM 2013–14 TO 2020–21

Year	AT&C Losses (%)	ACS-ARR Gap (Rs/kWh)
2015–16	24.53	0.65
2016–17	23.53	0.62
2017–18	20.76	0.58
2018–19	21.02	0.83
2019–20	21.25	0.73
2020–21	21.99	1.05
2021–22	18.28	1
2022–23	17.47	1.23
2023–24	19.42	0.97

The ACS-ARR gap refers to the financial shortfall in India's electricity supply industry, where the cost of power supply exceeds the revenue collected from consumers. Fig. 5 shows that there is a continuous increase in ACS-ARR gap from Rs. 0.65/kWh in FY2015-16 to Rs. 0.97/kWh in FY2022-23 though there is reduction of AT&C losses from 24.53 % in FY 2015-16 to 19.42 % in FY 2023-24. During this decade IEDUs outstanding debts increased from Rs.4,21,978 crores to Rs.7,52,677 crores from FY 2015-16 to FY2023-24 [35]. The ACS-ARR gap widens due to rising power costs, excessive manpower expenses, delayed subsidies &government payments, poor revenue collection, tariff order delays, and non-cost-reflective tariffs. These factors constrain ARR growth while ACS increases, threatening financial viability.

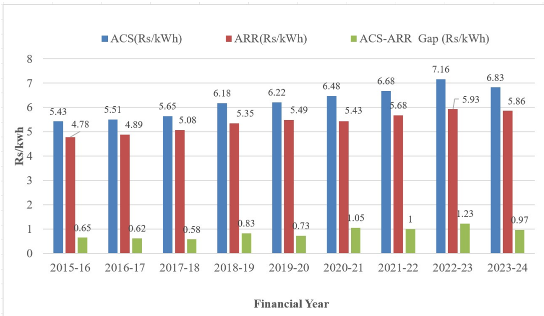

Fig. 5. The ACS-ARR gap [26].

Despite government interventions and capital infusion, distribution losses remain unacceptably high even after two decades of reform. Precisely identifying the underlying drivers is crucial for optimizing operational and financial efficiency at this pivotal stage [1, 31].A systematic evaluation of TE and Total Factor Productivity (TFP) of IEDUs is essential to (i) enhance operational efficiency, (ii) ensure reform effectiveness, (iii) secure long-term sector sustainability, and (iv) provide regulators and utility managers with evidence-based guidance for reform design, performance benchmarking, and implementation of incentive or penalty mechanisms based on relative efficiency and productivity.

International research has examined the benchmarking and efficiency analysis of India's electricity supply industry using parametric, non-parametric, and advanced approaches, with recent studies integrating machine learning into Data Envelopment Analysis (DEA) frameworks.

1) Dong *et al*. [36] applied Machine Learning-enhanced DEA to assess the performance scores of distributors in China using data from 1993 to 2021.
2) Omrani *et al*. [37] evaluated efficiency across Iran's 39 power utilities using parametric, non-parametric, and ML techniques for the period of 2011–220.
3) Ikram *et al*. [38] evaluated 11 distribution firms from Pakistan for period from 2016 – 2020 using a two-stage DEA.

Numerous studies have evaluated the efficiency of IEDUs using parametric and non-parametric methods. A comprehensive literature review reveals several key contributions:

1) Thakur *et al*. [39] assessed 26 integrated utilities using DEA.
2) Yadav *et al*. [40] analyzed 29 distribution circles in Uttarakhand [40].
3) Meher and Sahoo [41] analyzed 40 DISCOMs from 17 states for FY 2012–13.
4) Ghosh *et al*. [13] assessed 28 states for FY 2012–13.
5) Bishnoi and Guar [42] analyzed 55 DMUs for FY 2014–2015.
6) Bodbe and Tanaka [43] assessed impact of power sector reforms in IEDUs for FY 1995–2012.
7) Sarangi *et al*. [1] examined 45 DISCOMs across 21 states for FY 2018–19.
8) Ramaiah *et al*. [26] investigated regional disparities and reform impacts across 55 utilities (2018–2019).
9) Patyal *et al*. [4] applied an integrated DEA-IRP-TOPSIS model to 48 DISCOMs from 24 states (2015–2019).
10) Sufia, Singh, and Mishra [22] used a three-stage DEA with Malmquist Index and SFA to assess 19 DISCOMs, highlighting efficiency improvements post service quality adjustments.

Despite these contributions, the limited research exists on evaluation of the performance of 54 IEDUs following the implementation of series power sector reforms and initiatives. Consequently, there is a pressing need to investigate both efficiency levels and productivity trends across these DMUs, as well as within India's national and regional grids, utilizing data from the 2020–2023 period. This research applies an extensive efficiency evaluation of 54 IEDUs during the critical reform period of 2020–2023. This period was characterized by post-UDAY initiatives, the Revamped Distribution Sector initiative (RDSS), and the unprecedented disruptions caused by the COVID-19 pandemic. This research applies CCR-DEA and Malmquist TFP analyses, the research benchmarks utility efficiency, quantifies slack-based inefficiencies and decomposes productivity drivers underlying the ACS–ARR gap to address critical gaps of 54 IEDU operating within India's national and regional power grids. The findings offer strategic directions for policymakers, regulators, and financial institutions, thereby supporting ongoing distribution sector reforms and advancing long-term sustainability. To address this gap, our study evaluates the efficiency and productivity of 54 IEDUs from 2020 to 2023 using CCR-DEA and Malmquist TFP analyses.

This research pursues the following objectives:

1) To assess the TE of 54 IEDUs for FY 2020–2023 using the CCR model in DEA across India's national and regional grids.
2) To analyze Malmquist TFP of 54 IEDUs for FY 2020–2023 using the MPI by decomposing it into Scale Efficiency Change (SECH), Pure Efficiency Change (PECH), Overall Efficiency Change (EFFCH), and Technological Change (TECHCH) across India.

By employing CCR-DEA and Malmquist TFP, this research provides a systematic evaluation of efficiency and productivity trends, identifies inefficiencies, and highlights actionable areas for improvement. The manuscript is structured as follows: Section II covers DEA methodologies, including the CCR and Malmquist TFP; Section III describes the variables and datasets used; Section IV Provides an analysis and interpretation on the performance of IEDUs using CCR, and Malmquist-based TFP frameworks; and Section V concludes with key findings and policy recommendations for Artificial Intelligence (AI)-driven strategies for financially distressed and debt-burdened IEDUs towards Viksit Bharat 2047. This research presents a substantial i toward improving the performance and long-term sustainability of IEDUs, providing key strategic directions for policymakers, regulators, and utility managers.

II. DEA Methodologies

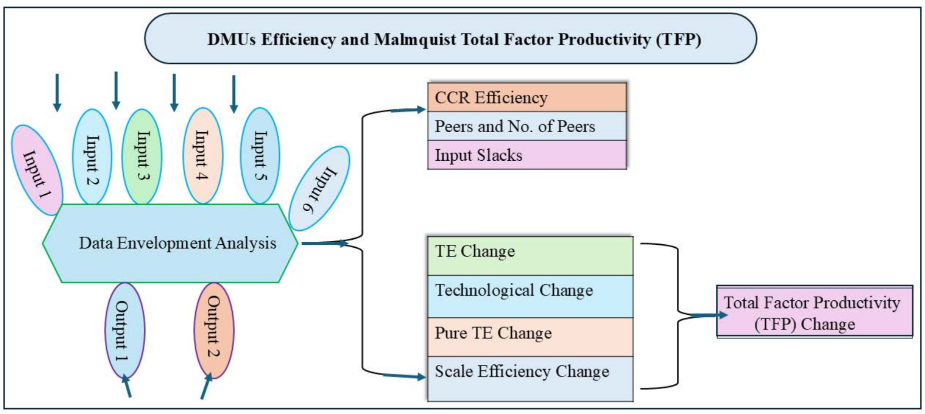

Fig. 6. The block diagram of research methodology using DEA.

DEA is a non-parametric linear programming methodology for evaluating the relative efficiency of homogenous DMUs. This method is extensively employed by mathematicians and data analysts to evaluate the operational performance of multiple utilities and plays a pivotal role in benchmarking their efficiency [44, 45]. DEA Serves as a cornerstone for comparative analysis, and it enables the identification of effective practices and opportunities for enhancement among utilities. The research methodology is represented in Fig. 6, outlining the framework for this analytical process. The fundamental efficiency of a DMU is determined by the ratio of the weighted sum of outputs to the weighted sum of inputs [26]. As part of improvements and developments, recently a ML enhanced DEA has been developed to benchmark IEDUs performance using multi-objective variable selection [36, 37]. In this research, the CCR model is utilized to assess efficiency, providing a comprehensive framework for performance assessment and Malmquist TFP index extends this by measuring productivity changes over time, revealing efficiency trends and technological advancements [40].

A. CCR Model

This CCR model integrates technical and scale efficiencies into a single composite measure, referred to as Overall Efficiency (OE), which is computed for each entity analyzed in DEA. The underlying principle of the CCR model involves evaluating the OE by consolidating both dimensions of efficiency into one metric. Below, the primal formulation of the CCR model is described [42].

Let the DMU be represented by the letter j. Let $x_{i,j}$ and $y_{i,j}$ be the values of the ith input and output on the DMU j. Let the weights assigned by the ith input and output be v_i and u_i, respectively.

The fractional programming problem (FPP) is given by:

$$\text{Maximize } R = \frac{u_1 y_{1k} + u_2 y_{2k} + \cdots}{v_1 x_{1k} + v_2 x_{2k} + \cdots}, k = 1,2, \cdots n \quad (1)$$

The above equation is subjected to the following constraint:

$$\frac{u_1 y_{1j} + u_2 y_{2j} \cdots}{v_1 x_{1j} + v_2 x_{2j} \cdots} \leq 1, \ j = 1,2, \cdots n \quad (2)$$

For every DMU, it is to be taken care that the input must not exceed the output. The major objective of this method is to maximize the DMUs with R being close to one. This method can be replaced with Linear Programming Problem (LPP) which is given by:

$$\text{Maximize } R(u, v) = u_1 y_{1k} + u_2 y_{2k} + \cdots, + u_s y_{s,k}$$
$$\text{Subjected to } v_1 x_{1j} + v_2 x_{2j} + \cdots v_m x_{m,j} = 1 \quad (3)$$

The ration scale is evaluated by using the primal problem where the primal becomes

$$\text{Maximize } R^*(v^*, u^*) = \frac{\sum_{r=1}^{s} u_r^* y_{r,k}}{\sum_{i=1}^{m} v_i^* x_{i,j}} \quad (4)$$

The LPP offers the optimal value of R^*, which is less than 1, where efficiency scores are called technical efficiency or CCR efficiency.

B. Malmquist TFP Index Analysis

The Malmquist TFP index measures the productivity change and decomposes this change into technical change and technical EFFCH [46]. DEA- MPI is defined as the product of EFFCH (catch-up) and TECHCH (frontier-shift). The EFFCH reflects to what extent a DMU improves or worsens its efficiency, while TECHCH reflects the change of the efficiency frontiers between two periods. In practice, this DEA-MPI has proven to be an excellent tool for measuring the productivity change of DMUs over time and has been successfully applied in many fields [47]. The input-based MPI can be formulated.

$$M_i^{t+1}(x^t, y^t, x^{t+1}, y^{t+1}) = \sqrt{\left[\frac{D_i^t(x^{t+1}, y^{t+1})}{D_i^t(x^t, y^t)} \times \frac{D_i^{t+1}(x^{t+1}, y^{t+1})}{D_i^{t+1}(x^t, y^t)}\right]} \quad (5)$$

where D_i^t is the input distance function and M_i^{t+1} $(x^t, y^t, x^{t+1}, y^{t+1})$ is the productivity of a most recent production unit, that is, $B(t+1)$, using period $t+1$ technology relative to the earlier production unit, that is, B (t), with respect to t technology. An equivalent way of writing this index by Fare *et al*. (1994) is M = TECHCH × EFFCH.

$$\text{EFFCH} = \frac{D_i^{t+1}(x^{t+1}, y^{t+1})}{D_i^t(x^t, y^t)} \quad (6)$$

$$\text{TECHCH} = \sqrt{\left[\frac{D_i^t(x^{t+1}, y^{t+1})}{D_i^{t+1}(x^{t+1}, y^{t+1})} \times \frac{D_i^t(x^t, y^t)}{D_i^{t+1}(x^t, y^t)}\right]} \quad (7)$$

A critical research gap exists due to the lack of comprehensive longitudinal studies evaluating the productivity changes of electricity distribution utilities in India over the past decade, despite these utilities being responsible for most of the electricity supply in the country. Thus, DEA estimates efficiency scores and MPI is used to decompose and analyze the trend of TFP growth into various components such as TECHCH, pure EFFCH and SECH [48, 49].

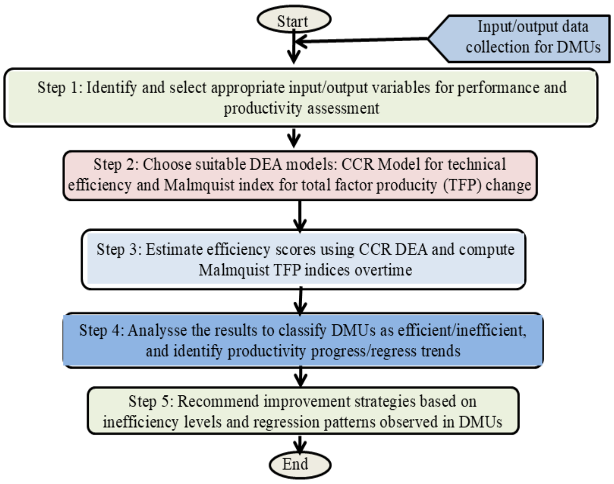

Fig. 7. Performance evaluation flow diagram.

Fig. 7 illustrates the research framework adopted to evaluate the efficiency and TFP of IEDUs using the DEA–Malmquist approach. The methodology involves systematic input–output data collection, application of the CCR DEA model, and computation of the MPI. It further includes the classification of efficiency levels and identification of progress or regress trends over time. This comprehensive framework provides a data-driven basis for formulating policy and strategic interventions aimed at improving utility performance.

III. Choosing Variables and Data

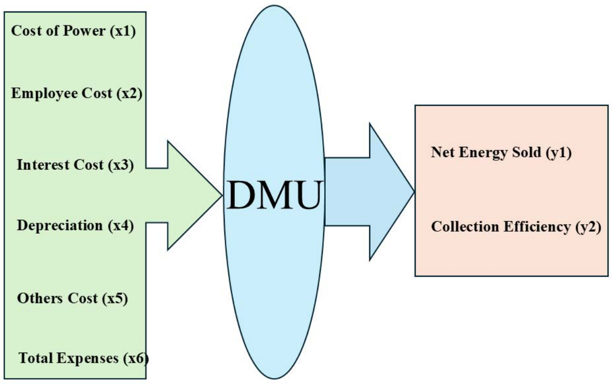

Fig. 8. Inputs and outputs considered in this work.

DEA requires careful selection of multiple input and multiple output variables at the outset of the study as it affects robustness a mathematical model used for efficiency measurement [50]. To ensure an accurate model, the number of DMUs should be at least three times the number of identified variables [51], a condition that can be satisfied through appropriate variable selection. The variables that impact the performance of DMUs are designated as inputs, whereas the gains obtained from their functioning are considered outputs [52]. The model explored in this research work, featuring 6 inputs and 2 outputs, is illustrated in Fig. 8. The arrow directed from the left towards the DMU represents inputs in crores of rupees. Conversely, the arrow directing from the right from the DMUs represents output: energy sold in millions of units (MU) and collection efficiency in percentages, respectively.

A. DEA-Input-Oriented Constant Returns to Scale (CRS)

Efficiency can be computed using alternatively an input-oriented or output-oriented approach. In this research, the input-oriented method was implemented to calculate the efficiency scores of 54 DMUs over the three-year period from 2020 to 2023 [35]. This Input-oriented CCR model under DEA with CRS assumption was chosen because Indian Electricity Distribution Utilities (IEDUs) have greater managerial control over input variables such as cost of power, operational expenses, interest costs, and depreciation. In contrast, output variables like energy sold are largely demand-driven and externally influenced. Hence, input orientation offers a more realistic benchmarking framework by focusing on minimizing controllable resources without reducing their output. Data was collected for these 54 DMUs, which are distributed across 28 states in India and operate under various management structures, including state-, private, joint ventures. All utilities, whether bundled or unbundled, operate under the common directives of the Electricity Regulatory Commissions and Central Electricity Authority under common input output framework. The physical data for the IEDUs were sourced from the Power Finance Corporation (PFC) Report (2020–2023). The Statistical data, along with the correlation between input and output variables for 2022–2023, are presented in Table II and Table III, respectively. Statistical analysis serves as a critical tool for examining relationships between inputs and outputs, with metrics such as mean, sum, standard deviation, minimum, maximum, and range used for evaluation. From Table III, it is apparent that the dataset exhibits significant variability in both input and output variables across the IEDUs, which is expected to yield precise and reliable findings Furthermore, Table III highlights the correlation between input and output variables, a crucial factor in ensuring the validity of the findings obtained from the DEA models,

TABLE II: STATISTICS OF IEDUS FOR 2022–23

Variables	Mean	Sum	Std Deviation	Minimum	Maximum	Range
Cost of Power(x1)	14006.96	756376	15141.91	180	89993	8981
Employee Cost(x2)	1352.04	73010	1898.19	96	10957	10861
Interest Cost(x3)	1262.75	68188.3	2398.14	0.1	13451	13450.9
Depreciation(x4)	647.91	34987.1	745.24	0.1	3850	3849.9
Other Costs(x5)	899.28	48561	1457.82	2	6549	6547
Total Expenses(x6)	18231.37	984494	20713.11	444	122912	122468
Net Energy Sold in MU(y1)	20502.93	1107158	21522.8	434	125466	125032
Collection Efficiency in %(y2)	96.54	521.33	4.68	833.2	100	16.18

TABLE III: CORRELATION BETWEEN INPUT AND OUTPUT VARIABLES FOR 2022–2023

Variables	Cost of Power(x1)	Employee Cost(x2)	Interest Cost(x3)	Depreciation (x4)	Other Costs(x5)	Total Expenses(x6)	Net Energy Sold(y1)	Collection Efficiency(y2)
Cost of Power(x1)	1.000							
Employee Cost(x2)	0.767	1.000						
Interest Cost(x3)	0.866	0.805	1.000					
Depreciation(x4)	0.892	0.823	0.919	1.000				
Other Costs(x5)	0.528	0.237	0.529	0.556	1.000			
Total Expenses(x6)	0.992	0.803	0.911	0.927	0.576	1.000		
Net Energy Sold(y1)	0.992	0.795	0.856	0.898	0.535	0.988	1.000	
Collection Efficiency(y2)	−0.137	0.011	−0.158	−0.071	−0.354	−0.156	−0.099	1.000

IV. Key Results and Discussions

A comprehensive performance evaluation of IEDUs was conducted using six inputs and two outputs, as outlined in Fig. 8. The analysis was performed under CRS, with an input-oriented approach. In this study, the CRS assumption was adopted in the input-oriented DEA model to assess overall TE by considering scale effects. Since all IEDUs operate under uniform regulatory and policy frameworks, proportional input–output scaling is appropriate for national-level benchmarking. CRS also provides a consistent and interpretable measure of total efficiency across utilities of varying size, ownership, and geography.

The findings are summarized in Table IV. Technical efficiency and slack analysis were assessed using the CCR model. The study computed several key metrics, including TE, the frequency of use as a peer or reference group by inefficient DMUs in the CCR model, and the average TE computed from the CCR model. The study further analyzed the trends in EFFCH, TECHCH, PECH, SECH, and changes in TFP using Malmquist index analysis during 2020–2021 to 2022–2023 across the 54 DMUs in 28 states of India. The subsequent sections provide a detailed discussion of these results.

TABLE IV: CCR EFFICIENCY ANALYSIS OF IEDUS FOR 2020–2021, 2021–2022, 2022–2023

Year/DMU	2020–2021	2021–2022	2022–2023			
	CCR/TE Score	CCR/TE Score	CCR/TE Score	Benchmarks/Peers	Number of Peers	Input Slack Total Expenditure (Rs.in crores) based on CCR Model
DMUs (09)-Eastern Region Grid (ERG)						
1 NBPDCL	0.6862	0.6388	0.7019	7,25,44,49	4	856.83
2 SBPDCL	0.6508	0.8363	0.6379	7,44,49,54	4	707.22
3 JBVNL	0.7106	0.9428	0.6828	7,44,49,54	4	1232.37
4 CESU	1	0.944	1	--	--	0
5 NESCO	1	1	1	---	---	0
6 SOUTHCO	1	1	1	---	--	0
7 WESCO	0.9859	0.7805	1	---	---	0
8 WBSEDCL	0.6404	1	0.8118	7,49,54	3	1851.03
9 Sikkim PD	1	0.7685	1	--	---	0
ERG DMUs average TE (CRS) score of 0.85 for 2020–2021 & 0.87 for 2021–2022 DMUs less than National average: 04 for 2020–2021(0.84) & 04 for 2021–2022(0.89)			ERG DMUs average TE (CRS) score of 0.87 for 2022–2023 DMUs less than National average: 04 for 2022–2023(0.88)			
DMUs (06)-Noth Eastern Regional Grid (NERG)						
10 APDCL	0.5549	1	0.595	7,50,54	3	191.66
11 MSPDCL	1	0.8541	1	---	--	0
12 TSECL	0.5887	1	0.8374	9,12,45	3	25.79
13 Arunachal PD	1	0.8256	1	--	--	0
14 Mizoram PD	0.7929	1	1	---	--	0
15 Nagaland PD	1	0.7665	1	---	---	0
NERG DMUs average TE (CRS) score of 0.82 for 2020–2021 & 0.90 for 2021–2022 DMUs less than the National average: 03 for 2020–2021(0.82) & 03 for 2021–2022(0.90)			NERG DMUs average TE (CRS) score of 0.90 for 2022–2023&DMUs less than National average :02 for 2022–2023(0.88)			
DMUs (17)-Northern Region Grid (NRG)						
16 BRPL	0.7355	0.7789	0.7823	7,44,49,54	4	968.34
17 BYPL	0.7631	0.7268	0.7586	7,25,44,49	4	737.32
18 TPDDL	0.6878	0.9444	0.7505	7,44,49,54	4	308.33
19 DHBVNL	0.8982	0.8762	0.928	33,44,46,49	4	100.23
20 UHBVNL	0.8568	0.9793	0.849	33,44,49,54	4	49.01
21 AVVNL	0.755	0.886	0.8594	7,49,54	3	2259.02
22 JdVVNL	0.7179	0.8725	0.8846	33,49,54	3	1662.71
23 JVVNL	0.7691	1	0.9428	33,49,54	3	1697.22
24 DVVNL	1	1	1	--	--	0
25 KESCO	0.8692	0.8486	1	--	--	0
26 MVVNL	0.8247	1	0.8833	7,25,27	3	3792.9
27 PaVVNL	1	0.9815	1	---	--	0
28 PuVVNL	0.7769	1	0.9679	7,25,27	3	6635.25
29 UPCL	0.9998	0.9986	0.9554	7,44,49,54	4	387.83
30 HPSEBL	0.9638	1	0.9508	9,42,54	3	1891.45
31 PSPCL	0.9528	0.9476	1	--	--	0
NRG DMUs average TE (CRS) score of 0.848 for 2020–2021 & 0.927 for 2021–2022. NRG DMUs less than National average: 06 for 2020–2021(0.845) & 06 for 2021–2022(0.890)			NRG DMUs average TE (CRS) score of 0.90 for 2022–2023 & DMUs less than National average :06 for 2022–2023(0.88)			
DMUs (12)-Southern Regional Grid (SRG)						

32 _APCPDCL	0.8632	0.9416	0.7723	31,33,54	3	660.02
33 _APEPDCL	0.8971	0.6969	1	---	--	0
34 _APSPDCL	0.6922	0.7177	0.676	7,49,54	3	1036.6
35_BESCOM	0.6614	0.7583	0.7317	7,49,54	3	1067.6
36_CHESCOM	0.6638	0.7608	0.736	4,7,9,54	3	295.02
37_GESCOM	0.6891	0.7258	0.7183	7,42,54	3	407.85
38 _HESCOM	0.8151	0.8531	0.7295	7,49,54	3	1028.82
39 _MESCOM	0.684	0.8015	0.881	4,9,42,54	3	103
40 _TSNPDCL	0.8549	1	0.7641	7,44,54	3	1018.49
41 _TSSPDCL	0.9578	1	0.9301	33,46	2	3471.98
42 _KSEBL	0.9556	0.8534	1	----	--	0
43 -TANGEDCO	0.9444	1	0.7663	31,54	2	11388.39
44_Puducherry PD	1	0.805	1	--	--	0
SRG DMUs average TE (CRS) score of 0.82 for 2020–2021 & 0.83 for 2021–2022 DMUs less than National average: 07 for 2020–2021(0.845) & 09 for 2021–2022(0.890)			SRG DMUs average TE (CRS) score of 0.82 for 2022–2023 DMUs less than National average :08 for 2022–2023(0.88)			
DMUs (10)-Western Regional Grid (WRG)						
45 _CSPDCL	1	1	0.9329	7,49,54	3	658.94
46 _DGVCL	0.9447	0.8959	1	--	--	0
47 _MGVCL	0.8791	0.9605	0.9317	33,44,49,54	4	79.81
48 _PGVCL	0.926	1	0.9683	44,46,49,54	4	415.92
49 _UGVCL	1	0.8581	1	---	--	0
50_MPMaKVVCL	0.7557	0.783	0.8786	7,49,54	3	1333.78
51 _MPPaKVVCL	0.8425	0.7649	0.9301	7,44,49,54	4	809.35
52 _MPPoKVVCL	0.6707	0.8099	0.8846	7,49,54	3	1125.32
53 _MSEDCL	0.7642	1	0.7513	7,49,54	3	13014.72
54 _Goa PD	1	0.6388	1	--	--	0
WRG DMUs average TE (CRS) score of 0.87 for 2020–2021 & 0.87 for 2021–2022 DMUs less than National average: 03 for 2020–2021(0.84) & 05 for 2021–2022(0.89)			WRG DMUs average TE (CRS) score of 0.92 for 2022–2023 DMUs less than National average :01 for 2022–2023(0.88) Input slack total Expenditure (Rs. in Crores):63,270.12			
National Mean score	0.845	0.890	0.88 (0.871)			63270.12
No. of Efficient DMUs & No. of inefficient DMUs out of 54	13(41)	16(38)	19(35)			

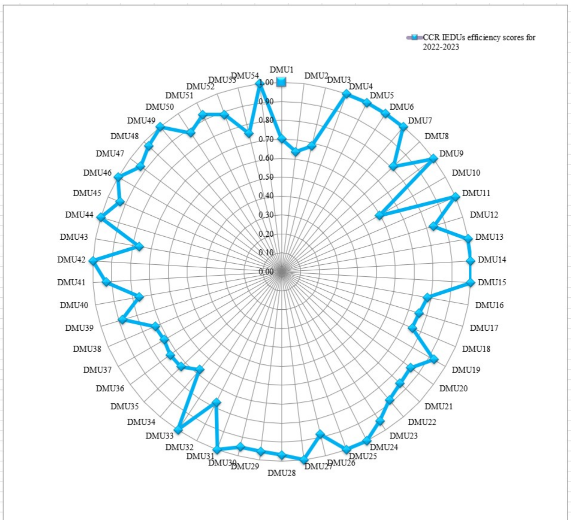

Fig. 9. CCR IEDUs efficiency analysis for the 2022-2023.

A. Input-Oriented TE Measurement Using the CRS Model:

The results were computed using the CCR model under the assumption of Constant Returns to Scale (CRS). Analysis of Table IV and Fig. 9 reveals several key observations. First, there is significant variation in the TE score levels among the DMUs. The national mean TE score across all utilities is 0.88, indicating an average inefficiency of 12.0%. Out of the 54 DMUs evaluated, 19 DMUs achieved a TE score of 1, classifying them as efficient, while the remaining 35 DMUs were found to be inefficient during 2022–2023.

It can be inferred that the 19 efficient DMUs emerge through the adoption of effective practices by achieving TE score of 1 regarded as benchmarks or peers for the 35 inefficient DMUs to enhance their performance. For instance, DMU 10 _APDCL (Assam), is an inefficient utility with a TE score of 0.595. For this utility, three peer/benchmark DMUs—specifically DMUs 7, 50, and 54—have been identified as peers that can guide improvements in its operational efficiency. These findings highlight the potential for inefficient utilities to adopt best practices from top-performing DMUs to optimize their performance.

The findings of the present work demonstrate an enhance in the national mean efficiency score from 0.86 to 0.89 (2018–19 to 2022–23), primarily attributable to a significant reduction in AT&C losses from 21.02% to 17.47%, despite a widening ACS-ARR gap [26, 49].

1) Slack-based inefficiencies

Table IV reveals a significant input overutilization of Rs.63,270.12 crore in India's electricity distribution sector. DMU-53 (MSEDCL) alone accounts for ₹13,014 crore of this overutilization, driven by high interest and depreciation costs, suboptimal technical efficiency (75%), a large ACS–ARR gap (₹1.52/kWh), and substantial

AT&C losses (15.95%) [18]. Strategic interventions such as debt restructuring under state schemes and targeted smart grid investments are recommended to reduce financial strain and enhance operational efficiency. These measures are expected to align performance with high-efficiency benchmarks (DMU-49 and DMU-54), leading to significant cost savings.

The findings of the present work indicate an increase in input overutilization from Rs. 24,960.68 crores to Rs. 63,270.12 crores, driven by the widening ACS-ARR gap from Rs. 0.83/kWh to Rs. 1.23/kWh [26, 49].

2) Efficiency disparities among regional grids

Table V and Fig. 10 present that the TE of IEDUs, measured using the CCR model, exhibits significant disparities across regional and national grid levels.

The Western Regional Grid (WRG) was the most efficient, with a mean TE score of 0.92 in 2022–23, while the Southern Regional Grid (SRG) was the least efficient, recording a mean TE score of 0.82. Despite this regional variation, the national average TE scores showed marked improvement, rising from 0.845 to 0.880 over the period 2020–2023. Notably, the CCR model reveals that 21 out of 54 EDUs (38.8%) operate below this national benchmark, underscoring substantial regional and inter-utility performance disparities during 2022-2023.

Current research reveals that high-performing DMUs (WRG: 92%) should lead structured knowledge and skill transfer initiatives to mentor lower-efficiency counterparts (SRG: 82%) [24, 49].

The findings align with existing literature, reinforcing that high-performing distribution utilities (WRG: 0.92) should spearhead structured knowledge and skill transfer programs to assist lower-efficiency counterparts (SRG: 0.82), thereby fostering institutional capacity and promoting regional convergence [24, 49]. Strategic grid modernization and the implementation of performance-based incentives are critical to enabling underperforming IEDUs to attain the national efficiency benchmark (88%) and strengthen overall sectoral performance.

TABLE V: CCR AVERAGE TECHNICAL EFFICIENCY SCORES OF IEDUS FOR 2020–2021, 2021–2022 AND 2022–2023 BASED ON REGIONAL /NATIONAL GRID

Region/Year	2020–2021	2021–2022	2022–2023	No. of DMUs below National Average for 2022–2023
Eastern (ERG-09)	0.85	0.87	0.87	04 out of 09
Northeastern (NERG-06)	0.82	0.9	0.9	02 out of 06
Northern (NRG-17)	0.848	0.927	0.9	05 out of 17
Southern (SRG-12)	0.82	0.83	0.82	08 out of 12
Western (WRG-10)	0.87	0.87	0.92	02 out of 10
Indian National Grid Average (ING-54)	0.845	0.89	0.88	21 out of 54

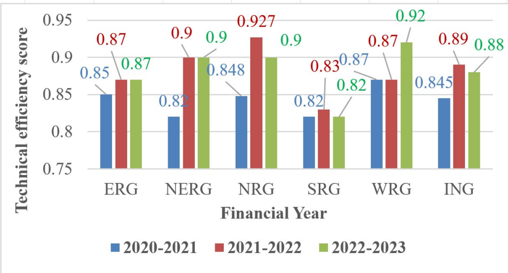

Fig. 10. CCR efficiency analysis of IEDUs for 2022–2023 based on regional/national grid.

3) Frequency of use as peer/benchmark group by inefficient DMU-CCR model

TABLE VI: FREQUENCY OF USE AS PEER/BENCHMARK GROUP BY INEFFICIENT DMUS WITH CCR MODEL IEDUS FOR 2022–2023

CCR Model	
Efficient DMU for 2022–2023	Frequency of use as peer/group by inefficient DMU
54 _Goa PD	29
49 _ UGVCL	25
7 _WESCO	24
44 _Puducherry PD	15
33 _ APEPDCL	8
9 _Sikkim PD	5
46 _ DGVCL	4
42 _KSEBL	4
25 _KESCO	4
31 _PSPCL	3
27_ PaVVNL	3
11 _MSPDCL	2

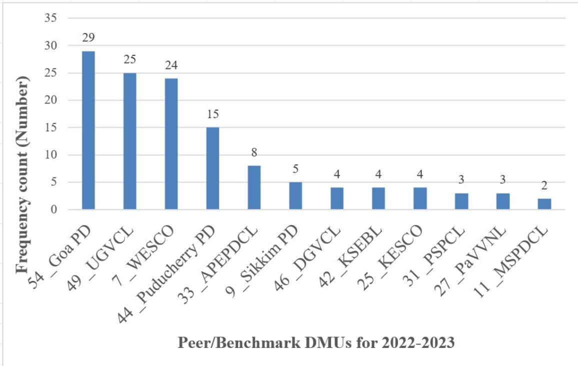

Fig. 11. Frequency of use as peer/benchmark group by inefficient DMUs with CCR model for 2022–2023.

As observed from Table VI and Fig. 11, the frequency of DMU54_Goa PD -WRG, DMU49_UGVCL-WRG, DMU44_Puducherry PD_SRGG, and DMU46_DGVCL-WR emerging in the benchmark set of efficient IEDUs is 29, 25, 15 and 4 respectively under the CCR model, which is considerably greater than other utilities. These findings are consistent with previous studies, highlighting that benchmark utilities play a key role in maintaining high performance and setting standards for other utilities [1, 26, 42, 49]. This high frequency indicates that these utilities can be considered as role models within the IEDUs. Conversely, IEDUs such as DMU11_MSPDCL_NER appear only once in the reference sets of inefficient IEDUs, indicating their limited robustness as benchmarks. Consequently, these utilities may be considered marginally effective in demonstrating best practices for inefficient DMUs seeking to improve their performance levels.

4) Efficient vs. inefficient DISCOMs: Cost disparities and operational impact on power distribution

Fig. 12, Fig. 13 and Table VII reveal that there is efficient DMUs demonstrate lower average costs per each input variables of DMU (INR 8,264 vs 15,982 crores) and average cost of power /MU energy sold (INR 0.60 vs 0.71 crores) compared to inefficient counterparts, underscoring operational inefficiencies in underperforming DISCOMs.

TABLE VII: COMPARISON OF AVERAGE COST OF EACH INPUT VARIABLE/DMUS & AVERAGE COST/ MU ENERGY SOLD BETWEEN EFFICIENT AND INEFFICIENT IEDUS FOR 2022–203

Average Cost of DMUS /Input variable expenditure	Average cost of efficient IEDUs	Average cost of inefficient IEDUs	Average Cost in Rs. crores/MU energy sold (efficient IEDUs)	Average Cost in Rs. crores/MU energy sold (inefficient IEDUs)
Number of DMUs	19	45	19	45
Mean of TE score	1.0	0.8217	1.0	0.8217
Cost of Power in Crores	8264.10	15981.65	0.600	0.708
Employee Cost	946.47	1572.2	0.068	0.0650
Interest Cost	430.31	1714.62	0.031	0.0709
Depreciation	355.63	806.57	0.0258	0.033
Other Costs	694.52	1010.42	0.0504	0.0418
Total Expenses	10690.94	22324.74	0.7766	0.9240

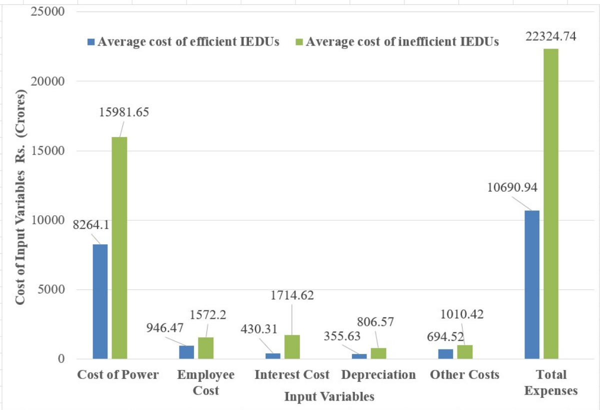

Fig. 12. The average cost Rs, in crores per efficient and inefficient DMUs using CCR model for 2022–2023.

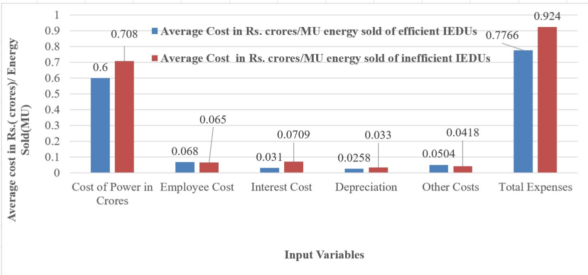

Fig. 13. The average cost Rs. in crores/MU energy sold basis for efficient and inefficient DMUs using CCR model for 2022–2023.

Efficient DMUs demonstrate a lower average total expenditure of Rs. 0.776 crores/MU energy sold basis, whereas inefficient DMUs incur a higher average total expenditure of Rs. 0.924 crores/MU energy sold basis. This cost differential highlights the pivotal importance of operational efficiency in influencing the financial viability of DMUs within the electricity distribution sector. These persistent and significant financial losses have severely impacted on the sector's productivity.

B. Trends in TE DMUs-Malmquist TFP Index

Table VIII presents the average trends in TFPCH, SECH, PECH, EFFCH, and TECHCH during the assessment period 2020–2023. The average TFPCH is graphically illustrated in Fig. 14. The table also reports the Malmquist index values for each DMU across the sub-periods 2020–2021 to 2022–2023. From Table VIII, it is evident that the Indian National mean of TFPCH is 0.947, indicating that the performance of IEDUs at the national level experienced an average TFP decline of 5.3% during the assessment period.

TABLE VIII: AVERAGE PRODUCTIVITY OF IEDUS DURING 2020–2023

DMU Name/ Productivity indices	EFFCH	TECHCH	PECH	SECH	TFPCH
1 _NBPDCL	1.011	0.934	1.011	1.000	0.944
2 _SBPDCL	0.990	0.907	0.988	1.002	0.898
3 _JBVNL	0.980	0.915	1.105	0.887	0.897
4 _CESU	1.000	0.866	1.000	1.000	0.866
5 _NESCO	1.000	0.715	1.000	1.000	0.715
6 _SOUTHCO	1.000	0.853	1.000	1.000	0.853
7 _WESCO	1.007	0.897	1.000	1.007	0.903
8 _WBSEDCL	1.126	0.928	1035	0.992	1.045
9 _Sikkim PD	1.000	0.990	1.000	1.000	0.990
10 _APDCL	1.035	0.919	1.249	0.829	0.952
11 _MSPDCL	1.000	0.773	1.000	1.000	0.773
12 _TSECL	1.193	0.840	1.274	0.936	1.002
13 _Arunachal PD	1.000	1.052	1.000	1.000	1.052
14 _Mizoram PD	1.123	0.942	1.081	1.039	1.058
15 _Nagaland PD	1.000	1.724	1.000	1.000	1.724
16 _BRPL	1.031	0.933	1.166	0.885	0.962
17 _BYPL	0.997	0.948	1.093	0.912	0.945
18 _TPDDL	1.045	0.908	1.008	1.036	0.949
19 _DHBVNL	1.016	0.916	0.974	1.043	0.931
20 _UHBVNL	0.995	0.910	1.013	0.982	0.906
21 _AVVNL	1.067	0.917	1.099	0.971	0.978
22 _JdVVNL	1.110	0.900	1.156	0.960	1.000
23 _JVVNL	1.107	0.904	1.099	1.008	1.001
24 _DVVNL	1.000	0.809	1.000	1.000	0.809
25 _KESCO	1.073	0.962	1.000	1.073	1.031
26 _MVVNL	1.035	0.882	1.032	1.003	0.913
27 _PaVVNL	1.000	0.937	1.000	1.000	0.937
28 _PuVVNL	1.116	0.949	1.123	0.994	1.059
29 _UPCL	0.978	0.930	0.988	0.989	0.910
30 _HPSEBL	0.993	0.936	1.000	0.993	0.930
31 _PSPCL	1.024	0.941	1.000	1.024	0.964
32 _ APCPDCL	0.946	0.927	0.970	0.975	0.877
33 _APEPDCL	1.056	0.960	1.002	1.053	1.013
34 _APSPDCL	0.988	0.933	1.026	0.963	0.922
35 _BESCOM	1.052	0.906	1.025	1.026	0.953
36 _CHESCOM	1.053	0.903	1.085	0.971	0.951
37 _GESCOM	1.021	0.926	1.034	0.987	0.945
38 _HESCOM	0.946	0.919	0.968	0.977	0.869

39 _MESCOM	1.135	0.898	1.172	0.968	1.019
40 _TSNPDCL	0.945	0.908	0.899	1.052	0.859
41 _TSSPDCL	0.985	0.872	1.000	0.985	0.859
42 _KSEBL	1.023	0.907	1.000	1.023	0.928
43 -TANGEDCO	0.901	0.926	1.000	0.901	0.834
44 _Puducherry PD	1.000	1.089	1.000	1.000	1.089
45 _CSPDCL	0.966	0.741	1.000	0.966	0.715
46 _DGVCL	1.029	1.049	1.000	1.029	1.079
47 _MGVCL	1.029	0.904	0.995	1.034	0.931
48 _PGVCL	1.023	0.941	1.000	1.023	0.962
49 _UGVCL	1.000	0.961	1.000	1.000	0.961
50 _MPMaKVVCL	1.078	0.955	1.125	0.958	1.030
51 _MPPaKVVCL	1.051	0.928	1.012	1.039	0.976
52 _MPPoKVVCL	1.148	0.915	1.181	0.973	1.051
53 _MSEDCL	0.992	0.937	1.000	0.992	0.929
54 _Goa PD	1.000	0.898	1.000	1.000	0.898
India National Mean	1.025	0.924	1.036	0.989	0.947

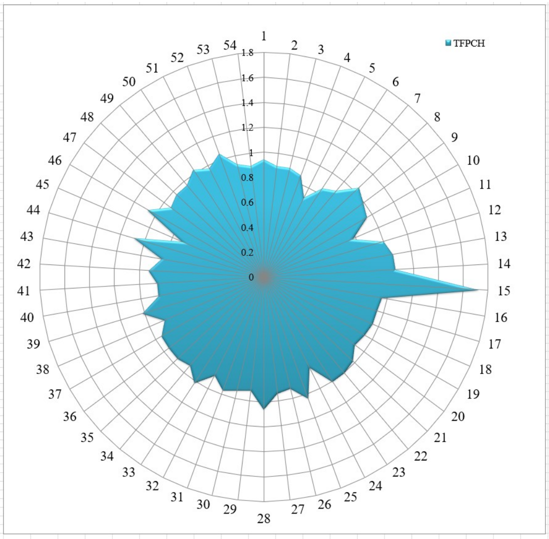

Fig. 14. Average TFPCH of IEDUs for the 2020–2023.

EFFCH is 1.025, showing a marginal 2.5% improvement in operational efficiency. EFFCH measures how well DMUs utilize their inputs to produce outputs. In the distribution sector, All India AT&C losses in the declining trend 21.99% to 15.37% and ARR gap almost constant Rs 0.556/kWh are key indicators of operational efficiency progress. This operational efficiency improvement results from gains in PECH 1.036 and despite of low SECH 0.989. However, this progress is counteracted by a substantial regression in TECHCH 0.924. The technological change is 0.924, reflecting a significant decline in technological progress of approximately 7.6% is due to outdated distribution infrastructure, poor governance and leading to consistent distribution losses with an all-India average 14.16% in the assessment period. As observed, the reduction in TFP (5.3%) mainly driven by a lack of technological change is 7.6%, despite some improvements in operational efficiency change is 2.5%. The findings revealed that out of 54 DMUs, 4(7.4%) have made progress (TE change value >1.00) and 92.59 percent of DMUs regressed (TE change value <1.00) during assessment period 2020-2023. The analysis indicates that while structural factors like outdated infrastructure and governance gaps remain core challenges and COVID-19 further constrained financial and operational performance, resulting in efficiency declines for 92.6% of distribution utilities.

1) The best performer case

Three DMUs were identified as the top performers based on a Total Factor Productivity (TFP) score greater than 1.00: DMU15 (Nagaland PD) with a TFP of 1.724, DMU44 (Puducherry PD) with 1.089, and DMU46 (DGVCL) with 1.079. DMU15 demonstrated exceptional productivity growth of 72.4%, driven primarily by a substantial technological advancement (TECHCH = 1.724) and a favorable revenue surplus (ACS-ARR of Rs. 0.12/kWh). The growth in the other two DMUs was more moderate but still significant. DMU44 achieved an 8.9% increase, attributable to positive technological change (TECHCH = 1.089) and a minimal ACS-ARR gap (Rs. 0.11/kWh), despite its high AT&C losses of 16.23%. Conversely, DMU46 recorded a 7.9% growth, supported by a solid TECHCH score of 1.049, exceptionally low AT&C losses of 4.02%, and a manageable ACS-ARR gap (Rs. 0.40/kWh) [18].

2) The poor performer case

Theee DMUs exhibited performance regression, marked by negative Total Factor Productivity (TFP) growth: DMU5 (NESCO), DMU45 (CSPDCL), and DMU11 (MSPDCL) with declines of 28.5%, 28.5%, and 22.7%, respectively. This regression is primarily attributed to a substantial technological regression, evidenced by low Technological Change (TECHCH) scores of 0.773, 0.741, and 0.773. A key contributing factor is the remarkably high AT&C losses of 23.11%, 17.44%, and 24.5% in these DMUs coupled with significantly high ACS-ARR gap. Such elevated losses signify operational inefficiencies and a failure in technological adoption, which constrains the amount of net energy sold and leads to the underutilization of resources [18].

3) Malmquist index of annual productivity in IEDUs

Fig. 14 displays average trends in TFP change, SECH, PECH, EFFCH, and TECHCH of the assessment period 2020-2023.

The analysis of Malmquist indices (TFPCH) across the selected periods from 2020-2021 to 2022-2023 (Table IX and Fig. 15) reveals a concerning trend in the EFFCH of IEDUs. The average EFFCH score declined from 1.055 in 2021-2022 to 0.986 in 2022-2023, with an overall mean EFFCH score of 1.022 during the assessment period. This gradual regression in efficiency change underscores a decline in productivity among electricity distribution utilities, primarily attributed to the suboptimal utilization of resources and overall decline in mean SECH score from 1.002 to 0.989. A significant contributing factor to these high all-India average AT&C losses, which stood at 17.71%, coupled with high average ACS-ARR gap on energy sold basis during the assessment period [18].

The annual mean analysis further highlights a mixed performance across IEDUs. While EFFCH showed marginal improvement (1.025), driven by gains in PECH (1.036), TECHCH experienced a significant decline (0.924). This resulted in an overall drop in TFP to 0.947. The outcomes of this research, differing from previous research, reveal an overall decline in TFP to 0.947 from 2020 to 2023, primarily due to persistent operational inefficiencies, particularly high AT&C losses, reduction in electricity consumption during lockdown of Covid-19 and significantly high average ACS-ARR gap, compounded by insufficient technological progress [22].

TABLE IX: COMPARISON OF MALMQUIST INDEX OF ANNUAL PRODUCTIVITY CHANGE DURING 2021–2023

Year	2020–2021	2021–2022	2022–2023	Mean (2021–2023)
EFFCH	1	1.060926	0.998704	1.029815
TECHCH	1	0.922593	0.942222	0.932407
PECH	1	1.058148	1.052778	1.055463
SECH	1	0.903148	1.04463	0.973889
TFPCH	1	0.941852	0.97963	0.960741

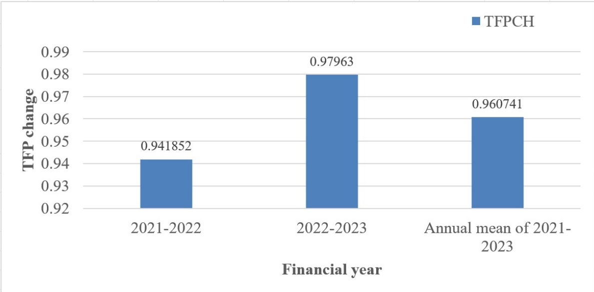

Fig. 15. TFP Change of IEDUs for the years 2021–22, 2022–23 and Annual Mean of 2021–2022,2022–2023 and 2021–2023.

V. CONCLUSION

This study evaluates the TE and TFP of 54 IEDUs over the reform critical period 2020–2023 encompassing the post-UDAY implementation phase, the launch of the RDSS, and COVID-19 recovery dynamics using DEA and the MPI. The findings reveal systemic inefficiencies that impose substantial economic costs while simultaneously identifying pathways for operational transformation and financial sustainability.

The CCR model identified only 35.18% of DMUs (19 out of 54) as efficient, with efficiency scores improving marginally from 0.84 in 2020–2021 to 0.88 in 2022–2023. DMU_54 Goa PD emerged as a consistent benchmark, indicating its potential as a role model for other utilities. This study identifies an estimated input overutilization of Rs.63,270.12 crore in India's electricity distribution sector, primarily driven by slack-based inefficiencies observed across utilities. This substantial inefficiency cost underscores the urgent need for managerial interventions and regulatory reforms. The analysis revealed a modest 2.5% improvement in operational efficiency (average efficiency change = 1.025), primarily due to gains in pure efficiency (1.036). However, this was offset by a 7.6% decline in TECHCH = 0.924, largely due to outdated infrastructure and regulatory delays. This technological regression reflects the persistent challenges of aging infrastructure, inadequate capital investment, and regulatory impediments that constrain the adoption of smart grid technologies, advanced metering infrastructure, and digital distribution management systems. Persistent AT&C losses averaged 17.71%, contributing to a 5.3% decline in total productivity. Efficient DMUs demonstrated lower average cost per million units' energy sold (Rs.0.776 crores) compared to inefficient ones (Rs.0.924 crores), underscoring the importance of operational optimization.

Key performers such as DMU15 (Nagaland PD), DMU44 (Puducherry PD), DMU46 (DGVCL) and achieved growth through efficiency improvements and reduced ACS-ARR gaps. Conversely, underperformers like DMU5 (NESCO), DMU45 (CSPDCL), and DMU11 (MSPDCL) suffered from high AT&C losses, ACS-ARR gaps and technological stagnation.

This study quantifies inefficiency costs at Rs 63,270.12 crore, identifies high-performing utilities as benchmarks, and demonstrates how operational efficiency directly impacts financial viability. These findings offer strategic directions for energy policymakers formulating reforms, regulators setting performance standards, utility managers pursuing operational improvements, and financial institutions assessing credit risk in India's distribution sector.

This research underscores the necessity of an AI-driven strategies for financially distressed and debt-burdened IEDUs to achieve efficient, sustainable, and consumer-centric power delivery in India by 2047.

A. AI-Driven Strategies for Financially Distressed and Debt-Burdened IEDUs

The adoption of AI solutions may appear challenging for financially distressed and debt-burdened Indian electricity distribution utilities (IEDUs), this roadmap proposes a low-cost, and incrementally scalable AI interventions tailored to one of the world's most complex and largest consumer bases. These interventions are designed to achieve measurable efficiency gains with minimal capital expenditure. The strategy emphasizes phased implementation, beginning with pilot projects in selected DMUs—supported by Central and State governments, as well as international funding agencies—followed by progressive scale-up across the entire distribution network.

The proposed framework focuses on digital transformation and operational optimization through the following key initiatives: (i) Deploy smart meters and IOT systems for real-time monitoring and control. (ii) Leverage AI analytics to detect theft, identify anomalies, and cut AT&C losses. (iii) Apply AI forecasting and bidding tools to optimize power procurement and close the ACS–ARR gap. (iv) Implement predictive maintenance to lower Operation &Maintenance costs and boost asset reliability. (v) Integrate renewables intelligently using AI-driven forecasting, storage, and demand response.

Importantly, without AI-enabled intervention, the sector's financial distress, operational inefficiencies, and ACS–ARR gap are likely to intensify, especially given the scale and complexity of its consumer base in India. For India's electricity distribution sector, the strategic adoption of AI presents a transformative opportunity to achieve operational resilience, fiscal stability, and sustainable growth.

B. Future Scope

The efficiency analysis of IEDUs can be extended in several directions in future research: (i) Smart Meter Impact: Investigate how smart meter adoption influences DMU efficiency scores and reduces AT&C losses (ii) Renewable Energy Integration: Examine how renewable energy penetration affects DMU performance and financial sustainability challenges. (iii) Long term efficiency assessment: extending the horizon beyond 2020–2023 for long-term reform evaluation for tracking sustained efficiency changes (iv) Service-quality indicators: Incorporating these indicators to DMU efficiency models to capture both operational and service delivery performance. Methodologically, (v)Advanced methodological approach: exploring hybrid DEA–ML models can provide more robust and predictive benchmarking. These extensions would strengthen the IEDUs evaluation framework, provide concrete evidence for policy formulation, and advance understanding of sustainable distribution sector reforms in IEDUs

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

V. Ramaiah conceptualized the study, performed data analysis, validated the methodology, and interpreted the results, while Dr. P. Chandrasekar contributed to the manuscript review. Both authors contributed equally to the final version of the manuscript. Both authors had approved the final version.

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