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Optimization of PV-BESS System Capacity Considering Battery Degradation for Nighttime Peak Load Supply: A Case Study of Guluk-Guluk, Madura

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ABSTRACT

The integration of photovoltaic (PV) generation into power systems presents operational challenges due to the temporal mismatch between daytime solar production and nighttime peak demand. This issue is particularly critical in tropical systems with limited local generation flexibility, such as Guluk-Guluk, Madura, where a PV–battery energy storage system (PV-BESS) is planned to support nighttime peak load demand. This study aimed to determine the optimal PV-BESS capacity configuration under a PV-only charging scheme, in which the battery is charged solely by PV generation without grid support. A 25-year time-series simulation based on historical solar resource data was integrated with Particle Swarm Optimization (PSO) to minimize the Net Present Cost (NPC) while penalizing unmet energy demand. Battery degradation was modeled using calendar and cycle aging, and the impact of Power Conversion System (PCS) charging capacity was evaluated through sensitivity analysis and re-optimization. The baseline optimal configuration consisted of 75.36 MWp of PV capacity and 570.98 MWh of initial BESS capacity with a 50 MW PCS, achieving 83.85% reliability and an NPC of USD 269.18 million. The results indicated that battery aging was not the dominant factor limiting system reliability; instead, daily solar variability and PCS charging constraints had stronger impacts. Increasing PCS capacity from 50 MW to approximately 56 MW significantly improved reliability, while further increases yielded diminishing returns as the system transitioned from power-limited to energy-limited operation. These findings emphasize the importance of integrated PV, BESS, and PCS planning for renewable peaker applications in tropical power systems.

INTRODUCTION

Power system planning is increasingly required to balance reliability, affordability, and sustainability under the ongoing energy transition (International Energy Agency [IEA], 2023; International Renewable Energy Agency [IRENA], 2023). The integration of renewable energy resources, particularly solar photovoltaic (PV) generation, has become one of the key strategies to reduce fossil fuel dependency and support long-term decarbonization targets (IPCC, 2022; IEA, 2023). However, the operational value of PV generation is strongly influenced by its temporal production profile. PV plants generate electricity predominantly during daylight hours, while in many power systems, peak electricity demand occurs in the evening or nighttime. This temporal mismatch creates an operational challenge, as daytime solar generation does not automatically contribute to nighttime peak load supply unless adequate energy storage is available (Denholm et al., 2021; IRENA, 2023).

This challenge is particularly relevant in power systems with limited local generation flexibility and constrained transmission capacity. Madura Island, especially the eastern area including Guluk-Guluk and Sumenep, represents such a case. Electricity supply in this region remains highly dependent on power transfer from the Java system through the 150 kV transmission network. Limited local generation makes the system more vulnerable to supply constraints during peak demand periods. Therefore, local energy resources capable of providing firm capacity during nighttime peak hours are increasingly important for improving regional reliability and reducing dependence on long-distance power transfer (Denis et al., 2021; Gani et al., 2020; International Energy Agency [IEA], 2023; Lund et al., 2017; Psarros et al., 2024).

Operational data from the Madura Subsystem indicate that nighttime peak demand is consistently higher than daytime peak demand. From 2022 to 2023, daytime peak load increased from 237.2 MW to 247.9 MW, while nighttime peak load increased from 317.1 MW to 341.7 MW. As a result, the gap between daytime and nighttime peaks widened from 79.9 MW to 93.9 MW. In 2023, the highest nighttime peak occurred on 22 November at 341.74 MW, while the highest daytime peak occurred on 12 April at 247.88 MW. On the peak day, load increased by approximately 110.30 MW from daytime to nighttime. These characteristics highlight the significance of nighttime demand and the need for energy storage to shift solar energy for evening supply.

In response to this requirement, PLN's Electricity Supply Business Plan (RUPTL) 2025–2034 includes the planned development of East Java Solar PV Quota I with a capacity of 50 MW and East Java BESS Quota I with a capacity of 50 MW in Guluk-Guluk, Madura, targeting commercial operation in 2027 (PT PLN (Persero), 2025). The project is expected to strengthen the regional electricity supply by enabling battery storage to support electricity demand during evening peak periods when solar PV generation is unavailable (International Energy Agency [IEA], 2024; International Renewable Energy Agency [IRENA], 2023). In this context, the PV–BESS system can function as a renewable peaker by storing excess daytime solar energy and discharging it during nighttime peak demand, thereby improving system flexibility, reliability, and renewable energy utilization.

A key issue in such systems is the battery charging configuration. In this study, the PV-BESS system was evaluated under a PV-only charging scheme, in which the battery is charged solely by PV generation without support from the grid or other sources. This configuration preserves the renewable nature of stored energy but increases dependence on solar resource availability. Under low irradiance conditions over consecutive days, the battery may not be sufficiently charged to meet nighttime demand (Assaad & El-Adaway, 2021; Gao et al., 2020; Meszek et al., 2019). Therefore, system sizing must consider not only average solar conditions but also daily and interannual variability (Javed et al., 2023; Sarr et al., 2021).

In addition to PV and BESS sizing, system performance is influenced by battery degradation and Power Conversion System (PCS) capacity (Schimpe et al., 2018; Xu, 2021). Battery degradation reduces effective storage capacity through calendar and cycle aging. If neglected, system adequacy may be overestimated at the beginning of operation and decline over time (Schimpe et al., 2018; Wang et al., 2023). Meanwhile, PCS capacity limits the power flow between PV, battery, and grid. Insufficient PCS capacity may restrict battery charging during high-irradiance periods, even when sufficient energy is available (Denholm et al., 2021). Therefore, PV-BESS planning must consider the interaction among PV capacity, BESS capacity, PCS capacity, battery degradation, and solar variability (Bolinger et al., 2023; Wang et al., 2023).

Previous studies have investigated PV-BESS systems for self-consumption, energy arbitrage, peak shaving, microgrid reliability, and optimal sizing using analytical and metaheuristic methods. However, studies integrating PV-only charging schemes, long-term time-series simulation, battery degradation modeling, PCS sensitivity analysis, and renewable peaker operation for nighttime peak supply remain limited. This gap is particularly relevant for tropical islanded or semi-islanded systems where high solar potential coexists with strong variability and limited system flexibility (Devlin, 2023; Kotla et al., 2026).

Therefore, this study aimed to determine the optimal PV-BESS capacity configuration for nighttime peak load supply in Guluk-Guluk, Madura, under a PV-only charging scheme while considering battery degradation and PCS constraints. A 25-year time-series simulation based on historical solar data was used, and Particle Swarm Optimization (PSO) was applied to minimize Net Present Cost (NPC) while penalizing unmet energy. The study's contributions are threefold: first, it developed an integrated simulation–optimization framework for PV-only charged PV-BESS systems for peak supply; second, it evaluated long-term battery degradation and replacement impacts; and third, it analyzed the influence of PCS capacity on system reliability and identified transitions between power-limited and energy-limited operation. These findings provide technical insights for renewable peaker design and PV-BESS planning in tropical power systems.

METHOD

Research Design

This study employed a quantitative approach based on engineering simulation and numerical optimization. The research was designed to evaluate the optimal capacity configuration of a photovoltaic–battery energy storage system (PV-BESS) for nighttime peak load support in a tropical power system. The case study was conducted in Guluk-Guluk, Madura, where a PV-BESS project has been planned as a renewable peaker under PLN's Electricity Supply Business Plan (RUPTL) 2025–2034.

The methodological framework integrated four main components: solar resource assessment, PV-BESS operational simulation, battery degradation modeling, and capacity optimization using Particle Swarm Optimization (PSO). The simulation was conducted over a 25-year project horizon to capture long-term operational performance, battery degradation effects, and economic implications. The optimization objective was to minimize Net Present Cost (NPC) while penalizing unmet energy, ensuring that the resulting configuration balanced system cost and supply reliability.

Study Location, Research Data and Assumptions

The case study is located in Guluk-Guluk, Sumenep Regency, Madura. Historical solar irradiation data for the 2015–2024 period were obtained from NASA POWER and processed into daily Peak Sun Hour (PSH) values as the main input for PV energy production simulation. The PV-BESS system is evaluated as a renewable peaker with a service target of 50 MW for 5 hours per day, equivalent to a daily energy requirement of 250 MWh. The main technical and economic parameters adopted in the model include a PV performance ratio of 0.74, a BESS degradation rate of 2% per year, PV CAPEX of 1,375 USD/kWp, BESS CAPEX of 218 USD/kWh, a discount rate of 7%, a project horizon of 25 years, and an unmet energy penalty of 2,000 USD/MWh. These assumptions were systematically defined to ensure that the simulation model could represent the operational and economic characteristics of the PV-BESS system in the context of project development in Indonesia.

PV-BESS System Operation Simulation Model

The PV-BESS system is modeled under a PV-only charging configuration, in which the battery is charged solely by PV generation without grid-charging support. During the daytime, the PV system produces electricity based on installed PV capacity, daily PSH, performance ratio, and PV degradation factor. The generated PV energy is then used to charge the BESS, subject to the charging power limit of the Power Conversion System (PCS), the available battery storage capacity, and the state-of-charge (SoC) condition.

At night, the BESS discharges energy to supply the peak load service target of 250 MWh per day. If the available deliverable energy in the BESS is sufficient, the target is fully met. If the available energy is lower than the required service target, the difference is recorded as unmet energy. The model also records unused PV energy, energy delivered to the load, SoC evolution, and battery cycling indicators. This daily time-series simulation enables the evaluation of system performance throughout the project horizon.

The PCS is modeled as a power-limiting component that constrains the maximum charging and discharging power between the PV, BESS, and grid. In the baseline configuration, PCS capacity is set at 50 MW. This value corresponds to the planned project capacity and the required nighttime discharge power. However, the same PCS capacity also limits the maximum charging power during the daytime. Therefore, even when sufficient PV energy is available, the battery may not be able to fully absorb the energy if the PCS charging capacity is insufficient.

Battery Degradation Model and Replacement Rules

Battery degradation is represented through two mechanisms: calendar aging and cycle aging. Calendar aging reflects the reduction of battery capacity over time, while cycle aging reflects degradation caused by charge and discharge processes. Cycle-related degradation is evaluated using the Equivalent Full Cycle (EFC) concept, which converts partial charge-discharge operation into an equivalent number of full cycles. This approach allows battery degradation to be linked to the actual operating pattern of the BESS.

The model updates the effective battery capacity over the 25-year project horizon based on the degradation mechanism. The State of Health (SOH) is used to represent the remaining effective capacity of the BESS relative to its initial capacity. As the SOH decreases, the deliverable energy of the BESS also decreases. This is important because the ability of the BESS to provide nighttime peak load service depends not only on the initial installed capacity but also on the remaining effective capacity after degradation.

A service-based replacement rule is applied in the model. Battery replacement or augmentation is triggered only when the deliverable energy falls below the service requirement of 250 MWh per day. Two replacement strategies are evaluated: full replacement and partial augmentation. In the full replacement strategy, the entire battery capacity is replaced when the service threshold can no longer be met. In the partial augmentation strategy, only the additional capacity required to restore the service capability is added. This approach enables the assessment of whether battery degradation creates replacement expenditure (REPEX) during the project lifetime.

Optimization and Sensitivity Analysis

The optimal PV and BESS capacities are determined using Particle Swarm Optimization. In the PSO framework, each particle represents a candidate solution consisting of PV capacity in MWp and initial BESS capacity in MWh. Each candidate solution is evaluated using the 25-year PV-BESS operational simulation. The evaluation produces key performance indicators, including NPC, unmet energy, reliability, battery cycling, SOH evolution, and potential REPEX.

The objective function minimizes the total fitness value, which consists of NPC and unmet energy penalty. NPC includes capital expenditure, operation and maintenance cost, and replacement cost when applicable. The unmet energy penalty is included to ensure that the optimization does not select a low-cost configuration that fails to provide adequate reliability. Therefore, the optimization process captures the trade-off between economic cost and supply adequacy.

After the baseline optimization is completed, additional analyses are conducted to evaluate the robustness and sensitivity of the optimal solution. First, the degradation and REPEX evaluation is performed to examine whether battery aging triggers replacement requirements over the project horizon. Second, PCS charging power sensitivity is carried out by keeping the optimized PV and BESS capacities fixed while increasing PCS capacity from the baseline value. This analysis is used to identify whether the system is limited by charging power or by available daily PV energy. Third, PSO re-optimization is performed under several PCS scenarios to evaluate how relaxing the PCS charging constraint changes the optimal PV-BESS configuration, reliability, NPC, and unmet energy.

RESULTS AND DISCUSSION

Solar Resource Characteristics and Energy Adequacy

The first stage of the analysis evaluates the solar resource characteristics in Guluk-Guluk, Madura. This evaluation is essential because the PV-BESS system is operated under a PV-only charging configuration, in which the battery can only be charged using energy generated by the PV system. Therefore, the ability of the system to supply nighttime peak load is strongly determined by the daily availability of solar energy.

Based on the processed NASA POWER data for the 2015–2024 period, the daily Peak Sun Hour (PSH) in Guluk-Guluk shows relatively favorable solar potential, with an average value of 5.56 hours per day. The median PSH is 5.67 hours, while the minimum and maximum daily PSH values are 0.79 hours and 7.57 hours, respectively. The standard deviation of 1.01 hours indicates that solar resource availability varies significantly on a daily basis. This variability is important because PV-only charging requires sufficient daily PV generation to charge the battery before it supplies the nighttime peak load.

The PV-BESS system is designed to provide a nighttime peaking service of 50 MW for 5 hours, equivalent to 250 MWh per day. Considering a round-trip efficiency of 95%, the minimum energy that must be supplied to the BESS during the charging period is approximately 263.16 MWh per day. With a baseline PCS charging capacity of 50 MW, the required Equivalent Full-Power Charging Hours (EFPCH) is approximately 5.26 hours. This value does not represent a strict irradiance threshold, but it provides a practical reference for evaluating whether the daily solar resource is sufficient to support the required battery charging.

The results show that approximately 31.7% of the observed days have PSH values below the EFPCH reference of 5.26 hours. This indicates that although the average solar resource in Guluk-Guluk is favorable, daily energy adequacy cannot be guaranteed based only on annual average PSH. On average, approximately 115.7 days per year fall below the EFPCH reference. In addition, consecutive low-PSH periods of up to 26 days were identified. These consecutive low-solar periods are critical because the battery may not be able to recover its state of charge sufficiently from one day to the next, thereby increasing the risk of unmet energy during the nighttime peak period.

Table 1. Solar resource characteristics and baseline service requirement

Parameter	Value	Interpretation
Average daily PSH	5.56 h/day	Indicates favorable average solar potential
Median daily PSH	5.67 h/day	Shows that the PSH distribution is relatively centered
Minimum daily PSH	0.79 h/day	Indicates the existence of very low solar days
Maximum daily PSH	7.57 h/day	Indicates high solar resource potential on clear days
Standard deviation	1.01 h/day	Indicates significant daily solar variability
Nighttime peaking target	50 MW × 5 h	Represents the service requirement
Daily energy target	250 MWh/day	Required energy output from BESS
Required charging energy	263.16 MWh/day	Input energy considering 95% round-trip efficiency
EFPCH reference	5.26 h	Equivalent full-power charging hours at 50 MW PCS
Days below EFPCH	31.7%	Indicates probabilistic daily energy adequacy risk
Average low-PSH days	115.7 days/year	Shows frequent low-energy days
Maximum consecutive low-PSH period	26 days	Indicates potential cumulative energy adequacy risk

Source: Author's calculation based on NASA POWER data (2015–2024)

These findings indicate that a PV-only charging system is exposed to probabilistic energy adequacy risk. Therefore, the PV-BESS system cannot be designed only based on nominal capacity or average solar resource conditions. Instead, capacity planning must account for daily solar variability, low-PSH events, and consecutive low-energy periods.

BASELINE PV-BESS OPTIMIZATION RESULT

The baseline optimization is conducted with a PCS capacity of 50 MW, corresponding to the planned service capacity of the project. The Particle Swarm Optimization (PSO) algorithm is used to determine the optimal combination of PV capacity and initial BESS capacity by minimizing the fitness value, which consists of Net Present Cost (NPC) and unmet energy penalty. Each candidate solution is evaluated using a 25-year time-series operation simulation that considers PV generation, BESS operation, battery degradation, and service reliability.

The PSO optimization produces an optimal baseline configuration consisting of 75.36 MWp of PV capacity and 570.98 MWh of initial BESS capacity. This configuration achieves a reliability level of 83.85%, with total unmet energy of 66,722 MWh over the simulation horizon. The resulting NPC is approximately USD 269.18 million, while the unmet energy penalty is approximately USD 133.45 million. Therefore, the total fitness value of the baseline configuration is approximately USD 402.63 million.

Table 2. Baseline PSO optimization result under 50 MW PCS

Parameter	Value
PCS capacity	50 MW
Optimal PV capacity	75.36 MWp
Optimal initial BESS capacity	570.98 MWh
Reliability	83.85%
Total unmet energy	66,722 MWh
NPC	USD 269.18 million
Unmet energy penalty	USD 133.45 million
Fitness value	USD 402.63 million
Total EFC	6,009.89 cycles
REPEX requirement	Not required

Source: Author's calculation using PSO simulation

The optimization result shows that a PV-BESS renewable peaker designed to supply 50 MW for 5 hours cannot be sized only based on the nominal daily energy requirement of 250 MWh. The optimal PV capacity is approximately 1.5 times the PCS capacity, while the optimal BESS capacity is approximately 2.28 times the daily energy target. This oversizing is required to compensate for solar resource variability, system losses, depth-of-discharge limitations, and battery degradation over the project lifetime.

The baseline result also indicates that the system remains unable to achieve full reliability under the PV-only charging configuration. Although the BESS capacity is relatively large, unmet energy still occurs because the daily PV energy input is not always sufficient to fully charge the battery, especially during low-PSH days or consecutive low-solar periods. This finding reinforces the importance of long-term time-series simulation in PV-BESS capacity planning, because a static sizing approach based only on average daily energy may underestimate reliability risk.

From the cost perspective, BESS investment is the dominant component of the system cost. The cost breakdown consists of approximately USD 103.62 million for PV capital expenditure, USD 12.08 million for PV operation and maintenance cost, USD 124.47 million for initial BESS capital expenditure, and USD 29.01 million for BESS operation and maintenance cost. No battery replacement expenditure is triggered in the baseline optimal configuration. This indicates that the initial BESS capacity selected by the PSO provides sufficient degradation margin to maintain the required service capability throughout the project horizon.

BATTERY DEGRADATION AND REPEX EVALUATION

Battery degradation is evaluated to determine whether the decline in effective BESS capacity becomes a dominant factor affecting system reliability. In this study, degradation is represented by calendar aging and cycle aging. Calendar aging reflects capacity fade due to time-dependent degradation, while cycle aging is estimated from the accumulated Equivalent Full Cycles (EFCs) resulting from the daily operation of the BESS.

The simulation results show that the battery State of Health (SOH) gradually declines over the 25-year project horizon. In the baseline configuration, the total accumulated EFC reaches approximately 6,009.89 cycles over 25 years. The SOH crosses the 80% level in the later part of the project horizon and continues to decrease until the end of the simulation period. However, crossing the 80% SOH threshold does not automatically imply operational failure. In this study, the replacement criterion is service-based, meaning that battery replacement or augmentation is triggered only when the deliverable energy falls below the required service threshold of 250 MWh per day.

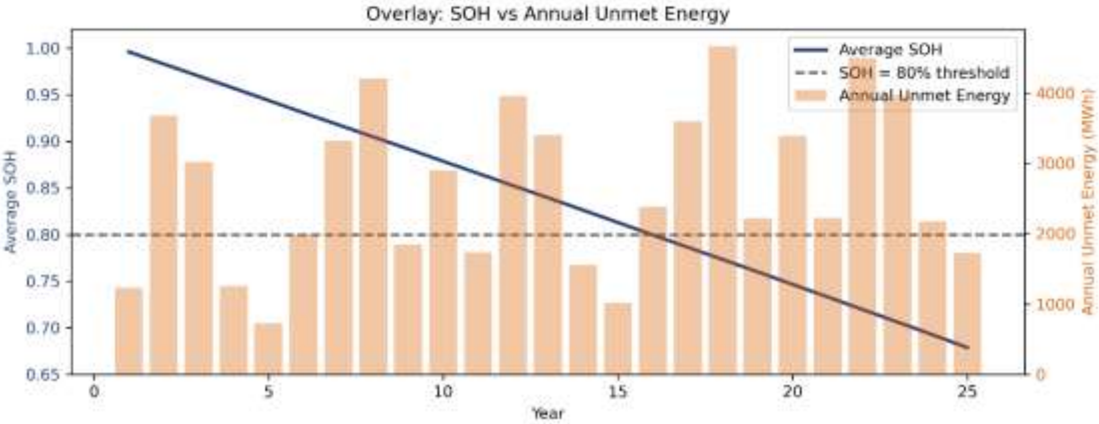

Figure 1. BESS SOH profile and annual unmet energy over the project lifetime

Source: Author's calculation from the 25-year PV-BESS simulation

The evaluation of annual deliverable energy shows that the minimum annual deliverable energy remains above the service requirement throughout the project lifetime. The lowest annual deliverable energy is approximately 299.9 MWh, which is still higher than the 250 MWh daily service target. Therefore, no full replacement or partial augmentation is required in the baseline optimal configuration. This finding confirms that the optimal BESS capacity provides a sufficient design margin to compensate for battery degradation.

The absence of REPEX does not mean that battery degradation is irrelevant. Rather, it indicates that the optimization process selects a sufficiently large initial BESS capacity to anticipate the decline in effective capacity. From a planning perspective, this result reflects a trade-off between installing larger battery capacity at the beginning of the project and delaying or avoiding future replacement expenditure. In the baseline configuration, the model favors a larger initial BESS capacity that can maintain service adequacy without triggering REPEX.

To identify the main driver of unmet energy, annual unmet energy is compared with the number of low-PSH days. The analysis shows a strong relationship between annual unmet energy and the occurrence of days with PSH values below the EFPCH reference. In contrast, the gradual decline in SOH does not produce a structural change in the unmet energy pattern after crossing the 80% SOH level. This indicates that system reliability is more strongly influenced by climate-driven solar variability than by battery degradation under the simulated conditions.

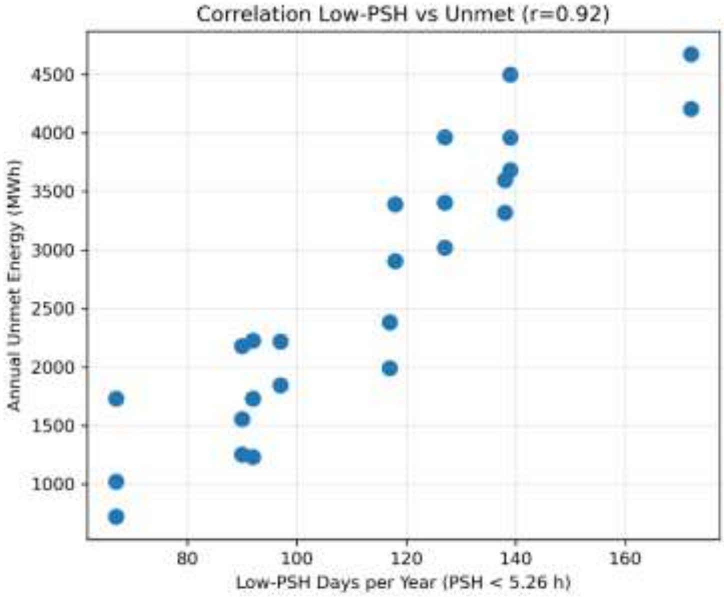

Figure 2. Relationship between annual unmet energy and low-PSH days

Source: Author's calculation based on simulation results

Overall, the degradation evaluation shows that battery aging is not the dominant limitation in the baseline optimal design. The main reliability limitation comes from the availability of daily solar energy and the ability of the system to transfer that energy into the battery. Therefore, improving reliability should not be focused primarily on accelerating battery replacement. Instead, the system design should consider whether PV capacity, PCS charging capacity, or operating strategy needs to be adjusted to improve the amount of energy captured and stored during the daytime period.

PCS Charging Power Sensitivity

The baseline optimization result indicates that the PV-BESS system with a 50 MW PCS achieves a reliability level of 83.85%. The degradation evaluation further shows that battery aging is not the dominant driver of unmet energy. Therefore, a PCS charging power sensitivity analysis is conducted to examine whether the reliability limitation is partly caused by a charging power bottleneck.

In this sensitivity analysis, the PV and BESS capacities are fixed at the baseline optimal values, namely 75.36 MWp and 570.98 MWh, respectively. Other technical and economic parameters are also kept unchanged. Only the PCS charging capacity is gradually increased from the baseline value of 50 MW. This approach isolates the effect of charging power on system reliability without changing the overall PV-BESS configuration.

Table 3. Reliability changes under PCS charging power sensitivity

PCS *capacity* (MW)	***Reliability* (%)**	***ΔReliability* vs 50 MW** *(percentage points)*
50	83.85	0.00

51	~86.6	+2.75
52	~87.9	+4.05
53	~88.7	+4.85
54	~89.4	+5.55
55	~89.6	+5.75
56	~89.6	+5.75
≥60	~89.6	~+5.75

Source: Author's calculation from sensitivity simulation

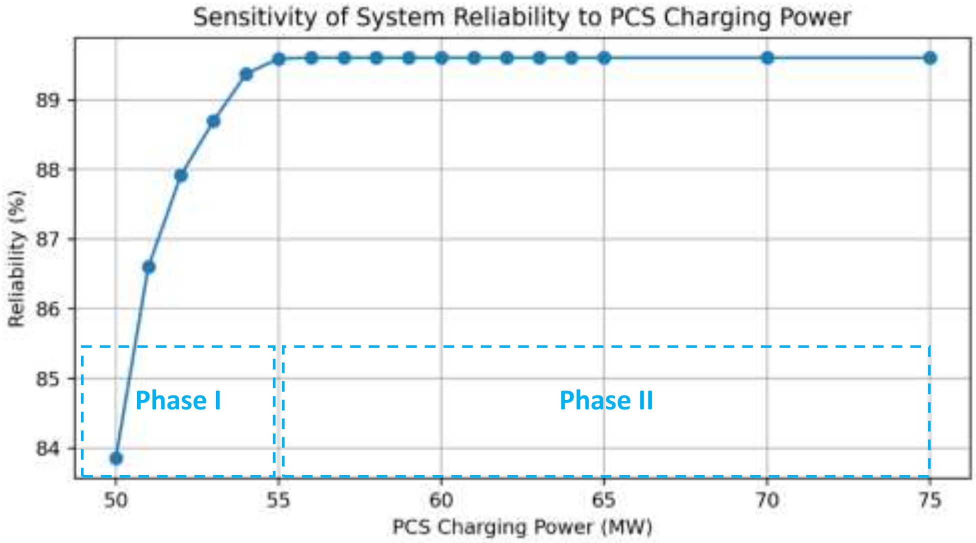

Figure 3. Reliability sensitivity to PCS charging power

Source: Author's analysis from fixed-capacity sensitivity simulation

The simulation results show that increasing PCS capacity from 50 MW to approximately 55–56 MW significantly improves system reliability. Reliability increases from 83.85% to approximately 89.6%, indicating an improvement of about 5.75 percentage points. This result shows that part of the unmet energy in the baseline configuration is not caused by insufficient battery energy capacity, but by limited charging power. In other words, on some days, PV energy is available but cannot be optimally transferred into the battery within the available solar window because the PCS charging capacity is constrained.

The sensitivity curve also shows that after PCS capacity reaches approximately 55–56 MW, the reliability improvement begins to plateau. Further increases in PCS capacity provide only limited additional benefits when PV and BESS capacities remain fixed. This behavior indicates a shift in the system limitation. At lower PCS capacity, the system is power-limited because the PCS cannot transfer available PV energy to the battery quickly enough. After the charging power bottleneck is relaxed, the system becomes energy-limited because the main constraint shifts to total daily PV energy availability, particularly during low-PSH periods.

This result provides two important insights. First, a moderate increase in PCS charging capacity can significantly improve system reliability without changing PV and BESS capacities. Second, increasing PCS capacity alone is not sufficient to achieve substantially higher reliability beyond the plateau region. Once the system becomes energy-limited, further reliability improvement requires changes in the overall configuration, such as increasing PV capacity, modifying the operating strategy, or allowing additional charging sources under clearly defined operational and commercial rules.

RE-OPTIMIZATION UNDER DIFFERENT PCS CAPACITY SCENARIOS

Although PCS sensitivity analysis shows that increasing charging power improves reliability, it does not answer whether the optimal PV-BESS configuration changes when a higher PCS capacity is assumed from the beginning. Therefore, PSO re-optimization is conducted for several PCS capacity scenarios, namely 56 MW, 60 MW, and 65 MW. In contrast to the fixed-capacity sensitivity analysis, the re-optimization allows PV and BESS capacities to change in each PCS scenario.

The re-optimization results show that increasing PCS capacity shifts the optimal PV-BESS configuration. At PCS 56 MW, the optimal configuration becomes 82.75 MWp PV and 562.53 MWh BESS, with 94.01% reliability, NPC of USD 278.26 million, and unmet energy of 26,821 MWh. At PCS 60 MW, the optimal configuration becomes 86.62 MWp PV and 551.50 MWh BESS, with 95.79% reliability, NPC of USD 281.23 million, and unmet energy of 18,787 MWh. At PCS 65 MW, the optimal configuration becomes 91.40 MWp PV and 530.88 MWh BESS, with 96.52% reliability, NPC of USD 283.03 million, and unmet energy of 15,506 MWh.

Table 4. PSO re-optimization results under different PCS capacity scenarios

PCS (MW)	PV (MWp)	BESS (MWh)	Reliability (%)	Unmet energy (MWh)	NPC (MUSD)	Penalty (MUSD)	Fitness (MUSD)	EFC
50	75.36	570.98	83.85	66,722	269.18	133.45	402.63	6,009.89
56	82.75	562.53	94.01	26,821	278.26	53.64	331.90	6,243.07
60	86.62	551.50	95.79	18,787	281.23	37.58	318.81	6,415.84
65	91.40	530.88	96.52	15,506	283.03	31.01	314.04	6,721.84

Source: Author's calculation from PSO re-optimization

The results indicate that higher PCS capacity enables the system to absorb more PV energy during high-irradiance hours. Consequently, the PSO responds by increasing the optimal PV capacity as PCS capacity increases. At the same time, the optimal BESS capacity tends to decrease gradually because higher charging power allows the battery to be charged more effectively during the available solar window. This confirms that PV capacity, BESS energy capacity, and PCS power capacity should not be planned independently. Instead, these components must be optimized as an integrated system.

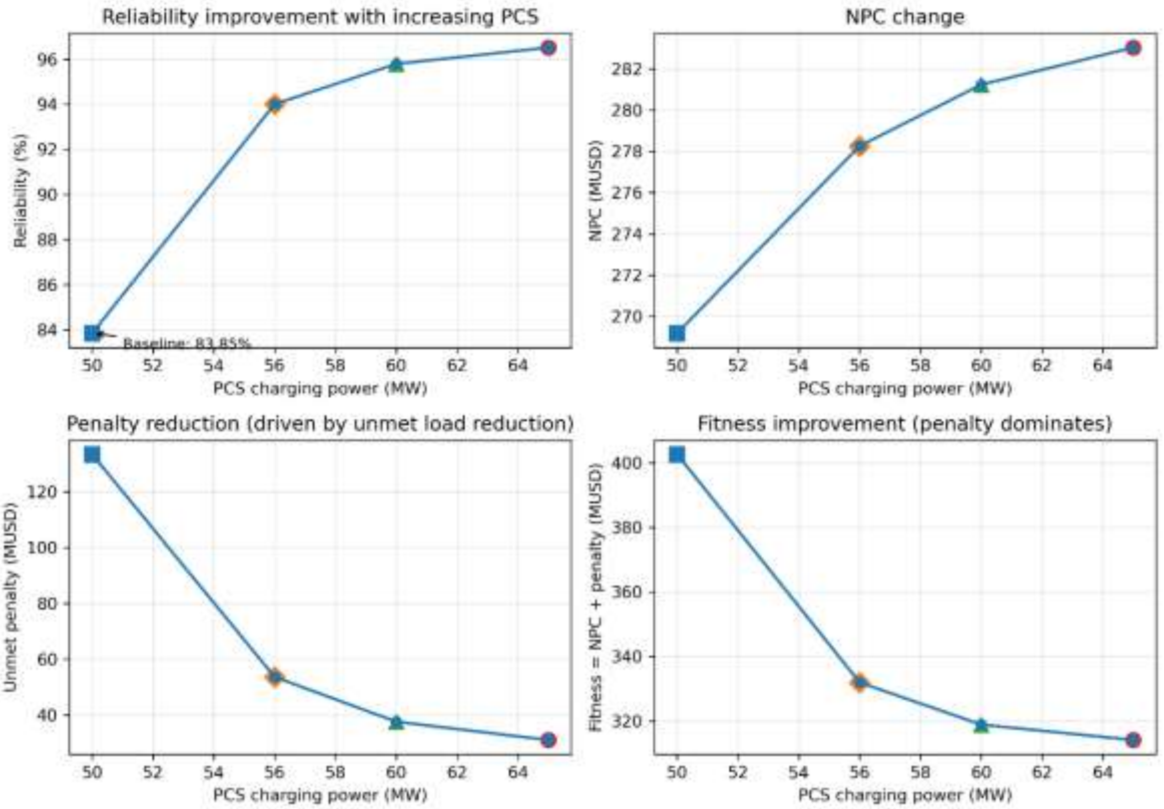

Figure 4. Re-optimization results under different PCS capacity scenarios

Source: Author's analysis from PSO re-optimization

The figure visually confirms that increasing PCS capacity improves reliability and reduces unmet energy penalty, although the marginal benefit decreases beyond approximately 56 MW.

The largest reliability improvement occurs when PCS capacity is increased from 50 MW to 56 MW, with reliability increasing from 83.85% to 94.01%. Beyond this point, the additional reliability gain becomes smaller. This result confirms that PCS capacity around 56 MW can be interpreted as a knee point in the system design. At this point, the charging power bottleneck is substantially reduced, and the system begins to shift from a power-limited regime to an energy-limited regime.

To quantify the marginal benefit of PCS increase, two indicators are evaluated: marginal reliability gain and penalty reduction efficiency. The marginal reliability gain decreases from approximately 1.12 percentage points per USD 1 million of additional NPC for the 50–56 MW increase, to approximately 0.60 percentage points per USD 1 million for the 56–60 MW increase, and further to approximately 0.40 percentage points per USD 1 million for the 60–65 MW increase. Similarly, the penalty reduction efficiency decreases from approximately USD 8.8 million penalty reduction per USD 1 million of additional NPC for the 50–56 MW increase, to USD 5.4 million for the 56–60 MW increase, and USD 3.7 million for the 60–65 MW increase.

Table 5. Marginal reliability gain and penalty reduction efficiency

PCS change	ΔReliability/ΔNPC *(percentage points/MUSD)*	-ΔPenalty/ΔNPC
50 → 56 MW	~1.12	~8.8
56 → 60 MW	~0.60	~5.4
60 → 65 MW	~0.40	~3.7

Source: Author's calculation based on re-optimization results

These marginal indicators show that increasing PCS capacity provides the highest technical and economic leverage at the initial stage. The improvement from 50 MW to 56 MW produces the largest reduction in unmet energy and penalty, while the associated increase in NPC remains moderate. However, beyond 56 MW, the marginal benefits decline because the system becomes increasingly limited by daily PV energy availability rather than by charging power capacity.

DESIGN IMPLICATIONS

The overall results demonstrate that the reliability of a PV-only-charged PV-BESS renewable peaker is governed by the interaction among solar resource variability, PV capacity, BESS capacity, PCS capacity, and battery degradation. In the baseline configuration, the system is not primarily constrained by battery degradation, because the optimized BESS capacity provides sufficient degradation margin and no REPEX is required. Instead, unmet energy is mainly associated with low solar energy availability and limited PCS charging capability.

The PCS analysis further shows that a system designed with PCS capacity equal to the discharge service capacity may not be sufficient for optimal PV energy absorption. In this case, a 50 MW PCS is adequate for delivering 50 MW during the nighttime peak period, but it can still constrain daytime charging when PV generation is available only within a limited solar window. Therefore, PCS sizing should consider both discharge requirements and charging requirements.

The re-optimization results also show that improving reliability requires integrated capacity planning. Increasing PCS capacity alone improves reliability only up to a certain level. Higher reliability requires a coordinated adjustment of PV capacity and BESS capacity. Therefore, PV-BESS planning for renewable peaker applications should not use a simple energy-matching approach based only on the daily target of 250 MWh. Instead, it should use a time-series simulation and optimization framework that captures solar variability, storage operation, degradation, power conversion limits, and economic trade-offs.

For project planning, the results suggest that a moderate PCS increase to around 56 MW provides a strong improvement in reliability with relatively efficient economic leverage. However, pursuing higher reliability beyond this point requires careful evaluation of additional PV capacity, larger PCS capacity, operating flexibility, and potential alternative charging strategies. In particular, limited grid charging or hybrid charging may be considered in future studies if supported by clear regulatory, metering, and commercial arrangements. This is important because a strict PV-only charging configuration preserves renewable energy integrity but exposes the system to low-PSH risk during consecutive low-solar periods.

In summary, the proposed simulation and optimization framework provides a practical basis for designing PV-BESS systems as renewable peakers in tropical power systems. The findings indicate that battery degradation should be included in long-term planning, but reliability improvement should focus primarily on solar energy adequacy and PCS charging capability. The integrated optimization of PV, BESS, and PCS capacities is therefore essential to achieve a balanced design between cost and reliability.

CONCLUSION

This study evaluated the optimal capacity configuration of a photovoltaic–battery energy storage system (PV-BESS) for nighttime peak load supply in Guluk-Guluk, Madura, under a PV-only charging configuration. The proposed framework integrated a 25-year time-series simulation, battery degradation modeling, and Particle Swarm Optimization (PSO) to determine the optimal PV and BESS capacities while considering the trade-off between Net Present Cost (NPC) and unmet energy penalties. The baseline optimization with a 50 MW PCS resulted in an optimal configuration of 75.36 MWp PV and 570.98 MWh initial BESS capacity. This configuration achieved 83.85% reliability, with total unmet energy of 66,722 MWh and an NPC of approximately USD 269.18 million over the project horizon.

These results indicate that a PV-BESS system designed to deliver 50 MW of power for a 5-hour nighttime peaking service cannot be sized solely based on the nominal daily energy target of 250 MWh. Additional PV and BESS capacities are required to compensate for solar resource variability, system efficiency losses, depth-of-discharge constraints, and long-term battery degradation. The degradation analysis showed that battery state of health (SoH) declined over the 25-year simulation horizon, with a total accumulated equivalent full cycles (EFCs) of approximately 6,009.89 cycles. However, battery degradation was not identified as the dominant factor limiting system reliability in the optimal baseline configuration. The minimum annual deliverable energy remained above the service threshold of 250 MWh; therefore, no full replacement or major augmentation was required during the project lifetime. This finding indicates that the optimized initial BESS capacity provided sufficient degradation margin to sustain the required nighttime peaking service.

The main reliability limitation was more strongly associated with daily solar resource variability and PCS charging constraints. The analysis showed that low-PSH days and consecutive low-solar periods increased the risk of unmet energy because the BESS could not receive sufficient charging support from the PV system. PCS sensitivity analysis further demonstrated that increasing PCS charging capacity from 50 MW to approximately 55–56 MW improved reliability from 83.85% to around 89.6%, when PV and BESS capacities were held constant. This indicates that part of the baseline unmet energy was caused by a charging power bottleneck rather than insufficient battery energy capacity.

The PCS re-optimization results showed that higher PCS capacity altered the optimal PV-BESS configuration. At 56 MW PCS, the optimal configuration became 82.75 MWp PV and 562.53 MWh BESS, achieving 94.01% reliability. Further increases to 60 MW and 65 MW PCS improved reliability to 95.79% and 96.52%, respectively, but with diminishing marginal benefits. The highest technical and economic leverage occurred when PCS increased from 50 MW to 56 MW, indicating that approximately 56 MW PCS represents a critical knee point in system design.

Overall, the findings confirm that PV, BESS, and PCS capacities must be planned as an integrated system for renewable peaker applications. Battery degradation should be considered in long-term planning; however, reliability improvements should not focus solely on battery replacement or BESS oversizing. Instead, system design must also account for solar resource variability, daily energy adequacy, PCS charging capability, and the interaction between power and energy capacity. Future research should evaluate more flexible operating configurations, including limited grid charging, hybrid charging, or integration with other local energy resources. Further studies should also incorporate more detailed PV production modeling, project-specific BESS technical parameters, thermal effects on battery degradation, and explicit PCS investment costs in the optimization objective. In addition, future work may expand the analysis to include power system impacts, regulatory arrangements, and commercial schemes such as capacity payments or peaking service compensation to support practical implementation of PV-BESS renewable peaker projects in Indonesia.

REFERENCE

Assaad, R., & El-Adaway, I. H. (2021). Guidelines for responding to COVID-19 pandemic: Best practices, impacts, and future research directions. *Journal of Management in Engineering, 37*(3), 06021001.

Bolinger, M., Seel, J., Robson, D., & Warner, C. (2023). *Utility-scale solar, 2023 edition: Empirical trends in deployment, technology, cost, performance, PPA pricing, and value in the United States*. Lawrence Berkeley National Laboratory. https://emp.lbl.gov/utility-scale-solar

Denholm, P., Nunemaker, J., Gagnon, P., & Cole, W. (2021). *The potential for battery energy storage to provide peaking capacity in the United States*. National Renewable Energy Laboratory. https://doi.org/10.2172/1783999

Denis, D., Sinuraya, E. W., Nugroho, A., Darmanto, N. A., Winardi, B., & Soetrisno, Y. A. A. (2021). Calculation of transmission lines and electrical equipment of 150 kV Main Guluk-Guluk, Madura Island, East Java, Indonesia. *International Journal of Advances in Scientific Research and Engineering, 7*(6), 23–35. https://doi.org/10.31695/IJASRE.2021.34026

Devlin, A. (2023). *The new steel map: Reconfiguring supply chains around renewable resources* (Doctoral dissertation). University of Oxford.

Gani, R. A., Facta, M., & Denis, D. (2020). Studi transformator 150/22 kV Gardu Induk Guluk-Guluk Pulau Madura Provinsi Jawa Timur. *Transient: Jurnal Ilmiah Teknik Elektro, 9*(2), 234–243. https://doi.org/10.14710/transient.v9i2.234-243

Gao, F., Zhou, H., Liang, H., Weng, S., & Zhu, H. (2020). Structural deformation monitoring and numerical simulation of a supertall building during construction stage. *Engineering Structures, 209*, 110033. https://doi.org/10.1016/j.engstruct.2020.110033

Intergovernmental Panel on Climate Change. (2022). *Climate change 2022: Mitigation of climate change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. https://doi.org/10.1017/9781009157926

International Energy Agency. (2023). *World energy outlook 2023*. IEA.

International Energy Agency. (2024). *Batteries and secure energy transitions*. IEA.

International Renewable Energy Agency. (2023). *World energy transitions outlook 2023: 1.5°C pathway*. IRENA.

Javed, M. S., Jurasz, J., Guezgouz, M., Canales, F. A., Ruggles, T. H., & Ma, T. (2023). Impact of multi-annual renewable energy variability on the optimal sizing of off-grid systems.

Renewable and Sustainable Energy Reviews, 183, 113514. https://doi.org/10.1016/j.rser.2023.113514

Kotla, R. W., Yarlagadda, S. R., & Devi, T. S. (2026). Resilient adversarial–evolutionary multi-agent intelligence for real-time EV charging and energy trading in renewable-integrated smart grids. *Global Energy Interconnection*. Advance online publication.

Lund, H., Østergaard, P. A., Connolly, D., & Mathiesen, B. V. (2017). Smart energy and smart energy systems. *Energy, 137*, 556–565. https://doi.org/10.1016/j.energy.2017.05.123

Meszek, W., Rejment, M., & Dziadosz, A. (2019). Disturbance analysis and their impact on delays in construction process. *IOP Conference Series: Materials Science and Engineering, 603*(5), 052002. https://doi.org/10.1088/1757-899X/603/5/052002

Psarros, G. N., Dratsas, P. A., & Papathanassiou, S. A. (2024). A comprehensive review of electricity storage applications in island systems. *Renewable and Sustainable Energy Reviews*. Advance online publication. *(Catatan: DOI yang benar untuk artikel jurnal ini sebaiknya menggunakan DOI jurnal Elsevier. DOI 10.48550/arXiv.2401.14712 adalah DOI preprint arXiv.)*

PT PLN (Persero). (2025). *Rencana Usaha Penyediaan Tenaga Listrik (RUPTL) PT PLN (Persero) Tahun 2025–2034*. Kementerian Energi dan Sumber Daya Mineral Republik Indonesia.

Sarr, A., Kebe, C. M. F., Gueye, M., & Ndiaye, A. (2021). Impact of temporal and spatial variability of solar resource on technical sizing of isolated solar installations in Senegal using satellite data. *Energy Reports, 7*, 753–766. https://doi.org/10.1016/j.egyr.2021.01.044

Schimpe, M., Naumann, M., Truong, C. N., Hesse, H. C., Santhanagopalan, S., Saxon, A., & Jossen, A. (2018). Energy efficiency evaluation of a stationary lithium-ion battery container storage system via electro-thermal modeling and detailed component analysis. *Applied Energy, 210*, 211–229. https://doi.org/10.1016/j.apenergy.2017.10.129

Wang, S., Li, Y., Li, J., Zhang, C., & Wang, J. (2023). Optimal sizing of photovoltaic-battery energy storage systems considering battery degradation and operational uncertainty. *Journal of Energy Storage, 72*, 108482. https://doi.org/10.1016/j.est.2023.108482

Xu, B. (2021). *Battery degradation modeling and valuation for grid-scale battery energy storage systems*. Stanford University. https://energy.stanford.edu/publications