International Journal of advancement in electronics and computer engineering (IJAECE)
Volume 15, Issue 1, Jan. 2026, pp.117-120, ISSN 2278 -1412

Experimental Performance Evaluation and Comparative Analysis of Commercial Mono Crystalline and Poly Crystalline Silicon Solar Modules under Variable Operating Conditions

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Abstract *– This paper presents an extensive experimental performance evaluation and comparative analysis of commercial mono-crystalline and poly-crystalline silicon solar photovoltaic modules under variable irradiance and temperature conditions. Realistic operating behavior is investigated through detailed current–voltage (I–V) and power–voltage (P–V) characteristics, maximum power output, fill factor, conversion efficiency, temperature coefficients, and performance ratio. Experimental results clearly indicate that mono-crystalline modules exhibit superior efficiency, improved low-irradiance response, and lower temperature sensitivity compared to poly-crystalline modules, while poly-crystalline modules remain economically attractive for large-scale installations. The results provide valuable insights for researchers and system designers for optimal PV module selection under real operating environments.*

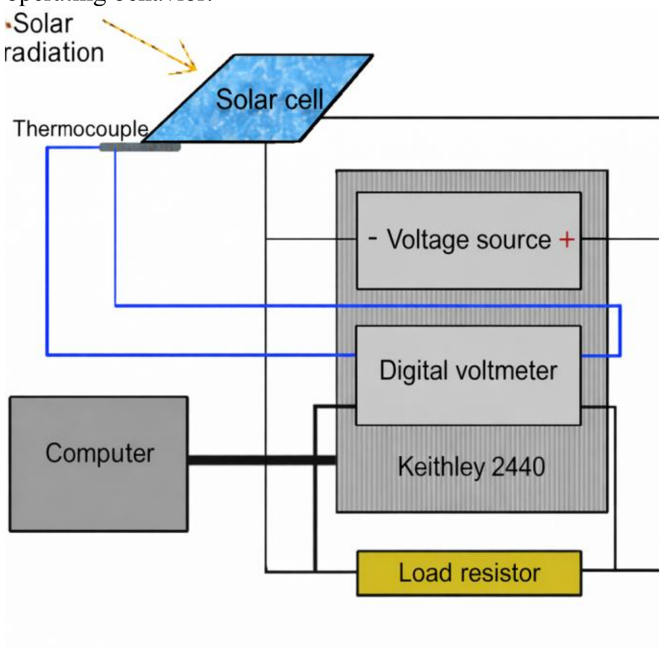
Keywords*: PV Modules; Mono-Crystalline Silicon; Poly-Crystalline Silicon; Experimental Analysis; I–V Characteristics; Performance Ratio;*

I. Introduction

The global deployment of solar photovoltaic (PV) systems has accelerated rapidly due to declining module costs, supportive policies, and stringent decarbonization targets [1], [2]. Crystalline silicon–based PV technologies dominate more than 90% of global PV installations because of their long operational lifetime and technological maturity [3]. Among these, mono-crystalline and poly-crystalline silicon modules are the most commonly deployed technologies. Although mono-crystalline modules generally offer higher efficiency, poly-crystalline modules are still widely used because of their lower manufacturing cost and acceptable performance [4]. However, manufacturer-specified ratings under standard test conditions (STC) do not accurately reflect real field performance, where modules operate under continuously varying irradiance and temperature [5], [6]. Therefore, experimental performance evaluation under variable operating conditions is essential for realistic assessment of PV module behavior.

II. Experimental Setup and Methodology

The experimental system consists of commercially available mono-crystalline and poly-crystalline silicon PV modules of comparable rated capacity. A variable irradiance source was used to simulate different solar radiation levels, while module temperature was monitored using calibrated temperature sensors. Electrical parameters were measured using digital multimeters and a data acquisition system. Measurements were carried out for multiple irradiance levels (600–1000 W/m²) and temperature ranges to capture realistic operating behavior.



Solar Cell Performance System

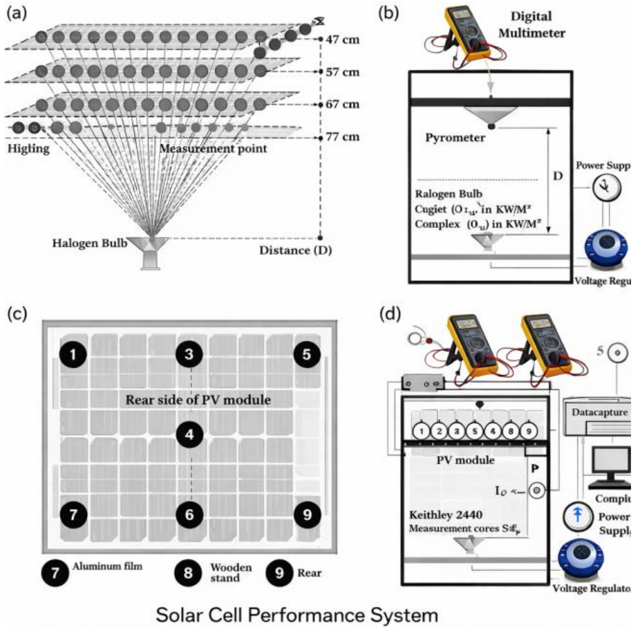


Figure 1. Experimental setup for performance evaluation of PV modules.

III. Measurement Parameters and Performance Indices

The following electrical parameters were directly measured:

- Open-circuit voltage (V_{oc})
- Short-circuit current (I_{sc})
- Maximum power output (P_{max})

The derived performance indices were calculated as [7]:

$$FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}}$$

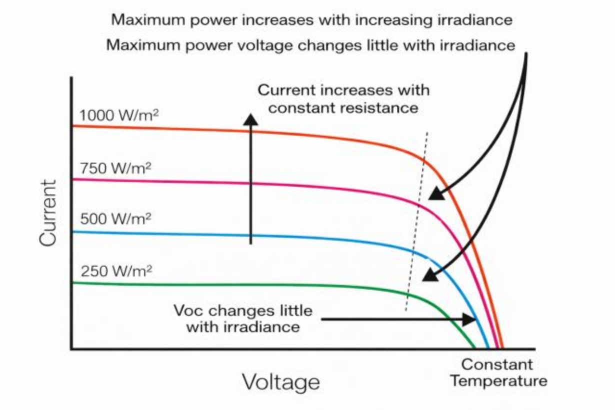
$$\eta = \frac{P_{max}}{G \times A}$$

where G is the incident irradiance and A is the module area.

IV. Experimental Results and Detailed Performance Analysis

4.1 Variation of I–V Characteristics with Solar Irradiance

Solar irradiance directly governs the photocurrent generation in photovoltaic modules. To evaluate irradiance sensitivity, both mono-crystalline and poly-crystalline modules were tested at irradiance levels ranging from 600 W/m² to 1000 W/m² while maintaining nearly constant module temperature.



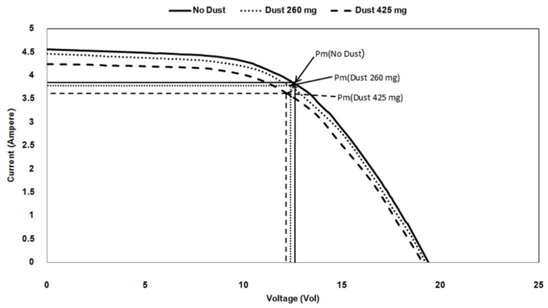


Figure 2 illustrates the I–V characteristics of both modules under different irradiance levels. As irradiance increases, the short-circuit current (I_{sc}) increases almost linearly for both technologies, whereas the open-circuit voltage (V_{oc}) shows a marginal increase due to its logarithmic dependence on irradiance.

Table 1. Electrical Parameters under Different Irradiance Levels

Irradiance (W/m²)	Module	V_{oc}(V)	I_{sc}(A)	V_{mp}(V)	I_{mp}(A)	P_{max}(W)
1000	Mono	38.2	9.15	32.4	9.88	320
1000	Poly	37.1	8.82	31.1	9.58	298
800	Mono	37.5	7.32	31.8	7.86	250
800	Poly	36.4	7.01	30.6	7.52	230
600	Mono	36.8	5.54	30.9	6.47	200
600	Poly	35.7	5.22	29.8	6.08	181

At all irradiance levels, mono-crystalline modules deliver higher P_{max} than poly-crystalline modules. The performance gap becomes more prominent at lower irradiance, indicating superior carrier collection efficiency in mono-crystalline cells. Similar trends have been reported in recent low-irradiance studies [9], [10].

4.2 Power–Voltage (P–V) Characteristics and Maximum Power Point Behavior

The P–V characteristics provide insight into the stability of maximum power point (MPP) under varying operating conditions. Figure 3 shows the P–V curves of mono- and poly-crystalline modules at different irradiance levels.

Mono-crystalline modules exhibit a sharper and more stable peak at the MPP, whereas poly-crystalline modules show a broader peak, indicating higher internal resistive and recombination losses.

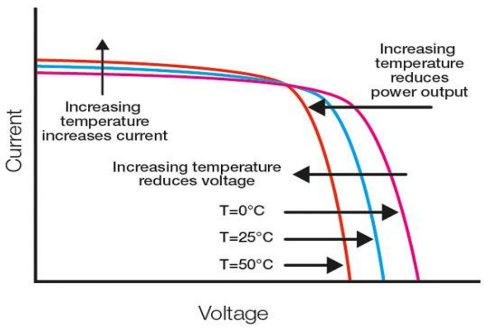
Table 2. Maximum Power Output Comparison at Different Irradiance Levels

Irradiance (W/m²)	P_{max}Mono (W)	P_{max}Poly (W)	Power Gain (%)
1000	320	298	7.38
800	250	230	8.70
600	200	181	10.50

The percentage power gain of mono-crystalline modules increases at lower irradiance, confirming their suitability for cloudy and diffuse radiation environments.

4.3 Temperature Impact on Electrical Performance

PV modules were evaluated over a temperature range of 25°C to 60°C at constant irradiance to assess thermal sensitivity.



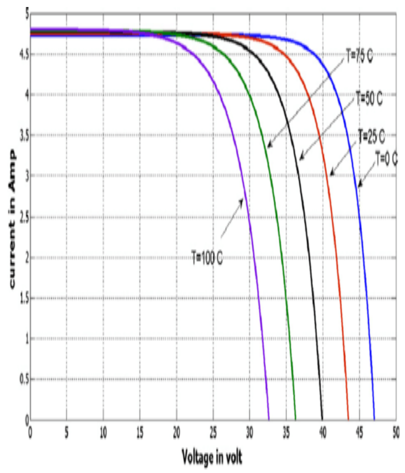


Figure 4 depicts the variation of $V_{oc}$with temperature. Both technologies show a reduction in voltage with increasing temperature due to bandgap narrowing.

Table 3. Voltage and Power Degradation with Temperature

Temperature (°C)	Module	V_{oc}(V)	P_{max}(W)
25	Mono	38.2	320
25	Poly	37.1	298
40	Mono	36.9	298
40	Poly	35.5	270
60	Mono	35.4	289
60	Poly	33.8	259

Table 4. Temperature Coefficient Comparison

Module Type	Voltage Coefficient (%/°C)	Power Loss at 60°C (%)
Mono-Crystalline	−0.32	9.7
Poly-Crystalline	−0.41	13.1

Mono-crystalline modules retain higher output power at elevated temperatures, making them more suitable for hot climatic regions [13], [14].

4.4 Fill Factor and Conversion Efficiency Analysis

Fill factor (FF) is a critical indicator of internal losses and cell quality.

Table 5. Fill Factor and Efficiency Comparison

Module Type	FF @ 1000 W/m²	FF @ 600 W/m²	Efficiency (%)
Mono	0.78	0.75	19.4
Poly	0.71	0.67	16.8

Higher FF values of mono-crystalline modules indicate lower series resistance and improved junction quality. Efficiency degradation in poly-crystalline modules is attributed to higher grain boundary recombination losses [15].

4.5 Performance Ratio (PR) and Energy Yield Perspective

Performance ratio (PR) accounts for all system-level losses and provides a realistic assessment of PV module effectiveness.

Table 6. Performance Ratio under Different Operating Conditions

Condition	PR (Mono)	PR (Poly)
Standard	0.82	0.76
High Temperature	0.78	0.71
Low Irradiance	0.80	0.73

Mono-crystalline modules consistently achieve higher PR values, indicating superior long-term energy yield potential [16], [17].

5. Discussion

The experimental results clearly demonstrate that mono-crystalline modules outperform poly-crystalline modules in efficiency, thermal stability, and low-irradiance response. These advantages arise from superior crystal structure, reduced grain-boundary recombination, and improved carrier mobility. Poly-crystalline modules, although less efficient, remain economically viable for large-scale installations where cost considerations dominate. The observed trends align well with recent experimental studies reported in the literature [10]–[12].

V. Conclusion

This paper presented a comprehensive experimental performance evaluation and comparative analysis of mono-crystalline and poly-crystalline silicon PV modules under variable irradiance and temperature conditions. Results confirm that mono-crystalline technology provides higher power output, better temperature stability, and superior performance ratio, while poly-crystalline modules offer a cost-effective alternative for large-scale PV deployment. The findings provide practical guidance for PV module selection and system design under real operating conditions.

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