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EFFICIENT STRATEGY FOR DISTRIBUTION TRANSFORMER REPLACEMENT: A STUDY ON REPLACEMENT METHODS IN POWER SYSTEMS

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ABSTRACT

A dependable and efficient electric power distribution system is increasingly required due to growing industrial and population demand. Many distribution transformers currently in use are outdated, which increases operating expenses and reduces efficiency. This study examines the issue of determining the most cost-effective time to replace aging distribution transformers to optimize operational expenses and enhance service performance. The purpose of this study is to calculate the annual operating costs of distribution transformers at PT PLN (Persero) Makassar Branch and to identify the optimal replacement time to support more effective decision-making. Using an economic feasibility analysis based on the annuity method and linear regression, this study compares the annual operating costs of old transformers with those of new ones. The findings indicate that the annual cost of old transformers is higher than that of new ones, suggesting that replacing old transformers is more economical. The results show that operating expenses can be reduced and distribution efficiency improved through a systematic transformer replacement approach. Based on economic engineering analysis, this study provides a practical and relevant model for transformer replacement decision-making that can assist asset management and investment planning in the power industry.

Keywords: *annual cost of transformer, distribution transformer, operational cost, replacement.*

I. INTRODUCTION

THE demand for a reliable and efficient electric power system continues to increase due to rapid industrial and population growth. Within this system, distribution transformers play a crucial role in stepping down voltage from the primary network to a level that consumers can directly utilize. These transformers are central to maintaining electricity supply continuity and quality [1], [2]. Developing and sustaining distribution systems, including the procurement of transformers, requires significant investment [3], [4]. Over time, transformer reliability declines, which increases operating expenses such as component replacement and maintenance [5], [6]. Operating transformers beyond their economic lifetime may lead to maintenance costs that exceed the benefits, resulting in inefficiencies and wasted resources [7], [8]. Electric utility companies such as PT PLN (Persero) must regularly evaluate the technical and economic feasibility of transformers to maintain service efficiency and quality. Global trends in energy infrastructure management are shifting toward data-driven decision-making and engineering economics to ensure sustainability, cost efficiency, and system resilience. As energy transition, urbanization, and transportation electrification progress, distribution transformers have become critical components that require management strategies grounded in quantitative analysis.

The main issue in this context is determining the optimal timing for rejuvenating or replacing distribution transformers to achieve a balance between cost and benefit. Although a transformer may remain technically operational, it may no longer be economically viable due to increasing maintenance costs and the risk of service disruption [9], [10]. Rising operating costs, including repairs and outages, may also drive up power generation costs [11], [12]. In the long term, this situation negatively affects both customers and the utility company. Early replacement may compromise investment efficiency. Alternatively, delaying replacement leads to substantial maintenance costs and higher risks of system failure [13], [14]. Therefore, quantitative methods that consider both technical and economic aspects are essential in modern electric asset management practices.

Replacement analysis is an appropriate solution to address this problem. Through this approach, the economic lifespan of a transformer can be calculated quantitatively by considering average annual costs, including depreciation, maintenance, energy losses, and downtime [15], [16]. The evaluation compares existing equipment (defender) with potential replacements (challenger), assessing both physical conditions and economic performance [17], [18]. This technique is increasingly relevant in the context of power system modernization and energy efficiency policies, especially amid the growing penetration of electric vehicles and the integration of renewable energy sources that demand high reliability from distribution infrastructure. The method is grounded in engineering economics, particularly in determining economic equipment life, defined as the point at which total annual cost is at its minimum [19], [20]. Analytical techniques such as Annual Worth (AW) and Equivalent Annual Cost (EAC) are employed to comprehensively assess depreciation, operating costs, investments, and related cost elements [21], [22].

Previous studies have widely discussed the technical aspects of distribution transformers; however, integrated economic approaches in equipment replacement strategies to determine optimal replacement timing based on real cost analysis remain limited [23], [24]. Recent works, such as Pradhan et al., emphasize the importance of maintaining transformer reliability in response to load changes due to electric vehicle adoption by applying optimization to reduce thermal aging [25]. Fant et al. highlight the need for adaptive policies and infrastructure replacement to mitigate long-term costs [26]. Zhang et al. demonstrate the influence of load on transformer lifetime and the importance of methodical assessment approaches [27]. Rahman et al. reinforce the relevance of technical evaluations since changing load patterns driven by electric vehicle adoption affect transformer performance [28]. However, none of these studies specifically evaluate transformer replacement timing using a techno-economic approach based on actual data from distribution systems. Therefore, this study addresses existing research gaps by determining optimal replacement timing for distribution transformers through real operational data and a microeconomic perspective in the context of PT PLN (Persero).

The main objective of this study is to determine the annual costs of distribution transformers at PT PLN (Persero), South and West Sulawesi Regional Office, Makassar City, using the replacement method to identify the most economically efficient replacement timing. The originality of this study lies in applying engineering economic analysis through the replacement approach, which considers not only technical elements such as operating age and insulation condition but also the company's actual annual cost data. By utilizing real operational data from transformers that have been or will be replaced, this study provides a concrete overview of cost efficiency based on load characteristics and field conditions. This distinguishes the study from previous work that relied mainly on predictive or simulation-based analysis.

The contribution of this study is both practical and theoretical. Practically, it offers strategic recommendations for PT PLN (Persero) in investment planning and asset management to ensure a reliable and efficient electricity distribution system. Theoretically, it enriches academic discourse in electrical engineering, particularly in applying engineering economics for revitalizing distribution equipment. Over time, consistent use of this technique may improve operational efficiency and service quality in Indonesia's electrical sector, while supporting more effective investment planning in the national energy system.

II. Research Method

This article employs a quantitative research approach. The study examines replacement strategies for distribution transformers using the replacement analysis method. Through mathematical computations and numerical data analysis, the method determines the yearly cost of transformers, compares the performance of old and new units, and identifies the optimal replacement timing based on technical and economic considerations.

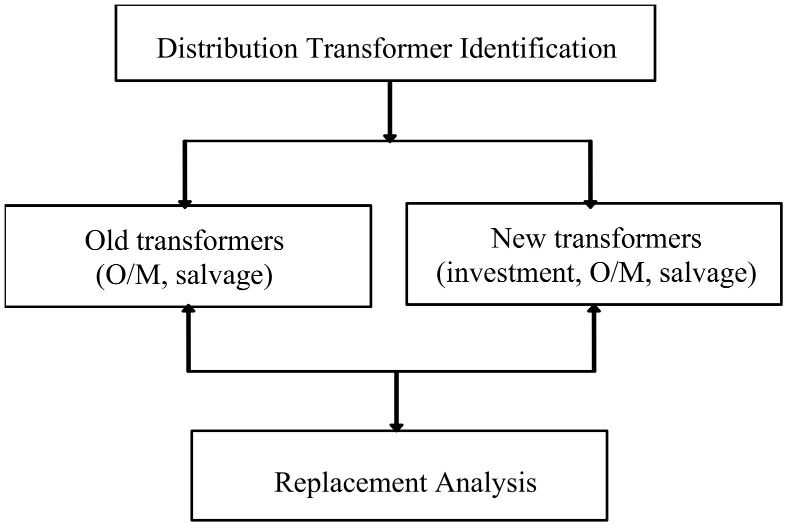

Figure 1. Conceptual Framework of Replacement Analysis

A. Research Location and Time

This study was conducted at PT PLN (Persero) Makassar Branch, one of PT PLN's operational units responsible for distributing power in Makassar and surrounding areas. The site was selected based on the relevance of distribution transformers to the study objectives and the availability of supporting data. The research took place over approximately two months, starting in March and concluding in April.

B. Data Collection Methods

Several techniques were applied to collect data for this study. First, documented data collection was conducted to examine events relevant to the research objective. This information was obtained from official documents or archives that provide records of operational conditions. Second, a literature review was performed by collecting various sources, including work reports, reference books, scientific publications, learning materials, and papers that support the theoretical foundation of the study. Third, interviews, sharing sessions, and discussions were conducted to validate field conditions and compare them with the documentation findings, resulting in a more comprehensive understanding. Finally, documentation such as photos, videos, field notes, and other physical evidence was gathered to support the primary data and strengthen the research findings.

C. Research Object

The object of this study is the distribution transformers operating within the 20 kV distribution network system at PT PLN (Persero) Makassar Branch.

D. Tools Used

The study utilized both hardware and software. The hardware consisted of a computer (laptop) and a printer. The software used was Microsoft Windows 7.

E. Data Analysis Techniques

The collected data were used to calculate the annual cost of the distribution transformers by applying predetermined formulas and analyzing the results based on the research objectives. The replacement analysis method was applied for the 20 kV distribution network system. The first step was to select two transformer units as samples, one aged unit and one new unit. Data were collected on transformer specifications, purchase prices, technician labor wages, number of workers, and loss costs of the 20 kV distribution transformers at PT PLN (Persero) Makassar Branch. After data collection, processing was conducted to calculate the average annual cost of each transformer. Costs for the new transformer included investment, operational and maintenance costs, and salvage value. For the old transformer, operational and maintenance costs and salvage value were considered. All calculated costs were then summed to obtain the total annual cost of each transformer. The final step was to estimate the annuity of the average annual costs for both transformers and conduct a comparison to support the replacement decision using the replacement method.

Figure 1 presents the Conceptual Framework for the Replacement Analysis of distribution transformers used in this study. The process begins with identifying the distribution transformer as the object of analysis. Subsequently, two categories of transformers, old and new, are evaluated by considering investment costs, operation and maintenance (O&M) expenses, and salvage value. Data from both transformer types are then compared in the replacement analysis stage to determine the most economical alternative. This diagram illustrates the logical flow of decision-making for transformer replacement based on a comprehensive assessment of annual costs.

III. RESULT AND DISCUSSION

A. Research Results

The collected data support the assessment of the essential components required for problem-solving. Comprehensive information is needed to calculate the annual cost of each piece of equipment, including labor costs, specifically the wages of equipment operators, the purchase price of both old and new transformers, transformer loss costs, and maintenance expenses.

1) Operational Cost Trend Analysis of Transformers: Labor

The equipment operators work in three shifts, with one operator assigned per shift. The labor wages for equipment operators are presented in Table 1.

The data in Table 1 show a consistent upward trend in operator wages across eleven years. The monthly wage increased from IDR750,000 in the first year to IDR1,250,000 in the eleventh year. This growth reflects adjustments for inflation, rising living expenses, or internal corporate policies related to employee welfare. Since one operator manages each shift, and there are three shifts per day, three operators work in rotation daily to ensure continuous transformer operation. The annual wage increase must be taken into account in long-term operational cost analysis, particularly when performing an economic evaluation of equipment sustainability or making replacement decisions using the replacement method. Therefore, the wage growth trend is a crucial component in calculating the total annual cost of transformer operations.

2) Operational Cost Trend Analysis of Transformers: Maintenance Costs

In Table 2, the maintenance costs for the old transformer show an increasing trend over twelve years. In the first year, maintenance costs were recorded at IDR10,578,000. As time progresses and the transformer ages, these costs rise gradually. For instance, in the second year, the cost increased to IDR11,004,500, then rose to IDR12,456,000 in the third year and IDR13,987,500 in the fourth year. This increase indicates the growing need for maintenance caused by declining equipment performance. In the sixth year, when the cost reached IDR15,400,500, a notable rise occurred, and it continued to increase to IDR18,236,000 in the seventh year. This trend shows that the intensity and frequency of maintenance activities rise as the equipment ages, directly impacting total costs. By the twelfth year, maintenance expenses reached IDR24,340,000, almost double the amount in the first year of operation. Replacement analysis relies on this growing trend because it shows that maintaining obsolete equipment for an extended period may cause significant cost accumulation and reduced operational efficiency.

The maintenance costs presented in Table 3 for the new transformer are recorded starting from the sixth year, which marks the beginning of its operation. In the first year of use (year 6), the maintenance cost was IDR15,400,500. As the transformer ages and its operating hours increase, the maintenance cost shows an upward trend. In year 7, the cost rose to IDR18,236,000, followed by a slight increase to IDR18,708,000 in year 8. A more noticeable rise occurred in year 9, when the cost reached IDR21,320,000. This upward trend continues in years 10 and 11, with respective costs of IDR23,056,000 and IDR24,100,000. By year 12, the maintenance cost of the new transformer reached IDR24,340,000. Although the transformer is still relatively new compared with the older unit, this rise shows the increasing requirement for maintenance as the equipment matures. This information is essential for assessing the economic viability of long-term transformer use, particularly in terms of operating cost efficiency.

Thus, based on the data in Tables 2 and 3, a comparison of annual maintenance costs between the old and new transformers can be made. For the old transformer, a significant cost increase is observed, from

TABLE 1.
EQUIPMENT OPERATOR WAGES

Year	Monthly Wage (IDR)
1	750,000
2	800,000
3	850,000
4	900,000
5	950,000
6	1,000,000
7	1,050,000
8	1,100,000
9	1,150,000
10	1,200,000
11	1,250,000

TABLE 2.
MAINTENANCE COSTS OF THE OLD TRANSFORMER

Year	Maintenance Cost (IDR)
1	10,578,000
2	11,004,500
3	12,456,000
4	13,987,500
5	14,000,300
6	15,400,500
7	18,236,000
8	18,708,000
9	21,320,000
10	23,056,000
11	24,100,000
12	24,340,000

TABLE 3.
MAINTENANCE COSTS OF THE NEW TRANSFORMER

Year	Maintenance Cost (IDR)
6	IDR15,400,500
7	IDR18,236,000
8	IDR18,708,000
9	IDR21,320,000
10	IDR23,056,000
11	IDR24,100,000
12	IDR24,340,000

TABLE 4.
LOSSES COST OF THE OLD TRANSFORMER

Year	Losses Cost
1	13,850,000
2	14,234,000
3	14,980,000
4	15,320,000
5	16,230,000
6	17,340,000
7	18,750,000
8	19,434,000
9	21,053,000
10	22,150,000
11	23,545,000
12	24,740,000

IDR10,578,000 in the first year to IDR24,340,000 in the twelfth year, indicating increasing maintenance needs due to declining performance. By comparison, the expenses of the new transformer are recorded beginning in year 6 and show a steady rise, although at a lower rate. This information supports the conclusion that maintaining a new transformer is more economical over the long term.

3) Operational Cost Trend Analysis of Transformers: Losses Cost

The losses cost of the old transformer in Table 4 shows a consistent upward trend as the equipment ages. In the first year, energy losses were recorded at IDR13,850,000. This figure continued to increase, reaching IDR14,234,000 in the second year and IDR14,980,000 in the third year. In the following years, the losses continued to grow, with fourth year losses at IDR15,320,000 and fifth year losses at IDR16,230,000. More notable increases occurred from the sixth to the eighth year, rising from

TABLE 5.
ENERGY LOSS COSTS OF THE NEW TRANSFORMER

Year	Losses Cost (IDR)
6	10,340,000
7	12,458,000
8	14,555,000
9	16,234,000
10	17,505,000
11	18,545,000
12	19,354,000

TABLE 6.
EQUIPMENT OPERATOR WAGES FOR THE OLD TRANSFORMER

Year	Monthly Wage (IDR)	Number of Operators	Total Wage (IDR)
1	750,000	3	2,250,000
2	800,000	3	2,400,000
3	850,000	3	2,550,000
4	900,000	3	2,700,000
5	950,000	3	2,850,000
6	1,000,000	3	3,000,000
7	1,050,000	3	3,150,000
8	1,100,000	3	3,300,000
9	1,150,000	3	3,450,000
10	1,200,000	3	3,600,000
11	1,250,000	3	3,750,000
12	1,300,000	3	3,900,000

IDR17,340,000 to IDR18,750,000 and then IDR19,434,000. This pattern reflects a time-related decline in transformer efficiency. By the twelfth year, the losses had risen sharply to IDR24,740,000. This gradual rise indicates that the older the transformer, the greater the energy wasted during distribution, which leads to inefficiency and increased operational burden. Replacement analysis must take this trend into account, because prolonged use of aging transformers increases energy loss costs and reduces overall system efficiency.

The energy loss cost of the new transformer in Table 5 indicates a gradual upward trend during its seven years of operation. In the sixth year, the loss cost was recorded at IDR10,340,000 and increased to IDR12,458,000 in the seventh year. This trend continued in the following years, reaching IDR14,555,000 in the eighth year and IDR16,234,000 in the ninth year. The rise indicates the effects of transformer aging and increasing load conditions over time. Further increases in the tenth, eleventh, and twelfth years reached IDR 17,505,000, IDR 18,545,000, and IDR 19,354,000, respectively. This consistent growth shows that although the transformer is still relatively new, its efficiency gradually decreases over time, affecting the associated energy loss cost. This information is important for long-term efficiency assessments and strategic asset management of distribution transformers.

Table 4 demonstrates an increasing trend in energy loss costs for the old transformer, starting at IDR 13,850,000 and rising to IDR 24,740,000 over twelve years. This suggests that transformer efficiency degrades significantly with age. By contrast, Table 5 shows that the new transformer experiences lower energy loss costs in its early years, although it also exhibits an upward trend. These findings emphasize that timely transformer replacement is essential for maintaining optimal power distribution efficiency.

4) Annual Cost of the Old Transformer

The transformer in this study is a 20 kV distribution transformer with a technical lifespan of 25 years. Since it has been in operation for 12 years, the remaining service life of the old transformer is 13 years. The operational and maintenance costs, energy losses, and salvage value of this transformer are shown in Table 6.

The data in Table 6 show the progression of equipment operator wages over 12 years. The number of operators remains constant at three people working in a three-shift system. In the first year, the monthly wage for one operator was IDR750,000, resulting in a total monthly wage of IDR2,250,000 for three operators. Each year, the monthly wage increased consistently, which reflects workplace policy, cost of living adjustments, or inflationary changes. From year two to year twelve, this rising pattern continues. For example, in the second year, the monthly wage per operator increased to IDR800,000, generating a total monthly wage of IDR2,400,000. This upward trend continued until the sixth year, when the

TABLE 7.
TOTAL OPERATIONAL AND MAINTENANCE COSTS OF THE OLD TRANSFORMER

Year	Operator Wages (IDR)	Maintenance (IDR)	Losses (IDR)	Total O & M (IDR)
1	3,170,687	9,394,876	24,829,708	37,395,270
2	3,118,972	10,487,165	24,536,488	38,142,626
3	3,067,894	11,520,584	24,242,802	38,831,279
4	3,017,452	12,497,353	23,948,845	39,463,650
5	2,967,645	13,419,622	23,654,805	40,042,072
6	2,918,473	14,289,467	23,360,862	40,568,803
7	2,869,934	15,108,898	23,067,186	41,046,019
8	2,822,027	15,879,856	22,773,939	41,475,822
9	2,774,750	16,604,218	22,481,274	41,860,242
10	2,728,099	17,283,799	22,189,338	42,201,237
11	2,682,074	17,920,352	21,898,269	42,500,695
12	2,636,671	18,515,572	21,608,198	42,760,441
13	2,591,888	19,071,096	21,319,250	42,982,234
		Total		529,270,391

$$a = \frac{\sum Y(t) - b \sum t}{n} \tag{1}$$

$$b = \frac{n \sum t.Y(t) - \sum t \sum Y(t)}{n \sum x^2 - (\sum t)^2} \tag{2}$$

$$A(O\&M) = P(\frac{A}{P}; 2.5\%, 13) \tag{3}$$

$$Salvage\ value = 25\% \times IDR230{,}000{,}000 \tag{4}$$

$$A(S) = F(A/F; 2.5\%. 13) \tag{5}$$

$$A(Old\ Transformer) = A(O\&M) - A(S) \tag{6}$$

$$A(O\&M) = P(A/P; 2.5\%; 18) \tag{7}$$

$$Salvage\ value = 25\% \times IDR255{,}000{,}000 \tag{8}$$

$$A(S) = L(A/F; 2.5\%; 18) \tag{9}$$

$$(A_{New}) = A(INV) + A(O\&M) - A(S) \tag{10}$$

monthly wage reached IDR1,000,000 per operator, resulting in a total wage of IDR3,000,000. By the twelfth year, the monthly wage per operator was IDR1,300,000, yielding a total monthly wage of IDR3,900,000 for all three operators. This consistent increase reinforces the need to carefully consider labor costs in long-term economic analysis, because these costs significantly influence total operational expenses. Therefore, this information is essential for calculating the annual cost of transformers, whether maintaining the old equipment or considering investment in new equipment.

The operator wages for the old transformer over 12 consecutive periods were analyzed using the linear regression method (Attachment 1). Each period is numbered from 1 to 12, representing a sequential time series without reference to specific calendar years. For each period, the monthly operator wage ($Y(t)$), the product of the period and wage ($t•Y(t)$), and the squared period value (t^2) were recorded. In the first period, the operator wage was IDR2,250,000, resulting in $t•Y(t)$ of IDR2.250.000 and t^2 of 1. These values increased in each period. For instance, in the sixth period, the wage was IDR3,000,000, with $t•Y(t)$ amounting to IDR18.000.000 and t^2 equal to 36. In the twelfth period, the wage was IDR3,900,000, with $t•Y(t)$ at IDR46,800,000 and and t^2 at 144. Across all 12 periods, the total of all periods ($\sum t$) is 78. The total operator wage ($\sum Y(t)$) is IDR36,900,000. The total of $t•Y(t)$ is IDR261,300,000, and the sum of t^2 is 650. These data form the basis for calculating the wage trend using a linear regression approach.

Based on the linear regression calculation results in (2), the regression coefficient (b) was found to be

IDR 26,916, indicating an average increase in operator wages per period. Furthermore, the regression equation's constant (*a*), or intercept, was calculated to be IDR 2,900,046, representing the estimated initial wage at period zero (before observations began), as shown in (1). Therefore, the linear regression model resulting from the operator wage data over 12 periods can be expressed as: $Y(t) = 2.900.046 + 26.916t$ where $Y(t)$ is the operator wage at period (t). The equation shows that wages increase by IDR 26,916 in every period, demonstrating a consistent upward trend.

After calculating operator wages using the linear regression method, the estimated annual wages ranged from IDR 3,170,687 to IDR 2,591,888, with Present Value (*PV*) decreasing over time (Attachment 2). Annual maintenance costs were also calculated using linear regression, with values ranging from IDR 9,394,876 to IDR 19,071,096, adjusted using the discount factor (Attachment 3). Meanwhile, transformer energy losses were estimated using regression, resulting in annual loss costs ranging from IDR 24,829,708 to IDR 21,319,250. After summing these components, the old transformer's total operating and maintenance costs over its remaining 13-year lifespan amounted to IDR 529,270,391, as shown in Table 7.

Table 7 presents the total combined cost of the three main components: operator salaries, maintenance costs, and transformer losses for the old transformer over its remaining service life of 13 years. These values were calculated using linear regression and adjusted with a 2.5% annual discount factor. This table serves as the basis for calculating the old transformer's annual annuity value. The annuity value of the total operational and maintenance costs must be determined to compute the annual operational and maintenance expenses.

Using the annuity method with an interest rate of 2.5% over 13 years, the annual operational and maintenance cost is IDR94,792,327 per year, as shown in (3). Furthermore, the salvage value of the old transformer is estimated at 25% of the initial price of IDR230,000,000, which amounts to IDR57,500,000 (see (4)). After being annuitized, it becomes IDR3,795,000 per year (see (5)). Thus, after accounting for the salvage value, the old transformer's total annual cost amounts to IDR90,997,327, as shown in (6).

5) Annual Costs of the New Transformer

The investment cost for the new transformer is IDR255,000,000, with a technical lifespan of 25 years. The annuity value of this investment is calculated using the formula A(P; 2.5%, 18), resulting in an annual cost of IDR17,518,500. The operation and maintenance costs consist of several components. First, the operator cost is calculated based on three workers in three shifts, with one person per shift. Monthly salaries from year 6 to year 12 increase gradually, starting from IDR1,000,000 per month and reaching IDR1,300,000 in year 12 (Attachment 4). Using the linear regression method, the regression equation yields a constant (a) of IDR3,333,136 and a regression coefficient (b) of IDR29,216 (Attachment 5). Using this model, the estimated wages up to year 25 are obtained and then discounted using the corresponding year's discount factor (DF) to calculate the Present Value (PV). The total annual operator cost from year 8 to year 25 ranges from IDR3,566,864 to IDR4,063,536. The PV values decrease in accordance with the annual DF, from IDR3,479,867 to IDR2,605,401 (Attachment 6).

For maintenance costs, data from 2006 to 2012 show a gradual increase from IDR15,400,500 to IDR24,340,000. Using the linear regression method, the resulting regression equation has a constant (a) of IDR14,609,429 and a regression coefficient (b) of IDR1,531,946 (Attachment 7). The estimated maintenance costs from year 8 to year 25 range from IDR26,865,000 to IDR52,908,089. The discounted PV values range from IDR26,209,756 to IDR33,922,863 (Attachment 8). The next component is energy loss cost, which refers to energy losses occurring in the transformer. Initial data show an increase from IDR10,340,000 in 2006 to IDR19,354,000 in 2012 (Attachment 9). Using linear regression, the resulting equation has a constant (a) of IDR8,376,590 and a regression coefficient (b) of IDR302,569 (Attachment 10). The estimated energy loss costs from year 8 to year 25 increase from IDR10,797,138 to IDR15,940,803. The PV values decrease from IDR10,533,793 to IDR10,220,700 (Attachment 11).

Overall, the annual cost of the new transformer consists of four main components: investment annuity, operator cost, maintenance cost, and energy loss cost. All components are calculated using the linear regression method and discounted to estimate real values up to year 25. The total operational and maintenance cost of the new transformer is presented in Table 8.

TABLE 8.
TOTAL OPERATIONAL AND MAINTENANCE COSTS OF THE NEW TRANSFORMER

Year	Operator Wages (IDR)	Maintenance (IDR)	Losses (IDR)	Total O & M (IDR)
1	3,479,867	26,209,756	10,533,793	40,223,417
2	3,422,801	27,028,623	10,564,861	41,016,284
3	3,366,448	27,791,952	10,588,146	41,746,546
4	3,310,808	28,501,968	10,604,011	42,416,786
5	3,255,879	29,160,815	10,612,803	43,029,497
6	3,201,660	29,770,568	10,614,858	43,587,086
7	3,148,149	30,333,230	10,610,499	44,091,879
8	3,095,344	30,850,735	10,600,039	44,546,118
9	3,043,242	31,324,951	10,583,776	44,951,969
10	2,991,840	31,757,682	10,562,002	45,311,523
11	2,941,135	32,150,669	10,534,993	45,626,797
12	2,891,124	32,505,594	10,503,018	45,899,736
13	2,841,802	32,824,080	10,466,337	46,132,219
14	2,793,167	33,107,693	10,425,196	46,326,056
15	2,745,214	33,357,944	10,379,836	46,482,994
16	2,697,938	33,576,293	10,330,487	46,604,718
17	2,651,335	33,764,147	10,277,370	46,692,853
18	2,605,401	33,922,863	10,220,700	46,748,963
		Total		801,435,443

The annuity value of the total operational and maintenance costs must be calculated to determine the annual operational and maintenance cost. In determining the economic feasibility of a new transformer, the total annual cost must be calculated by considering three components: investment cost, operational and maintenance (O&M) cost, and salvage value. First, the annuity value of the O&M cost is determined using the annuity factor over 18 years with an interest rate of 2.5%, resulting in IDR 55,860,050, as shown in (7). The purchase price of the new transformer is IDR 255,000,000, with an estimated salvage value of 25%. The salvage value is estimated at 25% of the initial investment cost of IDR 255,000,000, resulting in IDR 63,750,000 (see (8)). When annualized using the sinking fund factor for a uniform series (A/F; 2.5%; 18), the annuity value of the salvage becomes IDR 2,849,625 (see (9)). Therefore, the total annual cost of the new transformer is calculated by summing the annuity values of the investment cost and *O&M* cost and then subtracting the salvage annuity. This results in IDR 70,528,925, as shown in (10).

6) Analysis of the Old and New Transformers

The Kolmogorov–Smirnov test was conducted on the residuals to determine whether they follow a normal distribution, which is one of the key assumptions of classical linear regression analysis. The test results show a significant value of 0.10 for the old transformer model and 0.20 for the new transformer model. Since both significant values are greater than 0.05, it can be concluded that the residuals are normally distributed in both models. This indicates that the regression models meet the assumption of residual normality, making the estimation and prediction results valid and reliable for decision-making.

Since the significant value of the independent variable is greater than 0.05 and the standardized coefficient is low, it can be concluded that the regression model for both the old and new transformers does not experience multicollinearity issues. Therefore, the model can be reliably used for further analysis and decision-making.

The correlation test (R) is used to determine how much of the total variation in the dependent variable can be explained by the regression model. Based on the correlation test results, the coefficient of determination is approximately $r^2 \approx 0.3492$, indicating that about 34.92% of the variation in annual costs can be explained by the regression model. The correlation coefficient of $r \approx 0.591$ suggests a moderately strong and positive relationship between the operational age of the transformer and the increase in operational and maintenance costs. This supports the conclusion that replacing the old transformer with a new unit is an economically sound decision, as costs tend to increase with transformer aging.

The coefficient of determination, $R^2 = 0.3492$ or 34.92%, indicates that 34.92% of the variation in annual costs can be explained by the regression model based on the observed factors such as operational time, operator costs, maintenance costs, and energy losses. In other words, the model accounts for 34.92% of the changes in annual costs, suggesting it has a reasonable ability to predict cost increases based on transformer age and other related variables. Therefore, the model can be used as a supporting reference in making strategic decisions related to equipment replacement.

The analysis results show a significant value (Sig.) of 0.000, which is far below the threshold of α = 0.05. This indicates that the model is fit and suitable for supporting decision-making in determining an economically viable strategy for replacing distribution transformers.

The T-test results in the regression model indicate that the transformer (Trafo) variable has a significant effect on the annual cost, with a regression coefficient (B) of 1.058 and a t-value of 2416.673. The significance value (Sig.) of 0.000 is well below the critical threshold of α = 0.05, confirming that the influence of the transformer variable on the annual cost is statistically significant.

The positive B coefficient of 1.058 suggests that each one-unit increase in the transformer variable (i.e., the shift from the old transformer to the new one) leads to a predicted increase in annual cost by 1.058 units, according to the adjusted measurement scale. The standardized Beta coefficient of 1.000 indicates that this variable has a very strong influence in explaining variations in annual costs, reaching the maximum possible value. Therefore, the transformer variable plays a significant and dominant role in determining the total annual distribution cost. This finding supports strategic decision-making to replace old transformers with new ones, as the type of transformer has been shown to have a substantial impact on operational cost efficiency.

The selection of a 2.5% discount rate in this study is based on the assumption of a conservative long-term real interest rate that reflects macroeconomic stability and domestic monetary policy. This rate represents a low opportunity cost of capital and aligns with investment planning practices in utility infrastructure, which prioritize long-term sustainability and efficiency. To evaluate the robustness of the analysis against variations in the discount rate, a sensitivity test was conducted by assessing its impact on the annualized total costs of the old and new transformers under two additional scenarios: a lower rate of 1% and a higher rate of 5 percent.

Note: Calculations were performed using the annuity formula with standard annuity factors (*A*/*P*, *i*%, *n*) and (*A*/*F*, *i*%, *n*), corresponding to the analysis periods of 13 years for the old transformer and 18 years for the new transformer. The (*A*/*F*, *i*%, *n*) factor refers to the annuity factor for future value, which is a coefficient used to convert a future value (*F*) into a fixed annual value (*A*) over a given time period (*n*) and discount rate (*i*%). In this context, A represents the amount that must be allocated each year for n years to be economically equivalent to the future value *F*, based on the discount rate *i*%. This factor is commonly used in engineering economics to determine the annualized cost burden of residual equipment value at the end of its service life.

The results show that under all discount rate scenarios, the annual cost of the old transformer remains higher than that of the new transformer, with a consistent and significant difference. This finding indicates that replacing the old transformer with a new one remains economically viable, even when the discount rate assumption changes. Therefore, the model is robust and reliable for supporting strategic decision-making related to infrastructure renewal at PT PLN (Persero).

7) Comparison between the new and the old transformer

The annual cost calculation for the old transformer includes operational and maintenance expenses minus the salvage value. For the new transformer, the calculation includes the investment cost plus operational and maintenance costs, then subtracts the salvage value.

The results indicate that the annual cost of operating the old transformer (IDR90,997,327) is significantly higher than that of the new transformer (IDR70,528,925). This cost difference of approximately IDR20 million per year supports the recommendation to replace the old transformer, as it yields better economic efficiency and operational cost savings for PT PLN (Persero).

8) Problem Analysis

The analysis results show that the annual cost of the old transformer is higher than that of the new transformer. Specifically, the annual cost of the old transformer is IDR90,997,327, whereas the new transformer's cost is IDR70,528,925. Based on the comparison, A_Old > A_New; therefore, replacing the old transformer with a new one is recommended. Knowing the annual costs of both transformers enables PT PLN (Persero) to plan and determine the optimal timing for equipment replacement. Furthermore, PLN can estimate the average annual cost that must be allocated for replacement equipment while taking into account maintenance expenses each year to achieve maximum operational efficiency.

B. Discussion

This study aims to calculate the annual cost of distribution transformers at PT PLN (Persero) Makassar Branch using the replacement method to evaluate technical and economic feasibility. The annual cost of the old transformer, after accounting for operating expenses, maintenance costs, and salvage value, is estimated at IDR90,997,327. In contrast, the new transformer costs IDR70,528,925 per year when investment, operating, and maintenance expenses are included and the salvage value is deducted. The results indicate that the new transformer has a lower annual cost burden than the old transformer and is therefore more economical in the long run. The analysis applied the annuity approach and linear regression to forecast future expenses.

These findings align with the arguments presented by Li et al. and Kabeyi and Olanrewaju, which state that the economic life of equipment is reached when the average annual total cost attains its minimum point [7], [29]. Furthermore, rising operational expenses over time are a major factor driving the need for equipment replacement. West et al. also emphasize that replacement is not only prompted by equipment failure but also by the potential advantages of using new equipment, such as reduced maintenance costs, improved efficiency, and minimized downtime losses [30].

The results of this study show that replacing old distribution transformers with new units provides significant long-term economic benefits, as evidenced by regression analysis, normality testing, multicollinearity testing, and sensitivity analysis of the discount rate. These findings are consistent with prior studies that underline the importance of determining optimal replacement timing based on life-cycle cost and increasing operational cost trends [31]–[33]. This study also supports the conclusions of research that uses probabilistic approaches and discount rate sensitivity to evaluate the total cost of ownership (TCO) in electrical distribution systems [34], [35]. By integrating a deterministic approach with discount rate sensitivity at 1%, 2.5%, and 5%, this study demonstrates that the model remains efficient under different economic conditions. It provides strong evidence that a transformer replacement method based on annual cost evaluation and economic life can serve as a reliable and practical guideline for investment planning in Indonesia's power distribution infrastructure.

The results of this study are also consistent with the findings of Acaroğlu and García Márquez, who emphasized that the Life Cycle Cost Analysis (LCCA) approach can optimize investment decisions in electrical distribution systems [36]. Furthermore, electrical asset management theory supports the notion that replacing equipment before reaching peak maintenance costs can enhance operational efficiency, as stated by Lee et al. [37]. This study confirms that replacing the outdated transformer with a new unit is the most appropriate strategy for equipment rejuvenation. The main justification for investing in transformer replacement lies in the significant annual cost difference, which leads to greater efficiency in operational and maintenance expenditures. Previous studies have supported this conclusion by demonstrating that replacing equipment before complete failure can significantly reduce the Total Cost of Ownership (TCO) and increase the reliability of electrical distribution systems [38], [39]. According to Abubakar et al. and Zakaria et al., the Life Cycle Costing (LCC) theory also emphasizes the need for investment decisions to account for all expenses incurred during the asset's lifespan, not just initial costs [40], [41]. In addition, this upgrade will enhance the reliability of the distribution network and enable PT PLN (Persero) to manage its annual budget more effectively. This strategy is expected to optimize costs and maintain the quality of electricity services for customers. Gallegos et al. also argue that modernizing distribution infrastructure through a replacement approach can reduce the risk of technical failures and improve customer satisfaction with utility services [42].

Compared with previous research, the strength of this study lies in its practical and applicable approach to evaluating transformer replacement decisions through detailed annual cost calculations using the annuity method and linear regression while incorporating salvage value. Unlike earlier studies that primarily focused on external factors, such as the impact of electric vehicles on transformer aging [25], [28], the effects of climate change on electrical infrastructure [26], or the integration of building flexibility and distribution networks to extend transformer lifespan [27], this study directly addresses internal economic feasibility from the perspective of the utility company (PLN) in making equipment replacement decisions. Overall, this study remains aligned with previous studies that aim to optimize the lifespan, efficiency, and reliability of distribution transformers; however, it differs in focus. This study emphasizes internal economic evaluation based on direct costs, whereas previous studies concentrated on external factors such as electric vehicle loads, climate, and network configurations. Thus, this study complements earlier works by providing a robust quantitative foundation for investment decision-making in the electricity distribution sector.

Although the findings indicate that the new transformer is more economical than the old one, the replacement decision should not rely solely on annual cost calculations. It is essential to consider elements of uncertainty that may affect the reliability of long-term cost estimates. For instance, maintenance costs may fluctuate, energy prices may change, and seasonal load variations or unexpected demand growth may occur. The regression model used in this study has a coefficient of determination (R^2) of 34.92%, which means that only about one-third of the total variation in annual costs is explained by the model. The remaining 65.08% is influenced by other factors not yet included, such as environmental conditions, load volume, and system disturbance frequency. This indicates that there is substantial room for improving the model by incorporating additional relevant variables.

Furthermore, this study is limited to two transformer units at a single location, which restricts the generalizability of the results to the broader distribution system. The absence of an analysis on seasonal load patterns and other external factors, such as policy shifts or economic conditions, shows that the current model remains deterministic and does not yet capture real-world variability and risk. Therefore, future studies are encouraged to apply sensitivity analysis and Monte Carlo simulation. These methods enable the evaluation of various cost and risk scenarios, thereby strengthening the robustness and reliability of the results under uncertainty.

In a broader context, transformer replacement strategies should also account for future trends, including the increasing adoption of electric vehicles (EVs) and distributed energy resources (DERs). Several studies have shown that dynamic loading from EVs can accelerate transformer thermal aging [25], [43]. Consequently, replacement policies should include more realistic projections of future load behavior. Previous studies have demonstrated that Monte Carlo simulations are effective for analyzing operational cost uncertainties in distribution systems [44]. The integration of this probabilistic approach could further enhance decision-making models for Indonesia's power distribution infrastructure.

For comparison, several developed countries, such as Japan, have implemented the Asset Health Index to determine the optimal timing for equipment replacement [44], [45], while European countries apply risk-based approaches [46]. This study may serve as an initial foundation for developing more adaptive and risk-responsive asset management policies in Indonesia. Although the annuity method was applied to assess annual costs, alternative approaches such as Net Present Value (NPV) and Internal Rate of Return (IRR) could also be used if cash flow data are available. These methods would provide a more comprehensive assessment of financial feasibility.

The implications of this study suggest that implementing a replacement method based on systematic annual cost analysis can serve as an effective strategy for PT PLN (Persero) to enhance operational cost efficiency, extend the equipment's economic life, and maintain the reliability of the distribution system. By integrating an engineering economics approach into transformer rejuvenation planning, the company can optimize investments, reduce service disruption risks, and prepare annual budgets more accurately using data-driven analysis. Moreover, the findings of this study contribute to the academic field of electrical asset management by presenting a more practical and applicable evaluation model for replacement feasibility, thereby creating opportunities for developing more prudent infrastructure investment policies in the future.

IV. CONCLUSION

Based on the research findings, it can be concluded that the annual cost of the distribution transformer at PT PLN (Persero) Makassar Branch, using the replacement method, is IDR90,997,327 for the old transformer and IDR70,528,925 for the new transformer. These values were calculated by considering investment, operational, maintenance costs, and salvage value using the annuity and linear regression approaches. The most appropriate decision for equipment renewal is to replace the old transformer with a new one, as the new transformer demonstrates lower annual costs and greater long-term economic efficiency. However, this finding is limited by the scope of analysis, which was conducted at a single location with only two transformer samples. Therefore, the generalization of these results to other distribution conditions remains limited. External factors such as load variation due to renewable energy integration or electric vehicle penetration were not considered. Future research should expand the study area, include a larger number of transformer samples, and incorporate external variables that influence the reliability and operational costs of distribution transformers. This would allow for the development of a more comprehensive and adaptive replacement evaluation model responsive to future power system dynamics.

In addition, future studies are encouraged to integrate uncertainty modeling using the Monte Carlo method to better account for cost variability and dynamic operational conditions. Sensitivity analysis of the discount rate using NPV or IRR methods may also be applied to assess investment feasibility in greater detail. Implementing cross-country comparative approaches is also essential for identifying best practices in transformer replacement policies, particularly given the increasing penetration of electric vehicles and the expansion of distributed energy resources (DER). Accordingly, replacement strategies should be adapted not only to current cost structures but also to projected load changes and long-term system risks.

ATTACHMENT

ATTACHMENT 1.
OPERATOR WAGE CALCULATION USING LINEAR REGRESSION METHOD FOR OLD TRANSFORMER

Year	Period (t)	Wage Y(t) (IDR)	t × Y(t) (IDR)	t2
2001	1	2,250,000	2,250,000	1
2002	2	2,400,000	4,800,000	4
2003	3	2,550,000	7,650,000	9
2004	4	2,700,000	10,800,000	16
2005	5	2,850,000	14,250,000	25
2006	6	3,000,000	18,000,000	36
2007	7	3,150,000	22,050,000	49
2008	8	3,300,000	26,400,000	64
2009	9	3,450,000	31,050,000	81
2010	10	3,600,000	36,000,000	100
2011	11	3,750,000	41,250,000	121
2012	12	3,900,000	46,800,000	144
Total	78	36,900,000	261,300,000	650

ATTACHMENT 2.
OPERATOR WAGES UP TO 25 YEARS FOR THE OLD TRANSFORMER

Period (t)	Total Wage (IDR)	DF	PV
13	3,249,954	0.97561	3,170,687
14	3,276,870	0.95181	3,118,972
15	3,303,786	0.92860	3,067,894
16	3,330,702	0.90595	3,017,452
17	3,357,618	0.88385	2,967,645
18	3,384,534	0.86230	2,918,473
19	3,411,450	0.84127	2,869,934
20	3,438,366	0.82075	2,822,027
21	3,465,282	0.80073	2,774,750
22	3,492,198	0.78120	2,728,099
23	3,519,114	0.76214	2,682,074
24	3,546,030	0.74356	2,636,671
25	3,572,946	0.72542	2,591,888

ATTACHMENT 3.
MAINTENANCE COSTS UP TO 25 YEARS

Period (t)	Maintenance Cost (IDR)	DF	PV
13	9,629,747	0.97561	9.394.876
14	11,018,078	0.95181	10.487.165
15	12,406,409	0.92860	11.520.584
16	13,794,740	0.90595	12.497.353
17	15,183,071	0.88385	13.419.622
18	16,571,401	0.86230	14.289.467
19	17,959,732	0.84127	15.108.898
20	19,348,063	0.82075	15.879.856
21	20,736,394	0.80073	16.604.218
22	22,124,724	0.78120	17.283.799
23	23,513,055	0.76214	17.920.352
24	24,901,386	0.74356	18.515.572
25	26,289,717	0.72542	19.071.096

ATTACHMENT 4.
OPERATOR WAGES FOR NEW TRANSFORMER

Year	Monthly Wage (IDR)	Number of Operators	Total Monthly Wage (IDR)
6	1,000,000	3	3,000,000
7	1,050,000	3	3,150,000
8	1,100,000	3	3,300,000
9	1,150,000	3	3,450,000
10	1,200,000	3	3,600,000
11	1,250,000	3	3,750,000
12	1,300,000	3	3,900,000

ATTACHMENT 5.
OPERATOR WAGE CALCULATION USING LINEAR REGRESSION METHOD

Year	Period (t)	Operator Wage Y(t) (IDR)	t × Y(t)	t²
2006	1	3,000,000	3,000,000	1
2007	2	3,150,000	6,300,000	4
2008	3	3,300,000	9,900,000	9
2009	4	3,450,000	13,800,000	16
2010	5	3,600,000	18,000,000	25
2011	6	3,750,000	22,500,000	36
2012	7	3,900,000	27,300,000	49
Total	28	24,150,000	100,800,000	140

Where: b = 29,216, a = 3,333,136

ATTACHMENT 6.
OPERATOR WAGES UP TO 25 YEARS

Period (t)	Total Wage	DF	PV
8	3,566,864	0.97561	3,479,867
9	3,596,080	0.95181	3,422,801
10	3,625,296	0.92860	3,366,448
11	3,654,512	0.90595	3,310,808
12	3,683,728	0.88385	3,255,879
13	3,712,944	0.86230	3,201,660
14	3,742,160	0.84127	3,148,149
15	3,771,376	0.82075	3,095,344
16	3,800,592	0.80073	3,043,242
17	3,829,808	0.78120	2,991,840
18	3,859,024	0.76214	2,941,135
19	3,888,240	0.74356	2,891,124
20	3,917,456	0.72542	2,841,802
21	3,946,672	0.70773	2,793,167
22	3,975,888	0.69047	2,745,214
23	4,005,104	0.67362	2,697,938
24	4,034,320	0.65720	2,651,335
25	4,063,536	0.64117	2,605,401

ATTACHMENT 7.
MAINTENANCE COST CALCULATION USING REGRESSION METHOD

Year	Period (t)	Maintenance Cost Y(t) (IDR)	t × Y(t)	t²
2006	1	15,400,500	15,400,500	1
2007	2	18,236,000	36,472,000	4
2008	3	18,708,000	56,124,000	9
2009	4	21,320,000	85,280,000	16
2010	5	23,056,000	115,280,000	25
2011	6	24,100,000	144,600,000	36
2012	7	24,340,000	170,380,000	49
Total	28	145,160,500	623,536,500	140

Where: b = 1,531,946 a = 14,609,429

ATTACHMENT 8.
MAINTENANCE COST CALCULATION UP TO 25 YEARS

Period (t)	Maintenance Cost (IDR)	DF	PV
8	26,865,000	0.97561	26,209,756
9	28,396,947	0.95181	27,028,623
10	29,928,893	0.92860	27,791,952
11	31,460,839	0.90595	28,501,968
12	32,992,786	0.88385	29,160,815
13	34,524,732	0.86230	29,770,568
14	36,056,679	0.84127	30,333,230
15	37,588,625	0.82075	30,850,735
16	39,120,571	0.80073	31,324,951
17	40,652,518	0.78120	31,757,682
18	42,184,464	0.76214	32,150,669
19	43,716,411	0.74356	32,505,594

20	45,248,357	0.72542	32,824,080
21	46,780,303	0.70773	33,107,693
22	48,312,250	0.69047	33,357,944
23	49,844,196	0.67362	33,576,293
24	51,376,143	0.65720	33,764,147
25	52,908,089	0.64117	33,922,863

ATTACHMENT 9.
TRANSFORMER LOSS COST (NEW TRANSFORMER)

Year	Losses Cost (IDR)
2006	10,340,000
2007	12,458,000
2008	14,555,000
2009	16,234,000
2010	17,505,000
2011	18,545,000
2012	19,354,000

ATTACHMENT 10.
TRANSFORMER LOSS COST USING REGRESSION

Year	Period (t)	Losses Y(t)	t × Y(t)	t^2
6	1	10,340,000	10,340,000	1
7	2	12,458,000	24,916,000	4
8	3	14,555,000	43,665,000	9
9	4	16,234,000	64,936,000	16
10	5	17,505,000	87,525,000	25
11	6	18,545,000	111,270,000	36
12	7	19,354,000	135,478,000	49
Total	28	108,991,000	478,130,000	139

Where: b = 302,569; a = 8,376,590

ATTACHMENT 11.
TRANSFORMER LOSS COST CALCULATION UP TO 25 YEARS

Period (t)	Total Losses (IDR)	DF	PV
8	10,797,138	0.97561	10,533,793
9	11,099,707	0.95181	10,564,861
10	11,402,275	0.92860	10,588,146
11	11,704,844	0.90595	10,604,011
12	12,007,412	0.88385	10,612,803
13	12,309,981	0.86230	10,614,858
14	12,612,549	0.84127	10,610,499
15	12,915,118	0.82075	10,600,039
16	13,217,686	0.80073	10,583,776
17	13,520,255	0.78120	10,562,002
18	13,822,823	0.76214	10,534,993
19	14,125,392	0.74356	10,503,018
20	14,427,961	0.72542	10,466,337
21	14,730,529	0.70773	10,425,196
22	15,033,098	0.69047	10,379,836
23	15,335,666	0.67362	10,330,487
24	15,638,235	0.65720	10,277,370
25	15,940,803	0.64117	10,220,700

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