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Performance Analysis of Small-Scale Educational Solar Photovoltaic Modules Based on Irradiation Variations and Environmental Temperature in Cimahi City

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Abstract

This study aims to evaluate the operational characteristics of a 50 Wp polycrystalline photovoltaic (PV) module under actual environmental conditions as a basis for developing renewable energy practicum media. The research method was carried out through field testing in Cimahi City with parameters including solar irradiation, panel temperature, and electrical parameters (voltage, current, and power) recorded at five-minute intervals. The results of data analysis showed a strong correlation between irradiation intensity and output power, with a coefficient of determination (R2) of 0.93. The results showed that output power increased with increasing irradiation, while increasing panel temperature decreased output voltage. Panel efficiency was in the range of 9.2%-13.1%, lower than manufacturer specifications due to non-STC environmental conditions and system losses. Nevertheless, the PV module proved effective as a project-based learning medium that was able to provide students with a practical understanding of the influence of environmental factors on the performance of photovoltaic systems.

Keywords: energy; photovoltaic panels; panel efficiency; tropical climate; performance characterization; polycrystalline.

Abstrak

Penelitian ini bertujuan untuk mengevaluasi karakteristik operasional modul fotovoltaik (PV) polikristal 50 Wp pada kondisi lingkungan aktual sebagai dasar pengembangan media praktikum energi terbarukan. Metode penelitian dilakukan melalui pengujian lapangan di Kota Cimahi dengan parameter yang meliputi iradiasi matahari, suhu panel, serta parameter listrik (tegangan, arus, dan daya) yang direkam pada interval lima menit. Hasil analisis data menunjukkan adanya korelasi yang kuat antara intensitas iradiasi dan daya keluaran, dengan koefisien determinasi (R^2) sebesar 0,93. Hasil penelitian menunjukkan bahwa daya keluaran meningkat seiring dengan bertambahnya iradiasi, sedangkan kenaikan suhu panel menurunkan tegangan keluaran. Efisiensi

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panel berada pada rentang 9,2%–13,1%, lebih rendah dari spesifikasi pabrikan akibat kondisi lingkungan yang tidak sesuai dengan STC (Standard Test Conditions) serta adanya rugi-rugi sistem. Meskipun demikian, modul PV terbukti efektif sebagai media pembelajaran berbasis proyek yang mampu memberikan pemahaman praktis kepada mahasiswa mengenai pengaruh faktor lingkungan terhadap kinerja sistem fotovoltaik.

Kata Kunci: *energi; panel fotovoltaik; efisiensi panel; iklim tropis; karakterisasi kinerja; polikristalin.*

Introduction

The global transition toward renewable energy sources has become a strategic imperative for mitigating climate change and enhancing energy security (Akaev & Davydova, 2023; Bashir et al., 2025; Elkhatat & Al-Muhtaseb, 2024). Amid these challenges, photovoltaic (PV) technology has proven to be one of the most dynamic and cost-competitive solutions worldwide (Al-Addous et al., 2024; Rezaee & Silva, 2026). Tropical regions such as Indonesia possess substantial geographical advantages; data from the Ministry of Energy and Mineral Resources indicate that the average solar irradiation potential reaches approximately 4.8 kWh/m²/day (Samosir et al., 2024). This value highlights the critical role of PV systems as a cornerstone in achieving national energy mix targets and fulfilling Net Zero Emission commitments (Akaev & Davydova, 2023; Aleksandra et al., 2024; Almutairi et al., 2022; Aste et al., 2024; Noh et al., 2024; Shirinbakhsh & Harvey, 2024). Consequently, accelerating the deployment of PV technology requires comprehensive infrastructure support, not only in power plant construction but also in the development of competent human resources (Alhan, 2023; Rui & Yusof, 2024; Zhang, 2026).

The successful adoption of PV technology is highly dependent on the availability of skilled personnel with precise technical competencies (Amalu et al., 2023; Khatib et al., 2025). In engineering education, laboratory instruments serve as a crucial bridge between thermodynamic theory and electrical applications. Educational-scale PV laboratory modules are not merely demonstrative tools; rather, they function as measurement systems that must accurately represent physical phenomena, including the acquisition of solar irradiance, panel temperature, and electrical parameters. The accuracy of these modules in responding to environmental dynamics is essential for shaping the analytical mindset of future renewable energy technicians.

Although extensive research has been conducted on large-scale PV optimization (Song et al., 2023; Wang et al., 2024; Xiao et al., 2024; Zidane et al., 2023), the literature addressing the performance characterization of small-scale PV modules operating under outdoor conditions remains limited. Most educational devices rely solely on Standard Test Conditions (STC) specifications, even though humid tropical climate variability significantly influences efficiency degradation (Makhija & Bohra, 2023; Mohamad Radzi et al., 2025; Rahman, 2022). There is a pressing academic need, particularly in educational contexts, to validate adequate sensitivity and accuracy in capturing the correlations between temperature and voltage, as well as between irradiance and power output. Inaccurate measurements may lead to fundamental technical misconceptions.

Based on these considerations, this study aims to analyze the operational performance of an educational PV laboratory module through empirical testing under varying levels of solar irradiance and ambient temperature. Unlike previous studies, this research emphasizes the validation of laboratory instrument performance under specific microclimatic conditions (case study: Cimahi, West Java, Indonesia). The scientific contribution of this work lies in providing validated performance characterization data for small-scale PV systems, which can serve as a technical reference for the development of more representative and accurate renewable energy laboratory equipment.

Methods

The research methodology was designed to obtain accurate empirical data on the performance of an educational PV panel module under real operational conditions. A field-based experimental

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quantitative approach was employed, focusing on direct measurements of the physical and electrical parameters of the PV system. The methodological framework comprises several stages, including a comprehensive literature review, experimental testing, data acquisition, and data analysis, as illustrated in Figure 1.

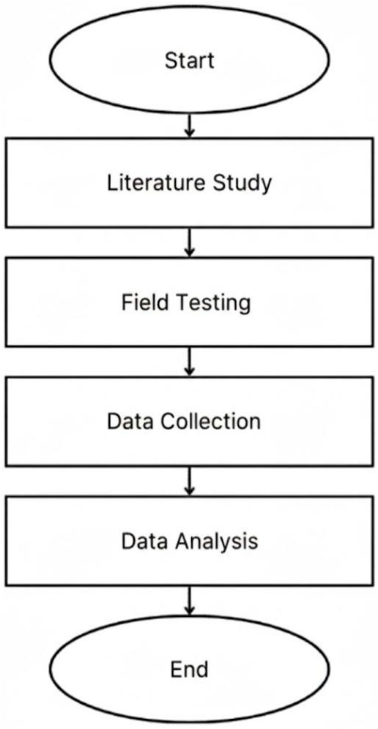

Figure 1. Stages of The Research Methodology.

The experimental testing was conducted in the Cimahi region, West Java, which was selected to represent a humid tropical microclimate characterized by dynamic fluctuations in solar irradiance. The system under investigation consisted of a 50 Wp PV module configured in an off-grid system. The measurement instruments included a solar power meter for irradiance measurement and a digital multimeter. The PV system configuration is summarized in Table 1.

Table 1. PV System Component Specifications

PV	Polycrystalline Model C-50-18-M (Pmax = 50 Wp; Vmp = 17.8V; Imp = 2,7 A; Voc = 21,8 V, A = 670 x 445 mm = 0,298 m^2)
Battery	Valve Regulated Lead Acid (VRLA) (12 V; 20 Ah)
Inverter	DC to AC (500 W, Output 220 V AC (Efficiency >85%))
Load	DC (3 x LED 12 V,20 W), AC (2 x Lamp 220 V,40 W) (Operation under DC and AC Loads)
SCC	Solar Charger Controller PWM (20 A, Input maks 50 V, Output 12 V)

Furthermore, the specifications of the instruments used to measure the PV parameters are summarized in Table 2.

Table 2. PV Parameter Measurement Instruments

Solar Power Meter	Lutron SPM-1116SD (Solar irradiance up to 2000 Wh/m^2) with ±5,0 % Accuracy)

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Temperature Meter	Fluke 59 Max (Temperature range (-30 °C to 350 °C) with ±2,0 % accuracy)
Multimeter	Sanwa CD800a (DCV, ACV, DCA and ACA accuracy ±(2.8%+5))

Before field testing, all measurement instruments were calibrated according to the manufacturers' standard procedures to ensure data accuracy and reliability. In calculating the efficiency (Equation 2), the effective panel area (A) used is 0.298 m^2. Data collection was conducted continuously at five-minute intervals for approximately 44 minutes (10:10-10:54) on a single test day. The limited duration of measurement is a constraint of this field study; thus, generalizing the findings for long-term or seasonal weather fluctuations needs to be explored further in future research.

During the data acquisition phase, the photovoltaic panel was operated under a combined configuration of DC and AC loads. Key system parameters were continuously monitored and recorded at consistent five-minute intervals. The primary data were directly measured using a solar power meter and a digital multimeter with an accuracy up to ±(2.8%+5). These measured parameters included solar irradiance (G) in W/m², panel temperature (T) in °C, voltage (V) in volts, and current (I) in amperes.

Following the data collection, two primary indicators were calculated to evaluate the overall performance of the PV module. First, the electrical output power (P_{out}) generated by the photovoltaic module was determined using the fundamental electrical relationship:

$$P_{out} = V \times I \tag{1}$$

where V represents the PV voltage and I denotes the PV current.

Second, the module's conversion efficiency (η) was calculated to assess its energy conversion performance under field operating conditions relative to the incident solar power. This efficiency was derived using the following formula:

$$\eta = \left(\frac{P_{out}}{G \times A}\right) \times 100\% \tag{2}$$

where G is the solar irradiance (W/m²) and A is the effective panel area (m²).

The collected data were analyzed to identify causal relationships between environmental variables (solar irradiance and temperature) and output variables (voltage, current, and power). The analysis focused on confirming fundamental PV principles, namely: (1) the positive linear relationship between irradiance and output power, and (2) the negative effect of increasing temperature on output voltage. Additionally, the average module efficiency was evaluated and compared with typical commercial PV panel specifications (15–18%) to assess the relevance of the module as an effective educational tool.

Results and Discussion

This section presents the results of the performance characterization of the PV module based on variations in environmental parameters at the test site. The acquired data provide insights into the electrical response of the system to fluctuations in solar irradiance and temperature under an educational-scale configuration. To provide a clear visualization of the field testing environment, Figure 2 illustrates the experimental setup configuration for the educational-scale PV module testing. Utilizing this physical arrangement, a comprehensive dataset was collected. The quantitative measurement results—encompassing solar irradiance, module temperature, and electrical power generation—are detailed in Table 2.

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Figure 2. Experimental Setup Configuration for The Educational-Scale PV Module Testing

Table 2. Measured Environmental and Electrical Parameters of The PV Module

Time (GMT+7)	Irradiance (W/m²)	Temp (°C)	PV Power (W)	Battery Power (W)	DC Load Power (W)	Load Configuration
10:10	835	35	27.54	2.43	0	Inverter
10:15	835	35	29.08	0	0	Inverter
10:20	836	35	30.02	0	8.16	Inverter
10:25	873	35	27.42	0	0	Inverter
10:30	874	35	30.35	0	0	Inverter
10:33	883	40	34.58	0	0	Inverter
10:36	890	42	3.48	0	0	Inverter
10:38	883	40	8.04	0	0	Inverter
10:40	905	45	6.07	0	0	Inverter
10:42	895	45	6.62	0	0	Inverter
10:43	907	42	29.39	14.66	15.53	DC + Inverter
10:44	906	41	29.46	14.42	15.8	DC + Inverter
10:45	899	39	28.77	14.8	15.8	DC + Inverter
10:46	906	40	26.28	115.61	0	DC + Inverter
10:47	960	41	28.91	115.61	0	DC + Inverter
10:49	982	41	27.59	104.82	0	DC + Inverter
10:50	970	38	27.59	109.69	0.44	AC & DC + Inverter
10:51	769	38	27.71	109.9	0.45	AC & DC + Inverter
10:52	1000	41	27.48	115.95	6.9	AC & DC + Inverter
10:54	1000	40	31.5	110.45	6.38	AC & DC + Inverter

Effect of Solar Irradiance and Temperature on Output Power

The performance evaluation of the PV educational module indicates that system performance is strongly influenced by operational environmental dynamics, namely solar irradiance (G) and panel temperature (T). The experimental data reveal a strong correlation between these parameters and the

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electrical power output. Figure 3 illustrates the relationship between variations in solar irradiance and panel temperature with respect to the output power of the photovoltaic module.

Relationship between Solar Irradiance (G) and Output Power (P_out)

Based on the experimental data, a strong positive correlation is observed between solar irradiance and output power. As irradiance increases from 835 W/m² to 1000 W/m², the output power correspondingly rises from approximately 27.5 W to 31.5 W. This behavior is consistent with fundamental photovoltaic principles, whereby an increase in light intensity enhances the number of photons absorbed by the solar cells, leading to higher generated current and a near-linear increase in output power. A simple linear regression model yields:

$$P_{out} = -2{,}3 + 0{,}031G \tag{3}$$

With a coefficient of determination $R^2 = 0.93$, indicating a very strong linear relationship between solar irradiance and output power.

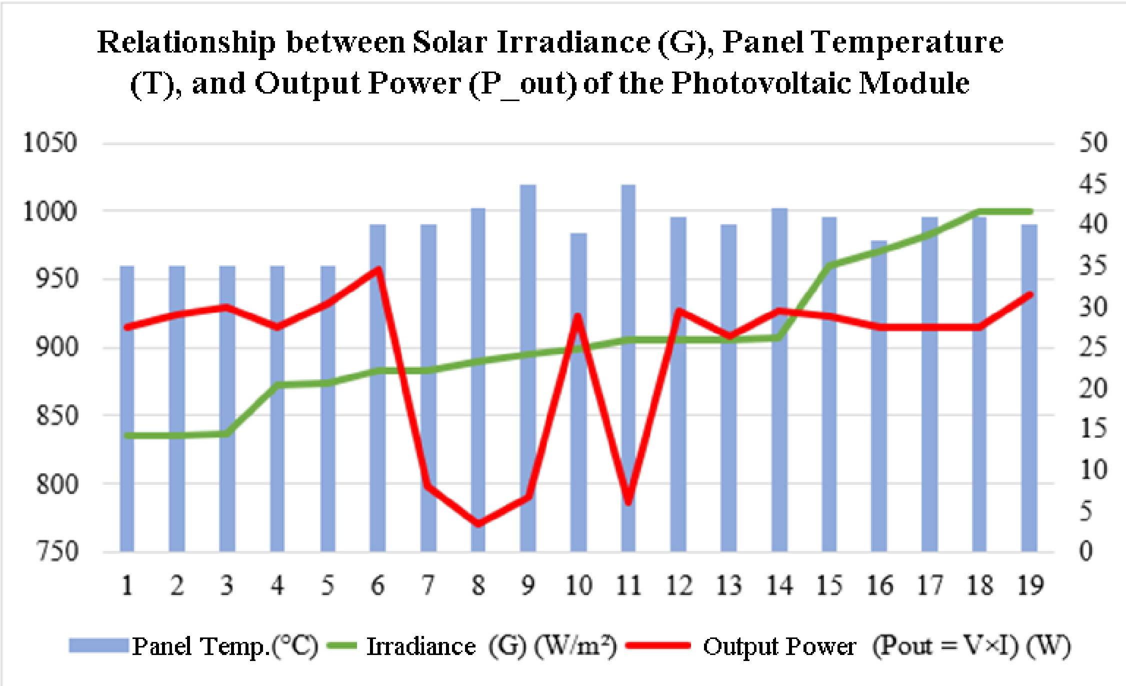

Figure 3. Relationship between solar irradiance (G) and panel temperature (T) on the output power (P_out) of the photovoltaic module.

Relationship between Panel Temperature (T) and Output Power (P_out)

Conversely, a negative correlation is identified between panel temperature and output power. As the panel temperature increases from 35 °C to 45 °C, the output power tends to decrease from approximately 30–34 W to 6–8 W.

This phenomenon is primarily attributed to the reduction in open-circuit voltage (V_{oc}) resulting from increased silicon semiconductor temperature. A temperature rise of approximately 1 °C typically leads to a voltage reduction of about 0.3%–0.5%, thereby decreasing the overall power output even under high irradiance conditions. The linear regression between temperature and power output is expressed as:

$$P_{out} = 52{,}1 - 0{,}62T \tag{4}$$

With an $R^2 = 0.78$, indicating a moderately strong negative correlation.

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Relationship between Irradiation (G), Panel Temperature (T), and Output Power (P_{out})

Building upon the individual relationships between irradiance and output power, and between temperature and output power, a multiple linear regression analysis was conducted to evaluate the combined influence of solar irradiance and panel temperature on output power. The resulting regression model is given by:

$$P_{out} = -3{,}85 + 0{,}030G - 0{,}21T \quad (5)$$

When both irradiance and temperature are considered simultaneously, the results demonstrate that these variables collectively explain the majority of the observed variation in output power. In other words, accurate understanding and prediction of PV system performance require an integrated consideration of both solar irradiance and panel temperature.

Module Efficiency Analysis

Based on the experimental data, a generally strong positive correlation between solar irradiance and output power is observed. As solar irradiance increases, the output power of the photovoltaic panel tends to rise accordingly. However, the relative efficiency—defined as the ratio between output power and incident solar irradiance—exhibits notable variations under different operating conditions.

The highest relative efficiency was recorded at 10:44 a.m., when an irradiance level of 906 W/m² produced an output power of approximately 29.46 W. This condition reflects near-optimal operating performance, as the panel temperature remained moderate (41 °C) and both voltage and current operated within their ideal ranges.

Conversely, a gradual decline in efficiency was observed after 10:47 a.m., despite consistently high irradiance levels, reaching up to 1000 W/m² at 10:52 and 10:54 a.m. This reduction can be attributed to sustained elevated panel temperatures and a decrease in operating voltage, which may indicate a deviation from the Maximum Power Point (MPP).

During the test, a data anomaly was identified between 10:36 and 10:42, where the output power dropped drastically (reaching 3.48 W) despite consistently high solar irradiation (883-907W/m²). This drastic drop was caused by temporary shading covering the solar panel, deviation from the MPP on the charge controller, or intermittent connection issues. Additionally, at 10:46, the recorded battery power was 115.61 W, which far exceeded the PV output power (26.28 W). This significant difference does not represent the charging power from the PV, but rather the discharging power of the battery to supply the overall load system.

Overall, the measured efficiency values ranged between approximately 9.2% and 13.1% under normal operating conditions (excluding the anomalous data point at 10:42 a.m.). These results indicate that the panel performs realibly in converting solar irradiance into electrical energy under real outdoor conditions, although the efficiency remains below the nominal efficiency of commercial 50 Wp PV panels, which typically achieve 15%–18% under STC.

Compared to previous research (Khan et al., 2018; Skoplaki & Palyvos, 2009; Susanto et al., 2022), the measured efficiency values in this study—ranging from 9.2% to 13.1% under real outdoor conditions—and the observed temperature-induced voltage degradation are highly consistent with the performance degradation profile of PV modules operating in tropical climates. Although the panel performs reasonably well outdoors, this actual efficiency remains lower than the 15%–18% nominal efficiency typically achieved by commercial 50 Wp panels under STC. Consequently, the experimental results in this study reinforce the finding that manufacturers' STC ratings are often too optimistic and do not fully capture the thermal losses inherent to hot and humid environments.

Implications of Experimental Results for Engineering and Vocational Education

Although the efficiency of the PV module is relatively low compared to industrial standards, the practicum module demonstrates strong relevance and effectiveness as an educational tool. This study provides empirical justification for the implementation of Project-Based Learning (PBL) models in renewable energy education. The experimental data generated by the module—such as the correlations

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between irradiance and power, and between temperature and voltage—offer meaningful learning opportunities for students.

The pedagogical advantages of the module as an instructional and research instrument in technical education include:

1. Understanding Non-Ideal Operating Conditions
   The practicum module allows students to directly observe that PV efficiency under real operating conditions is significantly lower than manufacturer-rated STC. This experience fosters an understanding of environmental effects, system losses, and the importance of system design considerations.
2. Enhancing Analytical Skills
   Through repeated measurements and efficiency calculations using fundamental equations, students can develop and refine analytical and problem-solving skills, which are essential competencies in vocational and engineering education.
3. Industry-Relevant Experience
   Hands-on interaction with the PV system helps bridge the gap between theoretical knowledge and industrial practice, preparing students to anticipate and address operational challenges encountered in real-world PV systems.

The novelty of this research lies in the validated performance characterization of an educational-scale photovoltaic module (50 Wp) used as a vocational learning medium in a humid tropical environment. Such studies remain limited within the context of vocational education in Indonesia. Furthermore, this work provides an empirical foundation for the development of PBL curricula in the field of renewable energy.

Conclusion

Based on the experimental results, the performance of the 50 Wp educational photovoltaic (PV) module demonstrates that the output power (P_{out}) increases with rising solar irradiance (G), while an increase in panel temperature (T) leads to a reduction in output voltage (V). The average module efficiency ranges from approximately 9.2% to 13.1%, which is lower than that of commercial PV panels due to the influence of non-standard environmental conditions and inherent system losses. From a technical perspective, these findings confirm the validity of fundamental photovoltaic energy conversion principles under real operating conditions.

From a pedagogical standpoint, the module exhibits high educational value, as it enables trainees to directly understand the relationship between environmental factors and PV system performance, while simultaneously developing analytical skills and efficiency calculation capabilities through a project-based learning approach. Accordingly, this study not only provides a technical evaluation of a small-scale PV system but also contributes to the strengthening of renewable energy vocational education within secondary technical and vocational learning environments.

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