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Optimizing Energy Consumption by Considering PV Rooftop Generation and Battery Storage in Power Plants: Study Case Palabuhanratu*

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Abstrak

Integrasi sistem Pembangkit Listrik Tenaga Surya (PLTS) Atap dengan Battery Energy Storage System (BESS) merupakan pendekatan strategis untuk meningkatkan efisiensi energi dan mendukung transisi menuju energi berkelanjutan. Penelitian ini mengevaluasi optimasi operasional sistem PLTS Atap + BESS skala bangunan yang diterapkan pada gedung *safety center* di Pembangkit Listrik Tenaga Uap (PLTU) Palabuhanratu, Indonesia. Fokus penelitian adalah pengaruh strategi manajemen baterai—khususnya pengaturan waktu pelepasan energi (*discharge timing*)—terhadap penghematan energi dan umur pakai baterai, dengan analisis rinci terhadap parameter C-rate (laju pengisian/pengosongan relatif terhadap kapasitas baterai) dan Depth of Discharge (DOD). Hasil penelitian menunjukkan bahwa penyesuaian waktu pelepasan energi berdasarkan profil beban pada hari kerja dan akhir pekan dapat secara efektif menurunkan nilai C-rate dari 0,18C menjadi 0,09C serta Depth of Discharge dari 80% menjadi 73%, yang berpotensi memperpanjang siklus hidup baterai. Melalui strategi load shifting, operasi yang dioptimalkan menghasilkan penghematan energi sebesar 3.442,5 kWh dan manfaat finansial sebesar USD 80 selama periode Oktober 2024 hingga Juli 2025. Temuan ini menegaskan peran penting manajemen energi yang adaptif dalam meningkatkan kinerja teknis dan umur pakai sistem PLTS Atap + BESS skala bangunan.

Kata kunci: *PLTS Atap, Battery Energy Storage System (BESS), optimasi energi, C-rate, Depth of Discharge (DOD).*

Abstract

The integration of rooftop solar photovoltaic (PV) systems with Battery Energy Storage Systems (BESS) represents a strategic approach to improving energy efficiency and supporting a sustainable energy transition. This study evaluates the operational optimization of a residential-scale PV+BESS system implemented at the safety center building of the Palabuhanratu coal-fired power plant (CFPP) in Indonesia. The research focuses on the influence of battery management strategies—particularly discharge energy savings and battery lifespan, with a detailed analysis of C-rate (current rate index value) and Depth of Discharge (DOD) parameters. Results demonstrate that adjusting discharge timing based on weekday and weekend load profiles can effectively lower C-rate levels from 0.18C to 0.09C and Depth of Discharge from 80% to 73%, potentially extending battery life cycle. Through load-shifting strategies, the optimized operations resulted in energy savings of 3,442.5 kWh and financial benefits of USD 80 between October 2024 and July 2025. These findings highlight the critical role of adaptive energy management in enhancing the technical performance and longevity of residential PV+BESS systems.

Keywords: *Rooftop Solar PV, Battery Energy Storage System (BESS), Energy Optimization, C-rate, Depth of Discharge.*

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1. INTRODUCTION

Increasing electricity production from renewable energy is a crucial approach to mitigating the global warming crisis and achieving sustainable development. With the support of policies, technological advances, and cost reductions, rooftop solar photovoltaic (PV) is increasingly accessible and widespread. Based on data published by PT. Perusahaan Listrik Negara (PLN Persero), the number of PV rooftop users is increasing year by year. Additionally, there is a government policy (PERMEN ESDM No.2 of 2024) that aims to accelerate the growth of PV rooftop by 1.5 GW each year. From a technical point of view, solar PV technology is an energy source that exhibits intermittency and dependence on weather (sunlight), so it needs to be considered in conjunction with the existing grid conditions. If PV rooftop penetration is not matched with existing grid capabilities, it can have an impact on energy balance instability. One of the mitigations that must be done in this system is to equip it with energy storage technology such as a Battery Energy Storage System (BESS) to overcome the intermittency.

This research aims to get the optimal use of rooftop solar PV and BESS energy. All data comes from rooftop solar PV and BESS that have been installed in the safety center building of PLTU Pelabuhanratu. This data can be a representation of the residential scale. PLTU Pelabuhanratu, as one of the plants owned by PLN, has a program related to the use of PV rooftops to improve efficiency in terms of lower self-consumption. The PV rooftop capacity built is quite large, up to 1.94 MWp, maximizing the potential of unutilized building roofs as a placement of solar module panels. However, the installed system is not yet equipped with energy storage facilities, so there is an opportunity to make improvements to the system that has been installed.

1.1. Solar Rooftop PV and BESS technology for residential scale

By 2050, solar PV will be the second-largest source of electricity generation, just behind wind power and leading the way for the transformation of the global power sector. Solar PV will generate about 25% of total electricity demand globally and become one of the leading sources of electricity generation by 2050 (IRENA, 2019). The deployment of PV rooftop systems has increased significantly in recent years. In major markets, such as Brazil, China, Germany, and Mexico distributed solar deployement become more competitive[1]. The dominant factors in the increase of rooftop solar adoption in Mexico include low installation costs and the potential for up to 95% savings on monthly electricity bills, while Brazil's is more due to the increasing competition of net-metering regulations across the country (IRENA, 2019). Some of the reasons cited by rooftop solar PV users include increased awareness of energy use, bill savings, perception of the outside of the house as a symbol of social position, and environmental benefits from reduced surrounding contamination, as well as meeting needs in retirement (Haryadi et al., 2021).

Based on data provided by PT PLN (Persero), it was discovered that the growth of rooftop solar PV users has continued to increase over a period of 5 years. As of June 2024, rooftop solar PV connected to PLN's electricity network has reached 9,324 customers with a total capacity of 197.25 MWp (PLN, 2024). They, as consumers, have motives that encourage them to install rooftop solar power plants. Some of the influencing factors are (1) rooftop solar PV is easy to find in residential or industrial locations, and the surrounding environment is already using rooftop solar PV; (2) environmental care and awareness; (3) knowledge of current technology trends; and (4) loyalty, namely, consumers generally choose to continue using rooftop solar PV even though the price is still relatively expensive (Haryadi et al., 2021).

The combination of solar PV and BESS in the United Kingdom has been shown to reduce electricity bills by 80-88% (Zakeri et al., 2021), while the integration of BESS with hybrid renewable energy in Kailua, Hawaii, has reduced costs and reduced energy consumption from the grid by 15.35% and can contribute to the grid (Singh & Kumar, 2023). In contrast to the conditions in Brazil, although BESS has many useful technical features, the investment in this technology is still not financially feasible (negative Net Present Value) at current interest rates (Goulart et al., 2024). BESS helps balance fluctuations in renewable energy output.

1.2. Electricity Supply Business Plan (RUPTL) 2025-2034

In the latest Electricity Supply Business Plan (RUPTL) 2025-2034, the development of Variable Renewable Energy (VRE) with BESS is mentioned. By combining BESS and VRE plants, it will reduce the intermittent nature of these plants. The potential of the BESS-VRE hybrid that can be developed includes load shifting, VRE smoothing, blackstart, peak shaving, frequency smoothing, and firming capacity. In order to increase the renewable energy mix, the government has also included a strategic initiative to develop hybrid solar power plants with diesel power plants for areas with low power hours (below 12 hours/day) as one of the priorities (PLN, 2025).

RUPTL 2025-2034 also plans for the installed capacity of solar PV and BESS to be 3.63 GW, while the stand-alone BESS capacity is 6 GW. This capacity is much higher than the previous RUPTL (PLN, 2025).

1.3. Literature Review

Several literature reviews related to energy optimization using rooftop solar PV and BESS have been widely conducted, including the following: evaluating the performance and economic feasibility of the PV and BESS system combination (Eum & Kim 2020), determining the optimal combination of renewable energy sources (solar PV, wind turbine, diesel generator) with BESS[5], developing an optimization approach to enhance household energy independence using PV and BESS systems through smart load management (Autuori *et al.*, 2024), proposing an energy management optimization strategy for residential buildings by considering load shifting and home battery energy storage systems (Faia *et al.*, 2025).

Table 1. Various Widely Used Energy Optimization Using Rooftop Solar PV+BESS and Their Findings.

No	Function	Research Results	Ref
1	Load Shifting	The proposed system (Kailua, Hawai) achieves a payback period of 5–7 years with a positive NPV	(Singh & Kumar, 2023)
2	Load Shifting & Peak Shaving	Currently not financially feasible given Brazil's interest rate of 13.75% (Negative NPV).	(Goulart et al., 2024)
3	Load Shifting	Optimal operating mode for BESS in Korean apartments is the one that prioritizes charging from PV and is supplemented by grid charging.	(Eum & Kim, 2021)
4	Load Shifting	The nighttime peak in consumption has successfully been shifted to daytime (when PV production is high), Several households experienced an increase in self-consumption after optimization.	(Autuori et al., 2024)
5	Load Shifting	The combination of load shifting and battery storage reduces energy costs by up to 20–30%.	(Faia et al., 2025)

As shown in table 1, the majority focus of previous studies is on providing an overview of cost optimization (load shifting) and operational optimization that can be achieved using rooftop solar PV and BESS. Our research aims to add considerations from the battery life cycle aspect by optimizing the use of C-rate (current rate index value) and Depth of Discharge (DOD) to extend the lifetime of BESS equipment.

2. METHODOLOGY

This research is focused on optimizing energy consumption in the safety center building through scheduling the operation of rooftop solar PV and BESS systems by considering battery operation (C-Rate and DOD) to extend equipment lifetime (battery life cycle)

2.1. Rooftop Solar PV & BESS at Safety Center Building

This research uses the safety center building as a pilot project because its location meets the technical criteria, as well as being quite strategic and easy for future development. In general, the installed rooftop solar PV and BESS system can be illustrated in Figure 1.

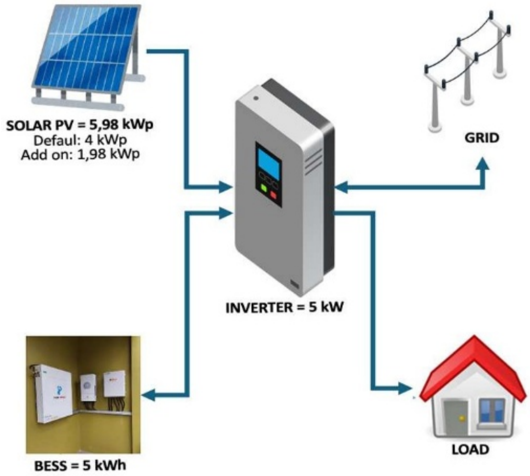


Figure 1. Schematic of Solar PV & BESS at Safety Center Building.

The PLTU Palabuhanratu safety center building receives its electrical power from the grid, rooftop solar PV, and BESS. The installed rooftop solar PV capacity is 4 kWp with an add-on of 1.98 kWp. The installed BESS capacity is 5 kWh. In this system, the hybrid inverter serves as both an Energy Management System (EMS) and a voltage converter (DC to AC or vice versa). However, the safety center building's solar PV and BESS system operates according to the following scheme:

- The BESS charging time is set at 05:00 - 18:00, where the electrical charging comes from solar PV. During the charging period, the PV system will prioritize charging the battery first, while the electricity source for the building comes from the grid (only during PV battery charging). After the State of Charge (SOC) of the battery reaches 100%, the solar PV will supply electricity to the safety center building. Excess electricity production from solar PV will be exported to the grid (internal).
- The BESS discharging time is set at 18:00 - 05:00. In this period it is assumed that the solar PV is no longer generating electricity, so that the electrical energy for the building will be supplied from the battery. After the battery SOC reaches a value of 20%, the electrical energy for the building will be supplied by the Grid (battery off).
- When solar PV or batteries are unable to provide electrical energy to the building, it will be supported or taken over (if problems occur) by the Grid.

This system design maximizes energy production and stores some of the energy during the day for use at night.

2.2. Data Acquisition

All data in this research uses primary data from the solar PV and BESS. Primary data was obtained through the website (https://pro.solarmanpv.com) provided by the inverter manufacturer. The data collection period was conducted from October 2024 to July 2025.

2.3. Effect of C-rate and Depth of Discharge on battery life

Batteries must be able to store enough energy, have high energy efficiency, have good discharge capability, accept charging well, and have a long cycle life. Batteries, when charging and discharging, will experience degradation due to the reversible reaction process experienced by the chemicals inside, thus reducing their maximum capacity. This phenomenon is called battery aging. Factors that greatly affect the aging of battery cells include DOD, C-rate (current rate index value), and temperature (Alim *&* Sudarmanta 2024).

Research conducted by Omar et al. discussed the evaluation of aging parameters of lithium iron phosphate batteries, using different current rates, working temperatures, and depths of discharge. The research concluded that battery capacity decreases faster at higher current rates, this is due to changes in carbon structure. The deeper/ higher use of depth of discharge on the battery causes the internal resistance to increase faster. The decrease in battery cycle life occurs faster due to the increase in internal resistance; this becomes the only stress factor on the battery. A battery's lifetime is highly dependent on the DOD. The DOD indicates the percentage of the battery that has been discharged relative to the battery's overall capacity (Omar *et al.*, 2023).

2.4. Load Shifting

Load shifting is an operational mode of a Battery Energy Storage System (BESS) that takes advantage of the difference in energy tariffs between peak and off-peak hours. During off-peak hours, when energy prices are lower, the battery is charged to full capacity, and this stored energy is used to supply the load during periods with higher energy tariffs (peak hours). Due to efficiency limitations in the battery charging and discharging process—primarily caused by power electronic converters and chemical losses within the battery, the additional energy required for this transaction must also be considered[6]. Most of these methods focus on optimizing battery capacity to achieve the best financial return, which is certainly a good starting point for battery systems that do not yet exist and require proper sizing.

In this article, load shifting is intended to illustrate the potential savings that can be achieved from the existing PV system with a predetermined energy storage capacity, without considering initial sizing optimization or other constraints.

3. RESULTS AND DISCUSSIONS

The next step after designing the PV+BESS system is the installation process to obtain technical data. In general, the stages carried out in this process include observation and evaluation after the design and installation phases (system improvement), observation of the load pattern (before optimization), evaluation of the load pattern (after optimization), and finally, providing recommendations regarding the benefits and application of the research results. It is important to note that based on the observed load patterns, we categorized them into two groups: load patterns during working days (weekdays) and load patterns during non-working days (weekends and long holidays).

3.1. Improvement System

The initial configuration of the PV+BESS system used has the following technical specifications:
PV = 4 kWp; Inverter = 5 kW; BESS = 5 kWh.

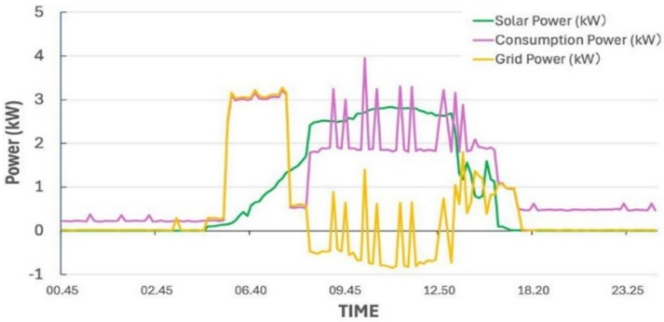


Figure 2. Load profile on 21 October 2024

As shown in Figure 2 the power demand (blue) exceeds the PV production capacity (green), requiring compensation from the grid (gray). Since during peak PV operation (midday), the load demand often surpasses the PV generation, we implemented an improvement by adding 1.98 kWp of solar panels to better match the load pattern. After the additional PV panels were installed (total installed capacity: 5.98 kWp), such occurrences no longer happened, as the PV system could fully meet the load demand at the Safety Center building.

3.2. Load Pattern Before Optimization

As explained in the design chapter (operation scheme), we observed the load pattern before the optimization was carried out. The load pattern is categorized into working days and non-working days (holidays).

a) Load Pattern During Holidays (Weekend & Long Holiday). The load pattern from April 1–6, 2025, is considered the most ideal reference for low-load conditions during the battery discharging period, as there were no work activities during this period due to the extended Eid al-Fitr holiday.

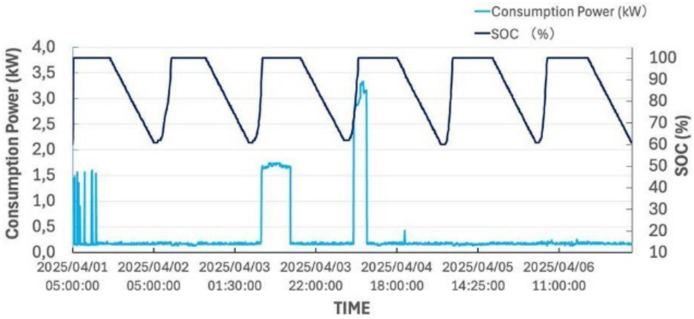


Figure 3. Load Profile on 1-6 April 2025

Based on the data obtained (Figure 3) during the long holiday period, an important finding emerged: the DOD used by the battery remained relatively low, with the final SOC staying above 60%, while the lowest nighttime load at the Safety Center building was recorded between 0.15 – 0.2 kW.

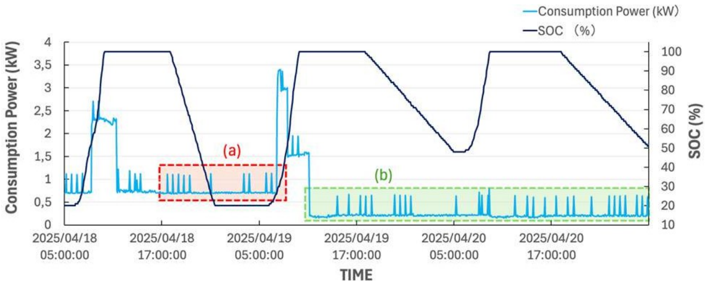


Figure 4. Load Profile on 18-20 April 2025

A similar low-load period occurred between April 18–20, 2025 (Fig.4), but an interesting contrast was observed. During this period, the battery experienced a higher DOD, with the final SOC dropping below 60%, which differs from the previous long holiday pattern (e.g., during Eid al-Fitr).

This reveals a key insight: two similar low-load conditions resulted in different discharge behavior. The red area (a) highlights inefficient load behavior, where some loads remain on during nighttime hours instead of being turned off. The green area (b) shows the lowest load conditions in the Safety Center building, but the final SOC value during battery discharge remains high (around 50%). This presents an opportunity for further optimization. Based on these two conditions, we recommend extending the discharge time by shifting the start and end times of the discharge schedule. This suggests a need for improved energy discipline and automation to ensure unnecessary loads are shut down during off-peak hours.

b) Load Pattern During Working Hours (Weekdays). The load pattern observed from April 7–11, 2025 represents the typical daily energy usage at the Safety Center building during normal working days. The peak load during daytime hours reached 4.86 kW.

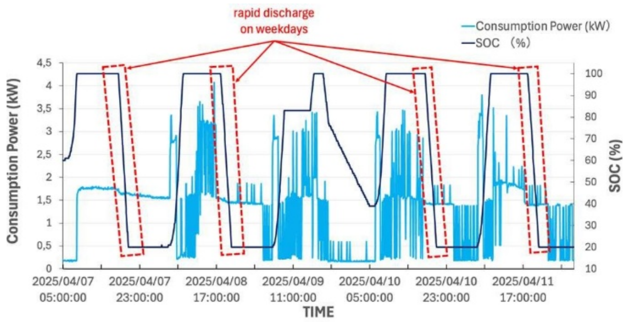


Figure 5. Load Profile on 7-11 April 2025

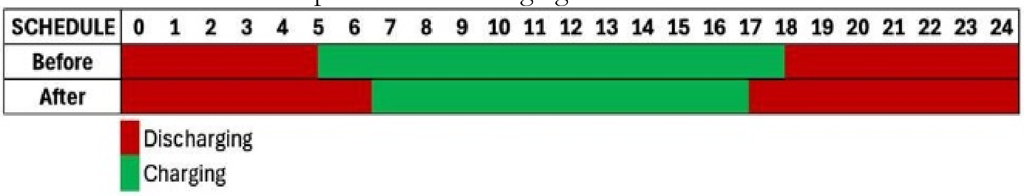
From the data shown in Figure 5, an important finding was identified: during working hours, the DOD of the battery was significantly high, indicating maximum utilization of the storage system, with the final SOC dropping to the lower limit of 20%. However, a concern during this period is the high battery C-rate and deep DOD, where the SOC drops from 100% to 20% in approximately 2 hours. This rapid discharge can negatively impact battery health and lifespan. We recommend an optimization strategy for weekday load patterns by reducing the high C-rate usage to help extend battery life. This can be achieved by shortening the discharging period, specifically by adjusting the battery discharge start time to begin after building activity decreases, i.e., after employees leave the office.

3.3. Load Pattern After Optimization

The optimization was carried out based on the evaluation of data presented in section 4.2, specifically:

a) Extending Discharging Time During Weekends and Long Holidays. The goal of this optimization is to maximize the use of stored energy in the battery by adjusting the charging and discharging schedule, as illustrated in Table 2.

Table 2. Optimation Discharging Time on Weekend Period



The charging time was changed from the previous schedule 05:00 a.m – 06:00 p.m to 06:30 a.m – 05:00 p.m, while the discharging schedule was shifted from 06:00 p.m – 05:00 a.m to 05:00 p.m – 06:30 a.m. Although we cannot configure two operating modes (weekdays and weekends/holidays) simultaneously due to inverter setting limitations, we have made a simulation assuming that the holiday setting is applied. The simulation results are shown in Figure 6.

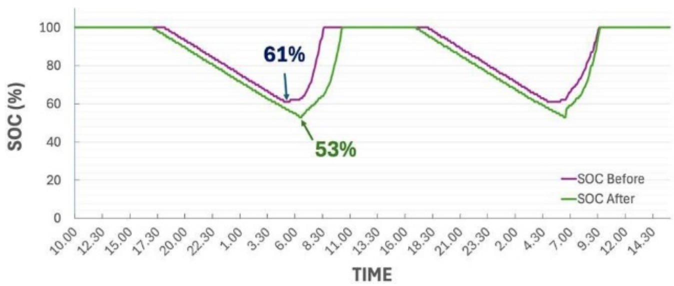
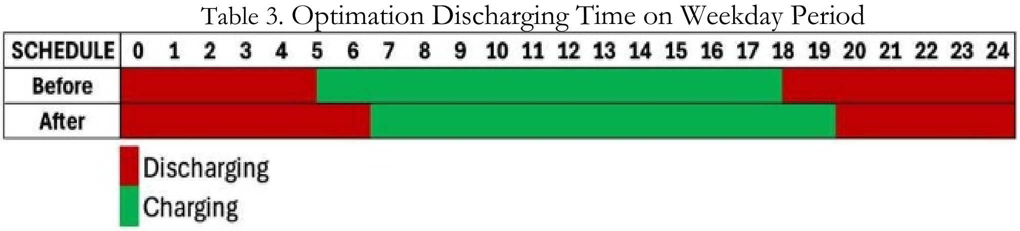


Figure 6. Simulation Discharging/ SOC Trendline Weekend Period (Before vs. After operational scheduling)

By optimizing the charging and discharging schedule, a noticeable difference in the final SOC can be observed. Before optimization, the final SOC remained relatively high at around 61%, whereas after optimization, the final SOC dropped to 53 %. This optimization is still considered safe, as the SOC decline is not too steep and the C-rate used remains low. Additionally, the amount of energy discharged (in kWh) can be maximized, with an increase of approximately 6%, equivalent to around 0.3 kWh.

b) Shortening Discharging Time During Weekdays. The objective of this optimization is to minimize the use of high C-rate and deep DOD by adjusting the battery charging and discharging schedule, as illustrated in Table 3.

Table 3. Optimation Discharging Time on Weekday Period



The charging time was changed from the previous schedule 05:00 a.m – 06:00 p.m to 06:30 a.m – 07:30 p.m, while the discharging schedule was shifted from 06:00 p.m – 05:00 a.m to 07:30 p.m – 06:30 a.m. The adjustment to the schedule has been made in accordance with official working hours. It is assumed that during the specified time, the room will be unoccupied and employees will have left the premises. While there may be occasional instances where staff members remain beyond regular hours, such occurrences are considered exceptional and are not expected to happen on a daily basis.

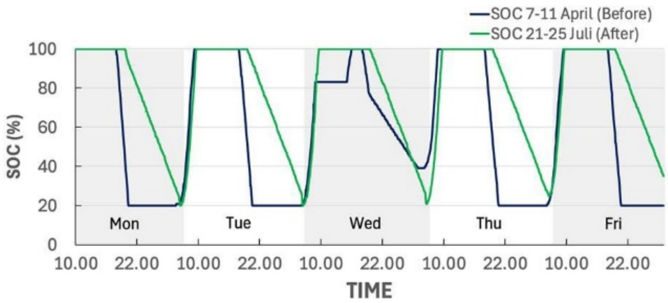


Figure 7. Real Time Discharging Trendline Weekday Period (Before vs. After scheduling)

Based on the results of the optimization process (see Figure 7), a noticeable improvement can be observed following the adjustment of the discharging schedule. The SOC decline curve becomes more gradual compared to the previous condition, indicating a slower rate of energy depletion. This change also reflects the use of a lower C-rate, suggesting a more efficient and controlled discharging process.

Table 4. A comparative analysis of C-rate and DOD utilization before and after operational rescheduling

Parameter	Before	After
Average C-Rate	0.18C	0.09C
Best DOD	80%	73%

Based on the data, it is evident that the change in scheduling significantly reduces the battery's discharging C-rate and avoids deep DOD usage (see table 4). This contributes to better battery health and potentially extends its lifespan.

3.4. Potential Benefits of Research Implementation

The implementation of energy optimization at the Safety Center Building of PLTU Palabuhanratu during the period of October 2024 to July 2025 resulted in an energy saving of 3,057 kWh from the Rofftop PV and BESS system (see table 5), while the load shifting function contributed a financial saving of 1.13 million rupiah. The multiplier of 1.5 was derived from the average coefficient applied to electricity prices during peak load hours.

Table 5. Energy Production and Possible Savings From Rooftop Solar PV+BESS Installed in Safety Center Building PLTU Palabuhanratu.

No	Item	Unit	Values
1	Solar Production	kWh	6,103
2	Consumption	kWh	6,375.2
3	Charge	kWh	1,030.3
4	Fed to Grid	kWh	2,496.1
5	Discharge	kWh	845.4
6	From Grid	kWh	2,932.7
7	Saving Energy = (2) - (6)	kWh	3,442.5
8	Electric Price	USD/ kWh	0.06
9	Total Saving = 1.5 × (5) × (8)	USD	80

Beyond energy savings, the optimization achieved through battery discharge scheduling—aligned with weekday and weekend load patterns—has provided valuable insights. This approach has proven effective in maintaining a low discharge C-rate and DOD, which is expected to extend battery lifespan. The other important thing in the PV system integrated with BESS is fostering user awareness in the building to use electricity wisely, especially after working hours. This includes turning off all unnecessary electronic equipment once employees have left the building.

4. CONCLUSION

This research demonstrates the significant potential of integrating rooftop solar PV with Battery Energy Storage Systems (BESS) to optimize energy usage at the Safety Center Building of PLTU Palabuhanratu. Through careful scheduling and operational adjustments, particularly in managing C-rate and DOD, the system not only achieved substantial energy savings but also contributed to financial savings through load shifting. Through load-shifting strategies, the optimized operations resulted in energy savings of 3,442.5 kWh and financial benefits of USD 80 between October 2024 and July 2025. The optimization strategies—extending discharging time during weekends and shortening it during weekdays—proved effective in reducing battery stress and enhancing its lifecycle. Results demonstrate that adjusting discharge timing based on weekday and weekend load profiles can effectively lower C-rate levels from 0.18C to 0.09C and Depth of Discharge from 80% to 73%, potentially extending battery life cycle. These findings highlight the importance of aligning energy management with actual load patterns and user behavior. Moreover, the study emphasizes the role of user discipline in maximizing system efficiency, especially in minimizing unnecessary energy consumption outside working hours. Overall, the integration of rooftop solar PV and BESS, supported by smart scheduling and user awareness, presents a viable model for residential-scale energy optimization and sustainability. The insights gained from this pilot project can serve as a reference for broader implementation across similar facilities.

5. ACKNOWLEDGMENT

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