Reliability Improvement of Tembilahan Steam Power Plant with Additional Generating Capacity

Fadhil M. Hanafi[1], Dian Yayan Sukma[2]

[1,2] Department of Electrical Engineering, Faculty of Engineering, Riau University, Pekanbaru 55281 INDONESIA (tel: 076166595; email:[1] fadhil.m5065@student.unri.ac.id,[2] dianyayan.sukma@eng.unri.ac.id)

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Corresponding Author: Fadhil M Hanafi

ABSTRACT — To ensure good generating system reliability, the presence of operating generating units or adequate power reserves in the generating system is very important. The availability of power reserves in the system depends on various factors, including the frequency of disturbances in generating units and the peak capacity required by the system. One example of a generating system is the Tembilahan steam power plant, which has a capacity of 2 × 7 MW and serves a peak load of 14.31 MW in 2019 until 2022. However, in that period, the reliability of the generating system, as measured by the loss of load expectation (LOLE) index, only reached 33 days/year, far below the standard of the State Electricity Company (Perusahaan Listrik Negara, PT PLN) 2021 to 2030 Electricity Supply Business Plan (Rencana Usaha Penyediaan Tenaga Listrik, RUPTL) of 1 day/year. To improve the reliability of the Tembilahan steam power plant generation system in 2027, an analysis is needed to consider the procurement period of the plant and the availability of land in the system. This analysis involves using the recursive convolution method to calculate the loss of load probability (LOLP)/ loss of load expectation (LOLE) index and the simple linear regression method to estimate the peak load in that year. Based on the results of the analysis, it was found that the addition of three generating units of 7 MW could improve the reliability of the generation system. The area required for these additional units was 2,030.91 m^2 and the available land was still sufficient. After the improvements were made, the reliability index LOLE of the generating system increased to 0.078 days/year for the year 2027, meeting the standards for the reliability level of the plant based on PT PLN's 20212030 RUPTL.

KEYWORDS — Reliability, LOLP, LOLE, Generation System.

I. INTRODUCTION

Power generation units have the role of generating electricity, both for household and industrial purposes. The breakdown of a generating unit, or in the worst case a power outage, can result in the unit being unable to operate. If several large generating units experience this simultaneously, load shedding or system losses may occur. If a generating unit experiences frequent load shedding, the generating unit is not reliable in serving the load. Given the important role of the generating unit in providing electrical power, the reliability of the generating unit needs to be maintained [1]. The cause of a generating unit not being able to operate can be internal disturbances (from the generating unit) or external disturbances (outside factors). The occurrence of disturbances in the generating unit will affect the level of reliability of the plant. In addition, the peak load that increases every year also affects the reliability of the plant. The state of the power plant that experiences interference during operation will result in a forced outage rate (FOR) [2]. The FOR value is used to determine the loss of load probability (LOLP), which is when the load exceeds the power plant's capability [3]. Furthermore, loss of load expectation (LOLE) is calculated to determine the duration of the generating unit outage in a year. The State Electricity Company (Perusahaan Listrik Negara, PT PLN) in the PLN 2021 to 2030 Electricity Supply Business Plan (Rencana Usaha Penyediaan Tenaga Listrik, RUPTL) sets the LOLP at 0.274% or equivalent to 1 day/year LOLE [4].

Tembilahan 2 × 7 MW steam power plant is one of the electricity service provider units whose ownership status is held by PT PJB Services, a subsidiary of PT PLN Nusantara Power. Tembilahan steam power plant has two generating units with a capacity of 7 MW each. Based on the results of the LOLE analysis of load data and FOR values at Tembilahan steam power plant in the 2019 until 2022 period, with a LOLE value of 33 days/year, it is known that these results are not in accordance with the PT PLN 2021 to 2030 RUPTL.

Therefore, it is necessary to improve the level of reliability. One method that can be used to improve the level of reliability is to increase the available generating capacity by increasing the number of generating units. The addition of the number of generating units must be done by considering the available area at the Tembilahan steam power plant so that the scenarios made can be realized based on actual circumstances. The method of adding generating units was chosen because it is a commonly used method to improve the reliability of a power plant and has been successfully applied in several previous studies.

Various studies on the analysis of reliability level of power plants have been carried out, including research on evaluating the reliability of the Suralaya steam power plant based on the FOR value [1]. Based on daily failure and discharge data in 2019, the reliability index of Suralaya steam power plant for Unit 1 to Unit 4 was 4.23 days/year or 1.23% [1].

Meanwhile, previous research has improved the reliability of power plants through the addition of capacity or the number of generating units, including the improvement of the LOLP reliability value of Pantai Baru Pandansimo PLTH, which initially had an LOLP value of 0.1407 or LOLE worth 51.3627 days/year [2]. Improvement scenarios were carried out, namely scenario 1 in the form of replacing new generating units and scenario 2 in the form of adding new generating units. Scenario 1 improves reliability with LOLP to 9.6908 days/year, while scenario 2 improves reliability with LOLP to 6.8186 days/year [2].

The next study, which added generating units to improve the reliability of the plant, is a study on efforts to improve the reliability index of the generating system in one of the plants in Riau province [5]. This system initially had a LOLE reliability index of 0.5627 days/year, then with the scenario of adding

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generating units, the LOLE reliability index of the plant was successfully changed to 0.000784 days/year [5].

Another study that uses the scenario of adding generating units to improve reliability is a study of scenarios to improve the reliability of power generation systems in the Bali [6]. Initially, the system had a reliability value with the LOLP calculation of the 150 kV system in the Bali, which was 6,184 days/year. The scenario that was carried out was adding one power plant of 380 MW, namely Celukan Bawang steam power plant of 380 MW, which could reduce the LOLP value to 1.78 days/year. The LOLP value had almost met the national standard of PT PLN, which is 1 day/year [6].

This study analyzes the calculation and improvement of the reliability level of the Tembilahan steam power plant plant to comply with the 2021 to 2030 PT PLN RUPTL by predicting the increase in peak load until 2027 using data from the 2019 to 2022 plant. The prediction of peak load increases is carried out until 2027 by considering the realization of the procurement of new generating units which can take four to five years.

II. PEAK LOAD INCREASE AND GENERATION RELIABILITY

Reliability analysis is carried out by considering the increase in peak load on the plant each year. The peak load increase is predicted using simple linear regression and the reliability level is calculated using the LOLP/LOLE index.

A. SIMPLE LINEAR REGRESSION

Regression is a statistical method used to identify and understand the relations of two or more variables. Regression is used to predict targets that have numeric data types, while classification is used to predict or classify data with categorical data type targets. In regression analysis, there are two types of variables, namely independent and dependent variables. Independent variables are factors that affect the target or dependent variable. For example, in a dataset of scholarship candidates, the independent variables are parents' salary, GPA, and distance from home. Meanwhile, the dependent variable is the target variable to be predicted. For example, in the scholarship candidate dataset, the information "accepted" or "rejected" is included in the dependent variable. Usually, regression analysis involves one dependent variable and more than one independent variable [7].

The trend method or simple linear regression method is a method in time series analysis that is based on the trend of historical data without regard to other factors (economic, climatic, and technological). This method produces a mathematical equation between data and time and is often used to estimate the future in the short term [8]. A simple linear regression equation is an equation model that describes the relationship of one independent variable or predictor (x) with one independent variable or response (y), which is usually described by a straight line [9].

The development of electricity load is described in the form of an equation that follows a linear trend pattern, defined by the following equation.

$$y = a + bx \tag{1}$$

$$a = \frac{\sum y \sum x^2 - \sum x \sum xy}{n \sum x^2 - \left(\sum x\right)^2} \tag{2}$$

$$b = \frac{n.\sum xy - \sum x.\sum y}{n.\sum x^2 - \left(\sum x\right)^2} \tag{3}$$

where y is the electricity load in the reference period x, a is the growth of electricity load, b is the average growth rate of electricity load, and n is the amount of data used.

The simple linear regression method can be performed if the trend of the historical data is linear. If the trend of the data is not linear, a nonlinear regression method with a geometric model is used and the result of the nonlinear equation is projected into a linear equation as follows [10].

$$y = ax^b \tag{4}$$

$$\log y = \log(ax^b) \tag{5}$$

$$\log y = \log a + \log x^b \tag{6}$$

$$\log y = \log a + b.\log x. \tag{7}$$

Equation (7) is then projected onto (1), thus forming (8) as follows.

$$P = A + BQ \tag{8}$$

with

$$P = \log y \tag{9}$$

$$A = \log a \tag{10}$$

$$Q = \log x \tag{11}$$

$$B = b \tag{12}$$

$$a = 10^A. \tag{13}$$

To obtain the values of A and B, (2) and (3) are transformed based on (8), resulting in the following equations.

$$A = \frac{\sum P \sum Q^2 - \sum Q \sum QP}{n \sum Q^2 - \left(\sum Q\right)^2} \tag{14}$$

$$B = \frac{n.\sum QP - \sum Q.\sum P}{n.\sum Q^2 - \left(\sum Q\right)^2}. \tag{15}$$

B. POWER AVAILABLE IN THE SYSTEM

The availability of power in the system must be sufficient to meet the needs of electric power services to customers. The availability of power in the system also depends on the installed power, as well as the readiness of the generating units in the system to operate. Generating units are not ready to operate if various factors, such as maintenance negligence, cause interference or damage.

To meet the load estimated from load forecasting and overcome the problem of maintenance of generating units, efforts are needed to ensure that the availability of power in the system is always sufficient to serve the existing load [11]. The availability of reserve power and the FOR value of the generating units operating during a certain period play an important role in determining the reliability of the generating system. The FOR value and system reliability are inversely proportional, so the smaller the FOR value, the better the availability of reserve power in the system.

$$FOR = \frac{Force\ Outage\ Hours}{Service\ Hours + Force\ Outage\ Hours}. \tag{16}$$

Force outage hours are the amount of time a unit experiences interference due to equipment failure that requires disconnecting the unit from the system, while *service hours* are the operating period of a generating unit connected to the transmission network, both under normal circumstances and when derating. The smaller the FOR, the higher the reliability assurance obtained. Conversely, the larger the FOR, the smaller the reliability assurance obtained. Changes in the FOR value can directly affect the total reliability of the system [12].

C. RECURSIVE CONVOLUTION ALGORITHM

Reliability evaluation of a generating system can be done with a recursive method based on the distribution of generator state variations. The generating unit has two possible states (dual state), namely state and outage condotions. The system supplied from *n* generator units has *2n* variation conditions. Manual calculations for systems with many generating units will be very difficult to do. Many recursive algorithms have been applied to evaluate the reliability of power systems [13].

The recursive method used in finding the reliability index in this study was a recursive convolution equation. A function that refers to itself is also called a recursive function and consists of a base case and a recursive case. The initial value that does not refer to the function itself is called the base case and serves to provide the value defined in the recursive function and stop the recursion process. Meanwhile, the part of the function that defines the function arguments in its own terms is called the recursive case and the function arguments must be closer to its base case each time the function performs the recursive case [14].

In the convolution equation, the recursive convolution function with the following equation is also used to find the reliability of the generating system.

$$F^i(L_e) = \int_{L_{oi}} F^{i-1}(L_e - L_{oi}) f_o(L_{oi}) dL_{oi}. \quad (17)$$

Equation (17) has the rule that $F^i(L_e)$ will equal $F(L)$ if i is 0 and $F^i(L_e)$ will equal $F(L_e)$ if i is not 0 [15]. When assuming L_{oi} is discrete, f_{oi} will be p_i if L_{oi} is equal to 0 and f_{oi} will be q_i if L_{oi} is equal to C_i, so the following equation is obtained.

$$F^i(L_e) = F^{i-1}(L_e).p_i + F^{i-1}(L_e - C_i)q_i \quad (18)$$

where L_e is the effective load, L_{oi} is the random load outage, IC is the installed generating unit capacity, $F^i(L_e)$ is the effective load probability function, p_i is the probability of available capacity, q_i is the probability of outage capacity, and Ci is the capacity of the generator at the ith order [15].

D. RELIABILITY INDEX

Power system reliability can be calculated by looking at the frequency of a system experiencing disturbance or the frequency of power outages. Data on the results of a system disturbance can be calculated using the LOLP formula. The smaller the LOLP value, the less the chance of a system experiencing interference, and the investment needed to support it is also greater [16]. LOLP is defined as the probability of a system load exceeding the available generating capacity, with assumptions that the daily peak load lasts all day. LOLP value = 0 means the load will always be met, while LOLP value = 1 means the load will never be met [17]. To measure reliability, the unit of days/year is used, indicating that the system load is smaller, equal, or greater than the available capacity. To perform the calculation, generating unit data and FOR values are used to calculate individual outage probabilities. Then, the LOLP can be calculated based on these results [15].

LOLE can be defined as the number of units at a time (hours or days) per time interval (year) whose load demand exceeds capacity. LOLE expresses a value that represents the number of hours or days in a given time period, when the load (i.e., power consumption) cannot be supplied [18]. A load duration curve is suitable to identify the percentage of time when the load is greater than the amount generated. Thus, this reliability index yields the probability of the load experiencing an outage during peak load at any one time. LOLE itself is the multiplication of the generating system's probability of failure, namely LOLP, with units of time, such as in days/year [19]. In short, the LOLE value is LOLP multiplied by the number of days in one year. The LOLP value itself refers to [18], namely LOLP is defined as the sum of the probability of an outage multiplied by the cumulative probability of the amount of load that is not provided, or in other words, the possibility of the load exceeding the available capacity after an outage [20]. Based on this explanation, (19) can be formed.

$$LOLE = (F^{i-1}(L_e).p_i + F^{i-1}(L_e - C_i)q_i).365 \quad (19)$$

where *365* is the assumed number of days in a year.

The standard used is the standard from the 2021 to 2030 PT PLN RUPTL, with LOLE of 1 day/year. LOLP and LOLE calculations are helpful in the design review and sizing of power system utilities. In the same way, they both estimate and indicate the length of time required to lose a generating unit (i.e., a generating unit or any component requires replacement or maintenance) [21].

III. METHODOLOGY

In this research, several stages are carried out systematically so that the research results can be achieved. The research flowchart is displayed in Figure 1.

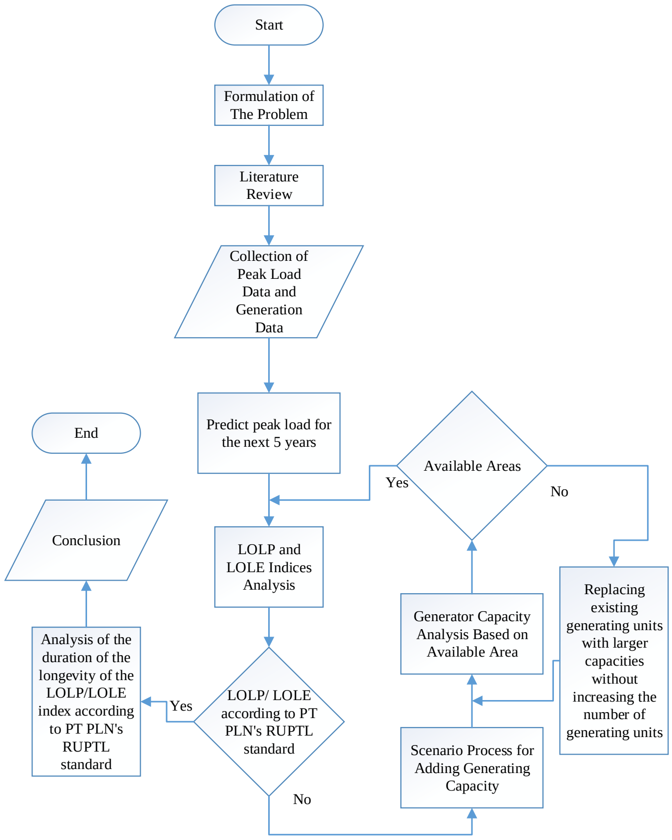

Figure 1. Research flowchart.

Research methodology is a method or steps used to design, collect, analyze, and interpret data in a study. Research methodology helps researchers to collect information in a systematic and organized manner, so that the data obtained is reliable and valid. The methodology in this study began with the formulation of the problem, which is about efforts to improve the reliability of the generating system by increasing the generating capacity at the Tembilahan steam power plant with an initial capacity of 2 × 7 MW. The next step was a literature study, which is studying theories related to the design of the power system to be discussed. These theories include various aspects, such as power plants, steam power plant, available power in the system, plant reliability, daily load curves, load probability distribution curves, convolution algorithms, LOLP, LOLE, and linear regression methods. Reference sources for these theories can come from books, journals, papers, and the internet. The next step was data collection, which includes predicting the increase in peak load, analyzing LOLP/LOLE, improving the reliability of the plant by considering the available area, analyzing the duration of reliability, and drawing conclusions.

A. DATA COLLECTION

In order to discuss the problems in this study, data collection is carried out to obtain the information needed. The collected data included peak load data and the FOR value of each generating unit at Tembilahan steam power plant from 2019 to 2022.

B. PEAK LOAD INCREASE FORECAST CALCULATION

Reliability indices, such as LOLP, are commonly evaluated to determine the future adequacy of bulk power systems [22]. Therefore, it is necessary to analyze the prediction of peak load increase for the next five years. It is done as a reference to determine the LOLP/LOLE value of the generating unit to be added. Electric power planning concentrates on load forecasting for the future. Expectation of future electricity load requires historical load data [23]. By using historical load data, future load increases can be forcasted.

C. RELIABILITY INDEX CALCULATION

LOLP and LOLE index analysis was carried out based on data obtained from the 2 × 7 MW Tembilahan steam power plant. If the LOLE obtained was more than 1 day/year, a scenario of improving the reliability of the plant was carried out by adding generating capacities.

There were two conditions being considered in this calculation: existing and five years in the future. The calculation in the existing condition involves analyzing the reliability of the plant with the current peak load, while the calculation in the next five years involves evaluating the reliability with the peak load in the fifth year of the existing condition. It needs to be done because the peak load tends to increase every year, along with the increase in population. The five-year condition was chosen because if the reliability evaluation in the next five years does not meet the standard, improvements need to be made by increasing the generating capacity.

D. RELIABILITY INDEX IMPROVEMENT

In order to improve the LOLP/LOLE index, it is necessary to increase the generating capacity by considering the area available at Tembilahan steam power plant. Tembilahan steam power plant is situated on an area of 10 hectares or 100,000 m^2. There is an unsude area of 22,173 m^2, with an effective area of 5,166 m^2, which can be utilized as an area for adding generating capacity. The purpose of this improvement is to obtain a LOLE index of less than 1 day/year. Based on this explanation, the requirement for additional generating capacity is made using the following equation.

$$Area\ of\ Generating\ Unit < 5.166\ m^2. \tag{20}$$

The area required based on the size of the generating capacity refers to Table I.

TABLE I
BUILDING AREA OF TEMBILAHAN STEAM POWER PLANT

Generation Capacity	Turbine Area	Boiler Area	Total Area of the Generating Unit	Area per Plant Unit
2 × 7 MW	1,012.5 m^2	341.44 m^2	1,353.94 m^2	676.97 m^2

TABLE II
PEAK LOAD DATA OF TEMBILAHAN STEAM POWER PLANT FROM 2019 TO 2022

Year	Peak Load (MW)
2019	9.64
2020	14.31
2021	13.09
2022	14.21

In general, the availability of land in the generating area enables the addition of generating units as the method for increasing generating capacities. By this mean, the available area can be optimally utilized. The addition of generating units initiated with the addition of more small units. When the addition of a large number of small units failed to improve reliability and the available area was insufficient (small units with large numbers required more area), existing generating units were then replaced with larger unit capacities (more than 7 MW capacity for one generating unit). However, the reliability improvement prioritizes the addition of units based on the existing capacity (7 MW) because the available data (FOR values) refer to this capacity.

E. RELIABILITY LEVEL DURATION ANALYSIS

The calculation of the duration of the LOLE index of less than 1 day/year obtained from the results of improving the level of reliability of the plant with the addition of generating capacity can be maintained based on the prediction of peak loads in the future.

F. CONCLUSION

After analyzing, the next step was to draw conclusions from the results based on the analysis that has been done.

IV. RESULT AND DISCUSSION

A. ANALYSIS OF PEAK LOAD INCREASE FOR THE NEXT FIVE YEARS

By considering the peak load data from 2019 to 2022, as shown in Table II, estimates were made to forecast the peak load in the next five years. It aims to take into account the possibility of unreliability of the power plant and prepare the scenario design of additional generating capacity which takes about four to five years. To perform the forecasting, a simple linear regression equation was used. The variable used in this calculation was peak load, which was also used to determine the LOLP/LOLE index of a generating system.

Using a recapitulation of the peak load data of Tembilahan steam power plant from 2019 to 2022, a forecast analysis was carried out using the simple linear regression method to obtain the values of *A* and *B* in the power regression equation. To

TABLE III
VARIABLE CALCULATION OF PEAK LOAD INCREASE FORECAST

Year	*x*	*y*	*Q*	*P*	Q^2	*Q.P*
2019	1	9.64	0.000000	0.98415	0.00000	0.00000
2020	2	14.31	0.301030	1.15559	0.09062	0.34787
2021	3	13.09	0.477121	1.11692	0.22764	0.53290
2022	4	14.21	0.602060	1.15260	0.36248	0.69394
Total	1	51.25	1.380210	4.40926	0.68074	1.57471

TABLE IV
PREDICTED INCREASE IN PEAK LOAD FOR THE NEXT FIVE YEARS

Year	Variable x: Year Period	Variable y: Peak Load (MW)
2023	5	15.65046
2024	6	16.41183
2025	7	17.08440
2026	8	17.68923
2027	9	18.24049

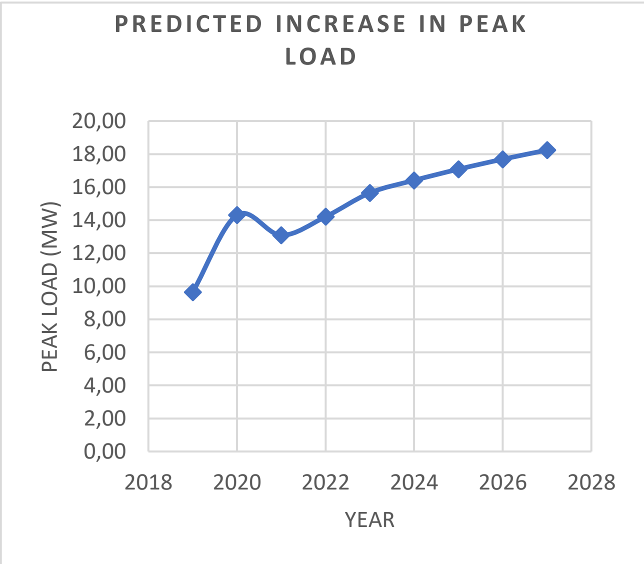

Figure 2. Predicted increase in peak load.

obtain the values of *P* and *Q*, the data in Table III was used to perform calculations using (9) and (11).

Next, calculations were performed using (14) and (15) to obtain the values of *A* and *B*. Then, the values of *a* and *b* were determined using (13) and (12), so the value of *y* is obtained as follows.

$$A = 1.012415$$

$$B = 0.260543$$

$$a = 10^{1,012415} = 10.29$$

$$b = 0.260543$$

$$y = 10.29x^{0,260543}. \quad (21)$$

Based on (21), the predicted peak load values for the next five years, starting from 2023 to 2027, can be determined, as shown in Table IV and Figure 2.

B. EXISTING CONDITION RELIABILITY ANALYSIS

To determine the level of reliability, the FOR value of each generating unit was first determined using (16). The FOR value was determined based on the data presented in Table V. Based on the data in Table V and utilizing (16), the FOR value for each generating unit is as shown in Table VI.

TABLE V
OPERATING DURATION DATA OF TEMBILAHAN STEAM POWER PLANT FROM 2019 TO 2022

Year	Service Hours Unit 1 (Hour)	Service Hours Unit 2 (Hour)	Force Outage Hours Unit 1 (Hour)	Force Outage Hours Unit 2 (Hour)
2019	3,377.00	5,140.00	107.00	51.00
2020	7,186.00	8,122.00	374.00	213.00
2021	6,965.97	7,569.75	520.15	139.93
2022	7,382.00	6,881.00	95.00	314.00
Total	24,910.97	27,712.75	1,096.15	717.93

TABLE VI
FOR VALUE AT TEMBILAHAN STEAM POWER PLANT UNIT

FOR Unit 1	FOR Unit 2
0.042148	0.0252519

TABLE VII
LOLP/LOLE ANALYSIS VARIABLES EXISTING CONDITIONS

Variables	Value
Unit 1 capacity (C_1)	7 MW
Unit 2 capacity (C_2)	7 MW
FOR value of Unit 1 (q_1)	0.0421480
FOR value of Unit 2 (q_2)	0.0252519
p_1 value	0.9578520
p_2 value	0.9742148
Installed capacity (*IC*)	14 MW
Peak load	14.31 MW
Base load	5.724 MW

Next, the LOLP/LOLE value was calculated based on the data shown in Table VII. Based on the data shown in Table VII, the calculation of the LOLP/LOLE value was analyzed using (19). The calculation was done using the Microsoft Office Excel 2013 application. It was obtained that the LOLP of Tembilahan steam power plant under existing conditions was 0.0901805, with a LOLE of 32.9158821 or 33 days/year.

C. RELIABILITY ANALYSIS FOR THE NEXT FIVE YEARS

To analyze the value of LOLP/LOLE in the next five years (2027), an analysis was carried out based on the existing system conditions with two existing generating units and a peak load that is expected to increase every year until 2027. To conduct the analysis, the predicted peak load value for 2027 was used, which amounted to 18.24049 MW and a base load value of 40% of the peak load, which amounted to 7.296195 MW.

This analysis is carried out to see the reliability of the plant if the generating capacity is maintained (two generating units) as the current condition. The condition variable for the next five years was also be used as a variable when additional generating capacity was needed. The variables that change compared to the existing conditions were peak load and base load, while the values of Unit 1 capacity, Unit 2 capacity, FOR value, p_1 value, p_2 value, and installed capacity follow the existing conditions in Table VII.

For the forecasting of the peak load increase in 2027, the LOLP value of Tembilahan steam power plant is 0.42809426 with LOLE of 156.254406 or 156 days/year. Based on the calculation results of existing conditions and forecast for the next five years (2027), it can be concluded that the more the peak load value increases, the higher the LOLE index value so

TABLE VIII
RESULTS OF IMPROVEMENT OF PLANT RELIABILITY LEVEL

Additional Capacity	**Total Capacity**	**Area Required**	**LOLE (Days/ Years)**	**Accordance with RUPTL PT. PLN Standards**
1 × 7 MW	3 × 7 MW	676.97 m^2	15.7998	No
2 × 7 MW	4 × 7 MW	1,353.9 m^2	1.19238	No
3 × 7 MW	5 × 7 MW	2,030.9 m^2	0.07827	Yes

TABLE IX
RELIABILITY LEVEL ENDURANCE DURATION

Years	**Peak load (MW)**	**LOLP**	**LOLE (Days/ Years)**
2027	18.24049	0.000214	0.078266
2028	18.74814	0.000233	0.0849232
2029	19.21953	0.000249	0.0907901
2030	19.66022	0.000263	0.0960204
2031	20.07453	0.000276	0.100728
2032	20.4659	0.000288	0.105000
2033	20.83711	0.000298	0.108904
2034	21.19045	0.000507	0.1850663
2035	21.52782	0.00086	0.3137872
2036	21.85082	0.001187	0.4333004
2037	22.1608	0.001492	0.5447239
2038	22.45895	0.001778	0.6489897
2039	22.74627	0.002046	0.7468826
2040	23.02364	0.002299	0.8390688
2041	23.29184	0.002537	0.9261187
2042	23.55155	0.002763	1.0085238

that it has not met the reliability target set by PT PLN in the PT PLN RUPTL based on the Decree of the Minister of Energy and Mineral Resources of the Republic of Indonesia Number 188.K/HK.02/MEM.L/2021 concerning the 2021 to 2030 RUPTL, namely with probability outage of 1 day/year. Therefore, an additional generating capacity scenario was needed to improve the reliability of the generating system under study. The addition of this generating capacity considered the available area in the 2 × 7 MW Tembilahan steam power plant.

D. RELIABILITY IMPROVEMENT

Based on the results of the reliability index calculation, it was found that the reliability index value did not meet the predetermined standard of 1 day/year. Therefore, a scenario was conducted wherein generating units were added to the studied generation system in accordance with the available area. The available area is described in (20), while the area for the added generating capacity refers to Table I. The predicted peak load value used in the scenario of adding generating capacity was 18.24049 MW in 2027, under the assumption that the addition of generating capacity takes about 4 until 5 years.

1) SCENARIO 1 OF 1 × 7 MW UNIT ADDITION

In scenario 1, a small unit capacity of 7 MW was added first due to the consideration that providing the largest capacity would require a larger area. Based on Table I, for the addition of one unit with a capacity of 7 MW, an area of 676.97 m^2 is required, which meets the requirements for additional generating capacity according to (20). The FOR value of 0.042148 followed the FOR value of Unit 1 in the generating

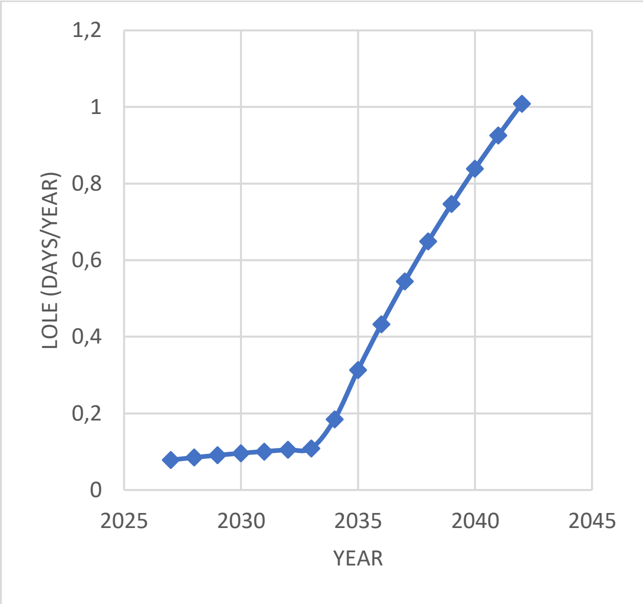

Figure 3. Reliability level endurance duration after repair.

system under study. From the calculation results using (19), the LOLP of 0.04329 and the LOLE index of 15.79975 days/year were obtained. Nevertheless, the resulting reliability index still did not meet the standards to be achieved.

2) SCENARIO 2 OF 2 × 7 MW UNITS ADDITION

Based on the results of the LOLE reliability index that had not been met in scenario 1, scenario 2 was performed by adding two units with a unit capacity of 7 MW. From Table I, it can be seen that the addition of one unit with a capacity of 7 MW required an area of 676.97 m^2, so the addition of two units required an area of 1,353.94 m^2.

Based on (20), it can be concluded that the area required for additional generating capacity in scenario 2 met the required requirements. Scenario 2 used the same FOR value as Unit 1 in the generating system under study, which was 0.042148. The calculation results using (19) showed that the LOLP reliability index in scenario 2 was 0.00327 and the LOLE reliability index is 1.19238 days/year. Although these results are better than scenario 1, the resulting reliability index still does not meet the standards to be achieved.

3) SCENARIO 3 ADDITION OF 3 × 7 MW UNITS

Taking into account the results of the LOLE reliability index that has not been met in scenario 1 and scenario 2, in scenario 3, three units with a capacity of 7 MW are added to the generating system under study. Based on Table I, an area of 676.97 m^2 is required for the addition of one unit with a capacity of 7 MW, so the total area required for the addition of three units is 2,030.91 m^2.

Based on (20), the available area is sufficient for additional generating capacity. Each generating unit has a FOR value of 0.042148 and the FOR value selected in the third scenario follows the FOR value of Unit 1 in the generating system under study. Based on the calculation results using (19), the LOLP reliability index value is 0.00021 and the LOLE reliability index is 0.078266 days/year. These results showed that the standard reliability index of the generating system had been met in the third scenario.

4) GENERATION CAPACITY ADDITION RESULT

The data obtained from the analysis of the scenario of additional generating capacity is shown in Table VIII. From the results of the addition of generating capacity that has been carried out, it can be seen that in scenario 1, by adding one generating unit with a capacity of 7 MW, the value of the LOLE reliability index still did not meet the desired standard. Likewise in scenario 2, with the addition of two generating units with a capacity of 7 MW each. However, in scenario 3, with the addition of three units with a capacity of 7 MW each, the LOLE reliability index value was obtained and met the standards set by PT PLN in the PT PLN RUPTL based on the Decree of the Minister of Energy and Mineral Resources of the Republic of Indonesia Number 188.K/HK.02/MEM.L/2021 concerning 2021 to 2030 RUPTL, namely LOLP of less than 0.274% or equivalent to LOLE of less than 1 day/year.

E. RELIABILITY LEVEL ENDURANCE DURATION ANALYSIS

The analysis is carried out to determine the duration for which the reliability of the plant can be maintained. This reliability duration was in accordance with the standards set by PT PLN's RUPTL based on the Decree of the Minister of Energy and Mineral Resources of the Republic of Indonesia Number 188.K/HK.02/MEM.L/2021 concerning the 2021 to 2030 RUPTL. The analysis involves predicting the increase in peak load each year and evaluating the LOLE index results to exceed 1 day/year. Information regarding the duration of resilience can be found in Table IX and Figure 3.

From the forcast results of the increase in peak load every year listed in Table IX and Figure 3, it can be concluded that the reliability of the plant from scenario 3 will be maintained until 2042 by maintaining a peak load value of 23.55155 MW, LOLP of 0.00276, and LOLE reliability index of 1.008524 days/year. It can be seen in Figure 3 that the LOLE value increased significantly between 2033 and 2035, from 0.108904 days/year to 0.3137872 days/year.

V. CONCLUSIONS

From research that has been conducted on the Tembilahan steam power plant generating system by utilizing the last four years of data, from 2019 to 2022, a LOLE reliability index value of 33 days/ year has been obtained under existing conditions and 156 days /year under the conditions of the next five years, with a predicted peak load increase of 18.24049 MW. By considering the standard of PT PLN in the RUPTL of PT PLN based on the Decree of the Minister of Energy and Mineral Resources of the Republic of Indonesia Number 188.K/HK.02/MEM.L/2021 concerning RUPTL 2021-2030, this value does not meet the desired standard.

To improve the level of reliability, additional generating capacity was carried out through a scenario of increasing the number of generating units by considering the available area. From the scenarios carried out, the results in scenario 3 met the reliability index standard, which was 0.078266 days/year. From the results of the study, it can be seen that the more generating units, the higher the level of reliability, but also followed by the wider the generating area. The reliability index in scenario 3 can be maintained until 2042 with a peak load of 23.55155 MW, a LOLP value of 0.002763, and a LOLE reliability index of 1.0085238 days/year.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest in this research. All analysis is done empirically based on the data that has been obtained.

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