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Study on Optimal Location Determination for 500 kV Extra High Voltage Substation Construction in Paiton Subsystem to Reduce to Transmission Loss

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Abstract

Electricity transmission losses are a significant challenge in the Java-Madura-Bali (Jamali) power system, especially in the Paiton subsystem, which is a critical point for power supply to the island of Bali. This study aims to identify the optimal location for the construction of a new Extra High Voltage Substation (GITET) to minimize transmission losses and improve the economic efficiency of the system. The method used is quasi-dynamic power flow simulation with electrical network modeling using PSS/E software integrated with Python, carried out in a time series throughout 2025 at four alternative locations: Watudodol, Jember, Genteng, and Banyuwangi. The simulation results reveal that the construction of GITET in Banyuwangi is technically the most optimal, capable of reducing transmission losses from 420.57 GWh to 94.71 GWh or around 77.5%. Economic analysis shows that the Jember location has the best financial parameters with an IRR of 15.01%, NPV of IDR 4.47 trillion, and a payback period of 9.35 years, even though the reduction in transmission losses is lower than in Banyuwangi. In conclusion, the selection of the GITET location must consider the trade-off between technical efficiency and financial benefits; Banyuwangi excels technically, while Jember is economically optimal, so that a combination of development strategies can maximize the performance of the Jamali electricity system.

Keywords: *Power Flow, 500 kV Substation, Financial Feasibility, Transmission Losses, Quasi-Dynamic Simulation.*

1. INTRODUCTION

PT PLN (Persero) UIP2B Java Madura Bali is one of the units within the PLN Group responsible for regulating transmission system and generation operations in the Java, Madura, and Bali (Jamali) electrical region at high voltage (HV) levels of 150 kV and 70 kV, as well as extra high voltage (EHV) of 500 kV. This system operation regulation considers economic aspects, reliability, and electrical power quality (Jacobsen, 2022; Kanchanapalli & Banka, 2024).

One indicator considered in system operation regulation is transmission losses, which is an important aspect in improving system operational efficiency (Parvizi et al., 2025). Transmission losses are an unavoidable phenomenon in the process of electrical energy transfer from power plants to consumer substations (Garip et al., 2022). These transmission losses are caused by factors such as resistance in conductors and other transmission equipment (Chen et al., 2024). In electrical transmission networks, the magnitude of current flowing through conductors is proportional to increased transmission losses (Pavičić et al., 2021; Swain et al., 2022). Maintaining current flow through conductors at optimal levels is crucial for minimizing transmission losses and ensuring efficient energy delivery (Bhushan & Sudhakaran, 2023; Ujah et al., 2022). Transmission losses are a common problem due to long distances between electrical energy sources (Sianipar et al., 2025) and electrical load centers (Rantaniemi et al., 2022). One way to address this is by building extra high voltage substations (GITET) closer to load centers (Adam et al., 2024). By bringing electrical energy sources closer to loads, transmission losses in the electrical system can be minimized (Adegoke et al., 2024).

Previous studies have discussed the optimization of transmission power losses using various methods, including optimal transmission switching and the placement of FACTS devices to reduce system losses (Aljaidi et al., 2025; Orbea et al., 2025) In addition, big data analytics-based algorithms and nature-inspired optimization methods have been employed to improve the accuracy of loss calculations and support multi-scale decision-making (Kumar & Singh, 2025; Li et al., 2024). However, most of these studies still focus on optimizing short-term operational parameters and have not explicitly integrated the evaluation of 500 kV GITET (Extra High Voltage Substation) placement as a long-term infrastructure planning strategy. Hence, this research addresses this gap by evaluating various alternative GITET locations in the Paiton subsystem to minimize transmission losses.

This is particularly in the Java-Madura-Bali electrical system where transmission losses are included as one of the performance indicators for electricity provider companies (Safarudin et al., 2020). In 2024, the transmission loss target for the Java-Madura-Bali electrical system was set at 1.94%. However, the actual achievement was 1.95%. Therefore, as transmission loss issues in electrical systems increase, in-depth research is needed.

In this paper, research on transmission loss reduction focuses on the Paiton subsystem with the addition of a new Extra High Voltage Substation (GITET). Recent research indicates a global trend towards using automated Python-based simulation platforms for power system analysis, including multi-scenario power flow evaluations and network infrastructure optimization (Jiménez-Ruiz et al., 2024; Schoen et al., 2023) This approach enables rapid and accurate data-driven decision-making and supports the evaluation of various alternative locations for Extra High Voltage Substation (GITET) development. Consequently, this study aligns with state-of-the-art advancements in modern transmission system planning. On the other hand, research on substation siting continues to evolve with the adoption of modern computational approaches. Several recent studies propose using artificial intelligence and geographic information system (GIS)-based methods to determine optimal substation locations by considering technical and environmental factors (Jin et al., 2024). Furthermore, integrated simulation frameworks that account for load distribution, investment costs, and land use have been developed to support more comprehensive substation siting processes (Xiong et al., 2024) Nevertheless, most of these studies still focus on distribution networks or medium-voltage systems and have not specifically addressed the planning of extra-high voltage substations (500 kV) within national interconnected transmission systems.

The focus was highlighted toward transmission loss reduction and electrical power adequacy in the Paiton subsystem. The Paiton subsystem is an important part of the Java Madura Bali electrical system. Based on the 2025-2034 Electricity Supply Business Plan (RUPTL) (PT PLN, 2025), there is a plan to construct a 500 kV Watudodol GITET with a target operation date of 2025 (Kementrian ESDM, 2020).

Although the Watudodol area has been selected as the GITET construction location, there are several other locations in the Paiton Subsystem that also have potential to become optimal locations based on various technical and economic aspects. This research will conduct quasi-dynamic power flow simulation studies to determine whether

Watudodol is the best location or if there are other alternative locations that are more optimal in reducing transmission losses from technical and economic perspectives.

With increasing attention to the Paiton subsystem in the Java-Madura and Bali system related to supply provision as it serves as the supply delivery location to Bali Island (Adam et al., 2024). The research objectives are to obtain solutions to transmission loss problems while maintaining electrical system supply reliability criteria, optimize planning for new 500 kV GITET construction with added focus on transmission loss reduction, and analyze alternative locations that are more optimal compared to Watudodol in terms of transmission loss reduction.

This research provides an original contribution by independently presenting a technical and economic verification of the plan to develop a 500 kV GITET in Watudodol as outlined in the 2025–2034 National Electricity Supply Business Plan (RUPTL). Unlike the RUPTL, which primarily presents strategic planning projections, this study applies Python and PSS®E-based quasi-dynamic power flow simulations across 8,760 hourly time points throughout 2025 to assess in detail the proposed location's technical effectiveness in reducing transmission losses. Furthermore, this study identifies alternative locations that are potentially more optimal than Watudodol based on transmission loss reduction and N-1 reliability criteria. The research also integrates a financial analysis to evaluate the economic feasibility of operationally viable alternatives, thereby generating data-driven recommendations for determining the optimal GITET site. This approach not only complements the strategic information in the RUPTL but also strengthens evidence-based decision-making for PLN's planning and investment in the Paiton subsystem.

2. RESEARCH METHODOLOGY

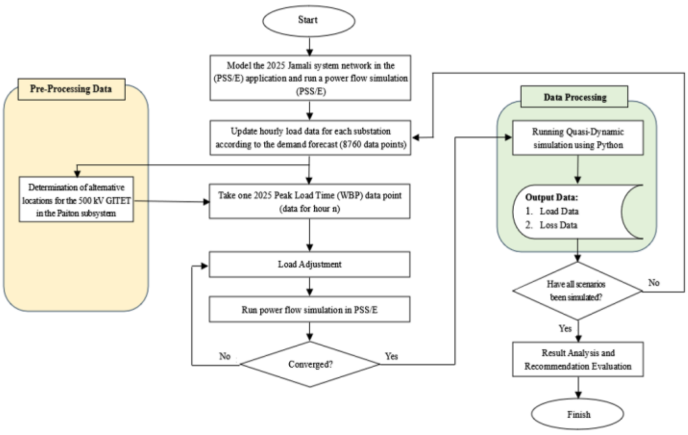

Figure 1. Research flowchart integrating RUPTL load data, jROS generation data, PSS®E power flow simulation, and Python-based automation for quasi-dynamic analysis.

The flowchart in figure 1 illustrates the research process, integrating RUPTL load data, jROS generation schedules, and PSS®E simulations. Python automates the quasi-dynamic analysis, handling hourly updates, scenario loops, and result extraction for a reproducible methodology.

2.1 Research Location and Time

This research was conducted at PT PLN (Persero) UIP2B JAMALI during November 2024 - April 2025. It was performed using PSS/E software integrated with Python programming to run quasi-dynamic simulations.

2.2 Data Collection Method

This study uses primary data from the Java-Madura-Bali (JAMALI) electricity system and system development data from the 2024-2033 RUPTL draft. The data includes plans for the development of power plants, transmission networks, and substations, which are used as the basis for simulating transmission losses in 2025. Load forecast data was obtained from the JAMALI system forecast, which was compiled hourly throughout 2025 (8,760 time points) and divided by subsystem area based on the previous year's load realization. The peak load assumption refers to the RUPTL 2024–2033 demand forecast.

Power plant load data was obtained through production simulations using the jROS (Joint Resources Optimization and Scheduler) application, which generated hourly power plant operating patterns for 2025. To maintain consistency in unit naming between applications, a power plant data dictionary was applied to standardize power plant identities between jROS and PSS®E (Power System Simulator for Engineering).

Power flow simulation was performed using PSS®E with a quasi-dynamic approach to calculate transmission losses in the Paiton subsystem. PSS®E was chosen for its ability to model generation, transmission, and distribution systems in an integrated manner and to analyze both normal operating conditions and disturbances.

The simulation process is automated using the Python programming language integrated with Visual Studio Code (VS Code) to speed up calculation execution and data processing. This automation simplifies the process of inputting loads and generator loading in PSS®E, which is difficult to do manually.

2.3 Data Analysis Method

The data analysis method is a way of processing obtained data to answer problem formulations and systematic steps of data processing methods. This research involves several steps explained in the following subsections.

2.3.1 Modeling for Power Flow Simulation and Energy Loss Estimation

In the Jamali electrical system, transmission energy losses are determined by two main components based on agreed transaction points:

a. High Voltage Network consisting of 500 kV SUTET and 150 kV/70 kV SUTT
b. IBT Transformers (500 kV/150 kV) and Power Transformers (150 kV/20 kV).

In this study, to calculate energy losses in the Jamali electrical system, a 'Simulation and Estimation' approach is used, namely power flow simulation and generation and loading estimation. The following explains system modeling for power flow simulation, formulas used to determine power losses, energy loss estimation, and formulas used to determine energy losses (Liu et al., 2020).

1. Network Modeling

a. High Voltage Network (HVN)

The parameters used in HVN modeling for the power flow simulation include impedance (R + jX) and line charging. Network data such as length, type, cross-section, and construction were obtained from the PLN UIP2B Jamali database.

b. Power Transformers

The parameters used in power transformer modeling for the power flow simulation include impedance (R + jX). Power transformer data such as KVA rating, no-load losses, rated-load losses, and impedance were obtained from the PLN UIP2B Jamali database.

c. Source/Interbus Transformer Modeling

Parameters used in Source/Generator modeling for power flow simulation conducted based on PLN UIP2B Jamali Database. Power flow simulation is performed at each substation loading measurement point with measurements taken every 1 hour for 1 year, so this simulation uses 8760 loading models in the Jamali electrical system.

2. Load Modeling

Parameters used in Load modeling for power flow simulation conducted based on PLN UIP2B Jamali Database. Power flow simulation is performed at each substation loading measurement point with measurements taken every 1 hour for 1 year, resulting in a total of 8760 loading models for each Substation.

A 1-hour interval is used for the quasi-dynamic simulation, yielding 8,760 annual time points. This aligns with the hourly resolution of the input data (load forecasts and generation schedules), accurately captures daily/seasonal load variations, and maintains computational efficiency for annual energy loss calculations.

The power flow simulation process is automated using a Python script integrated with PSS®E software. At each time step, the script updates the load and generator dispatch values according to their hourly profiles, then executes a power flow calculation. The solution's convergence status is monitored via the PSS®E solver's output indicator. If the solution does not converge, the script recalculates using the initial condition from the previous hour's converged simulation result. This approach aims to enhance numerical stability and maintain system condition continuity across simulation time intervals.

2.3.2 High Voltage Network and Power Transformer Power Loss Calculation

1. High Voltage Network Power Loss (kW)

For each 1-hour time interval, high voltage network power loss (kW) is obtained from power flow simulation.

$$KW_{loss-JTT-T} = KW_{losses\ JTT} \quad (1)$$

Where:

$KW_{loss-JTT-T}$ = Total power loss (kW) High Voltage Network per interval
$KW_{losses\ JTT}$ = Power loss (kW) from power flow simulation per interval

2. Power Transformer Power Loss (kW)

For each 1-hour time interval, power transformer power loss (kW) is obtained from power flow simulation.

a. Power transformer power loss (kW) per interval:

$$K_{loss-trf-L} = \left[\frac{KVA_{load}}{KVA_{rated}}\right]^2 \times KW_{loss-R} \quad (2)$$

Where:

$KW_{loss-trf-L}$ = Load losses (KW) transformer per interval
KVA_{load} = Transformer load that varies according to power flow simulation results per interval
KVA_{rated} = Transformer nominal capacity (rated capacity)
KW_{loss-R} = Transformer power loss (KW) at rated load

b. Total Power Transformer Power Loss (KW) per interval:

$$KW_{loss-trf-T} = KW_{loss-trf-N} + KW_{loss-trf-L} \quad (3)$$

Where:

$KW_{loss-trf-T}$ = Total transformer power loss (KW) per interval
$KW_{loss-trf-N}$ = Transformer power loss (kW) at no load (no load losses)
$KW_{loss-trf-L}$ = Transformer power loss (kW) at load (load losses) from power flow simulation

2.3.3 igh Voltage Network and Power Transformer Energy Loss

1. High Voltage Network Energy Loss (kWh)

With 1-hour time intervals, there are 8760 intervals in 1 year, and the High Voltage Network Energy Loss (kWh) for 1 year is determined:

$$E_{loss-JTT-T} = \sum_{1}^{n} KW_{loss-JTT-T} \quad (4)$$

Where:

n = number of intervals (8760 hours per year)
$KW_{loss-JTT-T}$ = Total High Voltage Network power loss (kW) per interval
$E_{loss-JTT-T}$ = Total High Voltage Network energy loss (kWh) per interval

2. Power Transformer Energy Loss (kWh)

With 1-hour time intervals, there are 8760 intervals in 1 year, and Power Transformer Energy Loss (kWh) for 1 year is determined:

$$E_{loss-trf-T} = \sum_{1}^{n} KW_{loss-trf-T} \quad (5)$$

Where:

N = number of intervals (8760 hours per year)
$KW_{loss-trf-T}$ = Total power transformer power loss (kW) per interval
$E_{loss-trf-T}$ = Total power transformer energy loss (kWh) per interval

3. Total Energy Loss (kWh) High Voltage Network and Power Transformers

$$E_{loss-Total} = E_{loss-JTT-T} + E_{loss-trf-T} \quad (6)$$

Where:

$E_{loss-JTT-T}$ = Total High Voltage Network energy loss (kWh) per interval
$E_{loss-trf-T}$ = Total power transformer energy loss (kWh) per interval

3. RESULTS AND DISCUSSION

3.1 Power Flow Analysis Before New GITET Construction

Power flow analysis for 2025 before new GITET construction in the Paiton subsystem was conducted with several cases considered to have significant impact on the system:

a. N-1 contingency of 500/150 kV IBT at 500 kV Paiton GITET
b. N-1 conductor contingency

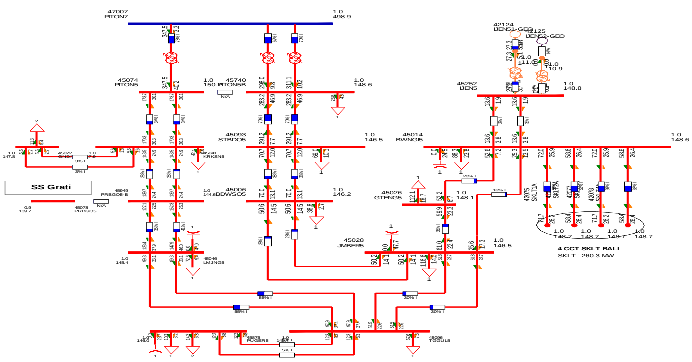

Figure 2. Power Flow 2025 Paiton Subsystem Before New GITET Operation

Figure 2 shows the power flow before the new GITET operates in the Paiton subsystem with IBT loading summary shown in table 1. From power flow simulation results, IBT 1,2,3 loading at 500 kV Paiton GITET was obtained at 70%, 67%, and 78% of their nominal capacity respectively. This condition does not meet the N-1 IBT reliability criteria. This peak load simulation serves as a reference for determining alternative locations for new GITET construction. Based on these simulations, alternative locations to be simulated were obtained at Situbondo, Bondowoso, Jember, Genteng, and Banyuwangi substations.

Table 1. IBT Contingency Summary Before New GITET Operation

No.	IBT	Normal (%)	OFF PITON5_ PITON7_3	OFF PITON5B_ PITON7_1	OFF PITON5B_ PITON7_2
1	PITON 5_PITON7_3	78		87.8	87
2	PITON 5B_PITON7_1	70.4	109		131.9
3	PITON 5B_PITON7_2	67.4	104.4	131.4	

Table 1 reveals that the normal load of the IBT is below its nominal capacity, with PITON 5_PITON7_3 at 78%, PITON 5B_PITON7_1 at 70.4%, and PITON 5B_PITON7_2 at 67.4%. Nevertheless, when a contingency occurs, i.e., when one of the IBTs is turned off, the load on the other IBTs increases significantly. For example, when PITON5_PITON7_3 shuts down, the load on PITON 5B_PITON7_1 increases to 109%, and PITON 5B_PITON7_2 to 104.4%, which exceeds the nominal capacity and indicates a risk of overload. A more extreme condition occurs when PITON5B_PITON7_1 or PITON5B_PITON7_2 shuts down, where several other IBTs experience loads of up to 131.9% and 131.4%, far above their nominal capacity.

3.2 Transmission Loss Simulation Results: Before New GITET Construction

The simulation results show that the transmission power loss in the Paiton subsystem throughout 2025 reached a total of 420.57 GWh, calculated using the quasi-dynamic method hourly and summarized monthly. The highest power loss occurred in October, coinciding with the increase in the system's peak load, while the lowest power loss occurred in May when the system load was relatively low. This indicates a strong correlation between the system load level and the magnitude of transmission power loss.

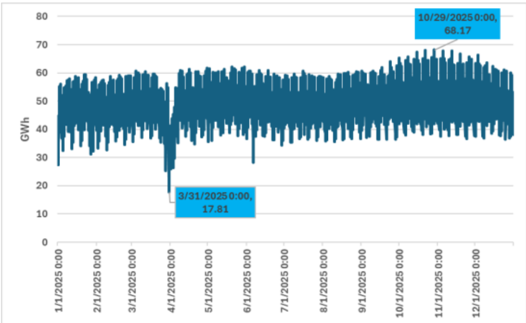

Figure 3. Hourly Transmission Loss Profile 2025: Before GITET Construction

Analysis of Figure 3 describes that monthly power loss fluctuations reflect seasonal variations in load and network operating conditions. These results shed light the importance of network planning and infrastructure improvements, including the construction of Extra High Voltage Substation (GITET), to reduce power losses, especially during peak load periods.

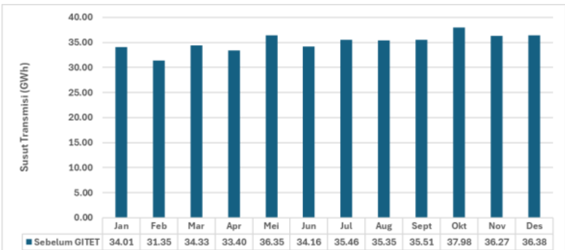

Figure 4. Paiton Subsystem Transmission Loss 2025: Before New GITET Addition

Based on Figure 4, the condition of the Paiton transmission system in 2025 prior to the new GITET development shows significant load fluctuations peaking in October, which could increase transmission power losses. The construction of the new GITET is expected to balance load distribution, reduce power losses, enhance reserve capacity in accordance with the N-1 criterion, and improve the reliability and efficiency of the Paiton transmission system.

3.3 Power Flow Analysis After New GITET Construction

The alternative locations for the construction of the new GITET were determined based on the 2025–2034 RUPTL plan at Watudodol, as well as simulation results at the Situbondo, Bondowoso, Jember, Genteng, and Banyuwangi substations. All alternatives were then selected based on operational feasibility, fulfillment of normal operating conditions, the IBT N-1 criterion, and transmission reliability, with the simulation results for IBT and conductor contingencies presented in Tables 2–7.

Table 2. IBT Contingency Summary After New GITET Operation (Watudodol Alternative)

No.	IBT	Normal (%)	OFF PITON5_ PITON7_3	OFF WTDDL 5B_WTDDL7_1	OFF WTDDL 5B_WTDDL7_2
1	PITON 5_PITON7_3	44.7		57.7	57.7
2	WTDDL 5B_WTDDL7_1	55.9	78.7		94
3	WTDDL 5B_WTDDL7_2	55.9	78.7	94	

Table 2 shows that under normal conditions, PITON5_PITON7_3 has an availability rate of 44.7%, while the two IBTs, WTDDL 5B_WTDDL7_1 and WTDDL 5B_WTDDL7_2, have a higher availability rate of 55.9%. When a disruption occurs on PITON5_PITON7_3, the availability of WTDDL increases to 57.7%, indicating mutual backup dependency between IBTs. If a disruption occurs on one of the WTDDLs, the other IBTs still show high availability of up to 94%, pointing that the system's ability to withstand disruptions is quite good.

Table 3. IBT Contingency Summary After New GITET Operation (Situbondo Alternative)

No.	IBT	Normal (%)	OFF PITON5_PITON7_3	OFF WTDDL 5B_WTDDL7_1	OFF WTDDL 5B_WTDDL7_2
1	PITON 5_PITON7_3	30.1		49.1	49.1
2	STBDO5_STBDO7_1	61.4	76.3		103.9
3	STBDO5_STBDO7_2	61.4	76.3	103.9	

Table 3 underscores that PITON5_PITON7_3 under normal conditions shows an availability of 30.2%, which is relatively low compared to IBT STBDO5_STBDO7_1 and STBDO5_STBDO7_2, which are 61.4% each. When PITON5_PITON7_3 is down, the availability of STBDO increases to 49.1% for PITON and up to 103.9% for STBDO, indicating effective load distribution and the ability to redistribute power in the Situbondo system. This proves that the system is more stable on IBT STBDO than on PITON.

Table 4. IBT Contingency Summary After New GITET Operation (Bondowoso Alternative)

No.	IBT	Normal (%)	OFF PITON5_PITON7_3	OFF BDWSO5_ BDWSO7_1	OFF BDWSO5_ BDWSO7_2
1	PITON 5_PITON7_3	46.2		59	59
2	BDWSO5_ BDWSO7_1	53.5	77.5		94
3	BDWSO5_ BDWSO7_2	53.5	77.5	94	

As evidenced by the data in Table 4, under normal conditions, PITON5_PITON7_3 has an availability of 46.2%, while BDWSO5_BDWSO7_1 and BDWSO5_BDWSO7_2 are in the range of 53.5%. When PITON5_PITON7_3 fails, BDWSO shows an increase in availability to 59%. If one of the BDWSOs experiences a disruption, the availability of the other IBTs remains at a high level (77.5%–94%), implying that the Bondowoso system has good redundancy to maintain supply continuity.

Table 5. IBT Contingency Summary After New GITET Operation (Jember Alternative)

No.	IBT	Normal (%)	OFF PITON5_PITON7_3	OFF JMBER5_ JMBER7_1	OFF JMBER5_ JMBER7_2
1	PITON 5_PITON7_3	50.2		60.7	60.7
2	JMBER5_ JMBER7_1	51.3	77.5		91.4
3	JMBER5_ B JMBER7_2	51.3	77.5	91.4	

Table 5 indicates that PITON5_PITON7_3 has an availability of 50.2% under normal conditions, while JMBER5_JMBER7_1 and JMBER5_JMBER7_2 are slightly lower at 51.3%. When PITON is down, JMBER shows an increase in availability to 60.7%, while if one of the JMBERs experiences a disruption, the availability of other IBTs remains high (77.5%–91.4%). This confirms that the Jember system is relatively stable and has good resilience to disruptions.

Table 6. IBT Contingency Summary After New GITET Operation (Genteng Alternative)

No.	IBT	Normal (%)	OFF PITON5_ PITON7_3	OFF GTENG5_ GTENG7_1	OFF GTENG5_ GTENG7_2
1	PITON5_PITON7_3	83.7		88.6	88.6
2	GTENG5_GTENG7_1	36.7	27.1		68
3	GTENG5_GTENG7_2	36.7	27.1	68	

Looking at the Table 6, PITON5_PITON7_3 has the highest availability at 83.7%, much higher than GTENG5_GTENG7_1 and GTENG5_GTENG7_2, which are 36.7% each. When PITON is down, GTENG5 shows an increase in availability from 27.1% to 68%, indicating that the Genteng system is highly dependent on PITON as its main source. This proves that Genteng has a higher vulnerability than other alternatives.

Table 7. IBT Contingency Summary After New GITET Operation (Banyuwangi Alternative)

No.	IBT	Normal (%)	OFF PITON5_ PITON7_3	OFF BWNGI 5_ BWNGI7_2	OFF BWNGI 5_ BWNGI7_2
1	PITON5_PITON7_3	37.3		50.3	50.3
2	BWNGI5_ BWNGI 7_1	56.8	75.4		96
3	BWNGI 5_ BWNGI7_2	56.8	75.4	96	

As shown in Table 7, PITON5_PITON7_3 has an availability of 37.3%, while BWNGI5_BWNGI7_1 and BWNGI5_BWNGI7_2 each have an availability of 56.8%. When PITON is down, BWNGI's availability increases to 50.3% for PITON and up to 96% if one of the BWNGIs experiences a disruption. This points to the fact that the Banyuwangi system is relatively resilient with IBT backup that is capable of withstanding major disruptions.

From power flow simulation results that are operationally feasible, namely alternatives based on RUPTL 2025-2034 plans at Watudodol, and alternative locations Jember, Genteng, and Banyuwangi. These alternative locations will be simulated to calculate transmission loss reduction.

3.4 Transmission Loss Simulation Results: After New GITET Construction

Simulation results indicate that the Jember location provides the most significant reduction in transmission power losses due to its proximity to the existing GITET, resulting in more efficient power flow. Although Banyuwangi has the largest additional capacity, it is less effective in reducing power losses because of its greater distance, while Watudodol and Genteng offer moderate benefits. This confirms that the determination of the new GITET location depends not only on additional capacity but also on its distance from existing infrastructure and its impact on main transmission pathways.

Table 8. New GITET Construction Alternative Plan for Paiton Subsystem

Location Alternative	Distance to Existing GITET (km)
Watudodol	131
Jember	80
Genteng	129
Banyuwangi	142

According to the 2025–2034 RUPTL plan, the construction of the GITET is fundamentally aimed at meeting electricity supply needs. However, simulation results show that the addition of the GITET also significantly reduces transmission power losses. Following the construction of the new GITET, total transmission losses in the Paiton subsystem decreased for all alternative locations, with the best results at the Banyuwangi site achieving a reduction of 77.48%, equivalent to an annual loss of 94.71 GWh. For the Watudodol alternative (Figure 5), the highest power loss occurred in October 2025 and the lowest in March 2025, with an upward trend observed in the second half of the year correlating with increased system load and seasonal factors.

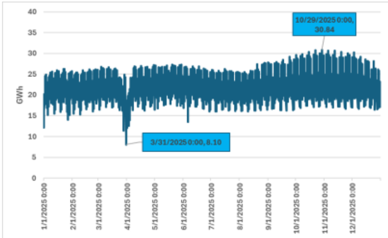

Figure 5. Hourly Transmission Loss Profiles 2025 After GITET Construction of Watudodol Alternative

Meanwhile, in the Jember Alternative GITET (see Figure 6), the maximum transmission loss value is slightly lower, at 29.39 GWh on November 12, 2025, and the minimum value is 9.46 GWh on March 31, 2025. Compared to Watudodol, the transmission loss profile in the Jember alternative looks more stable with a smaller fluctuation amplitude, pointing out to a better power distribution efficiency and a reduction in energy losses in the transmission network.

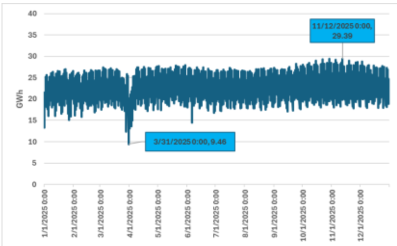

Figure 6. Hourly Transmission Loss Profiles 2025 After GITET Construction of Jember Alternative

Based on Figure 7, the hourly transmission loss in 2025 after the construction of the Genteng Alternative GITET reveals a stable pattern with relatively consistent daily fluctuations. The lowest loss value occurred on March 31, 2025, at 8.79 GWh, while the highest value was recorded on November 12, 2025, at 28.72 GWh. Compared to the Watudodol and Jember alternatives, the Genteng alternative shows a lower maximum loss rate and more stable variation, indicating better power distribution efficiency. This highlights that the construction of the Genteng GITET is capable of optimizing power flow and reducing energy losses in the transmission system, while maintaining network operational reliability throughout the year.

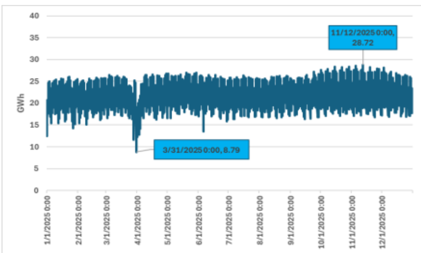

Figure 7. Hourly Transmission Loss Profiles 2025 After GITET Construction of Genteng Alternative

Figure 8 illuminates the hourly transmission loss profile for 2025 after the construction of the alternative Banyuwangi GITET. It can be seen that transmission losses are generally stable in the range of 10–15 GWh, with a sharp decline at the end of March (minimum of around 3.22 GWh), which is likely due to a decrease in load or system maintenance. Further, there is a gradual increase from mid-year to a peak of around 17.51 GWh at the end of October, reflecting increased system activity or network load. Overall, this pattern shows improved efficiency at the beginning of the year and increased energy losses as electricity demand rises towards the end of the year.

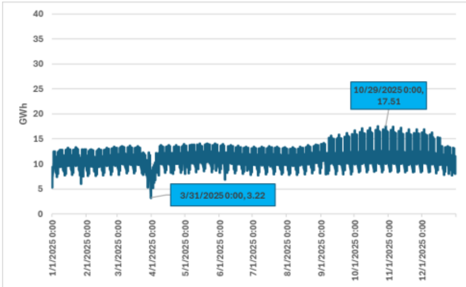

Figure 8. Hourly Transmission Loss Profiles 2025 After GITET Construction of Banyuwangi Alternative

As illustrated in Figure 9, after the construction of the new GITET, the Jember connection experienced the highest transmission loss, followed by Watudodol and Genteng, while Banyuwangi showed the lowest transmission loss, indicating an improvement in system efficiency. Overall, transmission losses remained relatively stable throughout the year, with a slight increase from May to October due to rising load, demonstrating that the GITET construction successfully balanced power flow and enhanced the reliability of the Paiton transmission system.

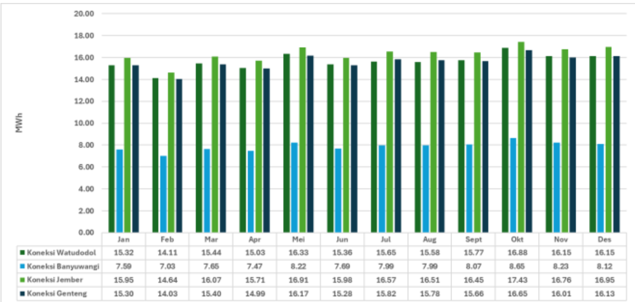

Figure 9. Paiton Subsystem Transmission Loss 2025 After New GITET Construction

3.5 Financial Feasibility Analysis After New GITET Construction

Financial feasibility analysis for new GITET construction in this research was conducted to identify the feasibility of new GITET construction in the Paiton subsystem for each alternative location. Investment assumptions for each location are shown in Table 9. GITET and SUTET construction assumptions include EPC cost and non-EPC cost.

Table 9. Investment Assumptions for Each Alternative Location

Component	Watudodol Connection (x 1,000 IDR)	Banyuwangi Connection (x 1,000 IDR)	Jember Connection (x 1,000 IDR)	Genteng Connection (x 1,000 IDR)	Remarks
EHV Substation (GITET)	780,495,384	594,471,360	603,471,360	594,471,360	Values include EPC and non-EPC cost
EHV Transmission Line (SUTET)	5,725,195,508	6,205,937,115	3,496,302,600	5,637,787,943	
Total	6,505,690,892	6,800,408,475	4,099,773,960	6,232,259,303	

Table 9 shows that the Jember location has the lowest investment cost of IDR 4.10 trillion, making it the most economically feasible alternative, while Banyuwangi requires the highest investment of IDR 6.80 trillion, primarily due to the cost of constructing the

SUTET. Although substation costs are relatively uniform, differences in power loss reduction and IBT loading levels significantly affect financial feasibility, as the main benefits stem from reduced power losses and increased electricity energy sales.

Table 10. Cumulative Transmission Losses for Each Alternative Location

Scenario	Cumulative Losses (KWh)	Loss Difference (KWh)
Before EHV Substation	420,566,041.53	-
Watudodol Connection	187,758,434.30	232,807,607.23
Banyuwangi Connection	94,710,838.23	325,855,203.29
Jember Connection	195,933,149.35	224,632,892.18
Genteng Connection	187,218,600.03	233,347,441.50

As presented in Table 10, the total cumulative power loss in the transmission system for several alternative GITET construction locations. The results highlight that the Banyuwangi location produces the smallest power loss (94.71 million kWh), resulting in the highest reduction in power loss of approximately 325.86 million kWh compared to the conditions before GITET existed. Thus, the Banyuwangi alternative is the most efficient location in reducing transmission losses, followed by Genteng and Watudodol with similar differences, while Jember shows the smallest reduction among the three.

Table 11. Financial Feasibility Calculation for the Construction of a New GITET: Watudodol Alternative

Component	Assumption	Unit
Voltage	150.00	kV
Lifetime	40	Years
Commissioning Year (Year 0)	2025	-
Total Investment	6,505,690,892	x 1,000 Rp
Total Cumulative Transmission Loss Reduction	232,807,607.23	kWh
IBT Load Reduction in Year -1	860	MW
Total Energy Transmitted in Year -1	3,693,216.00	kWh
Cost		
O&M Cost	130,113.818	x 1,000 Rp/Year
Fixed & Variable O&M Cost	-	-
O&M Cost Escalation	2.80%	Draft RUPTL PLN 2024
General Parameters		
Discount Rate	9.70%	PLN WACC 2023
Benefit		
Electricity Sale Tariff to Distribution	1,351	Rp/kWh
Revenue from Transmission Loss Reduction	314,618,528.48	x 1,000 Rp/Year
Revenue from New IBT Load Reduction	4,991,049,034.56	x 1,000 Rp/Year
Results		
IRR	11.29%	
NPV	1,841,894,506.88	x 1,000 Rp
B/C Ratio	1.02	
Payback Period	12.56	
KKF Conclusion	Feasible	

Financial feasibility calculation results for the Watudodol alternative location according to RUPTL 2025-2034 plans are shown in table 11. Calculation results show that new GITET construction at Watudodol location achieves an IRR of 11.29% where the discount rate assumption is 9.7% according to PLN WACC 2023, NPV of Rp.1.84 trillion, B/C Ratio 1.02, and payback period of 12.56 years. Hence, the Watudodol alternative location is categorized as financially feasible.

Table 12. Financial Feasibility Calculation for the Construction of a New GITET: Jember Alternative

Component	Assumption	Unit
Voltage	150.00	kV
Lifetime	40	Years
Commissioning Year (Year 0)	2025	-
Total Investment	4,099,773,392	x 1,000 Rp
Total Cumulative Transmission Loss Reduction	232,807,607.23	kWh
IBT Load Reduction in Year -1	862	MW
Total Energy Transmitted in Year -1	3,365,262.00	kWh
Cost		
O&M Cost	81,895.479	x 1,000 Rp/Year
Fixed & Variable O&M Cost	-	-
O&M Cost Escalation	2.80%	Draft RUPTL PLN 2024
General Parameters		
Discount Rate	9.70%	PLN WACC 2023

Benefit		
Electricity Sale Tariff to Distribution	1,351	Rp/kWh
Revenue from Transmission Loss Reduction	303,571,136.62	x 1,000 Rp/Year
Revenue from New IBT Load Reduction	4,924,498,403.60	x 1,000 Rp/Year
Results		
IRR	15.01%	
NPV	4,474,630,344.34	x 1,000 Rp
B/C Ratio	1.06	
Payback Period	9.35	
KKF Conclusion	Feasible	

Financial feasibility calculation results for the Jember alternative location are shown in table 12. Calculation results reveal that new GITET construction at Jember location achieves an IRR of 15.01% where the discount rate assumption is 9.7% according to PLN WACC 2023, NPV of Rp.4.47 trillion, B/C Ratio 1.06, and payback period of 9.35 years. Thus, the Jember alternative location is categorized as financially feasible.

Table 13. Financial Feasibility Calculation for the Construction of a New GITET: Genteng Alternative

Component	Assumption	Unit
Voltage	150.00	kV
Lifetime	40	Years
Commissioning Year (Year 0)	2025	-
Total Investment	6,232,593,303	x 1,000 Rp
Total Cumulative Transmission Loss Reduction	231,404,741	kWh
IBT Load Reduction in Year -1	805	MW
Total Energy Transmitted in Year -1	3,169,254.00	kWh
Cost		
O&M Cost	124,645.116	x 1,000 Rp/Year
Fixed & Variable O&M Cost	-	-
O&M Cost Escalation	2.80%	Draft RUPTL PLN 2024
General Parameters		
Discount Rate	9.70%	PLN WACC 2023
Benefit		
Electricity Sale Tariff to Distribution	1,351	Rp/kWh
Revenue from Transmission Loss Reduction	312,016,960.17	x 1,000 Rp/Year
Revenue from New IBT Load Reduction	3,906,746,997.65	x 1,000 Rp/Year
Results		
IRR	10.97%	
NPV	1,456,892,872.62	x 1,000 Rp
B/C Ratio	1.03	
Payback Period	13.31	
KKF Conclusion	Feasible	

Financial feasibility calculation results for the Genteng alternative location are shown in table 13. Calculation results suggest that new GITET construction at Genteng location achieves an IRR of 10.97% where the discount rate assumption is 9.7% according to PLN WACC 2023, NPV of Rp.1.45 trillion, B/C Ratio 1.03, and payback period of 13.31 years. As such, the Genteng alternative location is categorized as financially feasible.

Table 14. Financial Feasibility Calculation for the Construction of a New GITET: Banyuwangi Alternative

Component	Assumption	Unit
Voltage	150.00	kV
Lifetime	40	Years
Commissioning Year (Year 0)	2025	-
Total Investment	6,800,408.475	x 1,000 Rp
Total Cumulative Transmission Loss Reduction	325,855,203	kWh
IBT Load Reduction in Year -1	863	MW
Total Energy Transmitted in Year -1	3,745,338.000	kWh
Cost		
O&M Cost	136,080.170	x 1,000 Rp/Year
Fixed & Variable O&M Cost	-	-
O&M Cost Escalation	2.80%	Draft RUPTL PLN 2024
General Parameters		
Discount Rate	9.70%	PLN WACC 2023
Benefit		
Electricity Sale Tariff to Distribution	1,351	Rp/kWh
Revenue from Transmission Loss Reduction	440,363,980.28	x 1,000 Rp/Year
Revenue from New IBT Load Reduction	5,061,487,226.58	x 1,000 Rp/Year
Results		
IRR	11.54%	

NPV	2,192,226,904.91	x 1,000 Rp
B/C Ratio	1.04	
Payback Period	12.10	Years
KKF Conclusion	Feasible	

Financial feasibility calculation results for the Banyuwangi alternative location are shown in table 14. Calculation results show that new GITET construction at Banyuwangi location achieves an IRR of 11.54% where the discount rate assumption is 9.7% according to PLN WACC 2023, NPV of Rp.2.19 trillion, B/C Ratio 1.03, and payback period of 12.1 years. Therefore, the Banyuwangi alternative location is categorized as financially feasible.

4. CONCLUSION

Based on analysis results and discussion in the conducted research, the following conclusions can be drawn. Prior to the construction of the new GITET, transmission losses in the Paiton subsystem in 2025 are estimated to reach 420.57 GWh, with the highest losses occurring in October, which is the peak load period for the Java–Madura–Bali system. The determination of alternative locations for GITET construction was carried out through two approaches, namely: (1) the 2025–2034 RUPTL plan in Watudodol, and (2) the results of power flow simulations that identified alternatives in Situbondo, Bondowoso, Jember, Genteng, and Banyuwangi. As evidenced by the results of quasi-dynamic method simulations, there was a significant reduction in transmission losses after the addition of the new GITET, with the highest reduction of 77.5% in the Banyuwangi alternative, making this location the most technically optimal. Drawing from the financial analysis, all GITET development alternatives are economically feasible, with the Jember alternative showing the best performance (IRR 15.01%, NPV Rp 4.47 trillion, B/C ratio 1.06, and payback period 9.35 years) due to the closest transmission distance and most efficient investment requirements.

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