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Performance Analysis of an Off-Grid Solar Power Plant for Meeting Multi-Building Electricity Demands at Polytechnic State of Padang

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ABSTRACT
This study evaluates the operational performance and economic potential of an off-grid solar power plant (SPP) installed at the Polytechnic State of Padang's AC lecture building. Analysing data from January to May 2025, the research identifies a significant energy surplus, with the system generating between 10.36 kW and 36.84 kW against a maximum weekday demand of 15.54 kW. Technical analysis reveals that peak power reached a maximum of 40,298 W in April, reflecting optimal solar irradiation, while peak production consistently occurred between 09:00 and 10:00. The integrated battery system demonstrated robust performance, with the monthly average State of Charge (SoC) increasing from 57.12% in January to 63.23% in May, indicating progressive energy management optimisation. Charging and discharging efficiencies remained high, peaking at 93.19% in April. Despite a production decline in March due to inconsistent sky conditions, the system maintained a high total energy yield, with February recording the highest output at 2,960.07 kWh. Economic analysis indicates that the surplus energy presents a substantial opportunity for cost reduction. By redistributing excess power to adjacent buildings, the total potential cost savings for the five-month period were calculated at IDR 19,298,045.18. These findings suggest that the current off-grid installation is significantly underutilised and could serve as a primary energy source for a micro-grid network within the campus, enhancing both technical efficiency and financial sustainability.

1.0 Introduction

In Indonesian Strategic Planning of National Energy, Solar Power Plant (SPP) is one of the priority programs at Ministry of Energy and Mineral Resources as the strategy to increase renewable energy utilization in value 23% in year 2025. Besides that, replacing fossil energy with renewable energy can reduce atmospheric pollution (Rahman et al., 2023). The utilization of SPP can be on-grid, connected to electrical distribution system, or off-grid, used for one building only (Ukoba et al., 2019). SPP is environmentally friendly power plants because it utilizes renewable energy and produces electricity without greenhouse gas emissions and air pollution (Das et al., 2024; Sosnina et al., 2024; Zain and Ama, 2022). Polytechnic State of Padang has utilized a SPP generation system with an off-grid configuration located in the AC building of the Electrical Engineering Department. In this research, it will be evaluated the electricity supply from off-grid SPP at Polytechnic State of Padang and if the production energy is larger than consumption energy, it means that the electricity can be distributed to other buildings. The implementation of the existing SPP can produce excess electrical energy, especially during the day and when the sun is shining brightly (İsen and Kutluca, 2021; Meliala et al., 2021). Therefore, a system development is needed so that the surplus electrical energy can be utilized efficiently and appropriately by changing the SPP system from for one building becomes for some buildings.

The electrical power generated from the conversion of solar energy in this SPP is worth around 10.36 - 36.84 kW where the maximum electrical energy is generated at 9 am to 2 pm. The electrical power requirement in this building is worth between 5 to 15.54 kW on weekdays and is lower on holidays. This study aims to analyse off-grid SPP so that it can supply other buildings at Polytechnic State of Padang. On the other hand, the energy that can be supplied by this SPP is more than the demand of lecture building at Polytechnic State of Padang, so by supplying the electricity to other lecture buildings, it can support the status of Polytechnic State of Padang which has become a Public Service Agency at this time because it can decline the institutional outcome.

2.0 Experimental

2.1 Solar Power Plants at Polytechnic State of Padang

Solar Power System is an electricity generation system that utilizes solar energy as a renewable energy source. This solar energy is converted into electrical energy using photovoltaic (PV) technology embedded in solar panels. The PV technology directly generates direct current (DC) electricity from sunlight exposure. Solar power systems are considered an environmentally friendly solution to fossil energy depletion due to their abundant energy source and zero carbon emissions (Ding et al., 2023; Iqbal et al., 2024). The main components of this system include solar panels, inverters, batteries, and a Solar Charge Controller (SCC) (Sarraj et al., 2023). Solar panels can convert sunlight into DC electricity, and the SCC is a critical component that regulates the voltage and current coming from the solar panels before it reaches the battery. It protects the battery from overcharging, over-discharging, and ensures efficient energy transfer, which helps extend battery life and improve overall system performance (Ajiwiguna and Kirom, 2024).

The inverter plays a crucial role in converting the DC electricity from the panels or batteries into alternating current (AC), which is commonly used by household and industrial electrical devices. Meanwhile, the battery stores excess electrical energy produced by the solar panels when the energy supply exceeds the load demand, as shown in Figure 1a. This stored energy is then released during periods of low sunlight intensity or at night, ensuring the solar power system can continuously supply electricity in a reliable and sustainable manner (Abdolmaleki and Berardi, 2024; Ullah et al., 2024). Based on the installation location, the SPP system is divided into two types, namely, distributed PV plant systems and centralized PV plants. Based on its application and configuration, SPP is broadly classified into two, namely, off-grid PV plant systems or better known as stand-alone SPP, and grid-connected PV plant systems. If in its use SPP is combined with other types of generators, it is called a hybrid system.

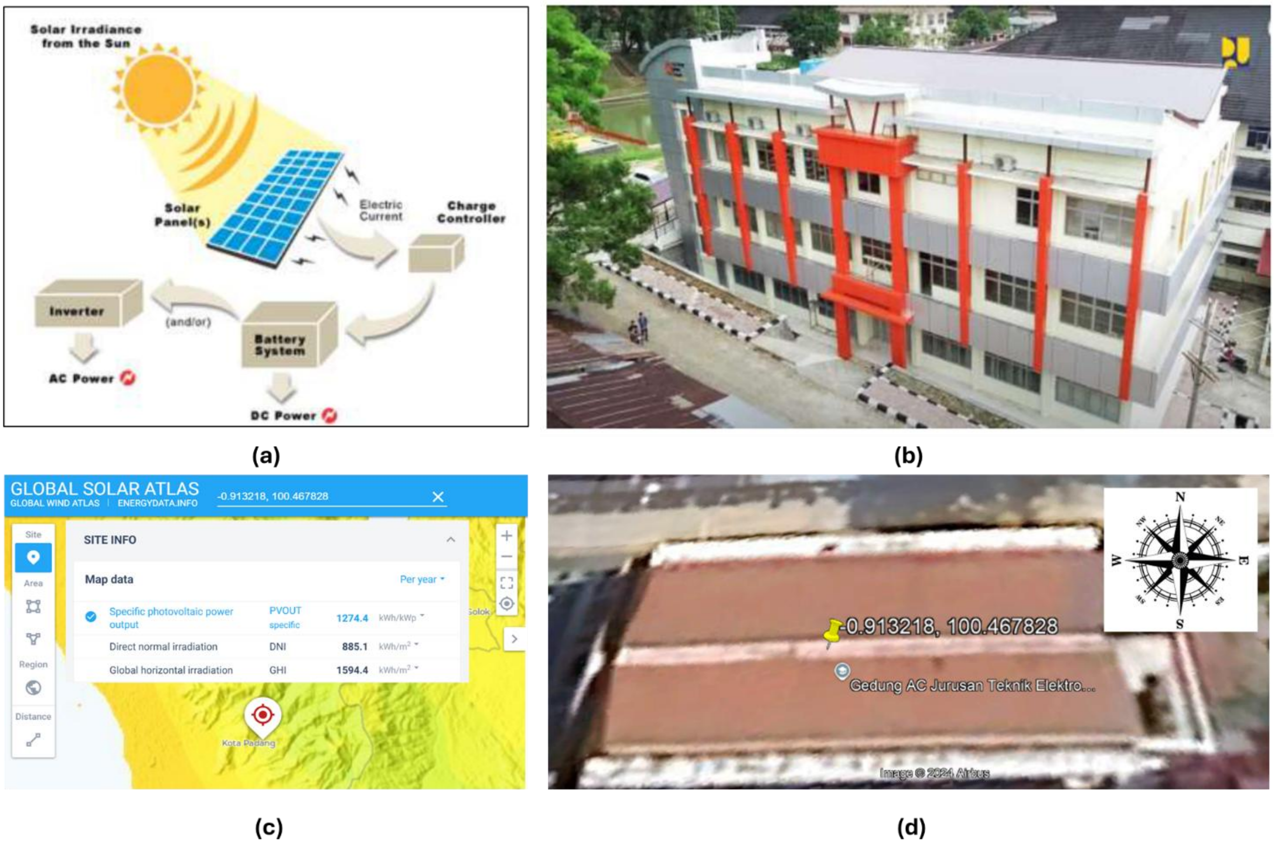
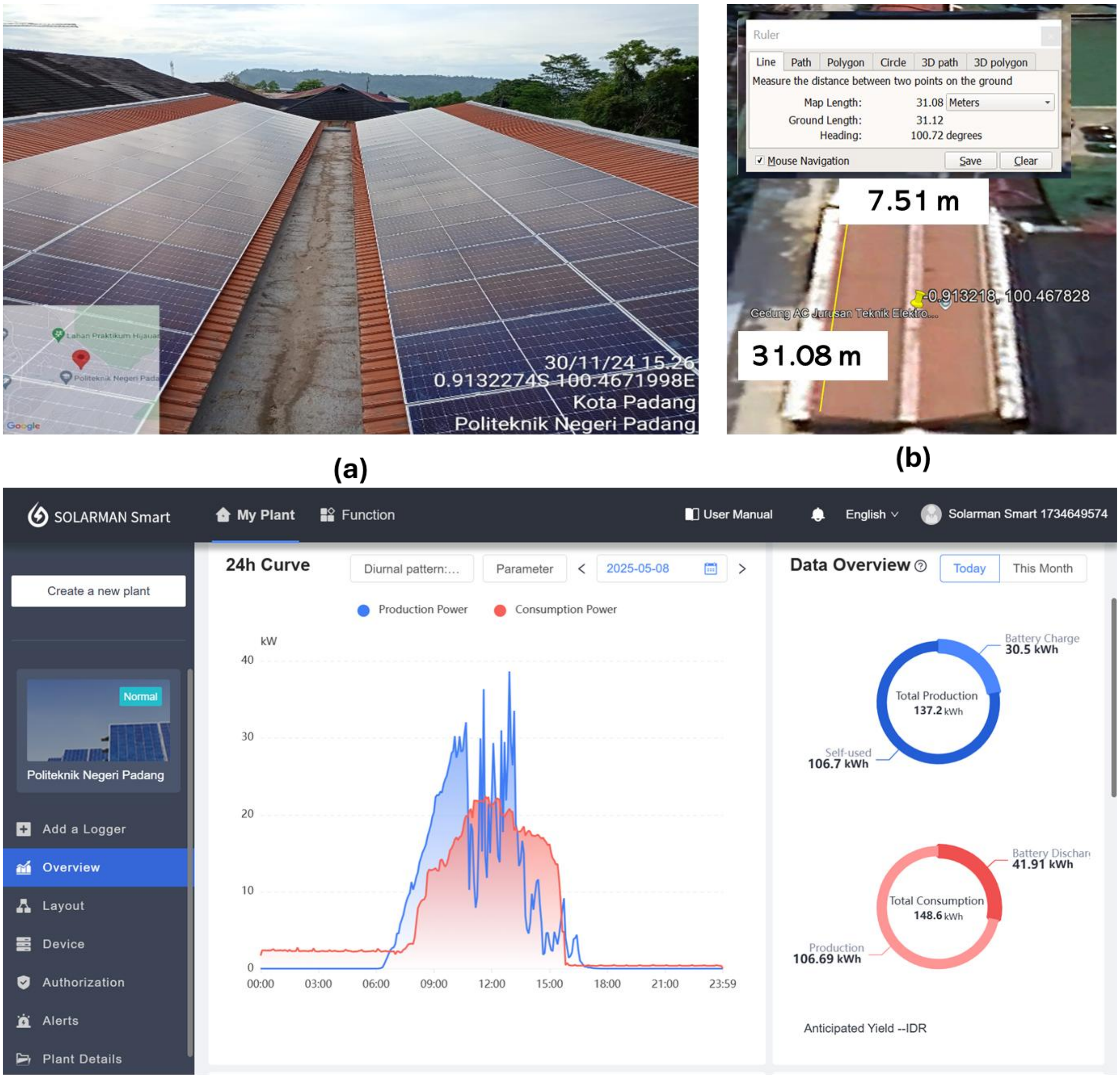


Figure 1: The off-grid SPP (a) Solar panel convert light energy to electricity and be saved in battery system then be inverted to AC power by inverter (Sarraj et al., 2023) (b) The utilization of off-grid SPP at AC Building, Polytechnic State of Padang (c) The global horizontal irradiation of this location is 1,594.4 kWh/m^2 (d) The coordinate of AC building (-0.913218, 100.467828)

Polytechnic State of Padang is one of the state colleges in West Sumatra, Indonesia and has potential solar energy to convert to electricity because of its location around the equator. The AC building is one of lecture buildings at Polytechnic State of Padang and the design of the roof top had been adapted for solar panel installation with tilting 15 degree (Figure 1b). The capacity of SPP at this building, installed in year 2024, is 50 kWp and has been used to supply the electricity for AC building only. The high intensity and long duration of sunlight at this college, with the global horizontal irradiation 1,594.4 kWh/m^2 (Figure 1c), indicates that the potency of the electricity can be supplied not only for AC building but also for other buildings, G building (south side) and the canteen (east side), as illustrated in Figure 1d.

3.0 Results and Discussion

The SPP at AC building, Polytechnic State of Padang consists of 96 units solar panels with the total capacity 50 kWp, as shown in Figure 2a. The dimension of roof top is 31.08 x 7.51 m^2 (Figure 2b) and the control room for inverter, battery and installation panel is installed in first floor of AC building. The data collection of production and consumption power of this SPP can utilize software Solarman smart, as shown in Figure 2c.



(c)

Figure 2: (a) The SPP at AC Building, Polytechnic State of Padang (b) The dimensions of roof top (c) The software to monitor the production and consumption power of SPP

3.1 Energy Production Overview

During the five-month period from January to May 2025, the photovoltaic system at Polytechnic State of Padang demonstrated significant variations in energy production. The highest total energy production, as shown in Figure 3a, was recorded in February with 2,960.07 kWh, followed by May (2,848.88 kWh), April (2,841.69 kWh), and January (2,787.73 kWh). The lowest production occurred in March with only 2,255.82 kWh, representing approximately a 24% decrease compared to February.

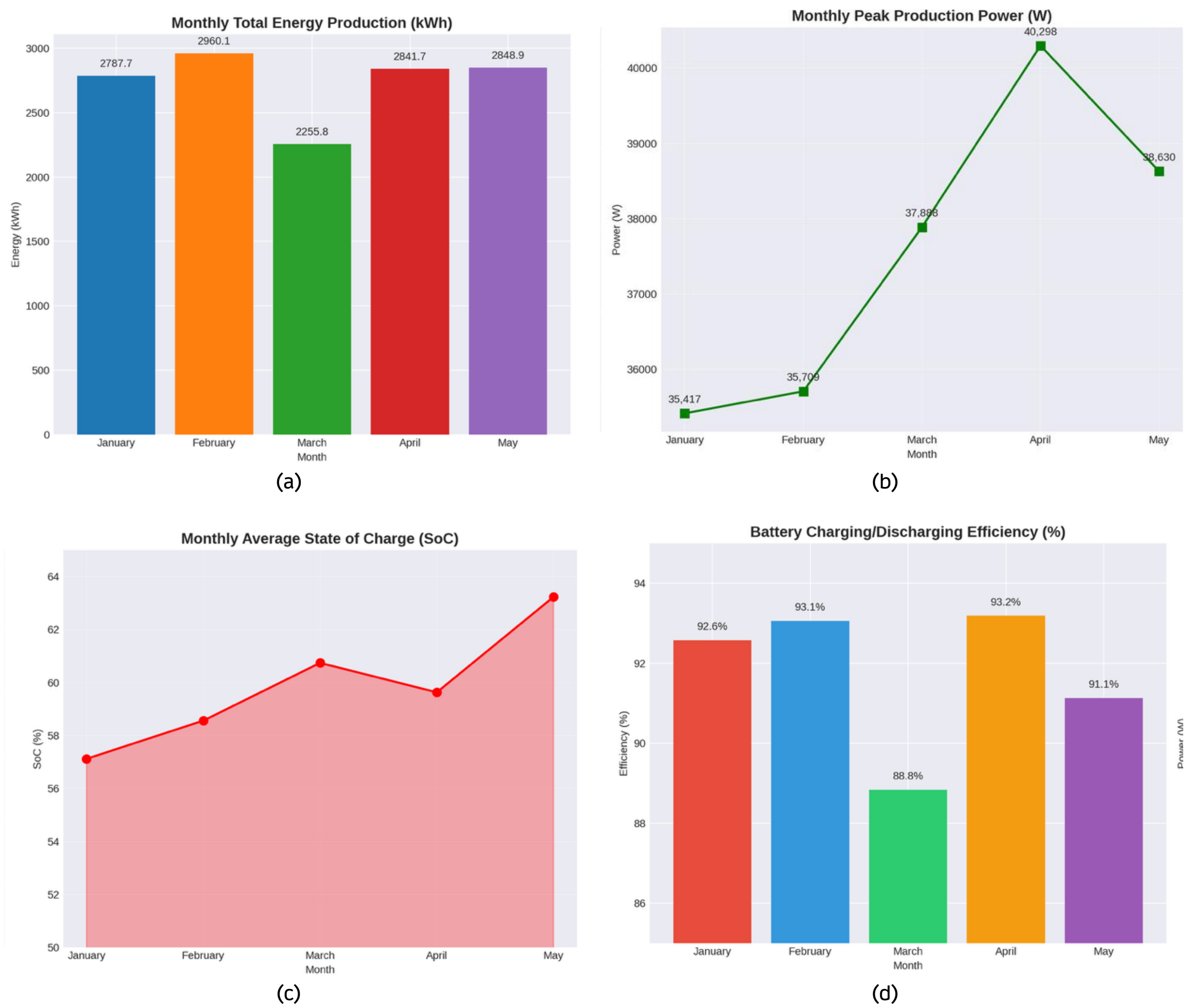


Figure 3: (a) Monthly total energy production (kWh), (b) Monthly peak production power (W), (c) Monthly average State of Charge (SoC) and (d) Battery charging/discharging efficiency (%)

3.2 Peak Power Characteristics and Production Patterns

Peak power analysis as shown in Figure 3b reveals an increasing trend from January through April. The highest peak power was recorded in April at 40,298 W, indicating optimal solar irradiation conditions. Interestingly, despite March having the lowest total production, its peak power reached 37,888 W, suggesting the presence of days with excellent clear-sky conditions but inconsistent throughout the month. Peak production hours generally occurred between 09:00-10:00, with February showing the highest average production during peak hours at 17,382.98 W.

3.3 Battery Storage System Performance

The battery system demonstrated consistent performance with monthly average State of Charge (SoC) ranging from 57.12% (January) to 63.23% (May). The increasing trend in average SoC from January to May indicates progressive optimization of energy management. Battery charging/discharging efficiency showed excellent performance, with the highest value in April (93.19%) and the lowest in March (88.84%). The efficiency drops in March likely correlates with higher production fluctuations during that month.

3.4 Variability and Consistency Analysis

Daily average production showed significant inter-monthly variability. February had the highest daily average production (105.72 kWh) with a standard deviation of 41.79 kWh, indicating relatively consistent production. Conversely, April and May showed higher standard deviations

(50.5 and 50.92 kWh), indicating greater weather variability. March, with the lowest daily average production (75.19 kWh), was likely influenced by transitional weather conditions or increased cloud cover.

3.5 Operational Implications

The analysis results demonstrate that the PV-BESS system operates effectively under the tropical climate conditions of West Sumatra. Battery efficiency consistently above 88% indicates good component quality and system management. The 24% monthly production variation between the highest and lowest months needs to be considered in energy demand planning. The increasing average SoC from January to May suggests system learning or operational adjustments that optimize battery usage over time. The comprehensive analysis of your PV-BESS system from January to May 2025 is complete. The data shows strong overall performance with 14,694 kWh total production, battery efficiency above 88%, and improving SoC management over time. The 24% production variability between months (highest in February, lowest in March) reflects typical seasonal patterns for your tropical location.

3.6 SOC Analysis

The State of Charge (SoC) of the battery in a photovoltaic (PV)-based Solar Power Generation System (SPPS) was analysed over a five-month period from January to May 2025 (Fig. 3c). The analysis focuses on the daily SoC profiles recorded on the 8th, 15th, 24th, and 30th of each month, with data presented in a 24-hour time frame to evaluate charging and discharging patterns. Results indicate distinct monthly and daily variations, reflecting the influence of solar irradiance, load demand, and system efficiency on battery performance. In January, which typically experiences lower solar insolation, SoC profiles remained relatively subdued. On January 8th and 15th, SoC levels were consistently low throughout the day, suggesting insufficient solar input to support battery charging, likely due to persistent cloud cover or seasonal atmospheric conditions. A moderate increase in SoC was observed on January 24th, indicating a short duration of effective charging. However, by January 30th, SoC declined throughout the day with negligible signs of replenishment, implying that load demand outweighed energy generation, leading to progressive battery depletion (Fig. 3d).

A slight improvement was noted in February, with more variable SoC behaviour. On February 8th, SoC increased steadily during the morning and early afternoon, although the peak level remained suboptimal, potentially due to partial shading or intermittent cloud conditions. The pattern on February 15th resembled January's performance, with low and stagnant SoC levels. In contrast, February 24th displayed a significant increase in SoC, reaching near-full capacity by mid-afternoon, indicating a day of strong solar availability and effective energy storage. No data were available for February 30th, as the month only includes 29 days in the 2025 calendar year. March data marked a transition into more favourable solar conditions. A sharp morning increase in SoC on March 8th reflected highly efficient charging, likely under clear-sky conditions with high solar irradiance. However, on March 15th, despite starting with a high SoC, the battery discharged rapidly over the day, suggesting high energy consumption or a drop in solar input. On both March 24th and 30th, a consistent SoC decline was observed, indicative of a slow but steady energy discharge pattern, with limited solar charging capability during the day.

April presented a more diverse range of SoC behaviours. On April 8th and 24th, SoC increased significantly from early morning until midday, demonstrating efficient battery charging under favourable solar conditions. Conversely, April 15th and 30th began with low SoC levels and only moderate increases, pointing to either suboptimal weather conditions or elevated load profiles that limited the net energy available for storage. This variability highlights the transitional nature of solar availability during early spring. In May, SoC profiles exhibited higher stability, consistent with improved and more predictable solar conditions. On May 24th, the battery maintained a high SoC throughout the entire day, indicating minimal discharge and a low overall load. May 8th and 15th started with low SoC values, likely due to night time consumption, but showed gradual recovery during daylight hours. Notably, May 30th featured a dynamic charge-discharge cycle, with SoC rising from 32% to 40% and subsequently decreasing, reflecting a balanced and responsive interaction between energy production and consumption.

Overall, the analysis underscores the strong correlation between solar irradiance patterns and battery SoC dynamics. Seasonal variability significantly affects system performance, with winter months demonstrating weaker charging cycles and spring months showing more favourable charging and storage behaviour. These findings emphasize the necessity of continuous SoC monitoring and the implementation of adaptive energy management strategies. Optimizing the timing and magnitude of charging and discharging can improve the reliability and efficiency of SPP systems. Moreover, insights from SoC trends are critical for system sizing, ensuring sufficient energy availability across varying environmental and load conditions, and achieving long-term sustainability in solar-powered energy systems.

3.7 Cost Saving Analysis

The cost savings achieved from January to May 2025 indicate a significant potential energy surplus from the excess capacity of the Solar Power Plant (SPP) system installed at the AC Building of the Department of Electrical Engineering, Polytechnic State of Padang (Table 1). The surplus energy generated by the SPP is calculated as potential cost savings if utilized to supply electricity to other buildings within the institution. This cost savings calculation is based on the electricity selling price set by PT Perusahaan Listrik Negara (Persero) Tbk, thereby quantifying the surplus energy produced by the SPP system in Rupiah per kWh. According to regulations from the Ministry of Energy and Mineral Resources, the electricity tariff for the business category under group B-2/TR covering customers with an installed capacity between 6,600 VA and 200 kVA is set at IDR 1,444.70 per kWh.

Table 1: Monthly cost saving from January to May 2025

Month	Cost Saving
January 2025	IDR 3,922,899.15
February	IDR 4,160,620.51
March	IDR 3,239,232.80
April	IDR 4,182,921.60
May	IDR 3,792,374.12
Total Cost Saving to Other Building	IDR 19,298,045.18

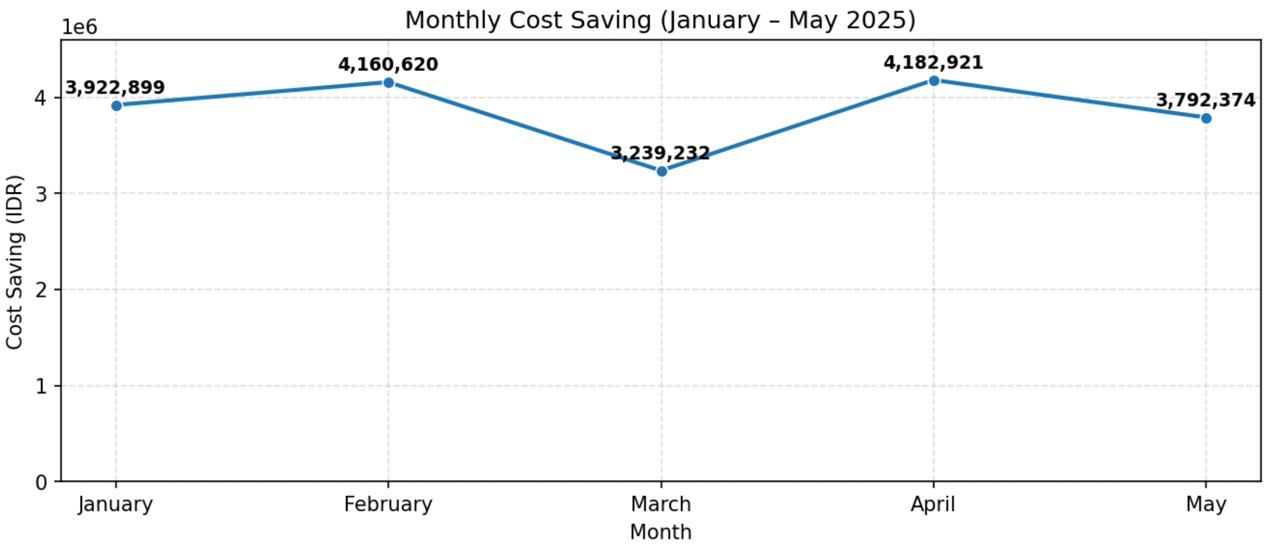


Figure 4: Monthly cost saving from January to May 2025

Based on the calculated data, the cost savings in January reached IDR 3,922,899.15 and increased in February to IDR 4,160,619.51. A decrease in surplus occurred in March, resulting in savings of IDR 3,239,231.80. However, an increase was observed in April, reaching the highest savings among all months at IDR 4,182,920.60. In May, the savings from surplus energy amounted to IDR 3,792,374.12. Overall, the total potential cost savings that could be achieved if this surplus energy were utilized in other buildings reached IDR 19,298,045.18. The cost savings from the SPP system at the AC Building are attributed to the surplus energy it generates (Fig. 4). The energy produced is relatively stable and consistent, making it suitable for reducing or saving costs when distributed to other buildings.

The cost saving analysis from January to May 2025 shows the existence of surplus energy from the Solar Power Plant (SPP) system installed at the AC Building of the Department of Electrical Engineering, Polytechnic State of Padang. The recorded monthly cost savings ranged from IDR 3.2 million to IDR 4.1 million, with total accumulated savings reaching IDR 19,298,045.18 over the five-month period. Although previous studies such as (Ukoba et al., 2019) and (Meliala et al., 2022) did not specifically address cost savings, their research demonstrated that the application of SPP systems improves energy self-sufficiency for buildings or facilities where they are installed. The decrease in cost savings observed in March in this study is associated with reduced energy production due to variations in weather conditions, while February and April exhibited higher cost savings aligned with more stable energy production. These findings indicate that the SPP system not only fulfills the energy demands of the building but also provides potential economic benefits when surplus energy is optimally utilized, particularly when redistributed to other buildings within the institution.

These results provide a strong foundation for developing a more integrated renewable energy utilization strategy within the institutional environment, particularly in efforts to reduce dependence on electricity supply from PLN and to lower the operational electricity costs of buildings supplied by surplus energy from the SPP system. This calculation indicates that the excess energy generated by the SPP not only contributes to cost savings for a single building but also holds economic potential if allocated to other buildings. The cost savings analysis demonstrates that redirecting this surplus energy to other buildings can result in significant financial savings. This finding can serve as a strong reference for developing effective energy-saving strategies.

4.0 Conclusion

This study investigated the performance of the Solar Power Plant (SPP) system installed at the AC Building of the Department of Electrical Engineering, Polytechnic State of Padang, focusing on energy generation, battery performance, and cost savings over a five-month period from January to May 2025. The SPP system effectively met the electricity demands of the AC Building while consistently generating surplus energy, with total energy production reaching 14,694 kWh. The system exhibited stable peak power performance, high battery charging and discharging efficiency (ranging from 88.84% to 93.19%), and positive trends in battery State of Charge (SoC). Additionally, the cost savings analysis indicated that surplus energy could contribute up to IDR 19,298,045.18 in savings over five months, suggesting strong economic potential if redistributed to other buildings. This study has certain limitations, primarily due to the relatively short five-month observation period, which does not capture the full annual seasonal variations. The analysis also did not account for the long-term effects of equipment degradation, such as battery capacity fading or inverter efficiency losses, nor did it consider detailed load fluctuations from multiple buildings. Based on the findings, several recommendations can be made: future studies should include data collection over a full annual cycle, incorporate load forecasting models, and integrate surplus energy distribution mechanisms to maximize system efficiency. It is also recommended to explore the potential of expanding the SPP system to supply other campus buildings, which could enhance energy self-sufficiency and reduce overall operational costs.

Future work should focus on the development of hybrid configurations that combine solar energy with additional backup sources, the application of smart energy management systems, and conducting long-term performance monitoring to assess sustainability and economic viability. Overall, the SPP system at the Polytechnic State of Padang demonstrates reliable performance and offers meaningful opportunities for cost savings and expansion, supporting efforts towards sustainable and efficient energy utilization within the educational environment.

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Author Contributions

Yandri V. R.: Writing - review & editing, Writing - original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Frasetyo M. B.**: Methodology, Data curation. **Kartika Sari D. A.**: Methodology, Data curation.**Negara R. B**: Writing – review & editing, Validation, Supervision, Methodology. **Wiharti W.**: Writing - review & editing, Validation, Supervision, Resources, Methodology. **Agre A.**: Investigation, Formal analysis, Data curation. **Yamashita Y.**: Validation, Resources, Formal analysis, Data curation.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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