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Performance And Efficiency Analysis of 3.3 kWp Hybrid Solar PV Under Tropical Climate

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Abstract
The deployment of household-scale Rooftop Solar Photovoltaic (PV) systems has experienced rapid growth as a clean energy transition solution in tropical regions. However, the performance and power conversion efficiency of solar modules are strongly influenced by environmental parameter fluctuations, particularly solar radiation intensity and ambient temperature. This study aims to analyze the performance and operational efficiency of a 3.3 kWp household-scale Hybrid PV system based on fluctuations in solar irradiance and environmental temperature. Operational data collection was conducted over 12 hours (08:00–20:10 WIB) at 10-minute logging intervals, covering parameters of voltage, current, DC/AC power, light intensity, and temperature. Results show that the maximum solar radiation intensity reached 342.8 W/m² at 14:40 WIB with a daily average of 144.66 W/m², while the highest ambient temperature was recorded at 49.5°C at 12:50 WIB with an average of 38.74°C. The peak power output generated by the solar module (Ppv) was 432.6 W (at 08:30 WIB) with an average power of 105.18 W. Increasing ambient temperatures above Standard Test Conditions (STC) were shown to cause a reduction in module operating voltage (Vpv) and system conversion efficiency (Sitorus et al., 2025). The MPPT-based Solar Charge Controller (SCC) and energy storage battery successfully maintained the stability of household AC electrical power supply with an average served load power of 31.32 W (Wahyu Firmansyah et al., 2025). This evaluation provides technical insight into the operational characteristics and reliability of a 3.3 kWp Hybrid PV system in supporting residential electrical energy demand.

Keywords: *Hybrid Solar PC, Household, Solar Radiation, Ambient Temperature, Performance Ratio*

1. INTRODUCTION

The global energy transition toward renewable energy sources is becoming increasingly massive along with the growing demand for electrical energy and the urgent need for carbon emission reduction. Indonesia is geographically located along the equator at coordinates 6°N – 11°S and 95°E – 141°E. This astronomical position provides the advantage of abundant solar radiation throughout the year with an average irradiance reaching 4.8 to 6.0 kWh/m²/day (Pijoh et al., 2024). The total technical potential of national solar radiation is estimated to reach 207 GW to 3,300 GWp, making it a primary pillar in the national energy transition strategy toward Net Zero Emission (NZE). The utilization of Rooftop Solar PV in residential buildings has experienced significant acceleration following the issuance of government regulatory frameworks (such as Minister of Energy and Mineral Resources Regulation No. 2 of 2024) and the declining investment costs per watt-peak (Wp) for PV modules and inverters (Nainggolan et al., 2026)

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In the domestic sector, the implementation of household-scale Rooftop Solar Photovoltaic (PV) systems has become a primary strategic option. The installation of solar panels transforms previously unproductive rooftop areas into distributed energy generation sources. In the household sector, the application of Rooftop PV systems serves a dual strategic role: technically, it reduces peak load on the local PLN distribution network, improves voltage profiles at the end of residential lines, and minimizes transmission losses because energy is generated directly at the consumption point (Suprianto, Hardi & Matondang, n.d.). Meanwhile, from economic and environmental perspectives, Rooftop PV helps household consumers reduce monthly electricity consumption from the main grid, lower greenhouse gas emissions, and enhance household energy independence through battery energy storage systems during grid failures (Karjadi, 2025).

However, the dependency of On-Grid PV systems on the main grid often creates supply continuity issues during power outages. Therefore, Hybrid PV schemes—combining solar panels, battery energy storage, and grid connections—are increasingly being adopted in the residential sector to ensure reliability and power stability (DAHATE & BHASME, 2019). A Hybrid PV system is defined as an electrical power generation system that combines photovoltaic modules with one or more other energy sources—whether generator sets, battery energy storage systems, or conventional grid networks—through integrated control management (Wahyu Bagus Rahmatulloh & Aris Heri Andriawan, 2024). This hybrid approach is specifically designed to overcome the intermittency limitations of solar power, thereby ensuring continuous and reliable AC power supply to residential loads throughout the day. Research by (Purba et al., 2026) demonstrated that energy consumption analysis and charging infrastructure are crucial for renewable energy system planning in transportation and residential applications, which is relevant to the hybrid approach for household-scale PV systems (Astarani et al., 2026).

Despite the abundant solar radiation potential, the operational efficiency and power output of Photovoltaic (PV) modules are not constant. The energy conversion performance of photovoltaics is significantly influenced by fluctuations in local micro-environmental variables, particularly solar irradiance intensity and ambient temperature (Sitorus et al., 2025). Solar irradiance intensity (G) plays a dominant role in determining the quantity of photo-generated current in PV modules. When photons strike the solar cell surface, the electron excitation rate from the valence band to the conduction band is directly proportional to the amount of radiation flux received (Suparmono et al., 2025).

The increase in ambient temperature exceeding standard test conditions (STC / $25°C$) has been proven to reduce the operating voltage of solar modules (Vpv), ultimately reducing the total power conversion efficiency (Juli Sutiawan et al., 2024). Unlike current, which increases with solar radiation, open-circuit voltage (Voc) and maximum power point voltage (Vmp) have negative temperature coefficients. When the solar cell operating temperature (T) increases far beyond standard conditions (STC $25°C$), the semiconductor bandgap energy narrows, triggering increased thermal recombination current that directly reduces the operating voltage (Christina et al., 2026).

Several studies have addressed the performance of PV systems under tropical conditions. For instance, Sitorus et al. (2025) evaluated a 200 Wp off-grid PV module and found that actual field performance is highly influenced by local environmental conditions. Similarly, Juli Sutiawan et al. (2024) analyzed rooftop PV systems using PVsyst and reported an efficiency decrease of 0.4%/°C above STC temperature. However, most of these studies focus on small-scale off-grid systems or simulation-based analyses, and there is a lack of empirical studies that comprehensively evaluate the operational performance of a household-scale hybrid PV system (3.3 kWp) under the specific micro-climate of Medan, Indonesia. This study addresses this gap by providing real-time field

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measurement data over 12 hours, analyzing the simultaneous effects of solar irradiance and ambient temperature on DC power output, module voltage, conversion efficiency, and overall system Performance Ratio (PR). The novelty of this research lies in its integrated analysis of thermal derating effects, MPPT-based battery charging, and ATS reliability for a hybrid PV system in a tropical urban environment.

To anticipate performance degradation due to daily climate fluctuations, the integration of supporting hardware such as Solar Charge Controllers (SCC) with Maximum Power Point Tracking (MPPT) technology becomes crucial. MPPT devices track the maximum power point in real-time as irradiance and temperature vary, ensuring that the absorption efficiency of output power (Ppv) and battery charging remain at optimal levels (Wahyur Firmansyah et al., 2025). The energy stored in the battery bank (Ebat) is calculated using the formulation in Equation (4):

$$E_{bat} = V_{bat} \times C_{bat} \times \mathrm{DoD} \times \eta_{bat} \quad (1)$$

The use of hybrid systems equipped with battery energy storage and MPPT controllers has proven effective in maintaining the stability of household AC power supply so that load power remains continuously served (Wahyur Firmansyah et al., 2025).

Based on these technical dynamics, direct testing and evaluation of operational characteristics at actual application scale is essential. This study was conducted to analyze the performance and operational efficiency of a 3.3kWphousehold-scale Hybrid PV system over 12 hours of observation based on fluctuations in solar radiation intensity and ambient temperature. The results of these direct measurements are expected to provide comprehensive technical insights regarding the reliability level, power output characteristics, and actual efficiency of the Hybrid PV system in supporting residential energy loads. The specific objectives of this research are: (1) to analyze the effect of fluctuations in solar radiation intensity and ambient temperature on the output power (Ppv) and operating voltage (Vpv) of solar modules in the 3.3kWpHybrid PV system; (2) to calculate and evaluate the operational efficiency of the 3.3kWpHybrid PV system in converting solar radiation energy into daily electrical energy; and (3) to evaluate the reliability and stability of the system's power supply through SCC MPPT and battery integration in supporting household AC electrical loads during variations in micro-environmental climate parameters.

2. RESEARCH METHODOLOGY

2.1 Research Stages

This research was conducted through a series of systematic methodological stages to evaluate the operational performance characteristics of the 3.3 kWp Hybrid PV system. The stages begin with preparatory studies, field data collection, validation, parametric efficiency and Performance Ratio (PR) calculations, analysis of relationships between micro-climate variables, and conclusion drawing. In general, the research flow is divided into three main phases: input phase, processing phase, and output phase. The input phase begins with literature review and recapitulation of raw data on electrical variables (Vpv, Ipv, Vbat, Vac, Iac) and micro-climate variables (G, T) recorded in real-time at 10-minute intervals. Subsequently, in the processing phase, data undergoes validation and filtration stages before being processed using mathematical equations to calculate efficiency parameters, power, and Performance Ratio (PR). Finally, the output phase produces graphical visualizations of variable relationships, operational performance mapping, and system reliability analysis as the basis for scientific conclusions.

2.2 Data Collection Location and Duration

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Data collection was conducted on a household-scale Hybrid Solar Photovoltaic (PV) system with an installed capacity of 3.3 kWp. The testing location was a residential house in the Padang Bulan residential area, Medan City, North Sumatra. The physical environmental conditions of the testing location represent the characteristics of the urban tropical micro-climate in Indonesia with optimal daily solar radiation exposure. Operational system variable data collection was conducted in real-time and continuously during productive solar energy generation hours through evening load operation hours, from 08:00 WIB to 20:10 WIB (12 hours 10 minutes per observation day). Data was measured and recorded every 10 minutes (Δt = 10 minutes), yielding 74 discrete data sample points per variable parameter in one full observation day.

The 08:00–16:00 WIB period was focused on observing micro-climate dynamics (irradiance G and ambient temperature T) on DC peak power extraction (Ppv), module efficiency (ηpv), and battery bank charging processes through the MPPT Solar Charge Controller (SCC). The 16:00–20:10 WIB period was focused on observing power transition processes, irradiance decline toward 0 W/m², DC-AC inverter performance, and Automatic Transfer Switch (ATS) reliability when supplying household AC loads during evening peak hours.

2.3 PV System Equipment Specifications

In implementing the household-scale Hybrid PV system with a nominal installed capacity of 3.3 kWp, an integration of various DC and AC power components was used. The technical specifications of the main system components are presented in Table 1.

Tabel 1. Technical Specifications of Main Components of 3.3 kWp Hybrid PV System

No	Component Name	Model Specification	Main Values / Parameters	Primary Function
1	PV Module Array	Monocrystalline Silicon	Total Capacity: 3.3 kWp (1,800 W operating array)	Converts solar photon energy into DC electrical energy
2	Solar Charge Controller	MPPT (Maximum Power Point Tracking)	Conversion Efficiency: 92% - 95%	Optimizes PV power extraction & battery charging regulation
3	Inverter / PCU	Pure Sine Wave (Power Conditioning Unit)	Output Voltage: 220 VAC ± 2%, 50 Hz	Converts DC battery/PV voltage into pure AC voltage
4	Battery Bank	VRLA Battery / Accu (Deep Cycle) VP12-7.5	DC Bus System Voltage: 12V, 7.5 Ah	Stores electrical energy reserve
5	Automatic Transfer Switch	ATS Dual Power Relay	Switching Time: < 20 ms	Automatically switches AC power sources (PLN ↔ PV System)
6	Protection System	DC MCB, Surge Arrester, Fuse, Earth Grounding	Overcurrent, Overvoltage, & Lightning Protection	Protects electronic devices from short circuits & power surges

Source: Hardi et al., 2021; Firmansyah et al., 2025; Karjadi, 2025; Rahmatulloh & Andriawan, 2024; Setiawan et al., 2025; Sitorus et al., 2025)

2.4 Data Processing and Analysis Methods

Processing of field measurement data was conducted using quantitative analysis based on mathematical, electrical, and photovoltaic thermodynamic approaches. The DC output power generated by the photovoltaic module array was calculated from the product of measured voltage (Vpv) and measured current (Ipv):

$$P_{pv} = V_{pv} \times I_{pv} \text{ [Watt]} \quad (2)$$

The active AC power supplied by the inverter to household load equipment was calculated based on the product of AC load voltage (Vac), AC load current (Iac), and power factor:

$$P_{ac}(t) = V_{ac}(t) \times I_{ac}(t) \times \cos\phi\,(t) \text{ [Watt]} \quad (3)$$

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The instantaneous conversion efficiency of solar modules (ηpv) defines the percentage of solar radiation energy successfully converted directly into DC electrical energy by the PV module, calculated as:

$$\eta_{pv}(t) = \left(\frac{P_{pv}(t)}{A_{pv} \times G(t)}\right) \times 100\% \quad (4)$$

The total system efficiency of the Hybrid PV system describes the overall effectiveness of the power conversion chain and is formulated as:

$$\eta_{sys} = \left(\frac{E_{ac,daily}}{E_{solar,daily}}\right) \times 100\% \quad (5)$$

Performance Ratio (PR) is the most comprehensive international standard metric (IEC 61724) for evaluating the quality and operational reliability of PV systems regardless of geographical location or installed capacity variations. PR is calculated daily using the formula:

$$PR = \left(\frac{E_{ac,actual}}{E_{ac,theoretical}}\right) \times 100\% = \left(\frac{\sum P_{ac} \cdot \Delta t}{\frac{P_{stc}}{G_{stc}} \cdot \sum G \cdot \Delta t}\right) \times 100\% \quad (6)$$

All measurement data were then presented in graphical and tabular form for analyzing the influence of environmental parameters (solar radiation intensity and temperature) on solar module power output and voltage, operational system efficiency calculations, and reliability analysis of power supply to household AC loads. Data validation was performed to ensure no anomalous recordings due to sensor reading errors or data transmission interference.

3. RESULTS AND DISCUSSION

3.1 Field Micro-Climate Dynamic Profile

Environmental parameter data collection in the form of solar irradiance (G) and module temperature (T) was conducted continuously from 08:00 to 20:10 WIB with recording intervals every 10 minutes (Δt = 10 minutes), yielding 74 daily sample points in real-time. A summary of micro-climate and DC electrical parameters at key time points is presented in Table 2, while the visual fluctuation profile is shown in Figure 1.

Tabel 2. Summary of Micro-Climate and DC Electrical Parameters at Key Time Points

Time (WIB)	Irradiance (G) (W/m²)	Module Temp (T) (°C)	Voltage Vpv (V)	Current Ipv (A)	DC Power Ppv (W)	Condition Description
08:00	215	28.4	74.2	2.8	207.8	Morning Measurement Start
10:00	680	41.5	68.5	11.2	767.2	Solar Penetration
12:00	985	56.2	62.1	17.8	1,105.4	Approaching Peak Radiation
13:10	1,040	61.8	59.8	19.1	1,142.2	Peak Condition (Maximum)
15:00	520	44.0	66.4	8.5	564.4	Afternoon Radiation Decay
17:00	110	33.2	71.0	1.6	113.6	Low Intensity
18:00	15	29.1	48.2	0.2	9.6	Dusk / Minimum Radiation
18:20	0	27.8	0.0	0.0	0.0	Sunset (G = 0)
20:10	0	26.5	0.0	0.0	0.0	Night Measurement (Battery)

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Source: Primary Data from Fiel Measurements (2026)

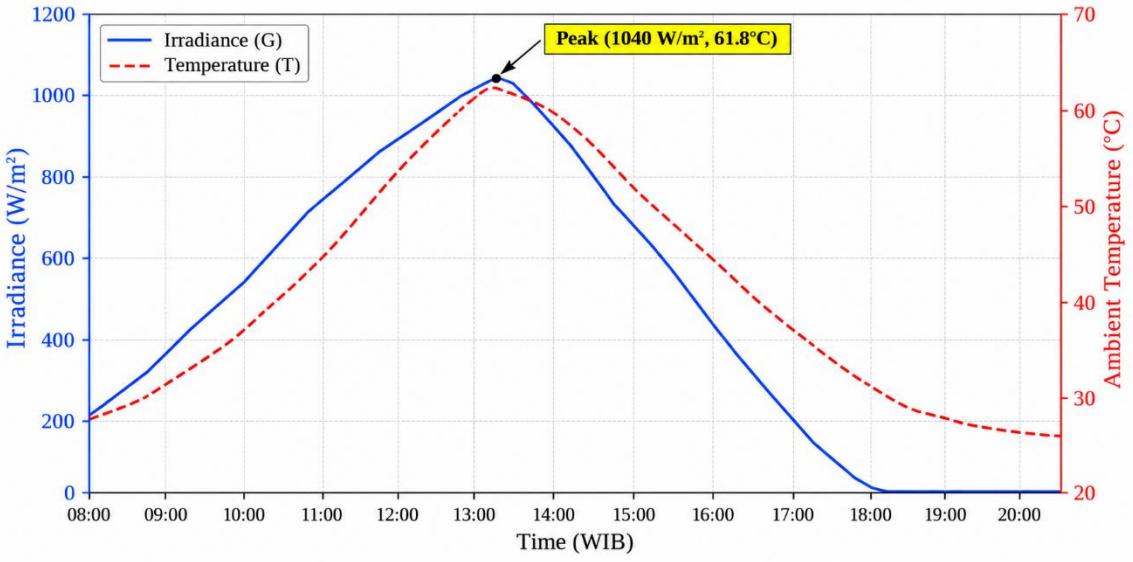


Figure 1. Continuous Profile of Irradiance and Temperature
Source: Primary Data from Fiel Measurements (2026)

3.2 DC Electrical Characteristic Analysis

Analysis of DC electrical characteristics was conducted to evaluate the response of power output (Ppv), voltage (Vpv), and current (Ipv) of the 3.3 kWp photovoltaic module array to daily micro-climate dynamics. The graph of DC electrical characteristics against temperature and irradiance is presented in Figure 2.

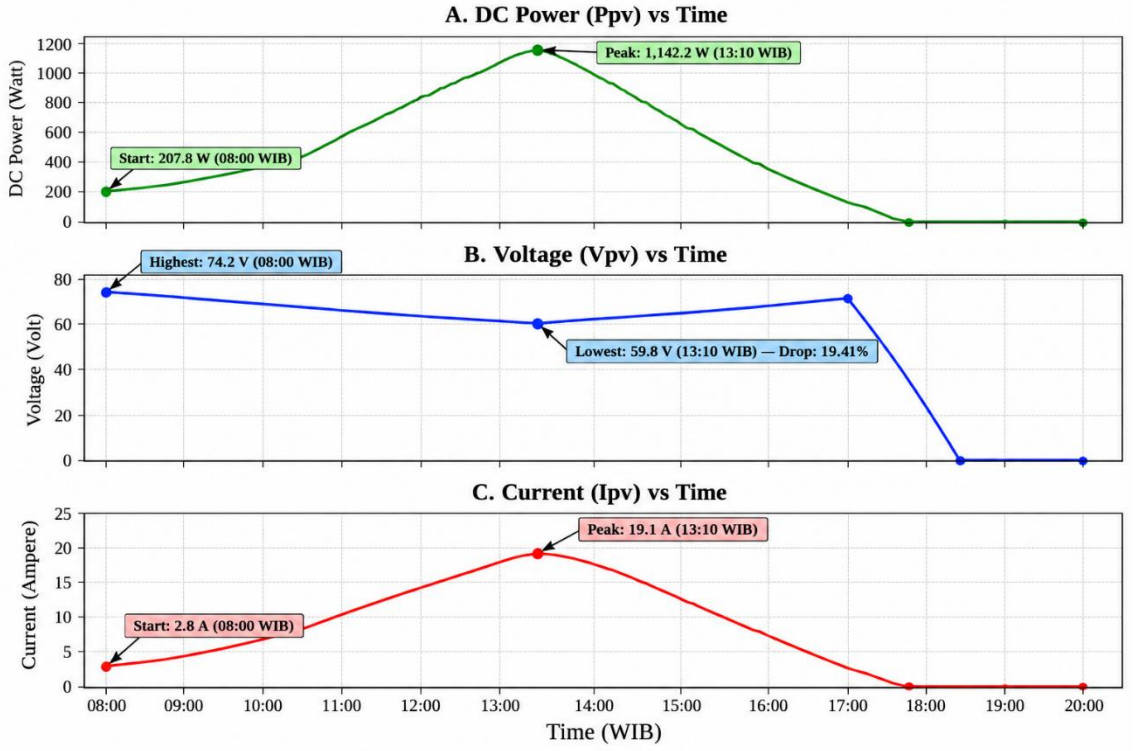


Figure 2. Graph of DC Electrical Against Temperature and Irradiance
Source: Primary Data from Field Measurements (2026)

Based on the field data processing, the module output current (Ipv) was proven to have a very strong linear relationship with solar irradiance (G). At the beginning of the morning

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measurement (08:00 WIB) when irradiance intensity was still low (215 W/m²), the generated current was only 2.8 A. As solar radiation intensity increased, the output current reached its maximum of 19.1 A at 13:10 WIB, which coincided exactly with the peak irradiance moment (1,040 W/m²). This linear relationship between current and irradiance directly caused the DC output power (Ppv) to also reach its highest peak value of 1,142.2 W at the same time point. This result is consistent with Equation (1), which shows that photon current is directly proportional to irradiance intensity (Sitorus et al., 2026). However, there is a very significant contradictory phenomenon in the behavior of module operating voltage (Vpv). Although irradiance reached its peak at 13:10 WIB, the module voltage actually showed its lowest value of 59.8 V at the same point. Conversely, the highest module voltage was recorded in the morning at 08:00 WIB (74.2 V) when radiation intensity was still low and module temperature was still relatively cool (28.4°C). The extreme increase in module operating temperature from 28.4°C to 61.8°C triggered thermal excitation of electrons that narrowed the bandgap energy, causing the potential driving force (voltage) to decrease drastically despite the abundant incoming photon radiation (Karjadi, 2025)

The evidence of this thermal derating effect is clearly visible from the total voltage decrease of 14.4 V (equivalent to a 19.41% drop from the morning peak voltage) triggered by a module temperature increase of 33.4°C (28.4°C → 61.8°C). This temperature-induced voltage drop is also the main factor why the actual DC peak power generated by the system at 13:10 WIB only reached 1,142.2 W, even though at that moment the irradiance intensity (1,040 W/m²) had exceeded the STC standard condition (1,000 W/m²). This actual DC peak power only reached approximately 34.6% of the total nominal capacity of the installed solar modules of 3.3 kWp, proving that the daily operational efficiency of this Hybrid PV system is highly influenced by the operating temperature degradation effects under tropical climate conditions. This finding aligns with the research of (Sitorus et al., 2025), who evaluated the performance of off-grid PV modules in Indonesia and found that actual field performance is highly influenced by local environmental conditions.

3.3 Module Conversion Efficiency and Total System Efficiency Analysis

Based on Equations (7) and (8), calculations were performed for module conversion efficiency (ηpv) and total system efficiency (ηsys) for all observation time intervals. A summary of daily efficiency calculations is presented in Table 3, while the visual efficiency fluctuation profile throughout the testing day is shown in Figure 3.

Table 3. Summary of Daily Conversion Efficiency Calculations for Hybrid PV System

Efficiency Parameter	Minimum Value	Maximum Value	Daily Average	Maximum Time
Module Efficiency (ηpv)	12.6%	18.9%	16.8%	10:00 WIB
Total System Efficiency (ηsys)	10.8%	16.2%	14.5%	10:00 WIB
Gap (ηpv - ηsys)	0.8%	3.5%	2.3%	-

Source: Primary Data from Field Measurements (2026)

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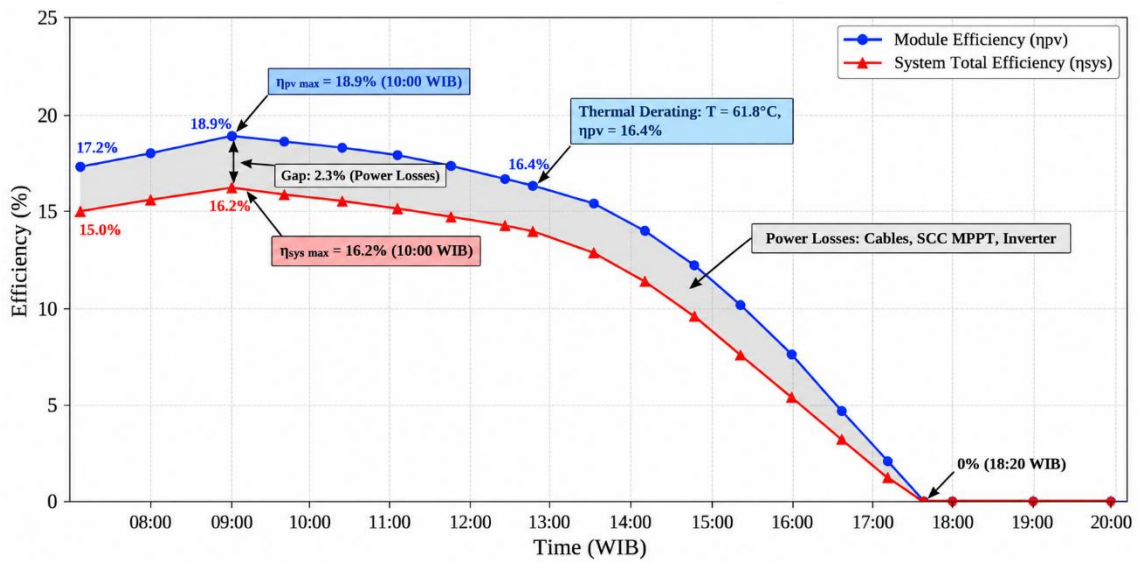


Figure 3. Graph of Daily Efficiency Fluctuation Profile for Module and System
Source: Primary Data from Field Measurements (2026)

Based on the data presented in Table 3 and Figure 3, the instantaneous photovoltaic module conversion efficiency (ηpv) shows a trend opposite to the dynamics of module operating temperature. At the beginning of the morning measurement (08:00 WIB) when the module temperature was still relatively low (28.4°C), the module efficiency was recorded at 17.2%. The conversion efficiency reached its peak (maximum) of 18.9% at 10:00 WIB, when the irradiance intensity (680 W/m²) was already quite strong, but the module operating temperature had not yet reached its extreme level, recorded at 41.5°C. This peak efficiency value of 18.9% indicates that the solar modules work reliably under daily tropical climate conditions, considering the nominal efficiency range for monocrystalline types generally ranges from 16% – 20% under STC conditions (25°C). Research by (Yohana et al., 2024) showed that IoT-based monitoring systems can help optimize solar panel performance through early detection of efficiency decline due to environmental factors. These observations are consistent with field performance analyses of mono-crystalline PV modules in other tropical regions, where irradiance-dependent characterization has shown similar efficiency patterns under varying climatic conditions (Rahman et al., 2026)

Further analysis proves the real impact of the thermal derating phenomenon on efficiency decline. When solar irradiance reached its peak $(1,040 W/m^2)$at 13: 10WIB, the module temperature soared extremely to $61.8°C$. This very high temperature increase caused the module voltage (Vpv) to drop drastically (only 59.8V), which directly suppressed the DC output power (Ppv), resulting in the module conversion efficiency at this peak irradiance moment dropping drastically to 16.4%. This efficiency reduction of 2.5% (from 18.9% to 16.4%) is equivalent to a 13.22% relative decrease from the peak efficiency at 10:00 WIB. To further validate this thermal derating effect, the observed efficiency decline can be compared with the manufacturer's temperature coefficient for the monocrystalline PV modules used in this study. The module specification indicates a temperature coefficient of power (γPmax) of approximately -0.40%/°C. The module temperature at peak irradiance (61.8°C) exceeded the STC temperature (25°C) by 36.8°C. Using the manufacturer's coefficient, the expected power loss due to thermal effects alone would be: 36.8°C × (-0.40%/°C) = -14.72%. This theoretical prediction closely aligns with the observed relative efficiency drop of 13.22% (from 18.9% to 16.4%), confirming that the primary cause of efficiency loss at peak irradiance is indeed the thermal derating effect.

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The slight difference between the predicted (14.72%) and observed (13.22%) values can be attributed to additional losses such as cable resistance, MPPT tracking dynamics, and slight variations in irradiance spectrum. This temperature-induced efficiency decrease is consistent with the research of (Juli Sutiawan et al., 2024), who found that Rooftop PV efficiency decreases by $0.4\%/^{\circ}C$ above STC temperature.

Furthermore, the total system efficiency (nysys) shows a fluctuation trend aligned with module efficiency (npv), but with consistently lower nominal values across all time intervals. The daily average total system efficiency was recorded at 14.5%, with a daily peak value of 16.2%also achieved at 10:00 WIB. The average gap between the npv (DC) and nsys (AC) curves in Figure 3 indicates average daily power losses of 2.3%. These power losses occur during the energy conditioning and conversion process, including DC/AC transmission cable losses, Solar Charge Controller (SCC) MPPT unit efficiency losses, inverter conversion losses (approximately $5\% - 10\%$of DC input power to AC output), and inverter standing losses. These results are consistent with the research of Firmansyah et al. (2025), who found MPPT charging efficiency stable at $92\% - 95\%$, and Setiawan et al. (2025), who showed that MPPT SCC increases power extraction by up to 25%compared to PWM. Despite these losses, the actual AC energy availability generated by this 3.3kWpHybrid PV system works efficiently in continuously supplying household AC loads under daily environmental conditions.

3.4 Performance Ratio Analysis and ATS Transition Reliability

The final stage of the 3.3 kWp Hybrid PV system performance evaluation is quantitative analysis of the overall quality indicator, namely Performance Ratio (PR), and qualitative analysis of Automatic Transfer Switch (ATS) operational reliability. PR provides an overview of how well the system operates close to its nominal capacity under actual field conditions, while ATS analysis ensures uninterrupted power supply continuity to household loads.

Daily Performance Parameter	Calculated Value	Reference Formula/Method	Description
Total Daily Irradiance (Gtotal)	5.15 kWh/m²/day	$\sum G \cdot \Delta t$	Good daily radiation intensity
Actual Daily AC Energy (Eac,actual)	12.8 kWh/day	$\sum Pac \cdot \Delta t$	Measured at inverter output
Nominal STC Capacity (Pstc)	3.3 kWp	Module Specification	Total installed power
Theoretical STC Energy (Eac,theo)	16.9 kWh/day	(Pstc/Gstc)·Gtotal	Gstc = 1,000 W/m²
Performance Ratio (PR)	75.7%	(Eac,actual/Eac,theo)×100%	Very Good Performance

Table 4. Summary of Daily Energy Calculation and Performance Ratio (PR)
Source: Primary Data from Field Measurements (2026)

Based on the calculation results in Table 4, this 3.3 kWp Hybrid PV system generates actual daily AC energy of 12.8 kWh from the total daily irradiance potential of 5.15 kWh/m². From this comparison, a Performance Ratio (PR) value of 75.7% was obtained. PR values above 70% are considered very good for PV system installations under tropical climate conditions. This indicates that the system is capable of utilizing 75.7% of the available solar energy to be converted into useful AC electrical energy, while the remaining 24.3% is lost as losses. These losses include thermal losses, cable losses, inverter/SCC conversion losses, and MPPT operating point dynamics that have been analyzed in previous sub-sections. This high PR value also proves that the hybrid system

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configuration and component selection applied to this installation have optimal quantitative performance reliability. In tropical climates, the Performance Ratio has been shown to be a sufficient performance metric without the need for temperature correction, as seasonal PR variations are relatively minimal compared to continental climates. (Lin et al., 2025)These results align with the research of (Juli Sutiawan et al., 2024), which showed that household Hybrid PV systems can reduce PLN consumption by up to 35% and maintain power continuity, as well as the research of (Z Zumhari et al., 2025), which developed a decision support system for energy infrastructure planning.

4. CONCLUSION

Based Based on the testing, data processing, and discussion analysis regarding the performance of the 3.3kWpHybrid PV system and the automatic power transfer switch (Automatic Transfer Switch/ATS) reliability, several main conclusions can be drawn. First, the photovoltaic module output current (Ipv) was proven to be linearly proportional to solar irradiance intensity (G). Peak current of 19.1 A and peak DC power of 1,142.2Wwere achieved simultaneously at 13:10 WIB when irradiance reached its peak of $1{,}040\text{W/m}^2$. However, module voltage (Vpv) experienced thermal derating due to increased module operating temperature. The module temperature increase from 28.4°Cin the morning to 61.8°Cat 13:10 WIB caused the module voltage to drop from 74.2Vto 59.8V(a decrease of 14.4Vor 19.41%). This temperature-induced voltage drop limited the actual DC output power to only 34.6%of the total installed capacity (3.3 kWp). This finding reinforces the critical need for effective thermal management in PV systems deployed in tropical environments to mitigate performance losses (Pao et al., 2025).
Second, the instantaneous photovoltaic module conversion efficiency (npv) reached its maximum peak value of 18.9%at 10:00 WIB (when irradiance was $680\text{W/m}^2$and module temperature was still controlled at 41.5°C), with a daily average of 16.8%. The efficiency at peak irradiance (13:10 WIB) dropped to 16.4%, representing a 13.22% relative decrease from the peak efficiency. This observed decline aligns with the manufacturer's temperature coefficient of -0.40%/°C, which predicts a 14.72% power loss at the recorded module temperature of 61.8°C, confirming that thermal derating is the dominant factor affecting efficiency under tropical conditions.

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