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Research Article

Techno-Economic Optimization of PV-BESS Peaker to Replace Thermal Plants: A Case Study of the Madura PV-BESS Project, Indonesia

Imam Tri Sulistyo[1*], Hikmah Susetyo[1], Mohamad Subkhi Priono[1]
[1] PLN Indonesia Power
***Email**: imam.trisulistyo@plnindonesiapower.co.id

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Abstract: An important challenge for the energy transition will be a triple challenge in island nations—between decarbonization, supply security, and cost affordability. We investigate the techno-economic viability of 75 MWp Solar Photovoltaic (PV) System integrated with 50 MW/250 MWh Battery Energy Storage System (BESS) in Madura. It is known that the electrical subsystem in the region is at the most significant risk due to the current power failure, which in N-1 contingency events resulted in a power deficit of 177 MW and a significant risk of full power outages. Based on different optimization schemes and waterfall sensitivity analysis, the current project has determined the impact of six scenarios on Levelized Tariff (ABEF components) outcomes. According to simulation results, while base case scenario results in a prohibitive tariff of 23.47 cUSD/kWh, the introduction of more strategic measures, particularly revenue stacking through off-peak energy sales, green financing (4% soft loan), local content exemption, and regulatory incentives, can considerably reduce the tariff by 31.52% to 16.07 cUSD/kWh. Specifically, this optimized tariff provides 28.85% lower fuel costs compared to the average pricing of fuel cost of current thermal peaker power plant owned by PLN Indonesia Power (22.59 cUSD/kWh) and is 46.38% lower compared to diesel and gas engines fuel cost in Indonesia (29.98 cUSD/kWh). These findings shows that utility-scale PV-BESS functions not only as a "Defender" asset for grid frequency and voltage stability but also as a financial hedge against fossil fuel price volatility, offering a strategic roadmap for policymakers in emerging markets.
Keywords: Battery Energy Storage System (BESS); Solar PV; Techno-Economic Analysis; Peaker Replacement; Levelized Tariff.

1. Introduction

Indonesia has the ambition of energy transition to Net Zero Emissions (NZE) in 2060 while simultaneously ensuring grid reliability. However, balancing decarbonization with energy security also poses specific issues, especially in semi-isolated sub-systems such as the Madura Island grid. Currently, electricity for Madura is sourced solely from 150 kV transmission cables directly through the Java grid which run through the Suramadu Bridge and the Bangkalan-Sampang line. A fundamental vulnerability with this configuration is the total absence of firm local generation assets within the Madura sub-system.

The peak load in Madura as described in the regional power balance (*Neraca Daya*) is expected to be 449 MW by 2027.

However, the transmission capacity is severely constrained during contingency events. Under N-1 conditions (where one circuit fails), the maximum transfer capability is reduced to 272 MW. This creates a deficit of 170 MW during peak hours and is likely to lead to excessive load shedding or complete blackouts for the island. Hence, there is a requirement for a local "defender" power plant, which can give the firm capacity and frequency support from the grid disruptions [1].

Research by Silalahi et al. shows that Indonesia has huge potential for solar energy generation, suggesting a proper integration of BESS could lead to competitive energy pricing, as well as reduced dependency on fossil fuels [2]. Optimizing solar PV and BESS is essential in addressing the intermittency of solar energy. The study by Buratynskyi and Nechaieva investigated how efficient BESS can enhance the reliability of solar PV systems by allowing energy storage during peak solar radiation hours and enabling discharge when energy demand surges [3].

In this study, Madura PV-BESS Project in Sumenep is represented as strategic pilot project. Constructed based on a 50 MWac (75 MWp) PV (Solar Photovoltaic) system fitted with a 50 MW / 250 MWh Battery Energy Storage System (BESS), this facility is a "clean peaker." Its key technical goal is to minimize the evening peak load (17:00–22:00) and provide a strategic backup to avoid service outages when interconnectivity is compromised.

The infrastructure needed for such utility-scale BESS solutions is practical, but there are economic considerations in deploying them. For the project, the preliminary study predicts a high initial tariff as capital expenditure (CAPEX) includes a large amount for battery, solar PV and land acquisition. Previous studies indicate that without techno-economic optimization, the Levelized Cost of Electricity (LCOE) for PV-BESS exceeds the generation cost of conventional thermal peaker power plant owned by PLN Indonesia Power.

The purpose of this paper is to connect the sense of technical urgency in the power balance to the financial constraints in the feasibility study. By leveraging specific project data, including the degradation profile and augmentation schedule, this research performs a techno-economic optimization to determine the "Levelized Tariff of Solar PV-BESS" (ABEF components). It examines how policy levers such as green financing (soft loans) and regulatory incentives can bring the tariff down, establishing the project as not only a green initiative but also an important contributor to Madura's energy security.

2. Materials and methods

This study employs a quantitative techno-economic analysis based on the specific study parameters of the Madura Project. The methodology is structured into site assessment, system configuration, and financial modeling.

2.1. Site Assessment and System Configuration

The project is located in Sumenep Regency, Madura, East Java. The are needed for this project is approximately 86 hectares. The site is strategically situated less than 1 km from the existing Guluk-guluk Substation, allowing for a cost-effective connection via a 150 kV underground transmission line (SKTT). The land cover consists primarily of mixed dry land agriculture and settlement areas, requiring significant land acquisition efforts.

The technical configuration is modeled to support a "Peaker" operation mode (discharge 17:00–22:00):

a) Solar PV Plant: A DC capacity of 75 MWp (50 MWac). Oversizing allows sufficient energy capture to charge the battery fully during daylight hours.
b) Battery Energy Storage (BESS): A 50 MW / 258.3 MWh (Usable) system. To maintain this usable energy capacity over the 25-year project life, a Capacity Maintenance Program

(Augmentation) is modeled. Battery modules are augmented at years 6, 11, 16, and 21 to compensate for degradation and ensure the system can consistently deliver 50 MW for 5 hours.

c) Grid Constraint: The simulation acknowledges the bottleneck in the Madura sub-system, assuming the BESS acts as a grid-forming or support asset during N-1 transmission events.

2.2. Financial Modeling Framework

Economic feasibility is evaluated using a discounted cash flow (DCF) model to calculate the Levelized tariff. The input parameters are derived:

- CAPEX: The total project cost is estimated at USD 137.25 Million. This includes:
  - EPC PV Plant: USD 33.14 Million
  - EPC BESS: USD 74.28 Million
  - Land Acquisition: USD 7.03 Million
  - Transmission: USD 3.36 Million
  - Development: USD 11.16 Million
  - Financing Costs: USD 8.27 Million
- OPEX: Annual average operational expenditure is estimated at USD 4.04 Million, comprising O&M for PV, BESS augmentation, and insurance premiums.
- Financial Assumptions:
  - Debt-to-Equity Ratio: 70:30
  - Interest Rate (Cost of Loan): 6.67%
  - Loan Tenor: 15 years
  - Target Equity IRR: 12.00%
  - WACC: 5.988%

2.3. Optimization Scenarios

A sensitivity analysis using a waterfall methodology is used to identify key parameters for tariff reduction. The study models a transition from a Base Case to a Final Optimized Case by sequentially applying six optimization levers. These scenarios are defined as follows:

a) Base Case: Assumes standard commercial financing, full land acquisition costs, and compliance with existing Local Content Requirements (TKDN).

b) Off-peak Sales Scenario: Simulates a hybrid operation mode where excess PV energy (curtailed energy which is not stored in the BESS) is sold to the grid during off-peak hours, generating secondary revenue.

c) No Augmentation Scenario: Evaluates the cost impact of deferring battery module replacement (augmentation), accepting capacity degradation over the project life to reduce sustaining CAPEX.

d) Land Free Scenario: Assumes a policy intervention where the project site is provided by the government or utility, removing land acquisition costs from the CAPEX.

e) No Transmission Scenario: Assumes the project is co-located with existing substation infrastructure, and the transmission cost responsibility is from government, eliminating the cost of constructing new high-voltage transmission lines.

f) TKDN exemption Scenario: Simulates a regulatory exemption from local content requirements, allowing the procurement of cost-competitive global Tier-1 solar PV module and imported battery components.

g) Soft Loan 4% Scenario: Models the impact of green financing schemes (e.g., JETP or

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concessional loans) by reducing the interest rate from 6.67% to 4.00%.

Each scenario is calculated to determine the contribution to lower the tariff, providing a roadmap for policy intervention.

3. Results and discussion

The simulation results of the Madura PV-BESS project are explained in this section. The analysis begins with the technical performance and augmentation strategy, followed by the financial breakdown of the base case, the optimization pathway (waterfall analysis), and finally, the strategic competitiveness of the project within the Madura power system.

3.1. Technical Performance and Augmentation Strategy

The simulation confirms that the proposed configuration of 75 MWp PV and 50 MW / 250 MWh BESS is technically capable of serving the peaking requirement (17:00–22:00) for the Madura grid. The PV system generates approximately 110 GWh in the first year, which is sufficient to charge the BESS (98.7 GWh input) and cover round-trip efficiency losses.

To maintain the firm capacity of 50 MW over the 25-year project life, managing battery degradation is critical. The study indicates that without intervention, the battery's State of Health (SoH) would degrade significantly, reducing usable capacity below the required 258.3 MWh threshold. To address this, the technical model incorporates a Capacity Maintenance Program. As detailed in the technical specifications, augmentation (adding new battery modules) is scheduled at years 6, 11, 16, and 21. This strategy ensures the system has a fix daily energy output of 258.3 MWh throughout the Power Purchase Agreement (PPA) period.

3.2. Financial Analysis of the Base Case

The financial analysis of the Base Case indicates the cost challenges of deploying utility-scale storage under current commercial conditions. Under the base scenario assumptions, the Levelized tariff result is calculated at 23.47 cUSD/kWh. While this tariff reflects the true cost of technology, it is significantly higher than the generation cost of gas-fired peaker power plant owned by PLN IP presenting a barrier to adoption without financial engineering

3.3. Optimization Scenarios (Waterfall Analysis)

To achieve a tariff that is economically viable for the utility (PLN), a sensitivity analysis was conducted using six optimization levers. Figure 1 illustrates the "waterfall" reduction from the Base Case to the Final Optimized Case.

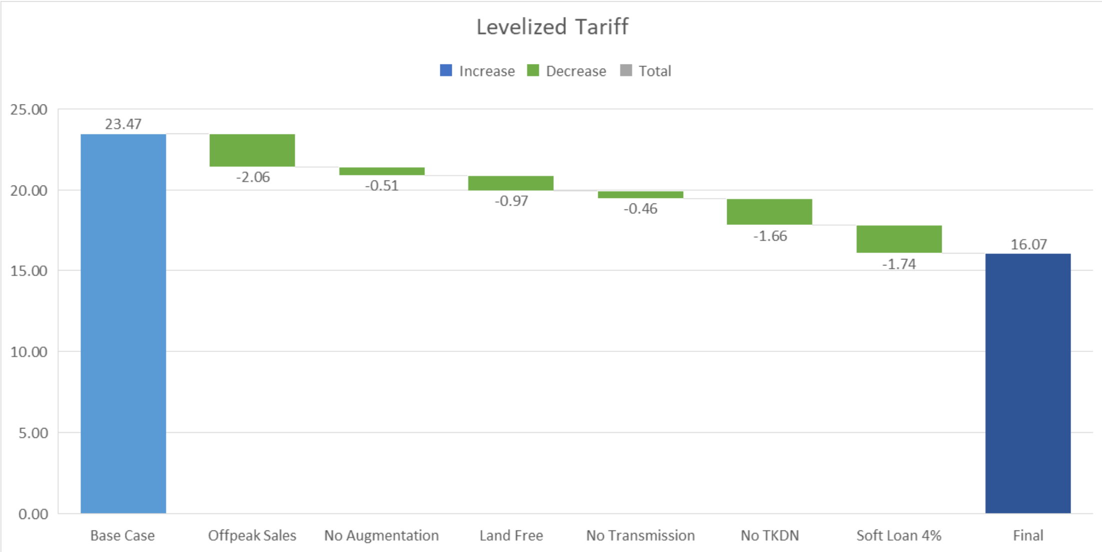

Figure 1. Waterfall diagram off Levelized tariff

The cumulative impact of these optimizations reduces the levelized from 23.47 cUSD/kWh to 16.07 cUSD/kWh, a reduction of 31.52%. The key drivers are analyzed below:

a) Revenue Stacking (Off-peak Sales): The most significant reduction (-2.06 cents) is achieved by allowing the sale of excess PV energy during off-peak hours (07:00–17:00) instead of curtailing it. In the base analysis, PV curtailment reaches 9.8 GWh (10.26%) in the first year. Monetizing this energy drastically improves the project's cash flow
b) Green Financing (Soft Loan 4%): Lowering the cost of debt is the second most impactful lever, reducing the tariff by 1.74 cents. This highlights the necessity of low-interest funding (e.g., JETP or concessional loans) to offset the high CAPEX of BESS infrastructure.
c) CAPEX Reductions (TKDN, Land & Technical):
   - Exemptions from TKDN (-1.63 cents) can lower significant tariff as impact of the USD 12.5 million of CAPEX reduction.
   - Land Free (0.97 cents): Eliminating the land acquisition cost of USD 7.03 million through government land concessions provides substantial relief.
   - No Augmentation (-0.51 cents): Optimizing the augmentation schedule or accepting a lower End-of-Life (EOL) capacity can further trim costs, though this must be balanced against grid reliability requirements.
   - Regulatory to avoid transmission line costs (-0.46 cents) provide the final necessary reductions

Table 1. Breakdown of waterfall tarif analysis

No.	Scenario	Project Cost	First Year kWh Sales	Annual Average O&M	Levelized Tariff	A+B	E	F
1	Base Case	$ 37,255,088	85,737,828	$ 3,789,348	23.47	5.81	0.34	17.32
2	Offpeak Sales	$ 37,255,088	95,548,299	$ 3,789,348	21.41	5.68	0.34	15.39
3	No Augmentation	$ 37,255,088	95,548,299	$ 3,434,532	20.90	5.68	0.34	14.87

4	Land Free	$ 29,772,622	95,548,299	$ 3,428,625	19.93	5.68	0.42	13.84
5	No Transmission	$ 26,197,001	95,548,299	$ 3,425,803	19.47	5.67	-	13.80
6	TKDN exemption	$ 13,693,888	95,548,299	$ 3,368,543	17.81	5.66	-	12.15
7	Soft Loan 4%	$ 12,216,299	95,548,299	$ 3,368,543	16.07	5.57	-	10.50

The optimized tariff of 16.07 cUSD/kWh must be evaluated not just against thermal generation costs, but against the value of Energy Security for Madura.

Based on the Madura System Power Balance (*Neraca Daya*) for 2027, the island's peak load is projected to reach 449 MW. However, the reliable supply capacity from the Java grid during an N-1 contingency (failure of one SKTT Suramadu circuit) is limited to 272 MW, creating a deficit of 177 MW during peak hours [1].

Without local generation or SKTT upgrade, this deficit would lead to widespread blackouts or power outage as recently happened in Madura [4]. The Madura PV-BESS project provides 50 MW of firm, fast-response capacity located inside the Madura subsystem. This "Defender" role justifies the premium over standard baseload coal or gas. Furthermore, the optimized tariff of 16.07 cUSD/kWh is competitive with the peaker fleet in owned by PLN Indonesia Power (22.59 cUSD/kWh). It also demonstrates superior economic viability when compared to diesel and gas engine generation in Indonesia which has average fuel cost at 29.98 cUSD/kWh [5], several independent studies in remote islands also found that the tariff is higher between 38-65 cUSD/kWh [6] [7]. Furthermore, this solution hedges against future fossil fuel price volatility.

4. Discussion

This section explains the optimization results presented in the previous chapter, benchmarking the findings against the actual generation costs (BPP) of specific thermal peaker power plants. The discussion contextualizes the economic viability of the Madura project by comparing it directly with the high-cost fleet it is designed to replace.

4.1. Comparative Economics: Optimized Levelized Tariff vs. Existing Peaker Fleet

The financial optimization in Chapter 3 yielded a final Levelized Tariff of 16.07 cUSD/kWh. To evaluate the project's competitiveness, this tariff is compared against the Component C (Fuel Cost) of the specific thermal units designated as "Peakers" by PLN Indonesia Power and average diesel and gas engine in Indonesia.

This comparison reveals a decisive economic advantage for the PV-BESS system:

a) Direct Cost Savings: The optimized PV-BESS tariff (16.07 cUSD/kWh) is 28.85% lower than the average fuel cost of the existing thermal peaker fleet (22.59 cUSD/kWh) own by PLN IP. If compared to average fuel cost of diesel and gas engine in Indonesia (29.98 cUSD/kWh), the saving will be higher at 46.38%. This indicates that transitioning from fossil-fuel peakers to PV-BESS is not an economic burden but a cost-saving measure.

b) Potential Power Plant Replacement: The economic case becomes even more compelling when targeting specific high cost power plant owned by PLN IP. For instance:
   - PLTG Pauh Limo 3: 41.40 cUSD/kWh (PV-BESS is 61% cheaper)
   - PLTG Teluk Sirih: 37.55 cUSD/kWh (PV-BESS is 57% cheaper)
   - PLTG Pemaron & Pesanggaran: 27.5 – 30.2 cUSD/kWh (PV-BESS is 42-47% cheaper)

These findings disprove the common misconception that energy storage is expensive. When positioned correctly as a substitute for inefficient open-cycle gas turbines or diesel generators, the Madura project offers immediate operational efficiency.

4.2. Financial Stability: Hedging Against Fuel Volatility

A critical limitation of the existing peaker fleet is its exposure to fuel price volatility. The high Component C values (e.g., 22.59 cUSD/kWh) are driven by the fluctuating prices of High-Speed Diesel (HSD) or LNG. Any increase in global oil prices directly inflates the utility's operating costs. In contrast, the PV-BESS tariff is predominantly driven by CAPEX recovery and fixed O&M. By locking in a tariff of 16.07 cUSD/kWh for the 25 year PPA tenure, PLN effectively creates a long-term hedge against fossil fuel inflation. This "price certainty" provides financial security that the current thermal fleet cannot offer.

4.3. Strategic Value: Mitigating the Madura Grid Vulnerability

The economic superiority of the project is complemented by its strategic necessity. The Madura System Power Balance (*Neraca Daya*) projects a peak load of 449 MW by 2027, exceeding the N-1 transmission import limit of 272 MW by 177 MW. Facing this deficit, the utility has two choices:

a) The Thermal Path: Install new mobile power plants (PLTMG/PLTD) or run existing inefficient peakers at a marginal cost of 22.59cUSD/kWh.
b) The Renewable Path: Deploy the Madura PV-BESS at a fixed cost of 16.07 cUSD/kWh.

Choosing the PV-BESS option essentially provides the "Defender" capability required to prevent blackouts while simultaneously reducing the average generation cost (BPP) of the subsystem.

4.3. The Role of Policy and Financing

Despite the clear economic advantage against the 22.59 cUSD/kWh benchmark, achieving the target tariff of 16.07 cUSD/kWh relies on specific financial structures.

- Green Financing and TKDN exemption are keys: The cost advantage is sensitive to the interest rate and CAPEX. Therefore, securing concessional financing (e.g., via JETP) is a prerequisite for realizing these savings.
- Revenue Optimization: The ability to stack revenues by selling excess energy during off-peak hours allows the high capital cost of the battery to be amortized more efficiently. This hybrid business model is essential to keep the tariff below the thermal peaker benchmark.

The Madura PV-BESS project is a "No Regrets" investment for the future. It replaces generation sources, which cost 22.59 cUSD/kWh with a cleaner energy costing 16.07 cUSD/kWh, which will have a similar effect on filling the critical 177 MW power deficit in the Madura grid.

5. Conclusion

This study confirms that the Madura PV-BESS project (75 MWp/250 MWh) represents a techno-economic improvement from traditional thermal peakers with potential to reduce the excess power deficit of 177 MW on Madura sub-system with less generation costs. Using targeted optimizations—mainly hybrid revenue stacking, the integration of 4% soft loans, and TKDN exemption—the Levelized tariff is reduced from 23.47 cUSD/kWh to a competitive 16.07

cUSD/kWh, which is 28.85% lower than the average fuel cost of PLN Indonesia Power's existing thermal peaker power plant (22.59 cUSD/kWh). Accordingly, the project confirms that with the right policy combination of concessional low-costfinancing and regulatory flexibility, utility-scale storage can serve as a cost-effective "Defender" asset, offering financial hedging for the fuel volatility, ensuring grid stability, and accelerating Indonesia's transition toward Net Zero Emissions. Furthermore, there is no applicable regulations of tariff setting methodology on PV-BESS in Indonesia at present, which enhances the significance of this study. The result of this study may provide significant information for policymakers as regards developing the necessary parameters and technical aspects for later regulation.

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