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Solar Energy Integration for Liquid Palm Sugar Processing in Rural Home-Industry

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Abstract: This study explicitly aims to evaluate the technical performance and feasibility of a photovoltaic (PV)–battery system in supplying the energy requirements of a liquid palm sugar production machine for rural home-industry applications. Electricity instability in rural areas often disrupts production activities, and although previous studies have demonstrated the potential of solar energy, real-world evaluations for palm sugar processing remain limited. In this research, two 565 Wp solar modules integrated with a 2.2 kW inverter and a $LiFePO_4$ battery were experimentally tested under actual operating conditions. Real-time data of PV output, irradiance, load demand, and battery condition were recorded. The results show that the PV system consistently supplied 950–1050 W under clear skies and 600–800 W during cloudy conditions, while the battery maintained a stable state of charge (SoC) of 71–85%, ensuring uninterrupted operation. Daily PV energy generation (4.2–4.6 kWh) exceeded load consumption (3.2–3.6 kWh), confirming a positive energy balance. Overall, the system demonstrated stable and reliable performance, indicating that PV–battery integration is feasible for rural MSME-scale liquid palm sugar production.

Keywords: palm; sugar; photovoltaic; $LiFePO_4$; home-industry



SDGs Problem Solving

Research and problem-solving in this study directly support SDGs Chapter 7. By designing and experimentally evaluating a photovoltaic–battery system for rural palm sugar MSMEs, the research addresses electricity instability through renewable solar integration, enhancing energy access, reliability, productivity, and sustainable rural economic development in Indonesia.

Conflict of Interest Statement: The author(s) declares that the research was conducted in the absence of any commercial or financial relationship that could be construed as a potential conflict of interest.

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Conflict of Interest STATEMENT
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1. INTRODUCTION

Palm sugar is one of Indonesia's traditional natural sweeteners derived from the sap of Arenga pinnata. This product plays an essential role in supporting rural livelihoods and contributes significantly to the local economy, especially through micro, small, and medium enterprises (MSMEs). In recent years, liquid palm sugar has gained wider acceptance due to its practical form, improved hygiene, and increasing commercial potential within the modern food and beverage industry (Asbanu *et al.*, 2025). However, the production capacity of palm sugar at the MSME scale remains limited. One of the major constraints is the absence of energy-efficient and integrated processing equipment that is compatible with rural conditions, where access to reliable electricity infrastructure is often inadequate (Erwin *et al.*, 2018). This condition creates a mismatch between the growing market demand and the ability of rural MSMEs to scale up production, highlighting the need for technological solutions that support continuous and stable processing.

Electricity instability in rural regions poses a critical challenge for palm sugar production, particularly for machines that rely on continuous electrical supply such as heating units, vacuum evaporators, and processing instruments. Frequent power outages and voltage fluctuations from the state electricity grid (PLN) disrupt production cycles, reduce product consistency, and increase operational costs. These issues highlight the need for an independent, reliable, and sustainable energy solution to support small-scale agro-industrial processes in rural environments (Silalahi *et al.*, 2021; Sulistiyono, Rifai and Sudiar, 2025). As a result, the inability of existing infrastructure to support uninterrupted production becomes a crucial barrier that has not been adequately addressed in current studies.

Solar photovoltaic (PV) systems have emerged as a promising alternative for rural industries due to their modularity, low operating costs, and ability to supply electricity independently of the grid. According to the FAO (Campen, Guidin and Best, 2020), solar energy can significantly enhance productivity and income in rural communities by providing dependable power for agricultural and food-processing activities. Indonesia's high solar irradiation potential—ranging between 4.8 and 6.0 kWh/m² per day—further strengthens the feasibility of decentralized solar energy systems (Sulistiyono, Rifai and Sudiar, 2025). Several studies have successfully demonstrated the application of PV systems in MSME-scale technologies, such as coconut grating machines (Asbanu *et al.*, 2025) and agricultural water pumps (Winati *et al.*, 2023), indicating that solar energy offers an effective solution for supporting rural industries. However, these existing applications mostly focus on general agricultural tools, and do not specifically address the unique thermal and operational requirements of palm sugar processing machines.

Despite these developments, research on the integration of PV systems with palm sugar production machinery remains very limited. Existing studies predominantly concentrate on conceptual designs or laboratory-based experiments, while real-world assessments of system performance under actual production conditions are still scarce. This gap highlights the need for empirical investigations into PV-driven palm sugar processing, particularly concerning energy output stability, operational efficiency, and practical feasibility in rural settings. Therefore, a clear research gap exists in evaluating how a PV–battery system behaves under fluctuating irradiance while supplying the

dynamic load profile of a palm sugar production process, which has not been explicitly examined in previous literature.

Based on these considerations, this study aims to investigate the integration and performance of a solar photovoltaic system as an independent energy source for a liquid palm sugar production machine. The system was implemented and experimentally tested at the Faculty of Engineering, Universitas Sultan Ageng Tirtayasa (UNTIRTA) under actual operating conditions. The novelty of this research lies in the direct performance evaluation of a PV-powered palm sugar production system at the MSME scale, which has not been extensively explored in previous works. Specifically, this study provides the first field-based assessment that simultaneously analyzes PV output, battery state of charge, and real machine load behavior during continuous palm sugar production. The objectives of this study are: (1) to evaluate the capability of the PV system in supplying stable electrical energy for the palm sugar production process; (2) to analyze the energy conversion efficiency and operational stability of the integrated system; and (3) to assess the practical feasibility of implementing solar-powered production machines for MSMEs in rural Indonesia.

2. METHODOLOGY

This research employs an experimental approach to evaluate the performance of a solar photovoltaic (PV) system as an independent power source for a liquid palm sugar production machine. The experimental approach was chosen because it provides accurate empirical data on the performance of the PV system under real operating conditions, allowing the results to reflect the system's reliability and efficiency in practical applications (Gulkowski, Zdyb and Dragan, 2019; Syahputra *et al.*, 2019). The complete research workflow is summarized in the flowchart shown in Figure 1, which outlines the sequential stages from site selection to system testing, data processing, and conclusion.

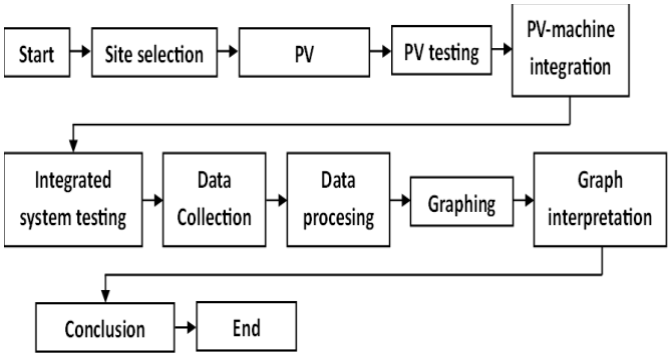


Figure 1. Research workflow

The research method includes system design based on the energy requirements of the production machine, installation and field testing of the system, as well as data analysis to assess energy conversion efficiency and operational stability. All procedures were carried out systematically to obtain a comprehensive understanding of the PV system's capability to supply stable and sustainable electricity for liquid palm sugar production at the micro, small, and medium enterprise (MSME) scale. To ensure a clear evaluation of system performance, this study focuses on several key performance indicators observed directly during on-site testing. These include: (1) the real-time PV output during operation, (2) the actual load profile of the production machine, (3) the alignment between PV power and load demand (PV–load matching), and (4) the observed battery capacity (state of charge,

SoC) throughout the production process. These indicators were assessed entirely through direct experimental measurements without additional energy calculations, providing an accurate representation of system behaviour under real operating conditions.

2.1. Research Location

This research was conducted at the Renewable Energy Laboratory, Faculty of Engineering, Universitas Sultan Ageng Tirtayasa (UNTIRTA), located in Cilegon City, Banten Province, Indonesia (coordinates: 5.9964° S and 106.0304° E, at an altitude of approximately 279 m above sea level). The research location is shown Figure 2.



Figure 2. Research location

The daily solar radiation data at this site were obtained from the Open-Meteo platform, which provides meteorological data based on numerical and reanalysis models with real-time updates. These data were used to analyze the solar irradiance profile variations throughout the study period. The solar radiation and temperature profiles obtained from Open-Meteo are presented in Figure 3.

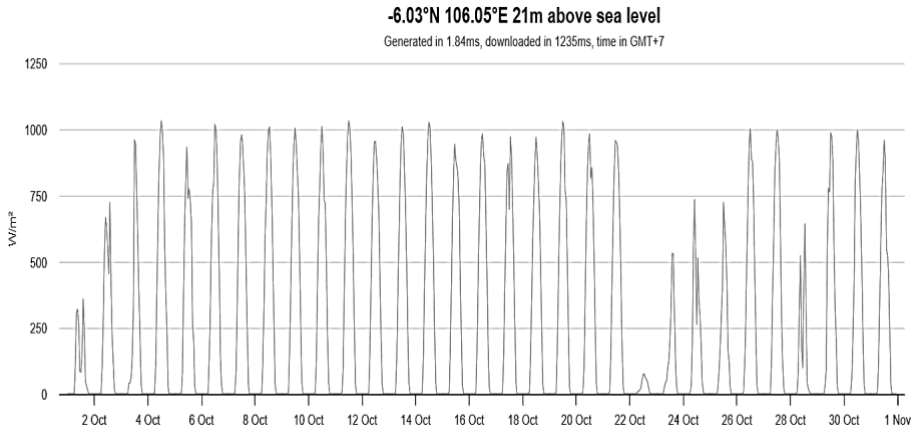


Figure 3. Daily irradiance profile at the research site based on Open-Meteo data.

The graph shows the solar irradiance (W/m²) measured at a place with a latitude of −6.03° and a longitude of 106.05° East, about 21 meters above sea level, from October 2 to October 31. The vertical axis denotes solar radiation intensity measured in watts per square meter (W/m²), whilst the horizontal axis illustrates the chronology throughout the month of October.

A distinct daily cycle pattern is evident for most of the month. Solar irradiation increases significantly in the morning, attains a zenith about midday, and thereafter diminishes in the evening, becoming zero at night. Peak values often reach or somewhat surpass 1000 W/m², signifying intense sun radiation characteristic of tropical areas. This consistent sinusoidal pattern indicates primarily clear-sky conditions for several days in early and mid-October.

From around 3 October to 21 October, the peaks exhibit constant height and form, indicating steady air conditions with negligible cloud interference. Nevertheless, between 22 and 26 October, the graph exhibits significant anomalies and diminished peak intensities. Multiple days have reduced maximum values and irregular curves, signifying the influence of cloud cover, precipitation, or air disturbances that restricted incoming solar energy.

At the conclusion of the month, beginning around 27 October, irradiance maxima rise to over 1000 W/m², indicating enhanced weather conditions and clearer sky. The consistent occurrence of zero irradiance at night validates the natural diurnal sun cycle.

The graph indicates a robust and consistently steady solar energy potential across the month, with only minor disruptions likely attributable to weather fluctuations. This pattern signifies advantageous circumstances for solar energy use, since the site constantly gets elevated quantities of solar radiation during daylight, especially at noon.

This information served as the basis for determining the optimal operating time of the solar power system and for evaluating the stability of the energy output during the palm sugar liquid production process (Perez *et al.*, 2002; Huld and Amillo, 2015).

2.2. Tools and Materials

The tools and materials used in this study consist of components of the solar photovoltaic (PV) power system and the liquid palm sugar production machine that serves as the experimental object. Each device has specific functions and technical characteristics that support the energy conversion process and system performance measurement throughout the experimental activities. The complete details of the tools and materials used are:

1). Solar Module (Solar Panel).

This research utilizes two units of LONGI Hi-MO X6 LR5-72HTH-565M solar modules. These monocrystalline panels have a peak power capacity of 565 Wp each, with a maximum power voltage (Vmp) of approximately 42.2 V and a maximum power current (Imp) of approximately 13.4 A. The solar modules function as the primary energy source, converting solar radiation into direct current (DC) electrical energy, the solar module shown in Figure 4.



Figure 4. Solar module (solar panel)

2). Integrated Inverter and Battery (ESS Unit).
The energy conversion system uses a Zamdon ESS-Li 222H unit, which consists of a 2.2 kW inverter integrated with a $LiFePO_4$ battery rated at 25.6 VDC with a capacity of 100 Ah. The inverter converts DC power from the panels or battery into alternating current (AC) required by the production machine, while the battery serves as an energy storage unit to ensure continuous power supply, the unit inverter shown in Figure 5.



Figure 5. Integrated inverter and battery

3). Liquid Palm Sugar Production Machine.
The production machine comprises a 500 W electric heating element and a 500 W vacuum evaporator pump, providing a total power requirement of approximately 1000 W. This machine is used to heat and evaporate palm sap to produce liquid palm sugar. The machine is equipped with an integrated digital control module for monitoring operational parameters, the machine shown in Figure 6.



Figure 6. Liquid palm sugar production machine

4). PV Cable.
A 10-meter photovoltaic cable is used to connect the solar panels to the inverter system. The cable is designed to safely carry DC current and minimize power losses during transmission.

5). Measurement Equipment.
Measurements of electrical power, voltage, current, and temperature are performed using the built-in digital control system installed on the production machine. This integrated unit enables accurate and automatic recording of operational data during testing.

2.3. Data Collection Technique

Data collection in this study was carried out through direct observation of the solar photovoltaic system and the liquid palm sugar production machine during operation. The electrical parameters generated by the PV system — including voltage, current, and battery capacity — were recorded directly from the inverter display at predetermined time intervals (Iksan, Purwanto and Sutanto, 2024). These real-time measurements reflect the actual performance of the PV system under varying solar radiation conditions (Figure 7).



Figure 7. PV data collected

Meanwhile, the electrical power consumption of the heating element and the vacuum evaporator pump was obtained from the digital control system integrated into the palm sugar production machine (Figure 8). This control unit displays operational parameters such as power demand, temperature, and process status during the heating and evaporation stages (Kamil, Arifin and Dewi, 2024). The recorded data include the instantaneous power requirements of each component and their variations throughout the production cycle.



Figure 8. Power consumption data collected

All measured parameters were documented systematically to evaluate the stability of power supply, energy demand characteristics, and the compatibility of the PV system with the operational needs of the production machine. The collected data serve as the basis for calculating system efficiency, energy consumption patterns, and overall performance analysis.

3. RESULTS AND DISCUSSION

The photovoltaic (PV) output recorded on 11, 12, and 25 October 2025 (Figure 9) reflects the variability of solar irradiance across different weather conditions. These variations align with

established findings that irradiance fluctuations directly affect PV power generation (Khatib, Mohamed and Sopian, 2013; Shahsavari and Akbari, 2018). A more detailed relationship between GHI and PV output for each test day is shown in Figure 10, demonstrating the strong correspondence between irradiance peaks and instantaneous PV power.

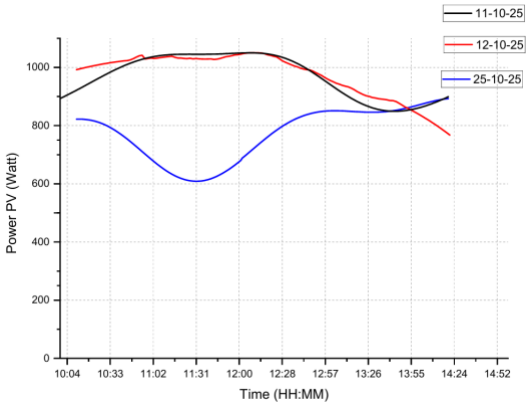
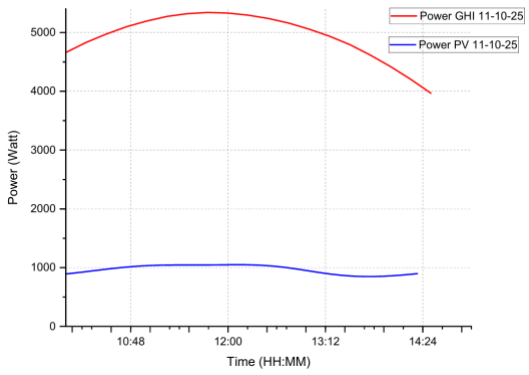
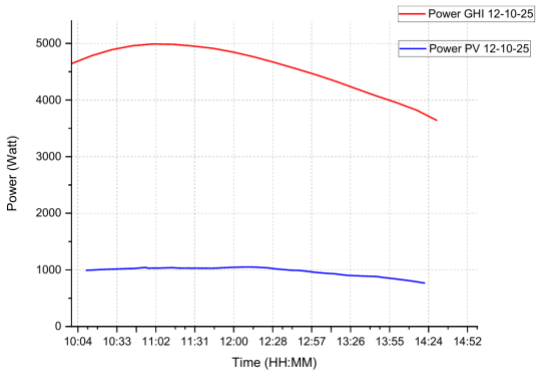


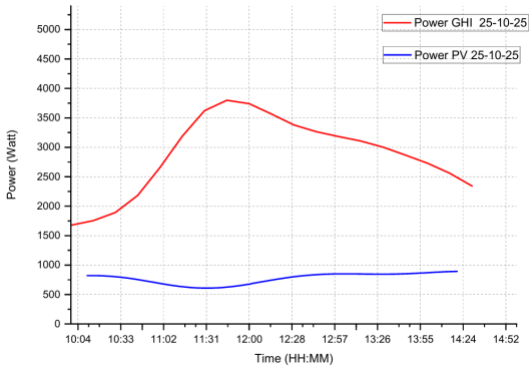
Figure 9. Photovoltaic output power on 11, 12, and 25 October 2025



(a). 11 October 2025



(b). 12 October 2025



(c). 13 October 2025

Figure 10. Comparison of GHI power and PV power output

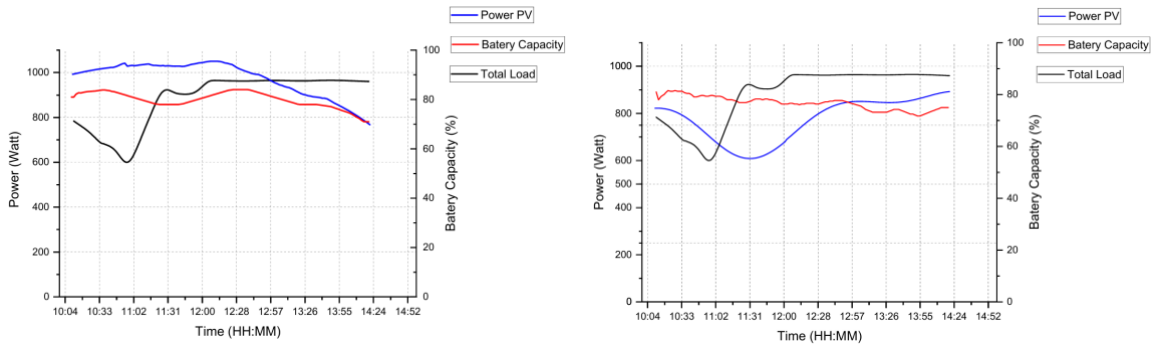
On 11 October, the solar panel output increased steadily from around 900 W in the morning and reached its peak at more than 1000 W between 11:00 and 13:00. This smooth pattern indicates clear-sky conditions, allowing the PV module to operate near its optimal efficiency (Shahsavari and Akbari, 2018). A similar condition was also observed on 12 October, although slight fluctuations at

the power peak indicates the presence of thin clouds. Despite the minor variations, the output remained relatively high—above 900 W—showing that the irradiance intermittency did not last long.

In contrast, the output power on 25 October exhibited a significant decrease to around 600 W at midday before increasing again later in the afternoon. This reduction indicates the presence of thick cloud cover or other weather disturbances that reduced the incoming solar radiation. Similar phenomena have been reported in previous research, which states that cloudy conditions can reduce PV power output by up to 40% from normal levels (Wang *et al.*, 2017).

The graphs in Figure 10. demonstrate a direct relationship between GHI and PV power output, where an increase in solar irradiance results in higher PV energy generation. Weather variations have a significant impact on PV performance, particularly on 25 October, which shows a substantial decrease in output due to cloud cover. These findings highlight the importance of integrating energy management systems and IoT-based monitoring to ensure reliable operation in rural home-industry applications for liquid palm sugar production (Khatib, Mohamed and Sopian, 2013).

The photovoltaic (PV) power output, battery capacity, and total load recorded during liquid palm sugar processing between 10:00 and 15:00 local time. Overall, the integrated solar energy system demonstrated stable performance in supplying the energy demand of rural home-industry operations.



(a). Clear weather (b). Cloudy weather

Figure 11. System performance profile during palm sugar processing

During clear-sky periods (Figure 11a), PV output consistently reached 950–1050 W, which matches the machine's operational demand of 600–1000 W. This indicates that the installed PV capacity is well-sized for the production process, as supported by solar engineering performance theory (Duffie and Beckman, 2013). The battery state of charge (SoC) remained within 80–85%, showing that PV power was not only sufficient to supply the load but also to maintain battery reserves. Similar system adequacy under clear irradiance has been reported in rural PV implementations (Winati *et al.*, 2023).

Under cloudy conditions (Figure 11b), PV output temporarily decreased to 600–800 W, reflecting a 20–40% reduction typical of cloud-related irradiance drops in tropical climates (Wang *et al.*, 2017). Even with this reduction, the system continued operating normally because the battery compensated for the shortfall, preventing any disruption of the production stages. The lowest observed SoC (71–75%) shows that the battery never approached a critical depletion level, consistent with best practices for off-grid energy reliability (Bhattacharyya, 2012).

The daily energy balance further confirms system sufficiency. On the representative test day, the PV system generated 4,2–4,6 kWh, while total load consumption was 3,2–3,6 kWh, resulting in an energy surplus of 0,6–1,4 kWh. This surplus provides a safety margin for short-term irradiance fluctuations or load spikes. Maintaining such a margin is recommended for stable PV system operation under intermittency (Khatib, Mohamed and Sopian, 2013).

The interaction between PV generation and battery storage throughout the measurement period (Figure 11) reveals the system's dependence on the battery. During clear irradiance, battery discharge remained low, indicating that the PV array directly supplied most of the load. In cloudy intervals, battery contribution increased, stabilizing the overall power supply. Importantly, the battery's minimum SoC remained relatively high, indicating low operational stress and good long-term durability for rural microgrid applications (Iksan, Purwanto and Sutanto, 2024).

To support the analytical discussion above, the key performance parameters of the PV–battery system during the representative test day are summarized in Table 1. The performance of a photovoltaic (PV) system during one representative test day, highlighting key operational parameters and their measured ranges. The total PV energy generated varies between 4.2 and 4.6 kWh, indicating stable solar production under typical daily conditions. This energy output exceeds the total load energy consumption, which ranges from 3.2 to 3.6 kWh. The surplus generation suggests that the system can meet daily demand while also maintaining battery reserves.

The minimum battery state of charge (SoC) remains relatively high, between 71% and 75%, demonstrating that the battery is not deeply discharged during operation. This reflects good energy balance and contributes to longer battery lifespan and improved system reliability.

Peak PV output depends significantly on weather conditions. Under clear skies, the system reaches 950–1050 W, close to its maximum potential. However, during cloudy conditions, peak output decreases to 600–800 W, showing the impact of reduced solar irradiance. Meanwhile, the typical load range is 600–1000 W, which aligns well with the PV production profile during peak sunlight hours.

Table 1. Summary of PV system performance during one representative test day

No	Parameter	Value (Representative Day)
1.	Total PV energy generated (kWh)	4,2–4,6 kWh
2.	Total load energy consumption (kWh)	3,2–3,6 kWh
3.	Minimum battery state of charge (SoC)	71–75%
4.	Peak PV output (W)	950–1050 W (clear), 600–800 W (cloudy)
5.	Typical load range (W)	600–1000 W

Compared with other PV-based agro-processing and rural MSME systems reported in the literature, the performance of the system in this study demonstrates a relatively strong operational margin. For example, Asbanu et al., implemented a PV system for a coconut grating machine with a lower load capacity and without integrated battery storage, resulting in limited operation during cloudy conditions (Asbanu *et al.*, 2025). Similarly, Winati et al., reported that MSME-scale PV applications often operate with minimal energy reserves due to undersized PV arrays (Winati *et al.*, 2023). In contrast, the PV–battery configuration used in the present study provides a higher degree of reliability, as reflected by the daily energy surplus (0,6–1,4 kWh) and the consistently safe minimum

SoC (71–75%). These results indicate that the system demonstrates greater resilience against irradiance fluctuations compared with many small-scale PV systems deployed in rural agro-processing contexts and thus is more suitable for continuous production workflows.

Overall, the integrated PV–battery configuration demonstrates sufficient capacity, operational robustness, and resilience for liquid palm sugar production. The system consistently met daily energy demands, maintained adequate reserves, and handled weather-induced fluctuations effectively. These results reinforce the feasibility of solar-powered agro-processing systems for rural MSME environments in Indonesia, supporting earlier findings on decentralized solar energy solutions (Asbanu *et al.*, 2025; Sulistiyono, Rifai and Sudiar, 2025).

4. CONCLUSION

This study demonstrated that the photovoltaic (PV)–battery system could deliver stable and continuous power for liquid palm sugar production under both clear and cloudy conditions. The PV array consistently supplied the machine's operational demand of 600–1000 W, while the battery maintained a safe state of charge throughout the entire processing period, ensuring uninterrupted operation. The daily energy surplus further indicates that the installed configuration provides sufficient operational margin to support rural MSME production activities.

However, these findings are limited by the short testing period, the single geographical location, and the specific weather conditions during the measurement days. Broader evaluations across different seasons, regions, and production scales would provide a more comprehensive understanding of long-term system performance.

Overall, the results confirm that the proposed PV–battery configuration is technically feasible, operationally robust, and suitable for MSME-scale liquid palm sugar processing. These findings indicate that this system can serve as a practical reference design for rural palm sugar enterprises, particularly in areas with unreliable grid electricity.

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