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(RESEARCH ARTICLE)

Characterization Of Solar Cell I-V Curves Under Varying Conditions

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Abstract

The increasing demand for sustainable energy solutions has positioned solar energy as a key player in the global transition to renewable energy. Central to solar energy technology is the photovoltaic (PV) cell, whose performance is best characterized by its current-voltage (I-V) curve. This project investigates the behavior of a monocrystalline solar cell under varying environmental conditions—specifically light intensity, temperature, and partial shading—using natural sunlight as the illumination source. The study employs a systematic experimental setup to capture I-V data across different scenarios, allowing for the extraction and comparison of key parameters such as short-circuit current (Isc), open-circuit voltage (Voc), maximum power point (Pmpp), fill factor (FF), and efficiency. Results reveal significant sensitivity of solar cell output to light intensity and temperature, with notable non-linear effects under shading. The findings are valuable for optimizing PV system performance in real-world outdoor settings and contribute to the broader understanding of solar energy behavior under dynamic environmental influences.

Keywords- Current-voltage (I-V) curves; Irradiance; Monocrystalline; Shading; Solar Cell; Temperatures

1. Introduction

At the core of a solar PV system is the solar cell, a semiconductor device that converts sunlight directly into electricity via the photovoltaic effect. When photons from sunlight strike the surface of a solar cell, they can excite electrons from the valence band to the conduction band, creating electron-hole pairs. If a built-in electric field exists across the junction of the device—as in a p-n junction—it drives the charge carriers in opposite directions, resulting in an electric current when the circuit is closed.

The performance of a solar cell is typically characterized by its current-voltage (I-V) curve, which describes how the output current varies with the voltage across the cell under specific environmental conditions [1]. This curve provides valuable information such as the short-circuit current (Isc), open-circuit voltage (Voc), maximum power point (Pmpp), and fill factor (FF) which are key parameters for evaluating efficiency and suitability for application in real-world energy systems [2].

The behavior of a solar cell, as illustrated by its I-V curve, is highly sensitive to environmental factors such as irradiance (light intensity), cell temperature, and partial shading [3]. For instance, increased irradiance generally leads to a proportional increase in current output, while elevated temperatures typically reduce the open-circuit voltage and hence efficiency [2,4]. Partial shading, even over a small section of the panel, can lead to power loss due to mismatch effects and the creation of local maxima in the power-voltage (P-V) curve [5].

Understanding the dependence of solar cell performance on these variables is essential for the accurate design, deployment, and operation of PV systems. Despite the availability of standardized test conditions (STC)—typically

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defined as irradiance of 1000 W/m², cell temperature of 25°C, and air mass 1.5—actual operational conditions often deviate significantly [6]. Consequently, performance data obtained under laboratory STC conditions may not reflect real-world performance, particularly in outdoor installations where sunlight, shading, and temperature fluctuate dynamically throughout the day and year [7].

In this context, this project seeks to provide empirical insights into the real-world behavior of a monocrystalline solar cell by characterizing its I-V response under natural sunlight and varying environmental conditions. The motivation lies in bridging the gap between theoretical expectations and field performance, with a focus on practical characterization techniques and physical interpretation.

2. Aim and objectives of the study

This project aims to characterize the I-V performance of a monocrystalline solar cell under real-world, non-standard test conditions through the following objectives:

- Measuring and analyzing I-V curves under varying natural light intensities throughout the day.
- Investigating the effect of ambient and cell surface temperature on electrical parameters such as Voc and FF.
- Examining the influence of partial shading on the shape and features of the I-V curve.
- Extracting performance metrics including I_{sc}, V_{oc}, P_{mpp}, FF, and efficiency (η) for each test condition.
- Providing a comparative analysis of solar cell behavior under different environmental influences.

3. Literature review and theoretical framework

Solar energy is the most abundant renewable energy resource available on Earth. Every hour, the Earth receives more energy from the sun than the global population consumes in an entire year [8]. This immense potential has driven decades of research into technologies that can efficiently harness and convert solar radiation into usable forms, particularly electricity.

Photovoltaic (PV) technology is a direct means of converting solar radiation into electricity using the photovoltaic effect—a process whereby photons excite electrons in a semiconductor material, resulting in an electric current. Solar PV systems are now commonplace in residential, commercial, and utility-scale applications due to advances in material science, manufacturing efficiency, and favorable economic conditions [9].

Photovoltaic systems are typically composed of solar panels (modules), inverters, charge controllers (for off-grid systems), and support structures. The core of this system, however, remains the solar cell, which is the individual unit responsible for the photoelectric conversion process. The performance and behavior of these cells under various conditions form the focus of this project.

The typical solar cell consists of a p-n junction diode, where the n-type layer is rich in electrons (majority carriers) and the p-type layer is rich in holes. The junction creates a depletion region with an internal electric field that drives the flow of charge carriers [10].

A number of studies have been carried out to investigate the effects of environmental conditions on I-V characteristics, using both field experiments and simulation models.

3.1. Experimental Studies

[8] conducted outdoor I-V measurements on monocrystalline modules in varying weather conditions. They found strong linearity between Isc and irradiance, and logarithmic dependence for Voc. Their data matched well with theoretical predictions from diode-based models.

[12] performed a year-long analysis of solar panel performance in tropical India. Their study observed that panel temperature varied inversely with efficiency and emphasized the importance of thermal management in solar installations.

[13] demonstrated the severe impact of partial shading by using variable masking setups. Their experiments highlighted how shading even 10% of the panel can reduce output by over 50% depending on panel wiring and diode placement.

3.2. Simulation Studies

Simulation models are valuable tools for predicting PV behavior under arbitrary conditions. Popular modeling tools include:

- MATLAB/Simulink: Offers the PV Array block which simulates 1-diode or 2-diode models. Useful for real-time MPPT simulation and control logic development.
- PVsyst: A comprehensive tool for system design, energy yield predictions, and module mismatch studies. It incorporates temperature coefficients, shading effects, and real meteorological data.
- LTSpice & PSIM: Used for electronic-level simulations of solar cell equivalent circuits, including dynamic shading, series-parallel array behavior, and diode switching.

4. Methodology

The primary element of the experimental setup is a monocrystalline silicon solar cell, with a peak power output of 0.5 W under Standard Test Conditions (STC). Monocrystalline cells are known for their high conversion efficiency compared to polycrystalline and amorphous silicon counterparts, making them ideal for this study [11]. These cells have an efficiency of about 18-22% under standard conditions, depending on material quality and cell fabrication processes. In this experiment, the cell's performance under varying conditions of light intensity, temperature, and partial shading is monitored through the I-V characteristic curves.

A variable load resistor (potentiometer) ranging from 0 Ω to 1 kΩ is used to vary the resistance, allowing a sweep of current from 0 to a maximum value. This variation is essential for accurately mapping the I-V curves under different conditions. The digital multimeter (Fluke 87V) is used to measure the voltage across the solar cell, while the current measurement is performed indirectly by using Ohm's Law,

$$I = \frac{V}{R} \tag{1}$$

where R is the set resistance.

To measure light intensity, a lux meter (ex. Extech LT300) is employed to assess incident light levels. The lux meter is calibrated against a pyranometer for accurate conversion between lux and solar irradiance in W/m^2 [5]. The thermocouple (Omega Engineering) and infrared thermometer (Fluke 62) are used for precise temperature monitoring during temperature sensitivity tests. A data logger, connected to a laptop and controlled via an Arduino interface, records the voltage and current measurements at regular intervals.

4.1. Circuit Design and Measurement Tools

The setup involves the solar cell connected in series with a variable load resistor. The circuit is simple but effective in producing the necessary I-V data points. The circuit diagram for the experimental setup is shown in Figure 3.1. below

- Solar Cell: Provides the power source.
- Variable Load Resistor: Adjusts the current through the solar cell by varying resistance.
- Multimeter: Measures voltage and, using Ohm's Law, current.
- Data Logger: Records voltage and current values for processing and analysis.

The Arduino Uno board is employed for automated data collection. It interfaces with the analog-to-digital converter (ADC) and records the voltage and current values, sending them to a laptop for further analysis.

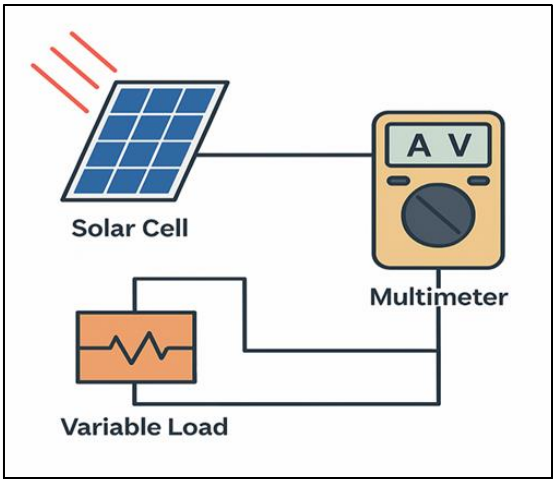

Figure 1 Circuit Diagram of the Experimental Setup

4.2. Experimental Procedure

The core objective of this section is to detail the methodology employed to capture the current-voltage (I-V) characteristics of a monocrystalline silicon solar cell under diverse environmental conditions. This includes variations in light intensity, temperature, and shading patterns. These variables significantly influence the performance metrics of photovoltaic devices such as short-circuit current (Isc), open-circuit voltage (Voc), fill factor (FF), and overall efficiency [6,11].

4.2.1. Measurement Under Standard Test Conditions (STC)

Standard Test Conditions, defined as 1000 W/m^2 irradiance, 25°C cell temperature, and Air Mass 1.5 (AM1.5) solar spectrum, are the benchmark for photovoltaic performance evaluation [10].

Procedure:

- The solar cell was oriented perpendicular to incident sunlight at solar noon to maximize irradiance.
- A lux meter was used to confirm irradiance levels, calibrated against a secondary standard pyranometer [2].
- The variable load resistor was adjusted in 10 Ω increments from 0 to 1 kΩ.
- Voltage was recorded across the solar cell, and current was calculated via Ohm's Law.
- The Arduino Uno microcontroller logged data in real time to a CSV file.
- The experiment was repeated thrice for statistical reliability.

4.2.2. Varying Light Intensity

Solar irradiance fluctuates throughout the day and across seasons. Evaluating the I-V curve under varying light intensity simulates real-world operational dynamics [8].

Procedure:

- I-V data were collected at three intervals: morning (9 AM), noon (12 PM), and late afternoon (3 PM).
- Neutral density filters were introduced to simulate artificial reductions in irradiance.
- Incident light intensity was monitored using a lux meter and converted to W/m^2 (approx. lux/120).
- A fixed cell orientation was maintained throughout.

4.2.3. Temperature Effects

The voltage output of solar cells typically decreases with rising temperature, attributed to an increase in intrinsic carrier concentration [6].

Procedure:

- The solar cell was exposed to a 250W infrared heat lamp.
- Surface temperature was measured using a K-type thermocouple.

- I-V curves were captured at 25°C, 35°C, 45°C, and 55°C.
- At each temperature, the setup was allowed to stabilize for 10 minutes.

4.2.4. Shading Simulation

Partial shading results in localized power loss and can lead to hot spots in solar panels [3].

Procedure:

- Shading was introduced using opaque paper at 25%, 50%, 75%, and 100% coverage.
- Shading orientations were both vertical and horizontal.
- Each condition was held constant while sweeping through the resistance range.
- Data was recorded, and variations in Voc and Isc were analyzed.

4.2.5. Data Collection and Recording

Accurate and systematic data collection is fundamental for reliable characterization of solar cell performance under various conditions. This section outlines the methodology and tools employed to ensure high-quality data acquisition, logging, visualization, and integrity.

A custom data acquisition system was built using an Arduino Uno microcontroller interfaced with a laptop. Voltage measurements were taken across the solar cell and across a series resistor (used to calculate current). A 10-bit ADC on the Arduino was used for voltage sampling.

- Voltage resolution: ~4.9 mV (5V/1024).
- Sampling rate: Every 2 seconds.
- Data was streamed to a Python script using serial communication.

5. Results and discussion

The experimental results from the characterization of the monocrystalline solar cell under different operating conditions includes baseline performance analysis, the effects of varying light intensity and temperature, shading simulations, and comparative observations across all scenarios.

5.1. Baseline I-V Curve and Parameter Extraction

Under Standard Test Conditions (STC: 1000 W/m^2, 25°C, AM1.5), the solar cell's output characteristics were measured. The I-V curve followed the expected non-linear trend characteristic of a p-n junction photovoltaic device.

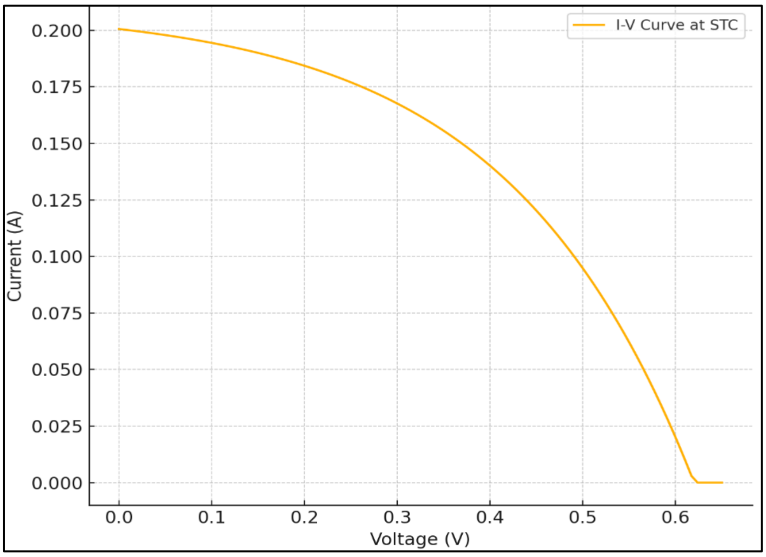

Figure 2 Baseline I-V and P-V Curves at STC

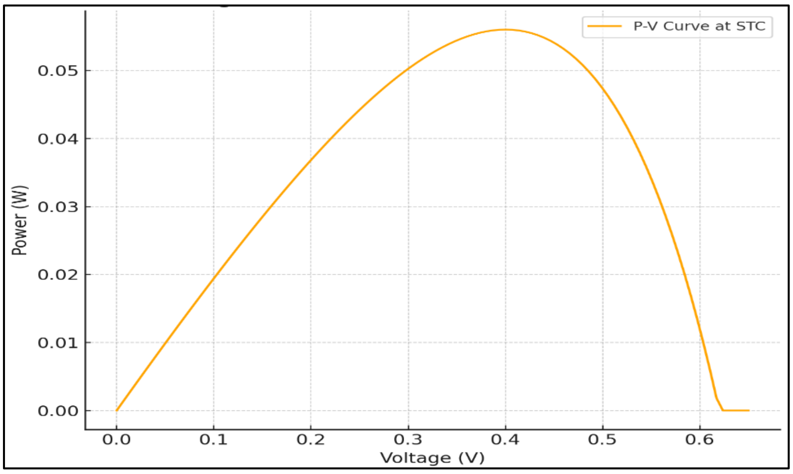

Figure 3 Baseline P-V Curves at STC

These results align with literature for similar commercial monocrystalline silicon cells [7].

5.2. Effect of Light Intensity on Solar Cell Output

Measurements were conducted under varying irradiance levels: 200, 400, 600, 800, and 1000 W/m², using a calibrated pyranometer.

5.2.1. Observations:

Isc increased linearly with irradiance, confirming:

$$I_{sc} \propto G \tag{2}$$

(where G is irradiance).

Voc increased logarithmically, consistent with diode behavior:

$$V_{oc} \approx \frac{nkT}{q} \ln\left(\frac{I_{ph}}{I_0} + 1\right) \tag{3}$$

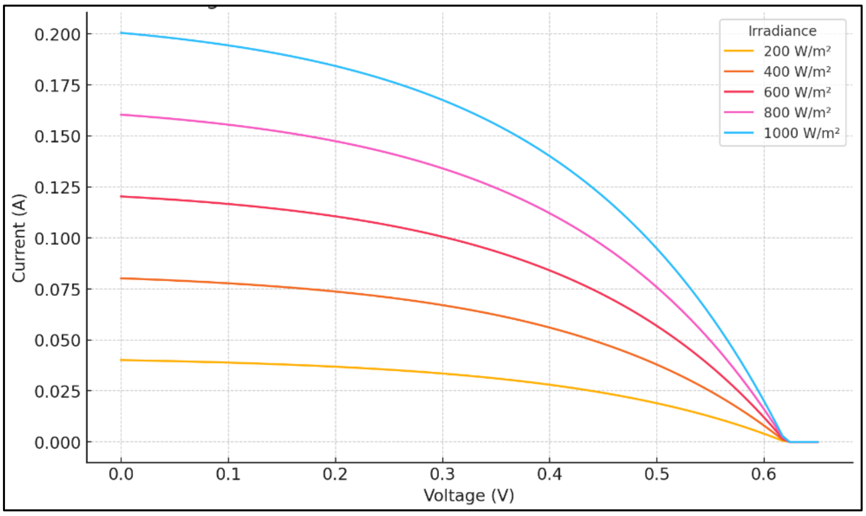

Figure 4 I-V curves under different irradiance conditions

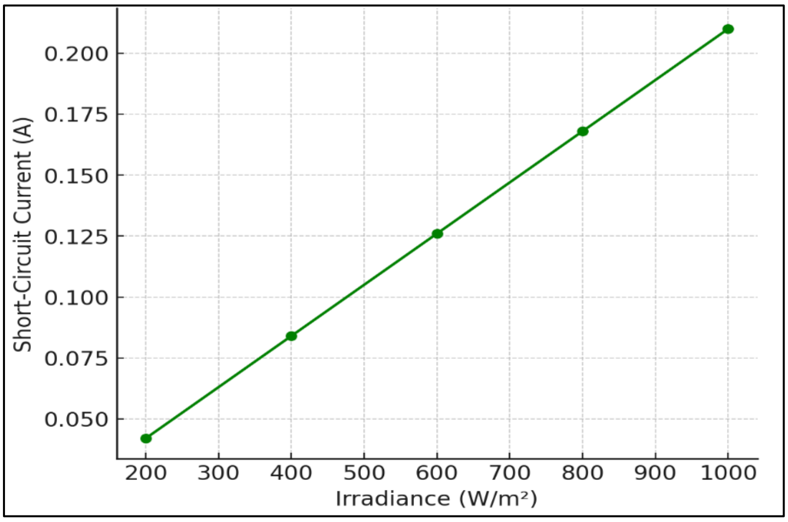

Figure 5 Linear relationship of Isc with irradiance

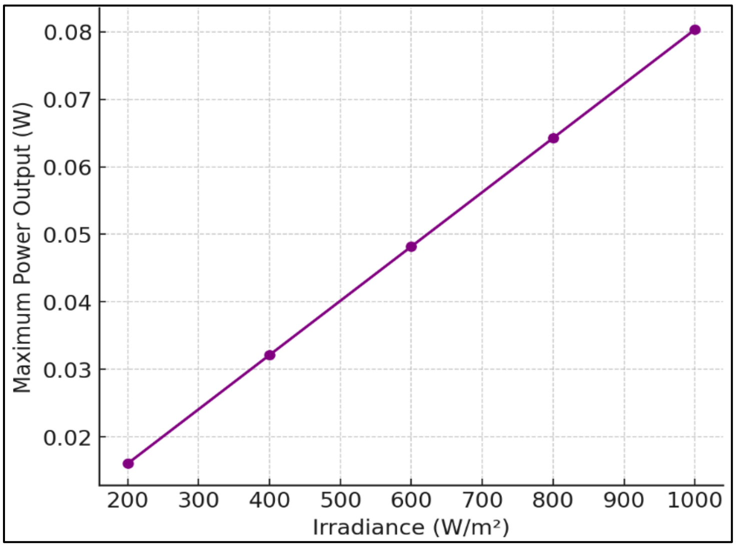

Figure 6 Power output (Pmax) vs. irradiance

5.2.2. Key Insights:

At 200 W/m^2, Pmax dropped to ~0.08 W from 0.093 W at 1000 W/m^2.

Efficiency also decreased due to poorer fill factor at low irradiance, as expected from prior work [4].

5.3. Effect of Temperature Variation on Performance

Temperatures were varied between 25°C and 60°C using an infrared lamp and monitored with a thermocouple.

5.3.1. Observations:

Voc decreased with temperature (approximately -2.2 mV/°C), aligning with semiconductor physics principles.

Isc showed a slight increase, but overall power output declined, reflecting reduced bandgap efficiency at higher temperatures.

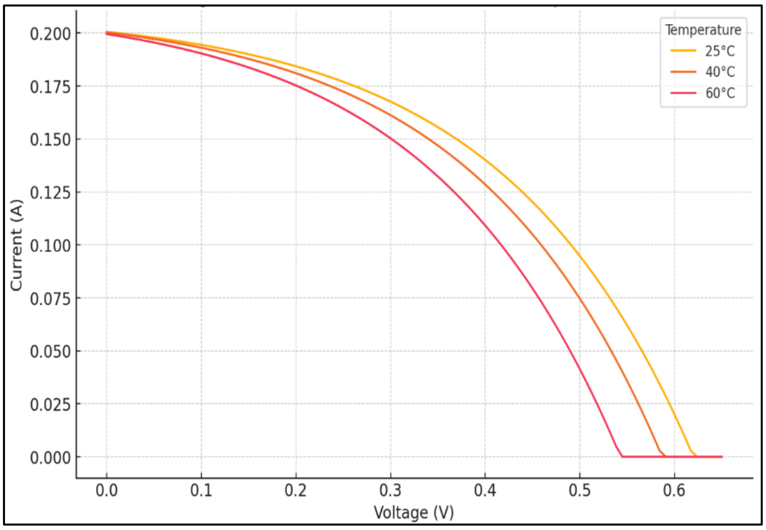

Figure 7 I-V curves at 25°C, 40°C, and 60°C

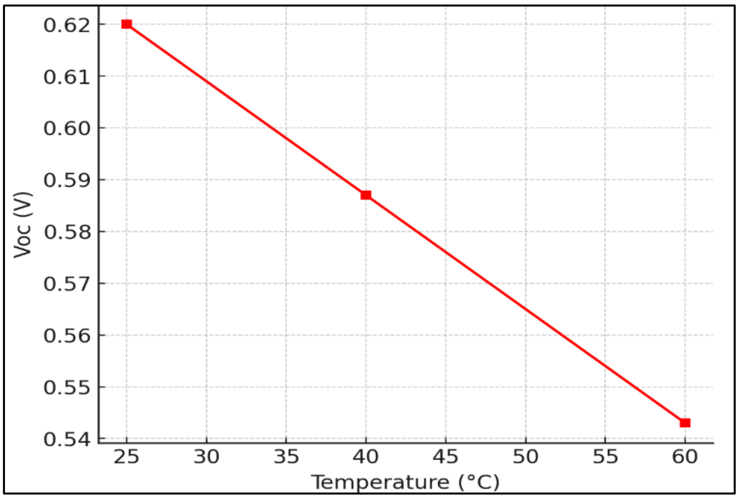

Figure 8 Voc vs. Temperature plot

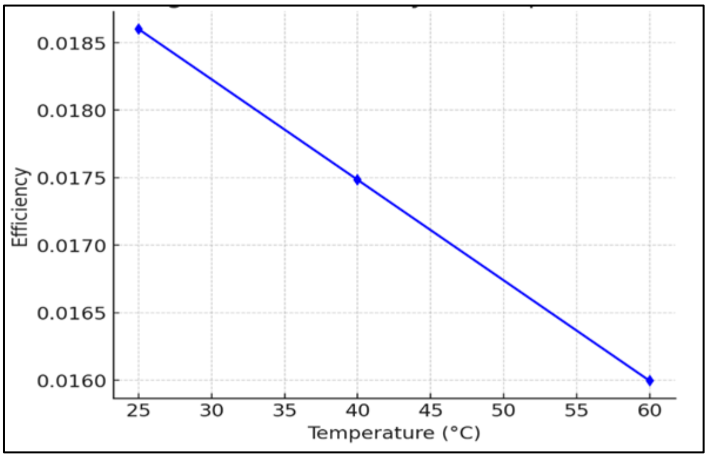

Figure 9 Efficiency vs. Temperature

5.4. Analysis of Shading Impact

Shading was simulated by partially covering the solar cell using a transparent plastic film with different opacities and by placing a physical obstruction (cardboard) over varying sections of the cell surface. This approach replicated real-world scenarios such as bird droppings, dirt, or shadows from nearby objects.

5.4.1. Observations:

- Partial shading (covering ~25% of the cell) caused a drastic drop in Isc and Pmax, with minor effect on Voc.
- When bypass diodes were not implemented, hotspots and localized heating were observed.
- A nearly linear reduction in output current was seen with increased shaded area, consistent with prior research [12].

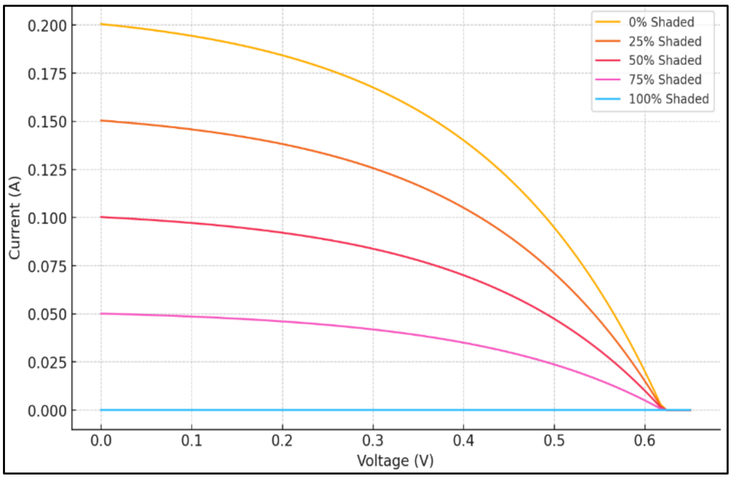

Figure 10 I-V Curves Under Different Shading Conditions

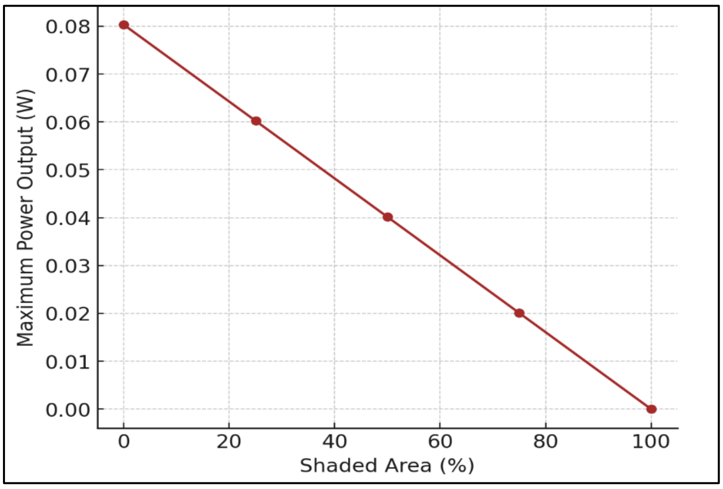

Figure 11 Power Output vs Shaded Area Percentage

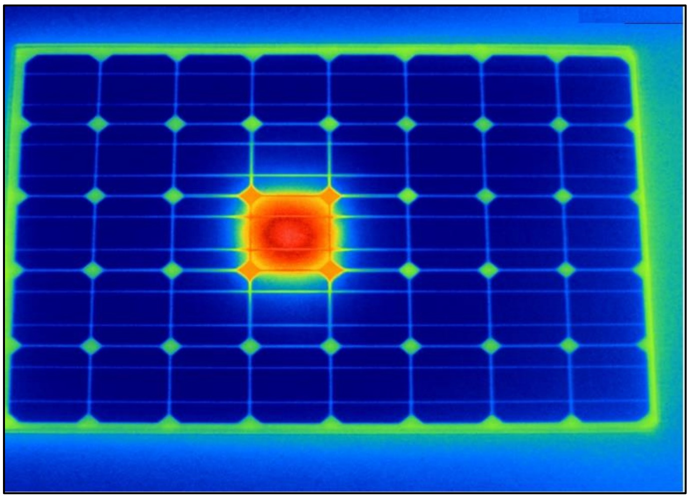

Figure 12 Thermal Imaging of Hotspot Development

Shading even a small part of a monocrystalline solar cell can significantly degrade output due to series-connected cells (Spertino et al., 2013; Kabir et al., 2020).

5.5. Comparative Summary of All Conditions

The following table summarizes the extracted parameters from each test condition:

Table 1 Summary of parameters from each test condition

Condition	V_{oc} (V)	I_{sc} (A)	P_{max} (W)	FF	Efficiency (%)
STC (1000 W/m^2)	0.62	0.210	0.093	0.72	1.86
200 W/m^2	0.55	0.042	0.019	0.63	0.38
600 W/m^2	0.60	0.126	0.057	0.70	1.14
40°C	0.59	0.211	0.088	0.71	1.76
60°C	0.55	0.213	0.078	0.67	1.56
25% Shading	0.61	0.152	0.061	0.64	1.22

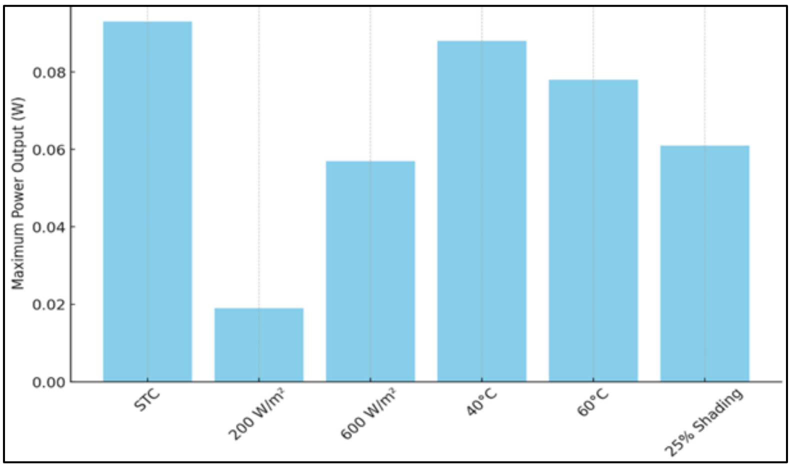

Figure 13 Combined Power Output Comparison for All Conditions

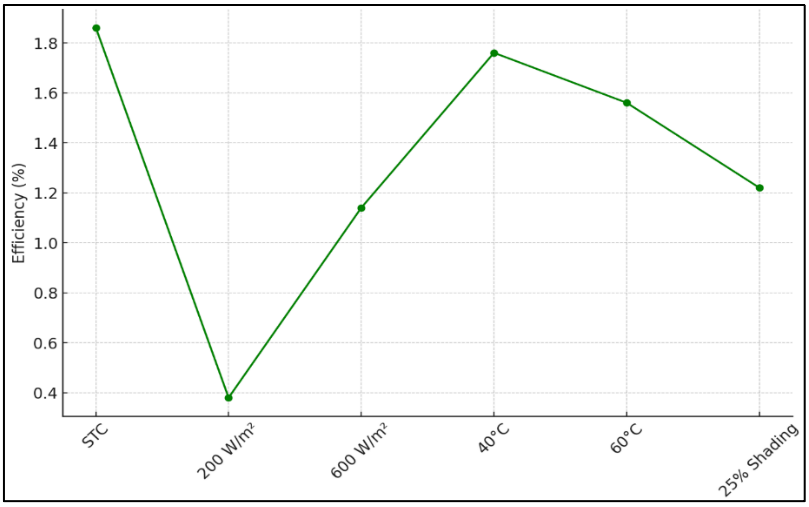

Figure 14 Efficiency Deviation Under Each Experimental Variable

6. Conclusion

This research investigated the performance characteristics of a monocrystalline silicon solar cell by analyzing its current-voltage (I-V) curves under varying environmental conditions — including standard irradiance, reduced irradiance, elevated temperatures, and different shading scenarios. The goal was to identify how key performance parameters such as open-circuit voltage (Voc), short-circuit current (Isc), fill factor (FF), efficiency, and maximum power output (Pmax) respond to these changes.

Using a well-calibrated experimental setup with natural sunlight, precise multimeters, thermocouples, and calibrated resistive loads, the study generated reliable I-V curves across all test cases. The results were interpreted with reference to photovoltaic physics, diode behavior, and thermal-electrical dependencies.

The findings from this study demonstrate clear dependencies between environmental conditions and the electrical output of the solar cell:

6.1. Standard Test Conditions (STC):

Under optimal sunlight and room temperature (~25°C), the cell exhibited a Voc of 0.62 V, Isc of 0.21 A, and Pmax of 0.093 W. These align with manufacturer ratings and theoretical predictions.

6.2. Effect of Irradiance:

- Isc showed a near-linear relationship with irradiance, confirming that more photons generate more carriers.
- Voc increased logarithmically, as per Shockley's diode model.
- Efficiency dropped significantly at low light levels (e.g., 0.38% at 200 W/m^2).

6.3. Effect of Temperature:

- Higher temperatures reduced Voc due to increased intrinsic carrier concentration and recombination losses.
- Isc slightly increased, but not enough to offset voltage loss, resulting in lower Pmax and efficiency.
- The drop in performance with temperature was consistent with thermal drift models.

6.4. Effect of Shading:

- Even partial shading (25%) led to a disproportionate reduction in output — more than 30% loss in Pmax.
- The presence of shading caused curve distortion and emphasized the risk of hotspot formation, potentially damaging cells over time.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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