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Evaluation the Effect of Radiation and Temperature on the Efficiency of Various Types of PV Panels Monocrystalline, Polycrystalline, and Thin Film

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ABSTRACT

Solar photovoltaic (PV) technology is a key solution for sustainable energy generation. However, its efficiency is significantly affected by environmental factors such as solar radiation and temperature. Understanding these impacts is crucial for optimizing PV performance under varying climatic conditions. The efficiency of PV panels varies based on material composition and environmental exposure. While single-crystal panels offer high efficiency, they are more sensitive to temperature fluctuations. Polycrystalline panels, though cost-effective, have lower efficiency, and thin-film panels exhibit better performance in low-light conditions but with lower maximum efficiency. This study aims to analyze how solar radiation and temperature affect these different PV technologies. This research evaluates the performance of three common PV modules monocrystalline, polycrystalline, and thin film by examining their efficiency under various radiation and temperature conditions. A real-time data logging system was used to monitor solar radiation, voltage, current, and temperature. The collected data were analyzed to determine efficiency variations in different environmental conditions. Monocrystalline panels achieved the highest efficiency, peaking at 27.70% within radiation intensities of 600–800 W/m². However, they are highly sensitive to temperature increases, with a coefficient of 0.35%/°C. Polycrystalline panels exhibited lower efficiency (20.80%) and a slightly higher temperature sensitivity of 0.40%/°C, making them less suitable for high-temperature regions. Thin-film panels had the lowest maximum efficiency (10.26%) but maintained stable performance under different temperature and radiation intensities, with a lower temperature coefficient of 0.25%/°C. Solar radiation directly impacts efficiency by determining the photon energy available for power generation. Efficiency peaks at moderate radiation levels (600–800 W/m²), while excessive radiation (>900 W/m²) leads to thermal losses. The study concludes that monocrystalline panels perform best in regions with stable sunlight and moderate temperatures, whereas thin-film panels are more suitable for low-light conditions. Further studies should focus on enhancing PV performance through advanced cooling mechanisms, hybrid material innovations, and improved Maximum Power Point Tracking (MPPT) algorithms to mitigate efficiency losses due to temperature variations and excessive radiation exposure.

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1. Introduction

The rapid advancement in renewable energy technology has driven significant interest in solar photovoltaic (PV) systems. As a clean and sustainable energy source, solar PV technology is increasingly being adopted for various applications, including rooftop solar power plants [1]. However, the efficiency and performance of PV panels are influenced by multiple environmental factors, primarily solar radiation and temperature. Understanding these influences is crucial for optimizing energy output and enhancing system reliability [2].

Indonesia, located in a tropical region, experiences high solar radiation levels, making it an ideal location for solar energy utilization. However, high temperatures can adversely affect PV panels performance [3-5]. Different types of PV panels, including monocrystalline, polycrystalline, and thin-film, exhibit varying levels of efficiency and thermal response. Thus, evaluating their performance under different environmental conditions is essential for selecting the most suitable technology for specific applications. In recent years, extensive research has been conducted to understand the impact of climate on PV panel performance, particularly in tropical regions where temperature fluctuations are more pronounced [6-8].

Recent advancements in PV technology have focused on improving energy conversion efficiency and developing innovative monitoring systems. The integration of Internet of Things (IoT)-based data loggers has enabled real-time performance tracking, allowing for letter system management and predictive maintenance. These advancements have led to improved accuracy in detecting performance losses and system failures. Studies have demonstrated that monocrystalline panels generally exhibit the highest efficiency due to their superior material purity, followed by polycrystalline and thin-film panels. However, each of these technologies has its own set of advantages and disadvantages, particularly in relation to cost, temperature tolerance, and adaptability to different environments. A study conducted by Adeeb *et al.,* [9] evaluated the effect of temperature on different solar cell technologies, highlighting the significant impact of heat on PV performance. Additionally, developed a PV panels data logger, demonstrating its effectiveness in monitoring power output variations [10]. These studies underline the growing interest in real-time monitoring systems as a means to optimize solar energy harvesting.

Furthermore, advancements in material science have led to the emergence of heterojunction and passivated emitter rear contact (PERC) technologies, which enhance panel efficiency under high-temperature conditions. These developments have been instrumental in improving the performance of PV systems in hot climates, where conventional panels often suffer from significant efficiency losses. However, traditional monocrystalline and polycrystalline panels remain the most widely used due to their cost-effectiveness and proven reliability. Future research directions in PV technology focus on reducing material costs while maintaining high efficiency levels, making solar energy a more viable option for widespread adoption [11].

Several previous studies have explored the relationship between solar radiation, temperature, and PV panel efficiency [12]. Highlights the importance of accurate solar energy forecasting in optimizing PV power generation. Similarly, Marausna *et al.,* [13] analyzed the impact of solar intensity on PV panels output, revealing a direct correlation between radiation levels and efficiency. Examined the effect of temperature variations on monocrystalline PV panels, showing that excessive heat reduces voltage output and overall efficiency [14]. This phenomenon is known as the temperature coefficient effect, where increased temperatures lead to reduced energy conversion efficiency in solar cells. Investigated how global solar irradiance affects multicrystalline silicon solar cells, demonstrating that efficiency drops as temperature rises [15].

In the realm of PV performance monitoring, developed an ATmega328-based data logger for real-time PV panel monitoring, proving its effectiveness in tracking performance variations. Additionally, Dud'ak *et al.,* [16] introduced a low-power data logger with a simple file system for long-term environmental monitoring, improving data collection accuracy. Such monitoring systems provide valuable insights into how environmental conditions influence PV performance over extended periods. Comparative studies such as those of Sapina *et al.,* [17] have analyzed heterojunction and PERC PV panels, concluding that these advanced technologies offer better efficiency under challenging conditions. Meanwhile, characterized thin-film PV panels using a metal halide sun simulator, providing insights into their efficiency under controlled illumination conditions [18]. These studies suggest that continuous innovation and testing are essential to refining PV technologies for better efficiency and sustainability.

Based on these studies, this research aims to bridge the gap in understanding how solar radiation and temperature variations affect different PV panel types in real-world conditions by Husai [19]. By employing a data logger system, this study seeks to provide accurate and continuous performance analysis to aid in future solar energy optimizations. The objective of this research is to analyze the effect of solar radiation and temperature on the efficiency of monocrystalline, polycrystalline, and thin-film PV panels [20,21], evaluate their efficiency under varying environmental conditions, and develop a reliable data logging system for real-time monitoring of PV performance [22]. Additionally, this research intends to examine the long-term degradation effects on these panels to determine their viability for prolonged use.

This research will contribute to the ongoing efforts to optimize solar PV technology for enhanced energy production, particularly in tropical regions with high solar potential [23,24]. By understanding the key factors affecting panel performance, stakeholders in the renewable energy sector can make informed decisions regarding panel selection, placement, and system optimization. In conclusion, the integration of advanced monitoring tools and innovative panel designs is vital for enhancing the sustainability and efficiency of solar power systems worldwide [25]. With continuous advancements in PV materials and monitoring methodologies, the future of solar energy looks promising, paving the way for cleaner and more sustainable energy solutions.

2. Methodology

2.1 Mathematical Framework

Mathematical modeling plays a critical role in analyzing the efficiency and performance of photovoltaic (PV) systems. This section provides a comprehensive mathematical framework, covering power calculations, energy losses, thermal effects, shading impacts, battery storage, and economic analysis.

2.2 Mathematical Modelling

This subsection provides detailed equations governing PV system performance, degradation, storage, and cost-effectiveness.

2.1.1 Temperature effect on output power

As temperature rises, solar cell voltage decreases, reducing output power [26]:

$$\mathrm{P_{out}}\ (\mathrm{T}) = \mathrm{P_{out,ret}} \times [1-\alpha(\mathrm{T}-\mathrm{T_{ref}})] \tag{1}$$

Advanced output power model including electrical losses
Power output considering system losses:

$$P_{out,net} = P_{out} \times (1-L_{temp}) \times (1-L_{mismatch}) \times (1-L_{wiring}) \times (1-L_{inverter}) \quad (2)$$

Final output power formula for solar panels

$$P_{out,total} = \eta \times E \times A \times (1-\alpha(T-T_{ref})) \times (1-d) \times (1-L_{temp}) \times (1-L_{mismatch}) \times (1-L_{wiring}) \times (1-L_{inverter}) \quad (3)$$

The final output power formula for solar panels accounts for efficiency, irradiance, temperature effects, soiling, and system losses. Power output decreases with rising temperature due to reduced voltage and is further affected by dust accumulation and shading. Electrical losses from wiring, module mismatch, and inverter inefficiencies also contribute to reduced net power. By incorporating these factors, the formula provides a realistic estimate of solar panels' performance under actual operating conditions. This comprehensive model helps optimize PV system efficiency and ensure stable energy production.

2.2 Optimization Techniques for Solar PV Systems

Optimization techniques enhance the performance of solar panels by maximizing energy conversion efficiency, reducing losses, and ensuring stable operation under varying environmental conditions.

2.2.1 Maximum Power Point Tracking (MPPT)

Solar panels operate at varying voltage and current levels depending on sunlight conditions. MPPT algorithms adjust the operating point to extract maximum power.

2.2.2 Incremental Conductance (IC) algorithm

The IC algorithm compares the incremental conductance (dI/dV) with the instantaneous conductance (I/V):

2.2.3 Artificial intelligence-based MPPT

Machine learning techniques, such as neural networks (NN) and fuzzy logic (FL), can predict P_{max} based on historical irradiance and temperature data.

$$P_{max} = f\,(E, T) \quad (4)$$

2.2.4 Solar tracking systems

A Solar Tracking System (STS) is a mechanism designed to optimize the efficiency of solar panels by adjusting their orientation to follow the movement of the sun. Unlike fixed solar panel systems, which remain in a stationary position throughout the day, solar tracking systems dynamically adjust their angles to maximize sunlight absorption.

2.2.4.1 Single-axis tracking

Single-axis trackers adjust panel orientation along one axis:

$$\Theta = a\ cos\left(\frac{cos_{ठ}cos_{\Phi}\ cos_{h}+sin_{ठ}sin_{\Phi}}{cos\Theta_{2}}\right) \tag{5}$$

2.2.4.2 Dual-axis tracking

Dual-axis tracking follows the sun's azimuth (α) and altitude (β):

$$\alpha = tan^{-1}\left(\frac{cos_{ठ}sin_{h}}{cos_{\Phi}sin_{ठ}- sin_{\Phi}\ cos_{ठ}\ cos_{h}}\right) \tag{6}$$

$$\beta = sin^{-1}(sin_{ठ}sin_{\Phi} - \ cos_{ठ}\ cos_{\Phi}\ cos_{h}) \tag{7}$$

2.2.4.3 Anti-Reflective Coatings (ARC) to improve light absorption

Reflections reduce the effective solar irradiance hitting the panels. The reflectance loss is given by:

$$R = \left(\frac{n1-n2}{n1+n2}\right)^{2} \tag{8}$$

2.2.4.4 Bypass diodes to minimize shading losses

When partial shading occurs, the affected cells act as resistors, reducing panel output. Bypass diodes prevent power loss by allowing current to flow through alternative paths.

$$V_{array} = V_1 + V_2 + \cdots + V_n - V_{blocked} \tag{9}$$

2.2.4.5 *Dust and soiling prevention for PV panels*

Dust accumulation reduces irradiance reception. The power loss due to soiling is:

$$P_{loss,dust} = P_{clean} \times (1 - d) \tag{10}$$

2.3. Mathematical Modeling for Different Types of PV Technologies

Different types of solar panels exhibit distinct electrical and optical characteristics. This section provides specific performance equations for each technology, including power conversion efficiency, temperature dependence, degradation, and spectral response.

2.3.1 Monocrystalline solar panels (mono-Si) model

Monocrystalline panels have higher efficiency (18-22%) due to their pure silicon crystal structure, but they suffer from higher temperature sensitivity.

2.3.1.1 Voltage-Current (I-V) relationship for monocrystalline cells

$$I = I_{ph} - I_0\left(e\frac{q(V+IR_S}{nkT} - 1\right) - \frac{V + IR_S}{R_{sh}} \quad (11)$$

2.3.1.2 Efficiency model for monocrystalline PV

$$\eta_{mono} = \eta_{ref} \times \left[1 - \alpha\left(T - T_{ref}\right)\right] \quad (12)$$

2.3.2 Polycrystalline solar panels (poly-Si) model

Polycrystalline panels are cheaper but less efficient (14-18%) than monocrystalline due to multiple silicon crystals increasing electron scattering.

2.3.2.1 Voltage-Current (I-V) relationship for poly-Si

$$I = I_{ph} - I_0\left(e\frac{q(V+IR_S}{nkT} - 1\right) \quad (13)$$

2.3.2.2 Efficiency model for polycrystalline PV

$$\eta_{mono} = \eta_{ref} \times \left[1 - \alpha_{poly}\left(T - T_{ref}\right)\right] \quad (14)$$

2.3.3 Thin-film solar panels model (Cd Te, CIGS, a-Si)

Thin-film panels have lower efficiency (10-15%) but perform better in low-light conditions and at higher temperatures.

2.3.3.1 Cd Te (Cadmium Telluride) voltage-current relationship

$$I = I_{ph} - I_0\left(e\frac{q(V+IR_S}{\eta\kappa T} - 1\right) \quad (15)$$

2.3.3.2 Efficiency model for thin-film PV (Cd Te, CIGS, a-Si)

$$\eta_{thin} = \eta_{ref} \times \left[1 - \alpha_{thin}\left(T - T_{ref}\right)\right] \quad (16)$$

2.3.4 Heterojunction (HJT) solar panels model

Heterojunction panels use amorphous silicon (a-Si) layers on crystalline silicon, improving efficiency (20-24%) and reducing temperature losses.

2.3.4.1 HJT Open-circuit voltage model

$$V_{oc,HJT} = \frac{\eta\kappa T}{q}\, ln\left(\frac{I_{ph} + I_0}{I_0}\right) + \frac{E_g}{q} \quad (17)$$

2.3.4.2 Efficiency model for heterojunction PV

$$\eta_{HJT} = \eta_{ref} \times [1 - \alpha_{HJT}(T - T_{ref})] \quad (18)$$

2.3.5 Perovskite solar panels model

Perovskite PV is a next-generation technology, achieving efficiencies of over 25% with low-cost manufacturing.

2.3.5.1 Open-circuit voltage for perovskite PV

$$V_{oc,Perow} = \frac{E_g}{q} - \frac{\kappa T}{q} \ln\left(\frac{I_{ph}}{I_0} + 1\right) \tag{19}$$

2.3.5.2 Efficiency model for perovskite PV

$$\eta_{Perow} = \eta_{ref} \times [1 - \alpha_{Perow}(T - T_{ref})] \tag{20}$$

3. Results

The results demonstrate that monocrystalline solar panels consistently produce higher voltage, current, and power output compared to polycrystalline and thin-film panels. This superior performance is due to the high-purity silicon structure in monocrystalline cells, which minimizes grain boundary defects and enhances charge carrier mobility. With an efficiency of approximately 20.82%, monocrystalline panels convert more solar energy into electricity than polycrystalline panels, which achieved an efficiency of 13.83%, and thin-film panels, which had the lowest efficiency at 8.01%. The polycrystalline panel's lower efficiency is attributed to increased recombination losses caused by crystal grain boundaries, while the thin-film panel performance is limited by its lower material absorption coefficient and thinner active layers.

Temperature has a significant impact on solar panels' performance, with monocrystalline panels showing the highest sensitivity to temperature fluctuations. As cell temperature increases, the open-circuit voltage V_{oc} decreases due to an increase in intrinsic carrier concentration, leading to a reduction in overall efficiency. The efficiency of monocrystalline panels, calculated using the temperature coefficient of 0.35%/°C, indicates that a rise in temperature from 25°C to 50°C results in an efficiency reduction of approximately 8.75%. Polycrystalline panels, with a temperature coefficient of 0.4%/°C, exhibit slightly greater losses, while thin-film panels, with a lower temperature coefficient of 0.25%/°C, maintain better performance in high-temperature environments. This makes thin-film technology preferable for regions with consistently high temperatures, whereas monocrystalline panels are more suitable for areas with controlled cooling strategies to mitigate thermal losses.

Solar irradiance directly influences the power output of all PV technologies, with maximum efficiency observed at irradiance levels between 700–800 W/m². Monocrystalline panels demonstrate the highest efficiency under direct sunlight due to their superior light absorption properties and optimized charge transport. Polycrystalline panels exhibit slightly lower peak efficiency because of increased scattering and recombination effects, while thin-film panels show relatively stable efficiency across a wide range of irradiance levels. This stability is attributed to their broader spectral absorption range, making them effective in diffuse light conditions, such as cloudy weather or morning and evening sunlight. Unlike monocrystalline and polycrystalline panels, which experience a sharp drop in efficiency at lower irradiance levels, thin-film panels maintain a consistent performance, making them suitable for installations where sunlight exposure varies throughout the day.

The impact of shading on solar panel performance is particularly severe for monocrystalline and polycrystalline panels in series connections, as even partial shading on a single cell significantly reduces the current flow through the entire string. In a typical series-connected PV system, a 30% shading on a single panel can result in a 50–70% reduction in overall power output due to the mismatch effect. To mitigate this, bypass diodes are implemented to allow current to flow around shaded cells, preventing drastic power losses. Thin-film panels, having a more uniform distribution of active material, exhibit lower shading sensitivity and can still generate power even when partially covered.

Long-term stability and degradation rates are crucial for assessing the economic viability of PV systems. Monocrystalline panels exhibit the lowest degradation rate, typically 0.3–0.5% per year, which ensures high efficiency over a lifespan of more than 25 years. Polycrystalline panels degrade at a slightly higher rate of 0.5–0.7% per year due to the presence of grain boundaries, which introduce additional defect sites that accelerate performance decline. Thin-film panels, with a degradation rate of 1–2% per year, have a shorter operational lifespan, but their lower initial cost makes them suitable for short-term energy applications. Over a 20-year period, a monocrystalline panel retains approximately 85–90% of its initial power output, whereas polycrystalline panels retain around 80–85%, and thin-film panels drop to 60–80%, depending on environmental conditions.

Considering these findings, monocrystalline panels are the optimal choice for applications that require maximum efficiency and long-term reliability, despite their higher upfront cost. Polycrystalline panels provide a cost-effective balance between efficiency and durability, making them suitable for medium-scale installations where budget constraints are a concern. Thin-film panels, while having lower efficiency, are advantageous in hot climates and low-light conditions due to their lower temperature sensitivity and stable performance under varying irradiance levels. To further enhance PV system performance, future research should focus on integrating advanced cooling mechanisms, hybrid PV technologies such as tandem perovskite-silicon cells, and improved maximum power point tracking (MPPT) algorithms to optimize energy extraction under fluctuating environmental conditions.

The data in Table 1 provides detailed measurements of voltage, current, and temperature for monocrystalline, polycrystalline, and thin-film solar panels throughout the day. The monocrystalline panels consistently produce the highest voltage output, reaching a peak of 24.79 V at 11:00, while the polycrystalline panels peak at 20.99 V at 13:00, and the thin-film panels achieve a maximum voltage of 16.77 V at 13:00. The differences in voltage output highlight the superior electronic properties of monocrystalline silicon, which minimizes recombination losses and improves carrier mobility. Polycrystalline panels, due to their multiple silicon crystal structures, exhibit slightly lower voltages because of increased grain boundary defects. Thin-film panels, with their lower material thickness and broader spectral absorption, generate the lowest voltage output but maintain relatively stable operation across varying irradiance conditions. The current output follows a similar trend, with monocrystalline panels generating the highest peak current of 5.57 A at 11:00, followed by polycrystalline panels at 4.96 A at 13:00, and thin-film panels at 3.55 A at 13:00. The variations in current output correspond to the panels' ability to convert solar irradiance into electricity, where monocrystalline panels exhibit superior photon absorption and charge carrier mobility. Despite producing lower overall voltage and current, thin-film panels demonstrate better stability in diffuse light conditions, making them more effective in partially shaded or cloudy environments.

Table 1
Daily expenditure data experimental results

	Monocrystalline				Polycrystalline				Thin film			
Time (h)	E_1 (W/m^2)	V_1 (V)	I_1 (A)	T_1 (°C)	V_2 (V)	I_2 (A)	T_2 (°C)	E_2 (W/m^2)	V_3 (V)	I_3 (A)	T_3 (°C)	E_3 (W/m^2)
6:00	89,51	2,77	1,42	23,12	2,33	1,4	23,69	89,51	2,6	1,39	23,62	89,51
7:00	128,4	12,72	1,42	28,62	14,87	1,41	29,37	128,4	14,4	1,4	30,12	128,4
8:00	129,4	12,94	1,47	35,13	15,5	1,12	39	129,4	14,33	1,6	34,13	129,4
9:00	367,3	21,54	3,34	43,44	16,77	2,6	47,06	367,3	14,98	1,78	40,94	367,3
10:00	406,7	22,71	2,74	41,75	16,63	2,36	43,63	406,7	15,92	1,65	37,13	406,7
11:00	678,3	24,79	5,57	51,88	20,21	3,5	53,44	678,3	16,8	2,07	36,69	678,3
12:00	847,4	24,67	5,5	55,94	20,77	4,88	56,31	847,4	11,98	2,97	35,88	847,4
13:00	719,98	24,76	4,49	51,81	20,99	4,96	55,13	719,98	16,77	3,55	47,88	719,98
14:00	624,41	24,63	3,18	51,38	18,31	3,78	54,19	624,41	16,5	2,63	48,5	624,41
15:00	534,9	19,53	4,43	37,06	14,94	1,45	38,25	534,9	15,21	1,4	37,25	534,9
16:00	345,7	18,26	2,98	35,25	14,77	1,45	36,56	345,7	14,92	1,44	35,56	345,7
17:00	285,9	16,63	2,48	32,75	14,43	1,45	33,69	285,9	14,75	1,44	33,38	285,9
18:00	89,5	1,22	1,26	30,06	1,2	1,23	30,81	89,5	1,12	1,2	30,62	89,5

The current output follows a similar trend, with monocrystalline panels producing the highest peak current of 5.57 A at 11:00, polycrystalline panels reaching 4.96 A at 13:00, and thin-film panels generating 3.55 A at 13:00. The variations in current output are largely influenced by solar irradiance, with all panels demonstrating their highest performance during peak sunlight hours between 11:00 and 13:00. Despite lower current output, thin-film panels maintain more stable current generation throughout the day due to their better performance in diffuse and indirect light conditions. This characteristic makes thin-film technology advantageous for environments with frequent cloud cover or non-ideal sunlight angles.

Temperature plays a significant role in panel performance, as shown in Table 1. The recorded temperature values indicate that monocrystalline and polycrystalline panels absorb and retain more heat, with peak temperatures exceeding 55°C, whereas thin-film panels remain cooler, peaking at 47.88°C at 13:00. The lower temperature of thin-film panels contributes to their reduced efficiency losses, as temperature affects the voltage output of a solar cell by increasing intrinsic carrier concentration, thereby reducing the open-circuit voltage V_{oc}.The higher temperature coefficients of monocrystalline (0.35%/°C) and polycrystalline (0.4%/°C) panels result in more substantial efficiency reductions compared to thin-film panels, which have a lower temperature coefficient of 0.25%/°C.

Table 2
Results of efficiency calculations on monocrystalline, polycrystalline, thin film panels

	Monocrystalline				Polycrystalline			Thin film		
Time (h)	E_1 (W/m^2)	P_{1in}	P_{1out}	η_1(%)	P_{2in}	P_{2out}	η_2(%)	P_{3in}	P_{3out}	η_3(%)
6:00	89,51	65,771	3,933	5,980	62,231	3,262	5,241	72,116	3,614	5,011
7:00	128,4	94,348	18,062	19,144	89,270	20,967	23,487	103,449	20,160	19,487
8:00	129,4	95,083	19,021	20,005	89,965	17,360	19,296	104,254	22,928	21,992
9:00	367,3	269,892	71,943	26,656	255,36	43,602	17,074	295,925	26,664	9,010
10:00	406,7	298,843	62,225	20,822	282,7582	39,247	13,880	327,669	26,268	8,016
11:00	678,3	498,414	138,080	27,703	471,588	70,735	14,999	546,492	34,776	6,363
12:00	847,4	622,669	135,685	21,790	589,154	101,360	17,204	682,732	35,580	5,211
13:00	719,98	529,041	111,172	21,013	500,566	104,110	20,799	580,072	59,533	10,263
14:00	624,41	458,816	78,323	17,070	434,121	69,212	15,943	503,074	43,395	8,625
15:00	534,9	393,044	86,517	22,012	371,889	21,663	5,825	430,957	21,294	4,941
16:00	345,7	254,020	54,414	21,421	240,347	21,417	8,910	278,523	21,484	7,713
17:00	285,9	210,079	41,242	19,631	198,772	20,924	10,526	230,343	21,240	9,221
18:00	89,5	65,764	1,537	2,337	62,224	1,476	2,372	72,108	1,344	1,863

Table 2 presents the calculated efficiency values for each panel type, considering the input power derived from solar irradiance and the panel's surface area. The monocrystalline panels exhibit the highest efficiency, reaching a peak of 27.70% at 11:00, while the polycrystalline panels attain a maximum efficiency of 20.80% at 13:00, and the thin-film panels peak at 10.26% at 13:00. The efficiency of monocrystalline panels remains above 20% for most of the day, confirming their superior energy conversion capability. However, their efficiency declines during high-temperature periods due to thermal losses. Polycrystalline panels show moderate efficiency throughout the day, with variations due to temperature effects and increased recombination losses. Thin-film panels, while the least efficient, maintain consistent performance across different irradiance levels, making them more adaptable to environmental fluctuations.

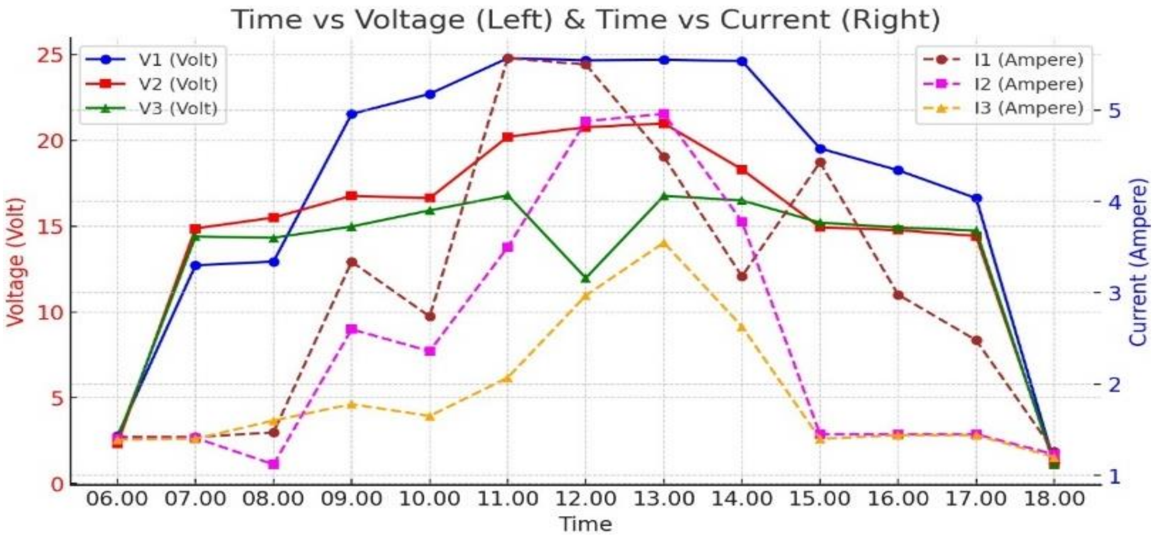

Fig. 1. Comparison of current and voltage in monocrystalline, polycrystalline, and thin film

Figure 1 provides a graphical comparison of voltage and current output trends for each panel type. The voltage curve shows that monocrystalline panels consistently maintain the highest voltage output, followed by polycrystalline and thin-film panels. However, all panels experience a gradual voltage decline as the temperature increases, which is expected due to the negative temperature

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coefficient of voltage in silicon-based cells. The current output graph demonstrates that the current generation increases with solar irradiance, peaking around midday when sunlight intensity is highest. Monocrystalline panels generate the most current, confirming their superior light absorption and charge carrier transport properties. Polycrystalline panels show slightly lower current values, while thin-film panels, although producing the least current, exhibit more stable performance across varying light conditions.

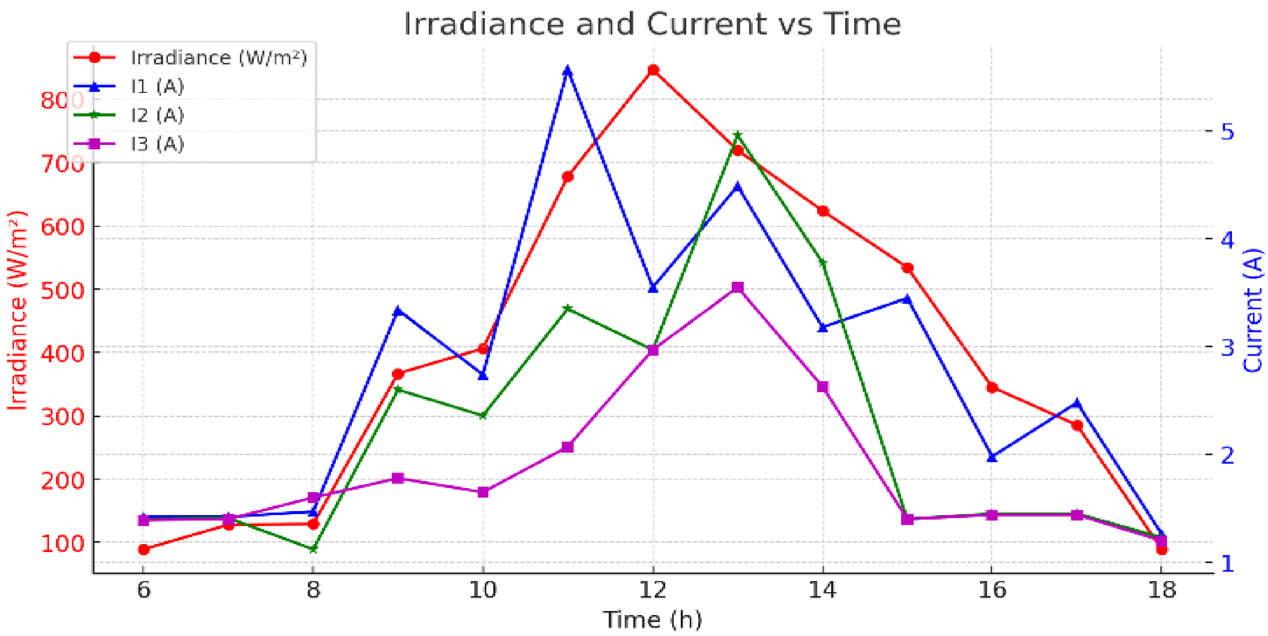

Fig. 2. Current and radiation graph against time

Figure 2 illustrates the relationship between solar radiation and current output over time for different photovoltaic panel types. The graph shows that as solar radiation increases, the current output also rises, reaching peak levels around midday when irradiance is at its highest. Monocrystalline panels generate the highest current, followed by polycrystalline and thin-film panels. After noon, both irradiance and current begin to decline, demonstrating the direct dependency of the current generation on sunlight intensity. While monocrystalline panels perform best under direct sunlight, thin-film panels maintain more stable current output in varying light conditions, making them suitable for areas with frequent cloud cover.

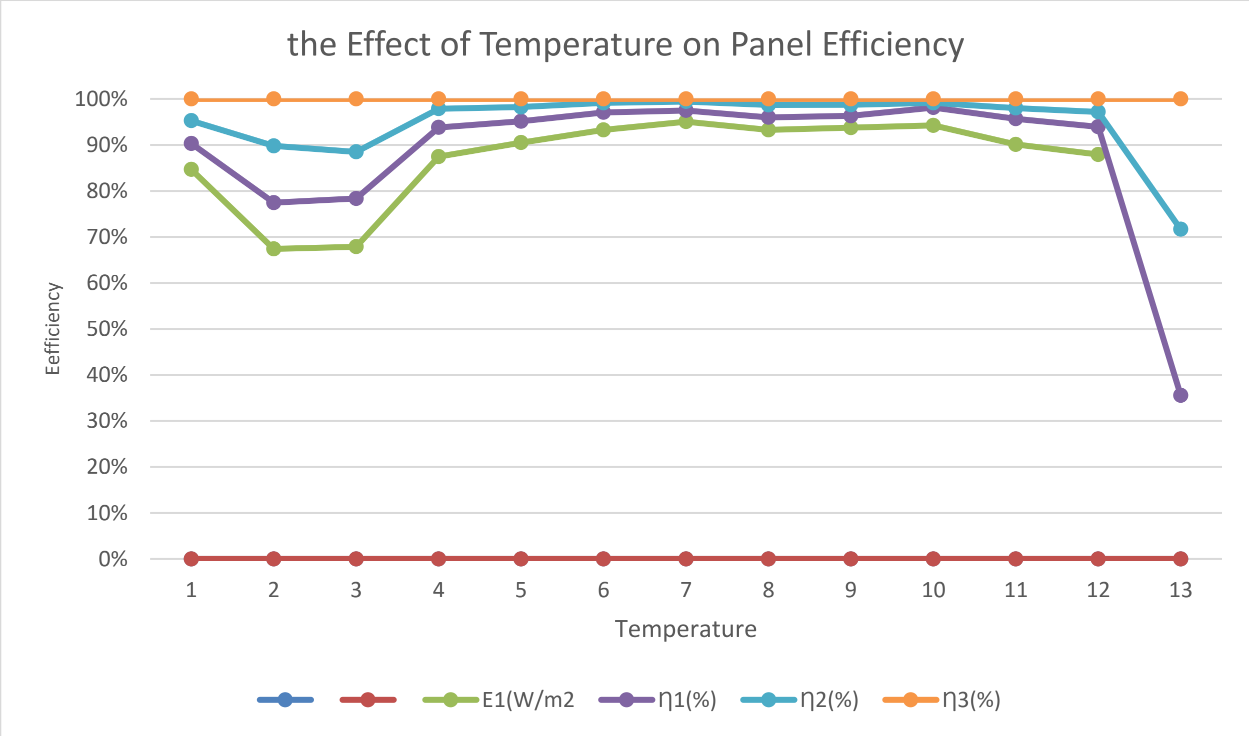

Fig. 3. Effect of temperature on panels efficiency

Figure 3 highlights the effect of temperature on the efficiency of solar panels. As temperature increases, efficiency declines for all panel types, but the rate of decline varies. Monocrystalline panels experience the most significant drop in efficiency due to their high temperature coefficient, followed by polycrystalline panels, which also show noticeable losses. Thin-film panels, on the other hand, exhibit greater stability at higher temperatures because of their lower temperature coefficient and better heat dissipation properties. The decrease in efficiency at higher temperatures is caused by increased recombination losses and a reduction in open-circuit voltage, which limits the ability of solar cells to convert sunlight into electricity. This trend suggests that thin-film panels are better suited for high-temperature environments, while monocrystalline and polycrystalline panels require cooling mechanisms to maintain optimal performance.

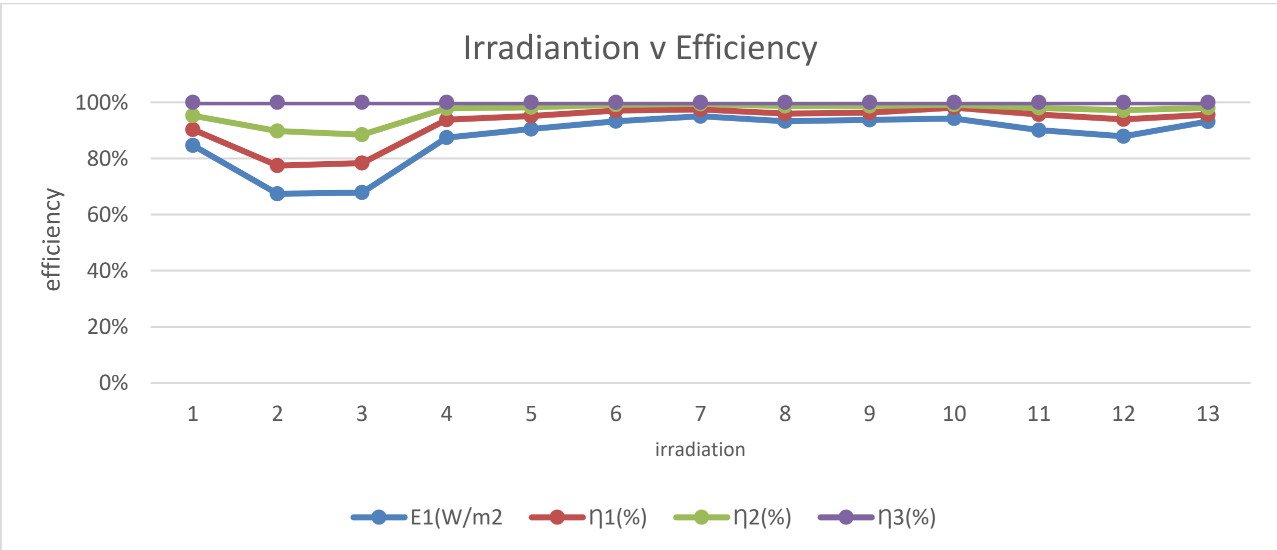

Fig. 4. Effect of irradiation on panel efficiency

Figure 4 examines the impact of solar irradiance on panels efficiency, showing that efficiency is highest at moderate irradiance levels between 600 and 800 W/m². Monocrystalline panels reach peak efficiency at around 27.70%, while polycrystalline panels perform slightly lower. At very high irradiance levels, efficiency begins to decline due to increased thermal effects, especially in silicon-based panels. Thin-film panels, in contrast, exhibit a more stable efficiency curve, performing consistently across a wider range of irradiance levels. The efficiency of all panels is lower at very low irradiance due to insufficient photon energy, while at very high irradiance, thermal losses become a limiting factor. These results highlight the importance of considering environmental conditions when selecting a PV technology, as different panels respond differently to variations in sunlight and temperature.

The analysis of Figures 2, 3, and 4 emphasizes the trade-offs between solar radiation, temperature, and efficiency for different photovoltaic panel types. Monocrystalline panels provide the highest efficiency and power output but are more affected by temperature increases. Polycrystalline panels offer a balance between cost and efficiency but exhibit slightly higher recombination losses. Thin-film panels, while less efficient overall, are more stable under high temperatures and varying irradiance conditions. These findings suggest that solar panel selection should be based on environmental factors, with monocrystalline panels ideal for maximizing energy production, polycrystalline panels suitable for cost-sensitive installations, and thin-film panels preferable for hot and cloudy regions where temperature stability and diffuse light absorption are advantageous.

Evaluation of the effect of radiation and temperature on the efficiency of various types of PV modules: The performance of photovoltaic (PV) modules is highly dependent on two key environmental factors: solar radiation (irradiance) and temperature. The efficiency of monocrystalline, polycrystalline, and thin-film PV panels varies under different irradiance levels and temperatures, affecting their overall energy conversion capabilities. The following analysis evaluates how these factors influence each PV type based on experimental data.

Effect of radiation on PV module efficiency: Solar radiation is the primary driver of energy generation in PV systems. Higher irradiance levels result in greater photon absorption, leading to an increase in the number of charge carriers and higher power output. However, beyond an optimal irradiance level, efficiency may begin to decline due to resistive and thermal losses.

Monocrystalline PV modules: Monocrystalline panels exhibit the highest efficiency under direct sunlight, peaking at around 600–800 W/m². At these levels, efficiency reaches a maximum of 27.70%, but beyond 900 W/m², efficiency declines slightly due to increased temperature effects and series resistance losses. These panels benefit from their high-quality silicon structure, which enables efficient photon absorption and electron mobility. However, at very low irradiance levels, efficiency drops due to insufficient charge carrier generation.

Polycrystalline PV modules: Polycrystalline panels achieve their best efficiency at moderate irradiance levels (~500–700 W/m²) but generally perform at lower efficiency than monocrystalline panels. Due to their multi-crystalline structure, they have more grain boundaries, leading to increased recombination losses. As irradiance increases beyond 800 W/m², their efficiency begins to decline due to internal resistive losses and the impact of rising temperatures.

Thin-film PV modules: Thin-film panels display the most stable efficiency across a wide range of irradiance levels. Unlike silicon-based PV panels, they do not show a sharp drop in efficiency at very high irradiance levels, making them suitable for areas with fluctuating sunlight. While their peak efficiency is lower than both monocrystalline and polycrystalline panels, they perform consistently well under low-light and diffuse radiation conditions, making them ideal for cloudy or shaded environments.

Effect of temperature on PV module efficiency: Temperature significantly affects PV efficiency, particularly for silicon-based panels, as higher temperatures lead to an increase in recombination losses and a reduction in open-circuit voltage V_{oc}. This temperature dependence is characterized by the temperature coefficient (α), which represents the percentage decrease in efficiency per degree Celsius increase.

Monocrystalline PV modules: Monocrystalline panels experience the most significant efficiency drop at high temperatures, with a temperature coefficient of approximately 0.35%/°C. As temperature increases beyond 25°C, efficiency declines due to increased thermal energy, which raises the intrinsic carrier concentration and accelerates recombination losses. This makes monocrystalline panels less effective in very hot climates unless proper cooling strategies, such as ventilation or heat dissipation mechanisms, are implemented.

Polycrystalline PV modules: Polycrystalline panels show similar temperature sensitivity to monocrystalline panels but with slightly worse performance, as indicated by a higher temperature coefficient of 0.40%/°C. The presence of multiple crystalline grains introduces more defect sites, increasing resistive losses and reducing charge carrier lifetimes. Consequently, efficiency decreases more rapidly in hot conditions compared to monocrystalline panels.

Thin-film PV panels: Thin-film panels exhibit the least efficiency loss due to temperature increases, with a temperature coefficient of around 0.25%/°C. Unlike silicon-based panels, thin-film technology absorbs and dissipates heat more effectively, making them more stable in hot environments. This characteristic makes thin-film PV an ideal choice for regions with high ambient temperatures, where monocrystalline and polycrystalline panels suffer significant efficiency degradation.

Table 3
Comparison of PV module performance under radiation and temperature variations

Parameter	Monocrystalline PV	Polycrystalline PV	Thin-film PV
Peak efficiency (%)	27.70% 600–800 W/m²	20.80% 500–700 W/m²	10.26% (Stable across irradiance)
Performance in low light	Moderate	Moderate	High (Best performance)
Performance in high irradiance	High but decreases at >900 W/m²	Moderate, efficiency loss at >800 W/m²	Stable, minimal loss at high irradiance
Temperature coefficient (α\alpha)	0.35%/°C	0.40%/°C	0.25%/°C
Efficiency loss in high temperature	Significant	High	Minimal
Best application	High-efficiency needs, moderate climates	Cost-effective, moderate climates	Hot climates, variable sunlight

4. Conclusion

The evaluation of solar radiation and temperature effects on PV module efficiency highlights the strengths and weaknesses of each technology. Monocrystalline panels provide the highest efficiency under optimal conditions but suffer from significant efficiency losses at high temperatures. Polycrystalline panels, while slightly less efficient, also exhibit substantial temperature-related losses, making them suitable for applications where cost is a concern, but moderate climate conditions exist. Thin-film panels, despite their lower overall efficiency, offer the best stability under high temperatures and varying irradiance levels, making them an excellent choice for hot and cloudy environments.

Selecting the appropriate PV module type depends on environmental conditions, cost considerations, and system requirements. In regions with consistent high sunlight and moderate temperatures, monocrystalline panels offer the best performance. In moderate-cost applications with stable climates, polycrystalline panels provide a good balance between efficiency and affordability. In hot climates or areas with frequent cloud cover, thin-film panels are preferable due to their temperature resilience and stable performance under varying irradiance. Future research should focus on hybrid solar technologies, improved cooling mechanisms, and advanced tracking systems to enhance energy efficiency across different environmental conditions.

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