

RESEARCH ARTICLE

Optimizing Generation Costs in Electricity Supply Business Plan for Electricity Companies in Indonesia: A Reliability-Based Approach for the Sumatra Power System

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Abstract

Ensuring a stable and sustainable electricity supply requires effective planning that balances cost efficiency and system reliability. This study explores the optimization of Basic Generation Cost (BPP) in Electricity Companies in Indonesia Electricity Supply Business Plan (RUPTL) 2025–2034 while considering the reliability of the Sumatra power system. Using DiGSILENT PowerFactory, simulations incorporating Unit Commitment and Economic Dispatch methodologies were conducted to achieve cost reductions without compromising system stability. The significant result of this theses is optimization with economic dispatch reduces BPP up to 41,4% compared to conventional methods, enhancing power system cost efficiency. Increasing voltage reliability from 0.99 pu in 2025 to 1.01 pu in 2034. Higher renewable energy integration in 2034 reduces fuel costs but increases challenges in maintaining frequency and voltage stability. Strategic recommendations include increasing transmission capacity, implementing energy storage systems, and optimizing unit commitment to balance cost and reliability. This research offers valuable insights for power system planning, addressing energy transition challenges and facilitating the integration of renewable energy sources in Sumatra.

Keywords: Basic Generation Cost, System Reliability, Economic Dispatch, DiGSILENT PowerFactory

1. Introduction

One of the main solutions to optimize the use of renewable energy in Sumatra is through more efficient management of the Cost of Generation (BPP). By reducing

BPP, renewable energy generators can not only compete with conventional generators but can also make a significant contribution to increasing the reliability of the electricity system. This reliability is very important to ensure a stable electricity supply, especially in remote areas or areas that are difficult to reach by the main electricity network [1].

Several previous studies have examined the effect of Economic Dispatch on cost efficiency and system reliability. For example, Shahidehpour et al. showed that reliability-based unit commitment optimization can reduce operating costs while maintaining system reliability [2]. Meanwhile, Conejo et al. suggested that coordination between dispatch strategy and cost optimization is important for multi-type systems [3].

In Sumatra, the electricity system faces its own challenges due to rapid load growth, uneven distribution of energy resources, and limited transmission and distribution infrastructure. The reliability of the electricity system is a major factor in ensuring stable and efficient electricity availability. Therefore, the analysis of BPP in the 2025–2034 RUPTL needs to consider the system reliability aspect to ensure that optimized generation costs do not sacrifice the stability of electricity supply [3].

The World Bank report states that the integration and mix of EBT in Sumatra has not been accompanied by the readiness of the transmission system and frequency control [4]. Based on the report on the results of the investigation into widespread blackouts in the Sumatran electricity system, when the 275 kV electricity network owned by PT PLN (Persero) which currently supports the reliability of electricity in Southern Sumatra experienced a blackout [5]. It had a serious impact on the reliability of the Sumatra electricity system [6].

This study aims to analyse the BPP in the RUPTL of Electricity Companies in Indonesia 2025–2034 by considering the reliability aspect of the Sumatra electricity system. The results of this study are optimizing generation costs without sacrificing system reliability as strategic recommendations for stakeholders to encourage the development of renewable energy, support the national energy mix target, and accelerate steps towards a sustainable energy system [2].

2. Cost of Generation (BPP)

Cost of Generation (BPP) is an important component in determining cost efficiency in the production and distribution of electrical energy. BPP describes the average cost required to generate and deliver one unit of electricity to consumers. This cost component includes initial investment, operation and maintenance (O&M), fuel, and other costs related to the operation of the power plant. In renewable energy generation, BPP calculations often have different challenges compared to fossil-based power plants. Some of the main factors that affect BPP include:

- a) High Initial Investment Costs;
- b) Dependence on Natural Resources;
- c) Government Policy and Support;
- d) Economies of Scale Effect;

In Indonesia, BPP is often used as a reference by the Electricity Companies in Indonesia to determine electricity rates. In addition, BPP is also a primary consideration in evaluating the feasibility of new power plant projects and ensuring the sustainability of existing power plant operations.

In the context of the Sumatra electricity system, BPP is influenced by the energy mix used in generation. Research by Bhattacharyya shows that systems with a high dependence on fossil fuels tend to have more volatile generation costs compared to systems with a larger share of renewable energy [7].

On the other hand, the reliability of the electricity system also has a close correlation with the cost of generation. A study conducted by Shahidehpour *et al.* (2002) [2] showed that unit commitment optimization can reduce generation costs without sacrificing system reliability. Similar results were also found by Conejo *et al.* (2006) who emphasized the importance of coordination between dispatch strategies and generation cost optimization.

According to a study conducted by Kirschen & Strbac (2019), the fuel price volatility factor also has a significant impact on BPP [8]. In recent years, fluctuations in natural gas and coal prices have caused significant variations in electricity generation costs in many countries, including Indonesia [9]. Another study by Wood *et al.* (2016) highlighted the impact of increasing renewable energy penetration on the cost of generation. In the long term, increasing the use of renewable energy can reduce BPP by reducing dependence on fossil fuels which tend to have higher operating costs [10].

Another factor that affects BPP is the level of efficiency of the power plant. According to a study conducted by Cárdenas *et al.* (2017), power plants with high efficiency have lower generation costs than power plants with older technology that are more wasteful of fuel. This is also reinforced by the World Bank report (2020) which states that increasing operational efficiency can significantly reduce BPP [11].

In addition to technical factors, government regulations also play an important role in determining BPP. A study conducted by Joskow (2008) shows that policy incentives and fuel price regulations can help stabilize generation costs in the long term. This is also confirmed by a report from the International Renewable Energy Agency (IRENA, 2021), which highlights the importance of policy support in reducing the cost of renewable energy-based electricity generation [12].

Overall, research conducted by various experts shows that optimizing generation costs requires a multidimensional approach that includes technical, economic, and energy regulatory factors. By considering aspects of system reliability, generation efficiency, and the energy policies implemented, it is expected that the optimal generation cost can be achieved for the Sumatra electricity system [13].

This study will examine in depth how BPP can be optimized, especially for renewable energy generation. The focus is to find a balance between cost optimization and reliability of the electricity system, so that renewable energy can play a greater role in meeting the electricity needs of the Sumatra Electricity System in a sustainable manner.

3. Reliability

The reliability of the electrical power system is one of the main aspects in the planning and operation of the electrical power system. Reliability reflects the ability of the system to provide continuous and quality electricity supply according to customer needs [14]. According to the North American Electric Reliability Corporation, the reliability of an electric power system consists of two main aspects [15]:

a) Adequacy

The ability of the electric power system to meet customer load needs with the available generating and network capacity.

b) Security

The ability of the system to continue operating under disturbance conditions, such as disturbances in generating units or disturbances in the transmission network (Kundur, 2007) [16]. The reliability of the electricity system is one of the important factors to ensure a stable and sustainable electricity supply. A reliable system can provide electricity without significant disruption, maintain network stability, and overcome challenges such as sudden increases in electricity load or technical disturbances. In the context of electricity, reliability is usually measured through several indicators [17].

Reliability is a very important factor in planning an electric power system. According to IEEE (2015) [18], the electric power system must have sufficient power reserves to deal with load uncertainty and power plant unit disruptions. A study conducted by Shahidehpour et al. (2002) showed that reliability-based commitment optimization can improve generation cost efficiency without sacrificing continuity of electricity service [2].

In modern power systems, the integration of renewable energy also affects system reliability. Power fluctuations from renewable energy sources such as solar and wind power increase the need for energy storage technologies and grid flexibility to maintain system reliability [19].

According to the International Energy Agency (IEA, 2023) report, smart grid-based approaches and Artificial Intelligence (AI) technologies are increasingly being used to improve the reliability of electric power systems by enabling more accurate disturbance predictions and faster system responses. Overall, the reliability of the electric power system is a complex aspect and requires a multidisciplinary approach to ensure that the electricity supply remains stable, efficient and sustainable [20].

This study aims to evaluate the reliability of the electricity system of the Sumatra electricity system, especially in the context of renewable energy development. Reliability is based on voltage according to PUIL (general regulations for electrical installations) 2011 regulation [21]. Through an optimization approach, this study will analyse how renewable energy can be integrated efficiently without reducing system reliability. Thus, Sumatra can develop an electricity system that is not only reliable but also supports energy sustainability.

4. Research Methodology

The flow diagram used in this study is below:

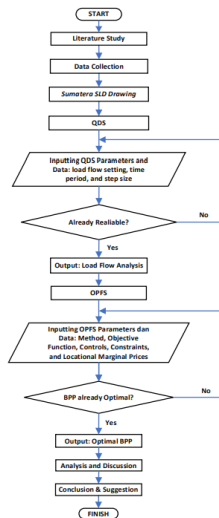


Figure 1. Research Flow Chart

Based on the flow chart, the research methodology used in this study is:

- Reliability measurement based on Quasi Dynamic Simulation (QDS) and Voltage Stability Indeks (VSI) with reference to the 2011 PUIL standard ($\pm 5\%$). The indices used include voltage per unit (pu), reserve margin, and voltage stability over time. Voltage Stability Index (VSI) is a measure used to assess the ability of a power system to maintain constant voltages at all its buses after being subjected to a disturbance;
- Economic dispatch based on Optimal Power Flow (OPF), Merit Order (MO), and Must Run Characteristic (MRC). Demand is modeled using daily load data from the 2025–2034 RUPTL and simulated in Time Series format on DIgSILENT. Power generation profiles are modeled based on dispatch merit order and must-run characteristics (PLTA, PLTP) and Dispatchable (PLTU, PLTG).

4.1 Voltage Stability Index and System Modeling

Quasi Dynamic Simulation (QDS) uses an iterative method to solve the power flow at each time step. In QDS, the Newton-Raphson (NR) method is used as the main solver in calculating the load flow at each time step. NR is an iterative method that is very effective in handling power systems with a large number of buses and complex impedances. This method has quadratic convergence, which means it is faster than other iterative methods such as Gauss-Seidel. The Newton-Raphson method solves the nonlinear equation of power flow with the following iterations:

$$J.\Delta X = -F(X) \quad (1)$$

Where:

- X = System variable vector (voltage V and angle θ);
- $F(X)$ = Vector mismatch of active power (Δ) and reactive power (ΔQ);
- J = Jacobian Matrix (Partial derivatives of the power function with respect to V and θ).
- ΔX = Change in the value of the updated variable in each iteration.

Each iteration is performed with the following steps:

1. Calculate the power mismatch ΔP and ΔQ ;
2. Calculate the Jacobian matrix (J) based on the current system;
3. Solve the linear equation to obtain ΔX ;
4. Update system variables;
5. Check convergence (if ΔP and ΔQ are smaller than the tolerance, the iteration is finished).

$$X^{k+1} = X^k + \Delta X \quad (2)$$

Voltage stability is a critical aspect of power system operation, ensuring that voltages remain within acceptable limits under normal and contingency conditions [22]. The VSI is a numerical indicator used to assess the proximity of a power system to voltage instability [23]. A higher VSI value suggests a higher risk of voltage collapse, while a value close to 1 indicates a stable system sauer [24]. VSI is formulated as follows:

$$VSI = \left(\frac{V_{max}}{V_{min}} \right)^2 \quad (3)$$

Where:

- V_{max} = Maximum voltage (per unit, pu)
- V_{min} = Minimum voltage (per unit, pu)

4.2 Economic Dispatch

In DigSILENT PowerFactory Operating Cost Analysis (OCA), operating cost optimization aims to minimize the total generation cost by considering technical and economic constraints. This optimization is very important in planning the power plant operation, economic dispatch, and renewable energy integration. The optimization methods used in each category can vary depending on the complexity of the system and the constraints applied. Optimization methods in OCA can be categorized as below:

- a) Economic Dispatch (ED) → Determines the distribution of load between generators at minimum cost. Economic Dispatch aims to distribute the load between generators so that the total fuel cost is minimum. The objective function used is:

$$\text{Min} \sum_{i=1}^n C_i(P_i) = \sum_{i=1}^n (a_i P_i^2 + b_i P_i + c_i) \quad (4)$$

- b) Unit Commitment (UC) → Determines the optimal generator operating schedule in a certain period. Unit Commitment aims to determine which generating units should be ON/OFF to minimize operating costs. Its objective function:

$$\text{Min} \sum_{i=1}^n C_i(P_i) = \sum_{i=1}^n (a_i P_i^2 + b_i P_i + c_i) \quad (5)$$

where μ_i is the ON/OFF status of the generator

- c) Optimal Power Flow (OPF) → Optimizes power distribution in the system by considering network constraints. OPF aims to optimize the power distribution in the system by considering network constraints. Its objective function:

$$\text{Min} \sum_{i=1}^n C_i(P_i) + \sum_{j=1}^m C_j(Q_j) \quad (6)$$

- d) Merit Order (MO) → Cost-based ranking system used by grid operators to dispatch electricity generation sources efficiently. When prioritizing renewable energy (highest rank) over fossil fuels (lowest rank), the system ensures the cheapest and cleanest power sources are used first, minimizing costs and emissions. The goal is to meet electricity demand at the lowest possible cost while ensuring reliability.
- e) Must Run Characteristic (MRC) → power generation unit that is required to operate at a minimum output level regardless of economic considerations (such as fuel costs or electricity market prices). These units are essential for maintaining grid reliability, stability, and contractual obligations. A must-run generator must satisfy:

$$P_i \geq P_{i,min} \quad (7)$$

Where:

- P_i = Actual output of generator i (MW)
- $P_{i,min}$ = Minimum required power (must-run level)

5. Results and Discussion

5.1 Voltage Stability Profile and Reliability Metrics (2025-2034)

The reliability of the Sumatra electricity system is simulated using QDS Simulation. For this, a single line diagram must be prepared first on DigSILENT. QDS simulation functions determine the reliability of the Sumatra system voltage in 2025. The results of the QDS simulation on the Sumatra system single line diagram are explained in Figure 1 as follows:

Figure 2 shows that most locations in Sumatra have stable voltages at 0.99 – 1.01 pu in various simulation periods in 2025. There are no indications of voltage drops, or excessive voltage increases that could potentially endanger the system. Small fluctuations within the normal range indicate that the system is still working within safe limits, with good reactive power management. 6_PLTU MT SUMSEL-8 #1 and

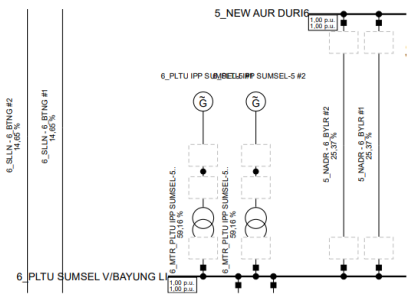


Figure 4. Sumatra power system SLD in 2029

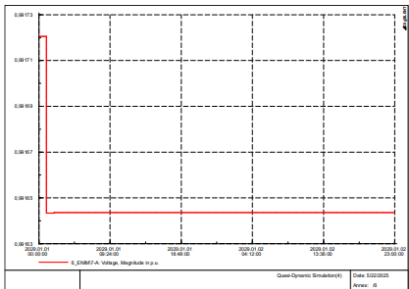


Figure 5. QDS simulation results in 2029

Figure 5 shows the voltage profile on the ENIM7-A bus during the period 1 January 2029 to 2 January 2029. This voltage is represented by a red curve with a vertical scale ranging from 0.99163 pu to 0.99173 pu. At the beginning of the simulation time, the voltage is slightly higher, around 0.99171 pu. In a short time, the voltage experiences a small decrease and stabilizes at around 0.99165 pu for the remainder of the simulation period. There were no significant fluctuations during the observed period, indicating that the system remained in stable condition without any major disturbances.

The results of the QDS simulation on the single line diagram of the Sumatra system in 2034 are explained in figure 6 as follows:

Figure 6 shows that the Sumatra electricity system in 2034 has good voltage reliability, with strong interconnection between North Sumatra and Lampung. Based on the QDS simulation results, the voltage at various buses is generally within the normal range (0.95 pu – 1.05 pu). The voltage at several points is relatively stable, but there is a slight decrease at the beginning of the simulation time. The 275 kV network in several areas with voltage reliability remains maintained despite load fluctuations. If there is a disruption on one of the main lines, the system can still maintain the voltage by distributing the load to other lines. Large power plants such as in South Sumatra and North Sumatra play a major role in supporting voltage stability. Even the distribution of power plants reduces the possibility of low voltage due to local power shortages. Loads in areas such as Riau and West Sumatra are supported by

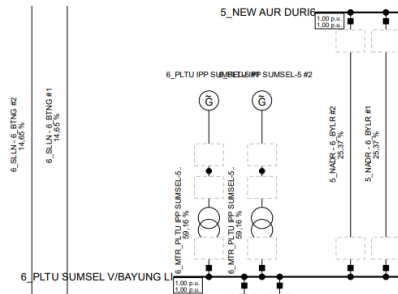


Figure 6. Sumatra power system SLD in 2034

power flows from the nearest power plant.

Based on the data, no points were found with voltages approaching the critical limit. However, it is necessary to further examine whether the system has sufficient reactive power reserves to anticipate future load changes. The voltage reliability of the Sumatra system in this simulation is very good. There is no indication of voltage outside the normal limit. The voltage is relatively stable at various points without major fluctuations indicating that the power system is operating with sufficient safety margins. Although these results indicate good reliability, continuous monitoring is still needed, especially with the increasing penetration of renewable energy which can affect the voltage profile in some areas. The voltage graph resulting from the QDS simulation of the Sumatra electricity system in 2034 is explained in Figure 7 as follows:

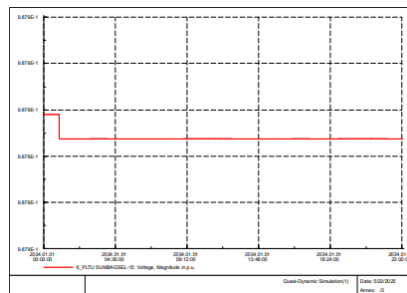


Figure 7. QDS simulation results in 2034

Figure 7 shows that the voltage reliability at PLTU SUMBAGSEL-15 is well maintained, with a value of 0.9879 pu still within the operational standard limits. The system shows good stability against load variations, without any indication of major disturbances. The voltage at the PLTU SUMBAGSEL-15 bus is consistently at 0.9879 pu at various points in time. This value indicates voltage stability without significant fluctuations throughout the simulation period.

The voltage of 0.9879 pu is still within safe limits, so there is no indication of undervoltage or overvoltage disturbances that can affect system reliability. Although still within safe limits, proactive measures such as voltage regulation optimization and

periodic monitoring are needed to prevent the risk of further voltage drops. Voltage stability continues to indicate that the system has good resistance to load variations around the SUMBAGSEL-15 PLTU. There is no indication of significant voltage drops, which can be caused by high loads or network disturbances.

5.2 Economic Dispatch Simulation and OPF Results (2025–2034)

The implementation of OPF in the Sumatra system successfully optimized the dispatch of generators, thus reducing the basic cost of generation by around 11.57%. This shows the potential for significant economic efficiency through optimization of generator allocation based on OPF. Before OPF was carried out, the total BPP per year was around \$46,043,962,348. After OPF was carried out, the total BPP per year was around \$40,699,829,052. So, the BPP savings per year were around \$5,305,551,971 with a savings percentage of 11.57%. The OPF simulation results graph on the Sumatra electricity system is explained in Figure 8 as follows:

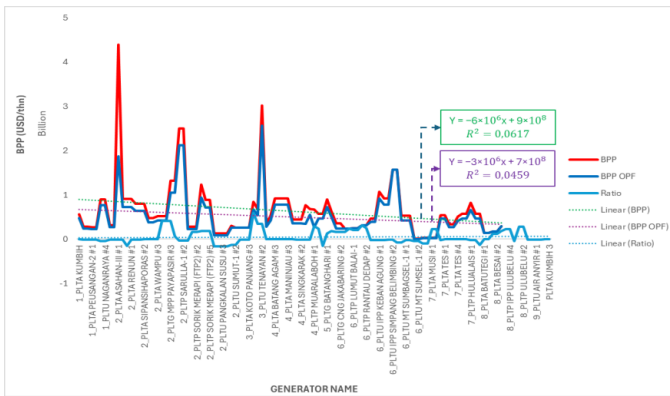


Figure 8. OPF simulation results for 2025

Figure 8 illustrates a linear downward trend indicating a downward trend in BPP after OPF. BPP before OPF has a larger gradient, indicating that without optimization, costs tend to be more volatile and higher. BPP after OPF has a more stable trend, indicating a more optimal generator allocation. The coefficient of determination (R^2) with the R^2 value indicates the level of fit of the linear trend to the data. The R^2 value for BPP before OPF (0.0617) and after OPF (0.0459) indicates that BPP still varies quite a bit between generators. The equation for the linear trend of BPP before OPF is:

$$y = -6x10^6x + 9x10^8, \text{ with } R^2 = 0.0617 \quad (8)$$

The linear trend equation of BPP after OPF is:

$$y = -6x10^6x + 9x10^8, \text{ with } R^2 = 0.0459 \quad (9)$$

OPF had successfully optimized generator dispatches to reduce the basic cost of generation by around 20.02%. This saving is greater than in 2025 which only reached

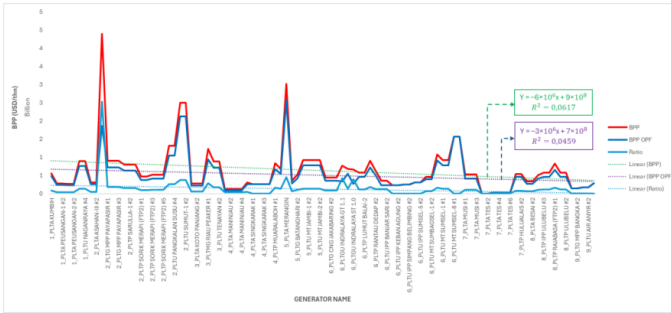


Figure 10. OPF simulation results for 2034

OPF has succeeded in redistributing the load to generating units with lower costs, especially to renewable energy or cheap fuel-based generators (PLTA, PLTU). It shows a downward trend in costs, but with larger fluctuations. The linear trend equation of BPP before OPF is:

$$y = 7x10^6x + 1x10^9, \text{ with } R^2 = 0.0545 \quad (12)$$

After OPF, the decrease in BPP becomes more controlled compared to before OPF, which indicates higher efficiency after optimization. The linear trend equation of BPP after OPF is:

$$y = -4x10^6x + 5x10^8, \text{ with } R^2 = 0.0481 \quad (13)$$

OPF has a positive impact in reducing generation costs in the Sumatra electricity system in 2034. Cost fluctuations are more controlled, especially for generating units that previously experienced high-cost spikes. The system becomes more efficient with more optimal utilization of low-cost generators and renewable energy. Efficiency of power plant operation schedule with:

- Unit Commitment optimization, power plants with low operating costs;
- Renewable energy-based power plants (PLTS, PLTB) operate intermittently according to the natural resource profile;
- PLTG is used as a peaker unit to meet load spikes.

5.3 Generation Cost 2025-2034

The configuration of must run and non-must run generators. ET generators such as PLTA and PLTP are included in must run generators which are given code number 1 and fossil generators such as PLTU, PLTG, PLTGU and PLTMG are included in non must run generators which are given code 0. Because renewable energy generators with mandatory absorption regulations (PLTA, PLTS, PLTB). Must run generators will be prioritized to operate in the Sumatra electricity system compared to fossil generators. So that a more optimal BPP will be obtained adjusted to voltage reliability. Because DIGSILENT has a solver that will sort the merit order of the generators to be operated. Merit order is a method to optimize the operation of power plants by

sorting the plants based on the cheapest operating costs, so that the plants with the lowest operating costs are prioritized to operate first.

The optimal BPP for hydroelectric power plants is around 5 – 1,210 USD/MWh with an average BPP for hydroelectric power plants of around 589 USD/MWh. The optimal BPP for geothermal power plants is around 662 – 1,075 USD/MWh with an average BPP for geothermal power plants of around 844 USD/MWh. The optimal BPP for coal-fired power plants is around 56 – 1,615 USD/MWh with an average BPP for hydroelectric power plants of around 545 USD/MWh. The optimal BPP for gas-fired power plants is around 223 – 3,061 USD/MWh with an average BPP for gas-fired power plants of around 1,689 USD/MWh. The optimal BPP for combined-cycle power plants is around 1,107 – 2,420 USD/MWh with an average BPP for gas-fired power plants of around 1,903 USD/MWh. The optimal BPP of hydroelectric power plants is around 1,001 – 2,681 USD/MWh with an average BPP for hydroelectric power plants of around 1,837 USD/MWh. Figure 11 explains the Optimal BPP of each type of power plant in Sumatra:

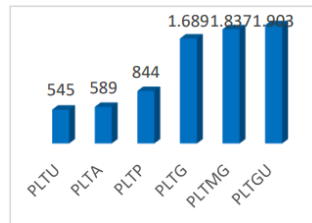


Figure 11. Average optimal BPP

In figure 11, PLTGU has the highest optimal BPP value. While PLTU has the lowest optimal BPP value. So PLTU is used as the baseload of the Sumatra electricity system because of its slow response. While PLTGU becomes a peaker generator because of the highest optimal BPP value and its fast response. The relationship between optimal BPP and voltage reliability is explained in figure 12 as follows:

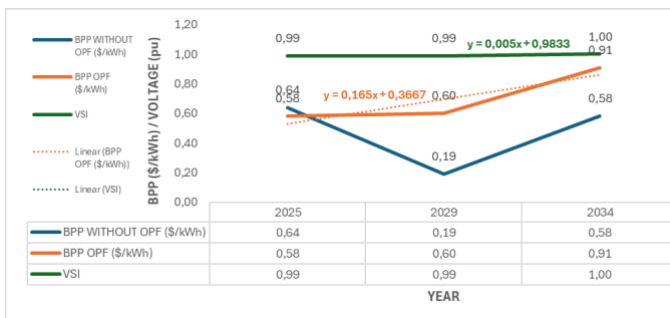


Figure 12. Relationship between BPP and VSI trends for 2025-2034

Figure 12 explains the relationship between BPP and VSI trends for 2025-2034. So that the optimal BPP is directly proportional to voltage reliability and year. The chart

shows how the Basic Production Price (BPP) and voltage stability evolve in Sumatra's power system between 2025 and 2034, comparing scenarios with and without Optimal Power Flow (OPF) implementation. Overall, the results suggest that OPF plays a crucial role in balancing cost efficiency and system reliability.

In 2025, the BPP without OPF is relatively high at \$0.64/kWh, while OPF manages to reduce it to \$0.58/kWh. By 2029, BPP without OPF drops sharply to just \$0.19/kWh—likely due to temporary conditions such as underutilized generation or lower demand. However, this low cost does not come with improved reliability. In contrast, BPP with OPF increases slightly to \$0.60/kWh but maintains system reliability, which is reflected in the steady Voltage Stability Index (VSI) of 0.99.

By 2034, the system reaches its most stable point. The VSI improves to a perfect 1.00, meaning the grid voltage remains consistently within the ideal range. At the same time, the BPP with OPF increases to \$0.91/kWh, suggesting that maintaining this high level of reliability may require more sophisticated generation scheduling and possibly higher-cost technologies, such as renewables or storage. Still, this cost remains lower than the potential inefficiencies that could arise in the unoptimized system.

The upward trend in VSI and the smoother trajectory of BPP with OPF suggest that OPF contributes to long-term system resilience. It provides predictable cost patterns, avoids major fluctuations, and supports grid stability, even as electricity demand grows and more renewable energy is integrated.

The two linear equations shown in the chart help us understand how the Basic Production Price (BPP) and the Voltage Stability Index (VSI) are expected to change over time when using Optimal Power Flow (OPF). The BPP with OPF linear trend follows the equation:

$$y = 0.165x + 0.3667 \quad (14)$$

This means that for every step forward in time (in this case, from 2025 to 2029, and from 2029 to 2034), the cost of generating electricity increases by about \$0.165 per kilowatt-hour. While this may seem like a cost increase, the important point is that the increase is gradual and predictable. This suggests that OPF helps keep the system economically stable, even as demand grows or new technologies are added. The VSI linear trend follows the equation:

$$y = 0.005x + 0.9833 \quad (15)$$

This shows that the system's voltage stability also improves slightly over time. Although the increase in VSI might look small (about 0.005 per time step), it's significant—because VSI is already close to the ideal value of 1.00. This trend confirms that the system is becoming more reliable each year, likely thanks to better dispatch strategies and the smoother integration of renewable energy.

In short, while the cost of generation (BPP) rises modestly, the overall reliability of the system (VSI) improves. This reflects a healthy trade-off: the power system becomes more stable and efficient with time, especially when OPF is used to guide operational decisions.

5.4 Future Grid Planning and Policy Implications

The findings from this study carry significant implications for Indonesia's power system policy, especially in the context of accelerating energy transition and achieving long-term reliability and affordability goals. The evidence clearly shows that cost optimization strategies, such as the implementation of Optimal Power Flow (OPF) and Economic Dispatch, can substantially reduce the Basic Production Price (BPP) without compromising system reliability. In fact, by 2034, the combination of optimized generator scheduling and increased use of renewable energy reduced generation costs by more than 40%, while improving voltage stability to near-perfect levels ($VSI = 1.00$). This proves that technical and economic performance can be aligned through smart planning, especially in large interconnected systems like Sumatra. These outcomes have direct implications for policy design:

- a) Grid planning must shift from a cost-centric approach to a cost-plus-reliability model. Instead of merely minimizing generation costs, planners should also factor in system stability indicators such as the Voltage Stability Index (VSI) and reserve margins.
- b) Renewable energy development must be integrated with system-level optimization. While renewable energy offers long-term cost benefits, its intermittent nature demands robust system planning tools—such as DigSILENT's Quasi Dynamic Simulation and OPF to maintain grid reliability.
- c) Transmission planning should prioritize strategic reinforcement in critical industrial zones, where the simulations revealed vulnerability in voltage stability. This also implies the need for more decentralized generation or reactive power support.
- d) The planning horizon for the RUPTL (Electricity Supply Business Plan) should include a layered scenario approach. Base case, disturbance, and high-renewable penetration scenarios must be simulated using reliability-based tools to guide investments in infrastructure and generation portfolios.
- e) Institutional coordination between PLN, EBTKE, and the MEMR should be strengthened to align economic dispatch strategies with national decarbonization targets.

This study underscores that Indonesia's energy planning should no longer separate technical reliability and economic optimization as competing priorities. Instead, through smart dispatch, grid reinforcement, and regulatory alignment, these goals can be achieved together. Going forward, policy frameworks must be updated to reflect the realities of modern grid management, where cost, stability, and sustainability must all be optimized in parallel.

6. Conclusion

This study demonstrated that optimizing generation cost through Economic Dispatch and Optimal Power Flow (OPF) not only reduces the Basic Production Price (BPP) but also enhances the reliability of the Sumatra electricity system. Simulation results show that BPP can be reduced by up to 41.4% by 2034 through optimal generator dispatch, especially with the prioritization of low-cost and renewable energy sources.

Meanwhile, the Voltage Stability Index (VSI) improved from 0.99 in 2025 to a perfect 1.00 in 2034, indicating excellent voltage reliability across the network.

The positive correlation between cost optimization and reliability reflects a robust system that remains stable under increasing load and renewable energy penetration. These findings highlight the strategic importance of implementing OPF and advanced planning methodologies in Indonesia's electricity supply business plan (RUPTL), particularly for regions like Sumatra that are undergoing rapid demand growth and energy transition.

To align electricity sector regulations with modern reliability and efficiency goals, we propose the following updates:

- a) Revise Peraturan Menteri ESDM No. 4/2020 (or latest) to include OPF-based dispatch principles as mandatory practice in grid operation and planning, particularly for high-voltage interconnection systems;
- b) Amend BPP calculation guidelines to include voltage reliability indicators (such as VSI or minimum voltage margin) as part of the cost-justification criteria in renewable project evaluation;
- c) Include Voltage Stability Index (VSI) thresholds (≥ 0.98 pu) as an operational compliance requirement in PUIL revisions, especially in areas with high renewable energy penetration;
- d) Expand the definition of "must-run units" in grid codes to encompass not only renewables but also critical grid-support units such as synchronous condensers or flexible ramping generators;
- e) Establish a national performance incentive scheme that rewards generation or transmission operators who achieve both cost savings and reliability improvements through optimization;

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