



Analysis of Technical Efficiency of Electricity Distribution at PT. PLN UP3 Parepare for 2019-2024: Stochastic Frontier Analysis (SFA) Approach

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Abstract

Background: Electricity distribution efficiency is essential for maintaining service quality, operational performance, and system reliability. Despite Indonesia's high electrification rate, efficiency at the service-unit level remains underexplored, particularly regarding network reliability and human resource quality.

Objective: This study aims to analyze the level of technical efficiency in electricity distribution and the factors influencing inefficiency at PT PLN (Persero) UP3 Parepare during the 2019–2024 period.

Methods: The research uses monthly panel data from seven *Customer Service Units (ULP)* and applies a Stochastic Frontier Analysis (SFA) approach with a translog production function. Output variables include the number of customers, electricity energy sold, and energy losses, while input variables consist of labor, distribution networks, the number of transformers, and transformer capacity. The inefficiency factors analyzed are System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), employee education level, and the COVID-19 pandemic.

Results: Technical efficiency was high, averaging above 0.97, with *ULP Mattirotasi* recording the highest efficiency score (0.986). Distribution networks and transformer capacity contributed positively to output. SAIDI was positively associated with inefficiency at the 10% significance level but was not statistically significant at the 5% level, while higher employee education levels were associated with reduced inefficiency.

Conclusion: These findings indicate that improving electricity distribution efficiency requires optimizing distribution assets, enhancing network reliability, and strengthening human resource competencies.

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INTRODUCTION

Electricity is a strategic infrastructure that plays an important role in supporting economic growth, increasing productivity, and improving the quality of community life. The availability of electricity is not only needed for household activities but also serves as a primary input for the industrial, trade, education, health, and micro- and small-business sectors. In the context of regional development, electricity has evolved from a basic need to a productive factor that determines economic competitiveness and equitable development (Blume, 2025). At the global level, electricity distribution efficiency remains a significant challenge, with technical and non-technical losses in distribution networks averaging 8–15% in developing countries, significantly higher than the 3–6% reported in developed nations (Rüstemli et al., 2025). The International Energy Agency reported that improving distribution efficiency could save up to 270

TWh annually across emerging economies, underscoring the urgency of this issue for utility companies worldwide.

The success of the distribution system is not determined solely by infrastructure availability, as reflected in the electrified-village ratio of 99.92% at the end of 2024 PLN (2025), but also by the company's ability to manage resources efficiently. However, high electricity access does not automatically guarantee efficient electricity distribution. As the network expands to serve more customers across diverse geographical areas, the complexity of managing distribution assets, maintaining network reliability, and minimizing energy losses increases substantially. Electricity distribution efficiency is therefore an important issue because it is directly related to service quality, system reliability, operational costs, and the sustainability of electricity supply to the community.

Various studies have measured efficiency in the electricity sector using Data Envelopment Analysis (DEA) and Stochastic Frontier Analysis (SFA) approaches. Altoé et al. (2017) applied DEA to evaluate the technical efficiency and financial performance of Brazilian electricity distribution operators, finding significant variations in efficiency across firms and identifying network infrastructure as a key determinant. Medeiros et al. (2022) combined DEA with service quality indicators to assess the performance of Brazilian distribution companies, demonstrating that efficiency measurement should incorporate both operational and service dimensions.

Mirza et al. (2021) employed SFA to examine total factor productivity growth in Pakistan's post-reform electricity distribution companies, incorporating SAIDI and SAIFI indicators into the efficiency model and finding significant effects on technical efficiency. Sufia et al. (2025) used a three-stage DEA and Malmquist index analysis for Indian distribution utilities, integrating service quality and operational efficiency. These studies confirm that the efficiency of electricity companies is influenced by network infrastructure, asset capacity, human resource quality, and distribution system reliability.

However, several important gaps remain in the literature. First, most studies have focused on efficiency measurement at the aggregate company or regional level Altoé et al. (2017), while studies at the Unit Layanan Pelanggan (ULP) level remain relatively limited. Second, previous studies generally measured efficiency levels without simultaneously modeling the determinants of inefficiency within a single-stage framework. In particular, the joint modeling of network reliability indicators (SAIDI and SAIFI), external shocks such as the COVID-19 pandemic, and human resource quality as determinants of technical inefficiency at the service-unit level has not been attempted in previous research. This is an important gap because reliability indicators such as SAIDI and SAIFI, pandemic conditions, and human resource quality are suspected to play important roles in determining electricity distribution performance, yet their simultaneous inclusion in an SFA inefficiency model at the ULP level has not been empirically tested.

In the context of electricity distribution companies, measuring technical efficiency is becoming increasingly important because companies are required to improve service quality while maintaining operational efficiency. Efficiency is influenced not only by the availability of physical assets, such as networks and transformers, but also by the company's ability to manage disturbances, optimize infrastructure utilization, and improve human resource competencies (Kumbhakar, 2003). Therefore, an analysis that integrates technical, operational, and human resource factors is needed to obtain a more comprehensive picture of electricity distribution performance and the factors that influence it.

PT PLN (Persero) UP3 Parepare, as one of the units under Unit Induk Distribusi Sulawesi Selatan, Sulawesi Tenggara, dan Sulawesi Barat (UID Sulselrabar), has a complex service area, serving seven Unit Layanan Pelanggan (ULP) spread across one city and three regencies with diverse regional characteristics. The service area includes coastal areas, lowlands, hills, industrial areas, agribusiness centers, and livestock-farming areas, which have different electricity needs and consumption patterns. During the 2019–2024 period, UP3 Parepare experienced notable variations in distribution performance: average SAIDI ranged from 3.21 to 11.14 minutes per customer across ULPs, SAIFI varied between 0.15 and 2.87 interruptions per customer, and distribution losses fluctuated between 4.12% and 7.89%. Customer growth averaged 3.2% annually, while total energy sold increased by approximately 18.6% over the six-year period. These differences in geographical conditions, number of customers, network infrastructure, and disturbance levels underscore the potential for efficiency variations between service areas and

justify the need for a detailed efficiency analysis at the ULP level.

This study aims to analyze the level of technical efficiency of electricity distribution at PT PLN (Persero) UP3 Parepare during the 2019–2024 period using the Stochastic Frontier Analysis (SFA) approach with a translog production function. In addition to measuring efficiency levels, this study also analyzes the factors associated with technical inefficiency, including SAIDI, SAIFI, the COVID-19 pandemic, and employee education levels.

The contribution of this research lies in three aspects. First, the use of monthly panel data from seven ULPs over six years (504 potential observations) provides granular temporal and cross-sectional variation that enables more precise efficiency estimation compared with annual or aggregate-level studies. Second, the integration of network reliability factors (SAIDI, SAIFI), external shocks (COVID-19), and human resource quality (education-level composition) into a single-stage SFA inefficiency model represents a more comprehensive analytical framework than previous studies that typically examined these factors in isolation. Third, this study generates new empirical knowledge about the relative importance of infrastructure, reliability, and human capital factors in explaining efficiency variations at the operational service-unit level, providing actionable evidence for distribution management and policy.

The theoretical contribution of this study lies in extending the application of SFA with a translog production function to electricity distribution efficiency measurement at a disaggregated service-unit level, thereby enriching the literature on utility performance evaluation in developing countries. The practical implications are significant for UP3/ULP management: efficiency rankings and elasticity estimates can guide network investment priorities, the identification of inefficiency determinants can inform asset management and reliability-improvement strategies, and the human resource findings can support competency development programs. Furthermore, the methodology and findings may serve as a reference for other PLN units seeking to evaluate and improve their distribution performance.

METHOD

This study used a quantitative approach with a descriptive-inferential design. The descriptive approach was used to describe the electricity distribution performance of PT PLN UP3 Parepare during the 2019–2024 period, while the inferential approach was used to measure the level of technical efficiency and analyze the factors that influenced electricity distribution inefficiency. The Stochastic Frontier Analysis (SFA) model was used because it could separate the technical inefficiency component from random noise (statistical noise), making it suitable for application in the electricity sector, which has complex operational characteristics and is influenced by both technical and external factors.

The data used in this study were monthly panel data covering seven Customer Service Units (ULP) under the working area of PT PLN UP3 Parepare, namely ULP Mattirotasi, ULP Barru, ULP Pangsidi, ULP Tanrutedong, ULP Rappang, ULP Soppeng, and ULP Pajalesang. The observation period extended from January 2019 to December 2024, with a total of 504 observations expected to be available. However, after data verification and cleaning, 483 observations were deemed complete and suitable for analysis. The 21 missing observations resulted from incomplete monthly reporting records: 9 observations were from ULP Barru (scattered across February–April 2019 and August–October 2020 due to severe flooding events), 6 from ULP Soppeng (March–May 2019 and January–March 2020), and 6 from ULP Pajalesang (June–August 2019 and November 2020–January 2021).

Observations were classified as incomplete when one or more key variables (energy sold, losses, SAIDI, or SAIFI) had missing or inconsistent values that could not be verified against the source reports. The resulting panel was therefore unbalanced; however, the T. J. Coelli et al. (2005) maximum likelihood estimator implemented in Frontier 4.1 accommodates unbalanced panels without requiring imputation. Data were obtained from official company documents, including PLN Statistics, UID Sulselrabar Statistics, UP3 Parepare operational reports, distribution loss reports, network asset data, employee data, and system reliability reports sourced from the Integrated Complaint and Complaint Application (APKT). In addition, this study used supporting data from publications of the Ministry of Energy and Mineral Resources, BPS, and relevant academic literature.

The research variables consisted of output variables, input variables, and inefficiency

determinant variables. The operational definitions of each variable are presented in Table 1.

Table 1

Operational Definition of Research Variables

Variable Group	Variable	Unit
Output	Electricity energy sold (Y1)	kWh
Output	Number of customers (Y2)	Customers
Output	Distribution losses (Y3)	Percentage (%)
Input	Permanent employees (X1)	Persons
Input	Outsourcing workers (X2)	Persons
Input	Medium Voltage Network length (X3)	kms
Input	Low Voltage Network length (X4)	kms
Input	Number of transformers (X5)	Units
Input	Transformer capacity (X6)	kVA
Inefficiency determinant	SAIDI (Z1)	Minutes/customer
Inefficiency determinant	SAIFI (Z2)	Times/customer
Inefficiency determinant	Expert (Z3)	Percentage (%), Proportion of S1 and S2 employees
Inefficiency determinant	Technical (Z4)	Percentage (%), Proportion of D1 and D3 employees
Inefficiency determinant	Covid-19 Dummy (Z5)	1 = Covid-19 period, 0 = otherwise

Employee education level was represented by the proportion of employees in the expert category (S1 and S2) and the technical category (D1 and D3), with employees with high school education serving as the baseline category in the estimation model. The frontier production model used in this study was the translog production function, formulated as follows:

$$\ln(Y_{1it}) = \alpha_0 + \sum_{m=1}^6 \alpha_m \ln(X_{m,it}) + \frac{1}{2} \sum_{m=1}^6 \sum_{n=1}^6 \alpha_{mn} \ln(X_{m,it}) \ln(X_{n,it}) + \alpha_7 \ln(Y_{2it}) + \frac{1}{2} \alpha_8 \ln(Y_{3it})^2 + \sum_{m=1}^6 \alpha_m \ln(Y_{2it}) \ln(X_{m,it}) \quad 2.1$$

$$+ \beta_1 \ln(Y_{3it}) + \frac{1}{2} \beta_2 \ln(Y_{3it})^2 + \sum_{m=1}^6 \beta_m \ln(Y_{3it}) \ln(X_{m,it}) + \gamma_1 t + \frac{1}{2} \gamma_2 t^2 + \sum_{m=1}^6 \varphi_m \ln(X_{m,it}) t + e_{it} - u_{it}$$

where Y is electricity distribution output, X is production input factors, vit is the random disturbance component assumed to be normally distributed, while u_{it} is the technical inefficiency component.

The elasticity model is as follows:

$$\varepsilon_{nit} = \frac{\partial y_{it}}{\partial x n_{it}} = \beta_n + \frac{1}{2} \sum_{n=1}^6 \sum_{m=1}^6 \beta_{nm} x m_{it} + \vartheta_{y2} \ln Y_{2it} + \vartheta_{y3} \ln Y_{3it} + \gamma_{nt} t \quad 2.2$$

The inefficiency model is formulated as follows:

$$u_{it} = \delta_0 + \delta_1 (SAIDI_{it}) + \delta_2 (SAIFI_{it}) + \delta_3 (Covid_{it}) + \delta_4 (Expert_{it}) + \delta_5 (Technical_{it}) + v_{it} \quad 2.3$$

Data processing was conducted using Frontier 4.1 software Coelli (1996) and Battese & Coelli (1995) time-varying inefficiency specification. The distributional assumption for the inefficiency term (u_{it}) follows a truncated-normal distribution. Data processing begins with data collection, verification, and tabulation of panel data. All variables are then transformed into natural logarithmic form to meet the estimation requirements of the frontier production function and facilitate interpretation of coefficients as elasticities. Variables with zero values were transformed using the ln(x+0.00001) approach. Selection of the production function form was conducted through Likelihood Ratio (LR) tests comparing the Cobb-Douglas and Translog models. The LR test statistic for the functional form comparison was 287.43 (df = 27, p < 0.001), strongly

rejecting the Cobb-Douglas specification in favor of the Translog model. Additionally, the LR test for the presence of inefficiency effects yielded a statistic of 34.68 ($df = 6$, $p < 0.001$), confirming that technical inefficiency is a significant component of the error structure and validating the SFA approach over ordinary least squares estimation.

RESULTS AND DISCUSSION

Results

Technical Efficiency Level Calculation Results

The level of electricity distribution efficiency can be analyzed after obtaining the best frontier production function, namely, the Translog model with inefficiency. Figure 1 illustrates the level of electricity distribution efficiency, which tends to show an increasing trend from 2019 to 2023, followed by a slight decrease in 2024. Overall, the electricity distribution system at PLN UP3 Parepare has operated at a fairly high level of efficiency. The consistent increase from 2019, starting at 0.913, indicates that although the system was already operating at a fairly high efficiency level, there is still room for further improvement to achieve optimal efficiency.

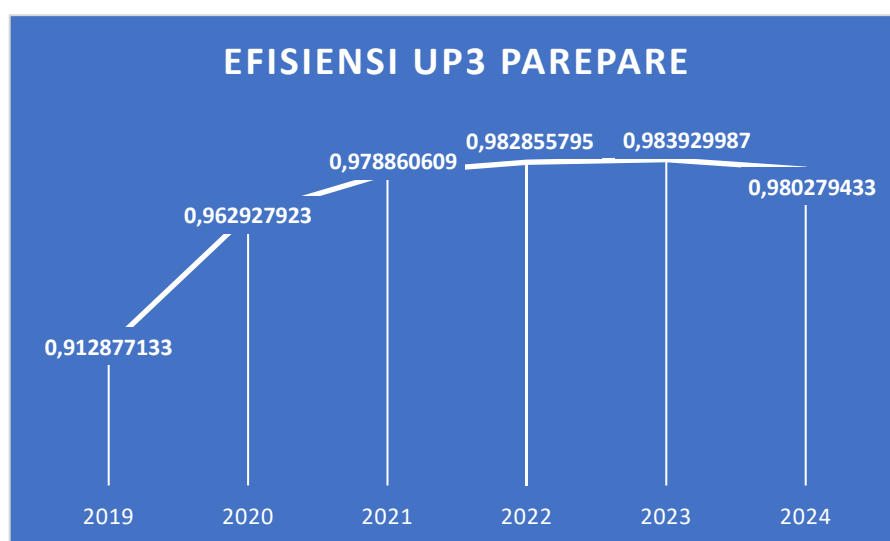


Figure 1. Technical Efficiency Level of UP3 Parepare 2019-2024

Infrastructure improvement efforts, maintenance quality, distribution system management, and utilization of owned assets showed significant performance improvements, with technical efficiency sequentially reaching its highest level of 0.984 in 2023. This indicates that the available inputs were utilized relatively optimally to produce electricity distribution output. In 2024, the efficiency value decreased slightly to 0.980. Although there was a decrease, the efficiency level remained high, indicating no significant decline in overall performance. This decrease may have been associated with an increase in the System Average Interruption Duration Index (SAIDI) of 7.93 minutes per customer in that year, as well as an increase in energy losses to 5.77%.

Increased energy losses directly reduce the amount of energy available for sale (kWh sold); therefore, the higher the losses, the greater the amount of energy lost within the electricity distribution system. In other words, even when other inputs are held constant, the system becomes less productive because some of the available energy is not optimally utilized (Simões et al., 2020; Tavassoli et al., 2022; Yi et al., 2025). A higher SAIDI indicates an increase in the duration of service interruptions experienced by customers; longer interruptions hinder electricity distribution, thereby reducing the amount of energy that can be delivered during the affected period and ultimately reducing output (de Mendonça et al., 2023). When energy losses and SAIDI increase simultaneously, their combined impact can be more significant. Energy losses reduce the amount of energy available for sale, whereas a higher SAIDI reduces the effective operating time of the distribution system. The combination of these two factors can therefore produce a compounding effect, reducing overall productivity.

Figure 2 shows the average distribution efficiency level for each Unit Layanan Pelanggan (ULP) during 2019–2024. Presenting the results by unit provides a more detailed picture of

fluctuations in ULP technical efficiency. Analysis at the ULP level is important because aggregate efficiency values at the UP3 level cannot always capture the actual conditions of individual ULPs. Comparisons among ULPs can also assist management in formulating targeted performance improvement strategies. Units with high efficiency values can serve as benchmarks for other units, whereas units with lower efficiency values can be prioritized for system improvements and optimization of existing assets.

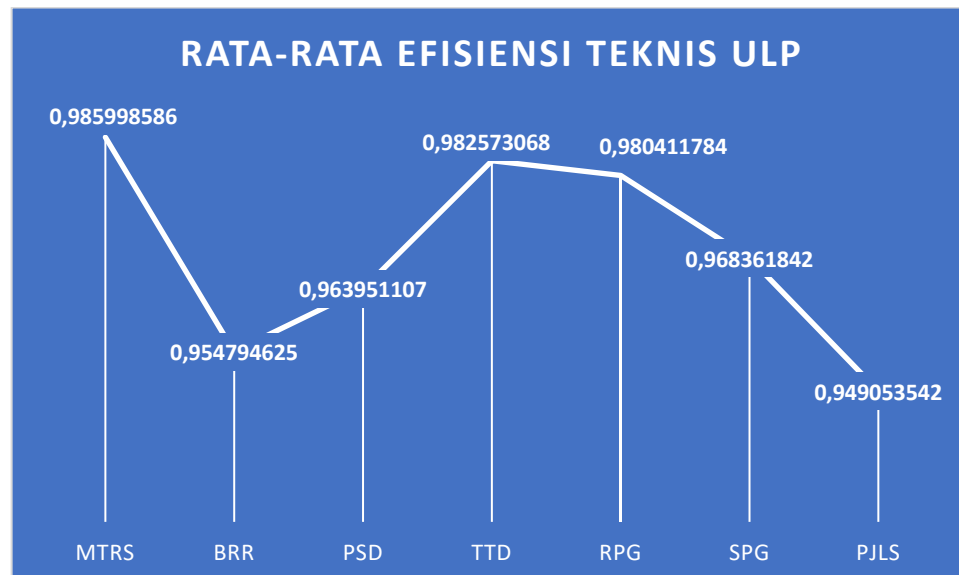


Figure 2. Average Technical Efficiency Level per ULP

Analysis of average efficiency at the Customer Service Unit (ULP) level shows performance variations between service areas. ULP Mattirotasi recorded the highest average efficiency of 0.986, followed by ULP Tanrutedong at 0.983 and ULP Rappang at 0.980. The high efficiency levels in these three units indicate a better ability to optimize the utilization of distribution assets and available resources to produce electricity distribution output.

Conversely, ULP Pajalesang and ULP Barru have relatively lower average efficiencies compared with other ULPs, at 0.949 and 0.955, respectively. Nevertheless, all ULPs are still in the efficient category because they have efficiency values above 0.90. These findings indicate that differences in efficiency between units primarily reflect variations in the level of resource optimization rather than substantial differences in overall performance. Therefore, management practices applied to ULPs with the highest efficiency levels can serve as benchmarks for efforts to improve efficiency in other service units.

Furthermore, the difference in average efficiency between the highest- and lowest-performing ULPs is only 0.037 points, indicating that efficiency levels across units are relatively consistent. This condition indicates that, in general, all ULPs under UP3 Parepare have been able to carry out electricity distribution functions effectively. However, opportunities for improvement remain through enhancing network maintenance quality, optimizing transformer capacity, and improving load management. These efforts are expected to enable units with lower efficiency levels to move closer to the efficiency frontier and improve overall operational performance. It should be noted that, with efficiency scores clustered in the 0.949–0.986 range, the practical significance of these differences is limited. Given the estimation uncertainty inherent in SFA-derived efficiency scores, confidence intervals for individual TE estimates may overlap substantially, suggesting that statistically distinguishing ULP performance rankings requires caution. The 0.037-point gap, while indicative of relative performance positions, should not be overinterpreted as a definitive performance hierarchy.

Production Elasticity Calculation Results

The analysis of production elasticity in this study is divided into two parts: elasticity at the aggregate UP3 Parepare level and elasticity at the individual ULP level. This separation is important because the picture at the UP3 level shows general company conditions, whereas analysis at the ULP level can explain variations in productivity between service units according to

regional characteristics, customer load, and asset structure. Thus, the elasticity results not only show the dominant input factors but also provide more specific policy directions for each unit.

At the UP3 Parepare level, the total production elasticity is 0.875, indicating decreasing returns to scale. This means that a 1% increase in all inputs results in only a 0.875% increase in output. This finding indicates that the distribution system, in general, has reached a relatively mature stage, such that additional inputs still increase output but no longer proportionally. Among all input variables, transformer capacity (kV) has the highest elasticity at 1.067, followed by the Medium Voltage Network (JTM) at 0.866 and the Low Voltage Network (JTR) at 0.598. These findings indicate that strengthening system capacity and network development remain the main factors driving increases in electricity distribution output. Conversely, the number of transformers shows negative elasticity at -1.686, indicating that adding transformer units without optimal utilization can actually reduce system productivity.

Analysis at the Customer Service Unit (ULP) level shows variations in production elasticity between service areas. ULP Barru, Pajalesang, Tanrutedong, and Pangsidi have total elasticity values greater than one, indicating increasing returns to scale. This condition shows that increases in inputs are still able to produce proportionally greater increases in output, suggesting that opportunities for distribution system development in these units remain relatively high. Conversely, ULP Mattirotasi and Rappang show negative total elasticity, indicating that additional inputs under current conditions have not been able to increase output proportionally. These findings indicate that performance improvement strategies cannot be generalized across all ULPs but need to be tailored to the characteristics of assets, networks, and resource utilization levels in each service area.

These findings indicate that the effectiveness of production input use differs across service areas. Differences in geographical characteristics, customer density, network structure, and asset utilization levels cause the response of output to additional inputs to vary across ULPs. Therefore, investment and distribution infrastructure development policies need to consider the specific conditions of each service unit. A needs-based regional approach will be more effective than uniform policy application, allowing available resources to be allocated more efficiently to support improvements in electricity distribution performance.

Table 2
Output Elasticity of Inputs in Electricity Distribution

	ULP MTRS	ULP BRR	ULP PSD	ULP TTD	ULP RPG	ULP SPG	ULP PJLSG	UP3
Labor Elasticity (Lt)	-0.091	-0.125	0.294	0.230	-0.147	0.111	-0.107	0.023
Outsourcing Labor Elasticity (Lk)	0.006	0.013	-0.019	0.013	0.014	0.014	0.001	0.006
Medium Voltage Network Elasticity (Jtm)	0.988	-0.618	-0.700	2.029	1.681	0.383	2.299	0.866
Low Voltage Network Elasticity (Jtr)	1.851	3.655	4.042	-0.581	-3.931	0.102	-0.950	0.598
Transformer Elasticity (Trf)	-4.902	-0.368	-3.043	-1.397	-0.827	-0.669	-0.595	-1.686
Transformer Capacity Elasticity (Kv)	1.918	-0.127	0.791	1.463	1.114	0.620	1.690	1.067
Total Elasticity	-0.232	2.430	1.365	1.757	-2.097	0.562	2.339	0.875

Source: SFA data processing results, 2026

Overall, the analysis results show that increasing electricity distribution output at UP3 Parepare cannot be sufficiently achieved through the uniform addition of all inputs. A more

effective policy is to direct investment toward variables with high elasticity, such as transformer capacity and distribution network capacity, while encouraging asset optimization in units that have experienced system saturation. With this approach, increases in output can be achieved more efficiently and sustainably.

Table 3*Stochastic Function Estimation Results*

Variable	Parameter	Coefficient	t-ratio
Production Function			
<i>Constant</i>	α_0	30.427	30.151
Y2	α_{y2}	8.216	5.818
Y3	α_{y3}	-0.990	-2.353
Lt	α_{lt}	-7.266	-4.658
Lk	α_{lk}	-0.082	-1.211
Jtm	α_{jtm}	47.048	31.037
Jtr	α_{jtr}	-109.202	-43.614
Trf	α_{trf}	41.402	26.904
Kv	α_{kva}	0.449	0.259
Lt^2	α_{ltlt}	-0.173	-0.304
Lk^2	α_{lklk}	0.004	1.349
Jtm^2	α_{jtmjtm}	-4.707	-5.503
Jtr^2	α_{jtrjtr}	2.614	1.070
Trf^2	α_{trftrf}	6.788	2.461
Kv^2	α_{kvkv}	-0.880	-1.570
Y2*Y3	α_{y2y3}	0.159	2.257
Lt*Lk	α_{ltlk}	-0.035	-2.388
Lt*Jtm	α_{ltjtm}	0.949	1.860
Lt*Jtr	α_{ltjtr}	0.681	1.270
Lt*Trf	α_{lttrf}	-3.411	-4.175
Lt*Kv	α_{ltkv}	1.250	3.801
Lk*Jtm	α_{lkjtm}	0.032	2.398
Lk*Jtr	α_{lkjtr}	-0.015	-1.014
Lk*Trf	α_{lktrf}	-0.084	-3.464
Lk*Kv	α_{lkkv}	0.035	4.028
Jtm*Jtr	α_{jtmjtr}	4.629	3.515
Jtm*Trf	α_{jtmtrf}	5.315	2.481
Jtm*Kv	α_{jtmkv}	-4.111	-5.781
Jtr*Trf	α_{jtrtrf}	-8.690	-3.322
Jtr*Kv	α_{jtrkv}	6.220	8.279
Trf*Kv	α_{trfkva}	-2.521	-1.862
Y_2^2	α_{y2y2}	-0.531	-6.063
Y2*Lk	α_{y2lk}	0.531	2.005
Y2*Lt	α_{y2lt}	0.022	3.015
Y2*Jtm	α_{y2jtm}	-3.570	-6.159
Y2*Jtr	α_{y2jtr}	5.153	7.455
Y2*Trf	α_{y2trf}	-2.703	-2.842
Y2*Kv	α_{y2kv}	0.833	1.832
Y_3^2	α_{y3y3}	0.010	5.482
Y3*Lt	β_{y3lt}	-0.117	-1.899
Y3*Lk	β_{y3lk}	0.001	0.682
Y3*Jtm	β_{y3jtm}	0.138	1.867
Y3*Jtr	β_{y3jtr}	0.050	0.639
Y3*Trf	β_{y3trf}	-0.600	-3.333

Variable	Parameter	Coefficient	t-ratio
$Y_3 * Kv$	β_{y3*kv}	0.198	3.951
t	γ_t	0.054	2.926
t^2	γ_{tt}	0.000	1.832
Production Function			
$t * Lt$	γ_{t*lt}	-0.016	-3.399
$t * Lk$	γ_{t*lk}	0.000	0.159
$t * Jtm$	γ_{t*jtm}	0.027	6.488
$t * Jtr$	γ_{t*jtr}	-0.050	-9.247
$t * Trf$	γ_{t*trf}	-0.007	-1.145
$t * Kv$	γ_{t*kv}	0.015	4.772
Inefficiency Function			
Constant	δ_0	0.591	5.225
SAIDI	δ_{saidi}	0.001	1.782
SAIFI	δ_{saifi}	-0.055	-2.464
Covid	δ_{covid}	-0.018	-0.737
Expert	δ_{expert}	-0.947	-4.847
Technical	$\delta_{technical}$	-1.335	-4.146
Sigma-squared	σ^2	0.010	10.240
Gamma		0.452	5.533

Inefficiency Factor Calculation Results

Based on the inefficiency model estimation results (Table 3), it was found that the level of technical inefficiency in electricity distribution at UP3 Parepare is influenced by network reliability factors and human resource quality, while external shocks have no significant effect. In the Stochastic Frontier Analysis (SFA) approach, inefficiency describes the distance between actual performance and the optimal performance level (frontier). The smaller the inefficiency value, the better the unit's ability to utilize available inputs to produce maximum output. Therefore, variables in the inefficiency model are important because they can explain the main sources of operational efficiency decline or improvement.

The SAIDI variable shows a positive coefficient (0.001) in the inefficiency model, with a t-ratio of 1.782. At the 10% significance level (critical value = 1.645), this coefficient is statistically significant, suggesting a positive association between disturbance duration and inefficiency. However, at the conventional 5% significance level (critical value = 1.960), this coefficient is not statistically significant. Therefore, while there is indicative evidence that longer disturbance durations are associated with increased inefficiency, the statistical evidence is not robust at the conventional significance level. This finding is directionally consistent with the research by Mirza et al. (2021), which included service indicators such as SAIDI and SAIFI in the efficiency model and found significant effects on technical efficiency.

This result also aligns with some of the findings of Medeiros et al. (2022), which state that distribution service quality, reflected through disturbance duration and frequency, is an important factor associated with the operational efficiency of electricity distribution companies. This can be explained by the fact that disturbances with long recovery times reduce the amount of energy that can be distributed to customers and increase the workload of operational personnel. Furthermore, long disturbance durations often reflect limitations in protection systems, difficult access to disturbance locations, or suboptimal restoration processes. Thus, the ability to accelerate network restoration becomes an important factor in reducing inefficiency.

Conversely, the SAIFI variable shows a negative coefficient (-0.055), with a t-ratio of -2.464, which is statistically significant at the 5% level. This counterintuitive finding—that higher disturbance frequency is associated with lower inefficiency—warrants careful interpretation. Several explanations merit consideration. First, SAIDI and SAIFI in this study exhibit a moderate positive correlation ($r = 0.47$), suggesting that when both are included in the model simultaneously, SAIFI may capture residual variation not explained by SAIDI. Since SAIDI (disturbance duration) already captures the more consequential dimension of service disruption, SAIFI's negative coefficient may reflect the possibility that units experiencing more frequent but shorter interruptions have better-functioning protection systems and faster automatic reclosing

mechanisms, which may indicate well-maintained networks. Second, simultaneity or reverse causality may play a role: ULPs that invest more in automated protection equipment (which improves efficiency) may also record higher SAIFI due to more sensitive trip settings, even though each interruption is brief and has minimal operational impact. Third, omitted variables such as network age and vegetation management intensity may confound the relationship. The results of this study are closer to the findings of Sufia et al. (2025), which showed that efficiency could be maintained even when SAIDI and SAIFI indicators were included in the model. Therefore, the SAIFI result should be interpreted with caution and should not be taken as evidence that more frequent disturbances improve efficiency.

The Covid-19 variable does not show a statistically significant association with technical inefficiency (coefficient = -0.018, t-ratio = -0.737). No statistically significant evidence was found of a relationship between COVID-19 and technical inefficiency in the study sample. This finding does not prove the absence of a pandemic impact; rather, it indicates that the available data do not provide sufficient evidence to conclude that the pandemic systematically affected electricity distribution efficiency in the research area. This condition can be understood because the electricity sector is an essential public service, so electricity distribution operations continued even during the pandemic.

The results of this study differ from the findings of Athira et al. (2024), Lazo et al. (2022) and Nurlia et al. (2023), which found statistically significant associations between the COVID-19 pandemic and the operational efficiency of energy companies. Previous research explained that social restrictions were associated with limited personnel mobility, maintenance delays, and service disruptions, which were related to declining operational performance. However, the results of this study are consistent with the findings of Esmaeili et al. (2023), which found that the COVID-19 pandemic did not have a significant effect on operational performance in the electricity industry. Companies generally made various adjustments, such as modifying work patterns, dividing field teams, implementing health protocols, and digitalizing work coordination so that services could continue.

The strongest factors contributing to reduced inefficiency are human resource quality, particularly the expert and technical variables. These results indicate that a greater proportion of employees with higher education, technical expertise, and operational competence is associated with a greater ability of the unit to manage the electricity distribution system. Competent employees are generally faster at diagnosing disturbances, more precise in operating equipment, more disciplined in asset maintenance, and more adaptive in adopting new technologies, making human resource quality a critical determinant of operational success. These findings align with Human Capital Theory proposed by Schultz (1961), which states that education is a form of investment that can increase individual and organizational productivity, while also supporting the findings of Samagaio & Rodrigues (2016), which state that employee competence directly contributes to improvements in organizational performance. The results of this study are also consistent with the findings of Kim & Shin (2019), Sun et al. (2024), and Dahiya et al. (2025), which confirm that human resource quality contributes to improvements in organizational efficiency.

Overall, the research results confirm that technical inefficiency in electricity distribution is not only a matter of physical assets but is also strongly influenced by the quality of system management. Reliable networks, rapid disturbance response, and competent workers will enable the system to operate more efficiently. Therefore, performance improvement policies should be directed in a balanced manner toward infrastructure investment, service reliability improvement, and human resource capacity development so that electricity distribution efficiency can be improved sustainably.

Discussion

The research results show that the technical efficiency level of electricity distribution at PT PLN (Persero) UP3 Parepare during the 2019–2024 period was in the high-efficiency category. Efficiency values approaching one indicate that the distribution units, in general, have been able to optimally utilize available inputs to produce electricity distribution output. The efficiency trend also shows improvement from 2019 to 2023 before experiencing a slight decrease in 2024. This condition illustrates improvements in operational performance through distribution asset management, network maintenance, and improvements in service quality for customers.

The year-to-year increase in efficiency indicates that UP3 Parepare has been able to gradually improve its electricity distribution processes. Increasing efficiency values indicate that the use of inputs such as labor, distribution networks, transformers, and transformer capacity has become increasingly effective in supporting electricity distribution. However, the slight decrease in 2024 warrants attention because it may indicate potential disruptions to distribution system productivity. This decrease is consistent with the increased duration of disturbances, as measured by the System Average Interruption Duration Index (SAIDI), as well as increased energy losses, both of which can reduce the amount of energy successfully delivered to customers.

When viewed by Customer Service Unit (ULP), variations in efficiency levels can be observed among the ULPs. ULP Mattirotasi, ULP Tanrutedong, and ULP Rappang show relatively higher efficiency levels compared with the other units. This indicates that these three ULPs have better capabilities in optimizing resources and distribution assets. The management practices of ULPs with high efficiency can therefore serve as benchmarks for other ULPs with lower efficiency levels.

Meanwhile, ULP Pajalesang and ULP Barru have lower average efficiency levels than the other ULPs, although they remain in the efficient category. This difference indicates that efficiency levels are influenced not only by the number of assets or available inputs but also by service-area characteristics, geographical conditions, customer density, network quality, and the effectiveness of disturbance management. Therefore, efficiency improvement strategies need to be formulated specifically according to the conditions of each ULP rather than applying a uniform approach across all service units.

The production elasticity analysis results show that the UP3 Parepare electricity distribution system, in aggregate, exhibits decreasing returns to scale. This means that a 1% increase in all inputs produces less than a 1% increase in output. This condition indicates that the distribution system has reached a relatively mature stage, such that additional inputs do not always generate proportional increases in output. Thus, improving distribution performance cannot be sufficiently achieved through additional inputs alone but should instead be directed toward optimizing the utilization of existing assets.

Transformer capacity, the medium-voltage network, and the low-voltage network are the most responsive inputs in increasing electricity distribution output. This finding shows that system capacity strengthening and network development continue to play important roles in improving distribution performance. However, the number of transformers exhibits negative elasticity, indicating that adding transformers without proper planning and optimal utilization may actually reduce system productivity. These findings confirm that investment in distribution assets should be based on actual demand, customer load, and network conditions in each service area.

At the ULP level, the elasticity results show differences in productivity characteristics among the units. Several ULPs remain in a state of increasing returns to scale, meaning that additional inputs still have the potential to generate proportionally greater increases in output. Conversely, some ULPs exhibit negative total elasticity, meaning that additional inputs under current conditions have not been able to increase output effectively. This difference reinforces the importance of region-based policies because each ULP has different network structures, customer numbers, load patterns, and operational challenges.

The inefficiency model estimation results show that SAIDI has a positive association with technical inefficiency at the 10% significance level. This suggests that longer durations of electricity interruptions experienced by customers tend to be associated with higher levels of distribution inefficiency. This relationship can be understood because prolonged interruptions reduce the duration of electricity service, decrease service continuity, and increase the operational burden on field personnel. Thus, reducing interruption duration is an important strategy for improving electricity distribution efficiency.

Unlike SAIDI, the System Average Interruption Frequency Index (SAIFI) variable shows a negative association with inefficiency. This finding indicates that the frequency of interruptions occurring during the research period does not necessarily reduce efficiency when the interruptions are minor and can be resolved quickly. In the context of distribution systems, a high interruption frequency does not necessarily have a substantial impact if restoration times are short and protection systems operate effectively. Therefore, what determines efficiency to a

greater extent is not simply how often interruptions occur, but how quickly the company can restore service.

The COVID-19 variable does not show a statistically significant effect on technical inefficiency. No statistically significant evidence of a pandemic effect on electricity distribution performance was found in this sample from UP3 Parepare. This condition may have occurred because the electricity sector is an essential service that must continue to operate under various circumstances. Furthermore, adjustments to work patterns, the division of operational teams, the implementation of health protocols, and the use of digital coordination systems may have helped maintain the continuity of electricity distribution services during the pandemic.

The strongest factor associated with reducing inefficiency is human resource quality, as represented by the education and technical expertise variables. A higher proportion of employees with adequate educational qualifications and technical expertise is associated with lower levels of electricity distribution inefficiency. Employees with stronger competencies tend to be better able to identify disturbances more quickly, operate equipment more precisely, perform asset maintenance more effectively, and adapt to the operational technologies used by the company.

These findings indicate that electricity distribution efficiency is determined not only by physical assets but also by management quality and human resource competence. Good network infrastructure needs to be supported by a workforce capable of managing the system professionally. Therefore, technical training programs, improvements in employee education, competency certification, and the strengthening of disturbance-analysis capabilities are important steps toward improving efficiency sustainably.

Overall, the research results confirm that improving electricity distribution efficiency at UP3 Parepare requires three main strategies. First, distribution asset optimization, particularly of transformer capacity and distribution networks. Second, improvement of system reliability by reducing interruption duration through accelerated service restoration and preventive maintenance. Third, strengthening human resource quality through improvements in technical and managerial competencies. Through these strategies, UP3 Parepare can maintain high efficiency levels while promoting sustainable improvements in electricity service performance.

This study has several limitations that should be acknowledged. First, the analysis relies on administrative data from a single UP3 unit (Parepare), which limits the generalizability of the findings to other PLN distribution units with different geographical, economic, and operational characteristics. Second, the SFA approach, while separating inefficiency from random noise, does not establish causal relationships; therefore, the associations identified between inefficiency determinants and technical efficiency should be interpreted as correlational rather than causal. Third, the 21 missing observations (4.2% of the planned sample) result in an unbalanced panel that, although accommodated by the estimator, could introduce selection bias if the missing data are systematically related to efficiency levels. Fourth, the use of a COVID-19 dummy variable (binary indicator) may not fully capture the heterogeneous and time-varying nature of pandemic impacts across different phases of restrictions and recovery. Future research could extend this analysis to multiple UP3 units for cross-regional comparison, incorporate additional environmental and regulatory variables, employ panel-data methods with causal identification strategies such as instrumental variables or difference-in-differences designs, and explore the use of dynamic SFA models to capture temporal patterns in efficiency evolution.

CONCLUSION

This study analyzed the technical efficiency of electricity distribution at PT PLN (Persero) UP3 Parepare during 2019–2024 using Stochastic Frontier Analysis (SFA) with a translog production function. The findings demonstrate that all seven ULPs operated at high efficiency levels (mean efficiency above 0.97), with ULP Mattirotasi achieving the highest average efficiency (0.986), followed by ULP Tanrutedong (0.983) and ULP Rappang (0.980). The efficiency trend showed consistent improvement from 0.913 in 2019 to 0.984 in 2023, followed by a marginal decline to 0.980 in 2024. The distribution system exhibited decreasing returns to scale in aggregate (total elasticity = 0.875), with transformer capacity, the medium-voltage network, and the low-voltage network identified as the inputs most responsive to increases in output. Regarding the determinants of technical inefficiency, human resource quality, measured by the proportion of employees with expert and technical educational backgrounds, emerged as the

strongest factor associated with reduced inefficiency. SAIDI showed a positive association with inefficiency at the 10% significance level, while no statistically significant evidence was found for an effect of the COVID-19 pandemic on distribution inefficiency.

The study contributes to the literature by demonstrating that integrating reliability indicators, human capital variables, and external shocks into a single-stage SFA inefficiency model at the service-unit level yields nuanced insights that are not captured by aggregate-level analyses or efficiency measurement alone. The findings suggest that improving electricity distribution efficiency requires a balanced approach encompassing distribution-asset optimization (particularly transformer capacity and network infrastructure), reliability enhancement through accelerated outage restoration and preventive maintenance, and sustained investment in employee competency development. A key limitation of this study is its focus on a single UP3 unit, which constrains the generalizability of the findings. Future research should extend this framework to multiple UP3 units across different geographical contexts, incorporate dynamic efficiency models to capture temporal evolution, and employ causal identification strategies to establish the direction of the relationships between reliability indicators and technical efficiency.

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AUTHOR CONTRIBUTION STATEMENT

Endah Suryaning Wulandari and Dyah Wulan Sari contributed to the conceptualization, methodology, data collection, data analysis and interpretation, manuscript preparation, validation, and final revision of the study. Both authors have read and approved the final version of the manuscript.

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