

# Performance Characterization and Comparative Evaluation of Commercial Mono Crystalline and Poly Crystalline Silicon Solar Modules

Anuj Kumar Singh<sup>1</sup>, Ashish Bhargava<sup>2</sup>

<sup>1</sup>M. Tech Scholar, Dept. of EEE, BHABHA University, Bhopal M. P, anuj Singh5741@gmail.com, India

<sup>2</sup>Asso. Prof., Dept. of EEE, BHABHA University, Bhopal M. P, ashi.sonali12@gmail.com, India

**Abstract** – Solar photovoltaic (PV) technology plays a crucial role in the global transition toward sustainable and low-carbon energy systems. Among various photovoltaic technologies, mono-crystalline and poly-crystalline silicon solar modules dominate the commercial market due to their technological maturity, reliability, and economic feasibility. However, the performance of these modules is strongly influenced by crystal structure, solar irradiance, operating temperature, and intrinsic material losses. This paper presents a comprehensive performance characterization and theoretical comparative evaluation of commercial mono-crystalline and poly-crystalline silicon solar modules. The study systematically investigates solar radiation geometry, photovoltaic conversion principles, electrical modeling of PV cells, irradiance and temperature effects, loss mechanisms, degradation behavior, and long-term performance indicators. Analytical expressions for key performance parameters such as open-circuit voltage, short-circuit current, fill factor, efficiency, and performance ratio are discussed in detail. The comparative analysis provides valuable insights for researchers, system designers, and policymakers regarding optimal photovoltaic technology selection under diverse environmental and operational conditions.

**Keywords:** Solar Photovoltaic, Mono-Crystalline Silicon, Poly-Crystalline Silicon, PV Modeling, Performance Characterization, Renewable Energy;

## I. Introduction

The rapid growth in global energy demand and increasing environmental concerns have intensified the deployment of renewable energy technologies worldwide. Solar photovoltaic energy has emerged as one of the most promising renewable solutions due to its abundance, scalability, and continuous reduction in cost per watt [1]. Recent global energy outlooks indicate that solar PV is expected to become the largest source of electricity generation by 2050 [2]. Crystalline silicon photovoltaic technologies dominate the commercial PV market, accounting for more than 90% of installed capacity [3]. Among these, mono-crystalline and poly-crystalline silicon solar modules are the most widely adopted technologies. Although both technologies are based on silicon semiconductor material, their electrical and thermal performances differ significantly due to variations in crystal structure, defect density, and carrier recombination mechanisms [4], [5]. Accurate performance characterization of PV modules is essential for predicting energy yield, optimizing system design, and improving economic viability. While experimental studies provide practical insights, theoretical and analytical performance modeling is equally important for understanding fundamental performance-limiting factors beyond standard test conditions [6]. Therefore, this paper focuses on a comprehensive theoretical comparison of mono-crystalline and poly-crystalline silicon solar modules.

## II. Solar Radiation Geometry and Irradiance Modeling

The electrical output of a photovoltaic module is directly proportional to the solar irradiance incident on its surface. Solar irradiance varies with geographical location, time of day, season, and atmospheric conditions [7]. Consequently, an accurate understanding of solar radiation geometry is a prerequisite for realistic performance assessment of PV modules.

Solar radiation incident on a PV surface is governed by several geometric parameters, including latitude angle ( $\phi$ ), declination angle ( $\delta$ ), hour angle ( $\omega$ ), solar altitude angle ( $\alpha$ ), and solar zenith angle ( $\theta_z$ ). These angular parameters collectively determine the direction and intensity of solar radiation reaching the module surface.

The latitude angle ( $\phi$ ) represents the angular position of the observation point on the Earth's surface relative to the equatorial plane. The declination angle ( $\delta$ ) is defined as the angular displacement of the sun from the Earth's equatorial plane and varies throughout the year due to the axial tilt of the Earth. The hour angle ( $\omega$ ) describes the angular displacement of the sun from the local meridian as a function of solar time.

The declination angle is expressed as [7]:

$$\delta = 23.45 \sin \left[ \frac{360}{365} (284 + n) \right]$$

where  $n$  is the day of the year.

The hour angle is given by:

# solar Radiation Geometry

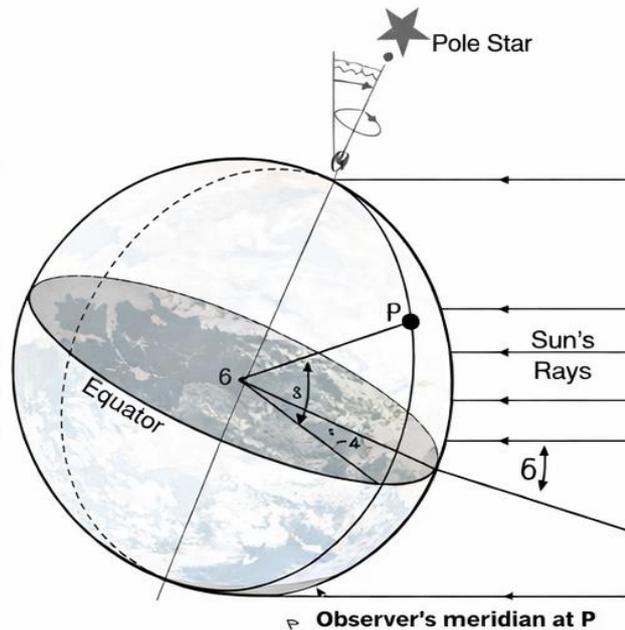
## Latitude or Angle of latitude ( $\phi$ ):

The *latitude angle* is the **angle** between a line drawn from a point on the **earth's** surface to the center of the earth and the earth's equatorial plane.

## Declination angle ( $\delta$ ):

If a line is drawn between the center of the earth and the sun, the angle between this line and the **earth's** equatorial plane is called the *declination angle* ( $\delta$ ).

$$\delta = 23.45 \times \sin[(3600/365)(284+n)] \text{ degrees}$$



**Hour angle ( $\omega$ ):** is the angular distance between the meridian of the observer and the meridian whose plane contains the Sun.

$$\omega = [T_s - 12:00] \times 15, \text{ where } \omega = \text{Hour Angle (Degrees)},$$

$T_s$  = Solar time (+ve in afternoon and -ve in forenoon since at solar noon the hour angle is zero)

**Solar altitude angle ( $\alpha$ ):** is defined as the angle between the central ray from the Sun, and its projection on horizontal plane containing the obs-

**Solar zenith angle ( $\theta_z$ ):** is the angle between the Sun ray and the normal to the horizontal plane.

**Solar azimuth angle ( $\gamma_s$ ):** measured clockwise angle from true north to the projection of the Sun ray on the horizontal plane.

**Solar azimuth angle ( $\gamma_2$ ):**  $\gamma_s$  measured clockwise angle from true north to the projection of the Sun ray on the horizontal plane.

**Solar azimuth angle ( $\gamma_1$ ):** is measured clockwise  $\gamma_e$  from true north to the projection of the Sun ray on the horizontal plane.

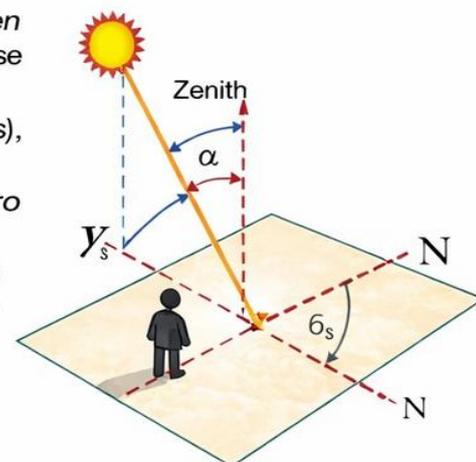


Figure 1 Illustrates the solar radiation geometry used for photovoltaic performance analysis.

$$\omega = (T_s - 12) \times 15$$

where  $T_s$  represents solar time in hours.

The solar zenith angle, which directly determines the effective irradiance intensity on the PV module surface, is calculated as:

$$\cos \theta_z = \sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega$$

Higher solar zenith angles correspond to reduced effective irradiance due to increased atmospheric path length. Recent studies have emphasized the role of air mass ratio in PV performance analysis, showing that increased air mass leads to higher atmospheric attenuation and altered spectral distribution of sunlight [8]. Mono-crystalline modules generally demonstrate improved spectral response under high air-mass conditions compared to poly-crystalline modules due to superior carrier collection efficiency [9].

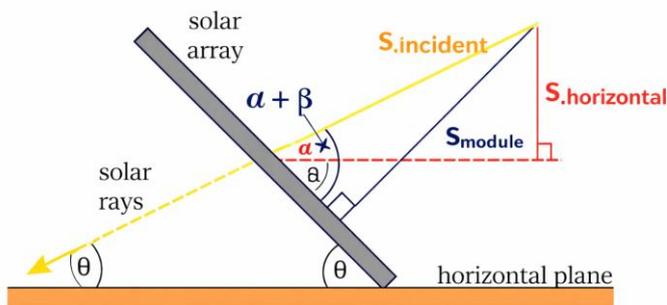
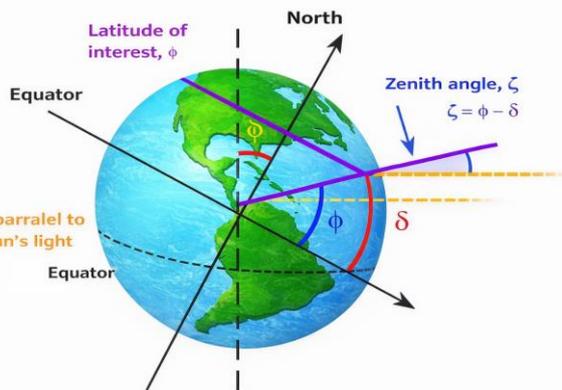
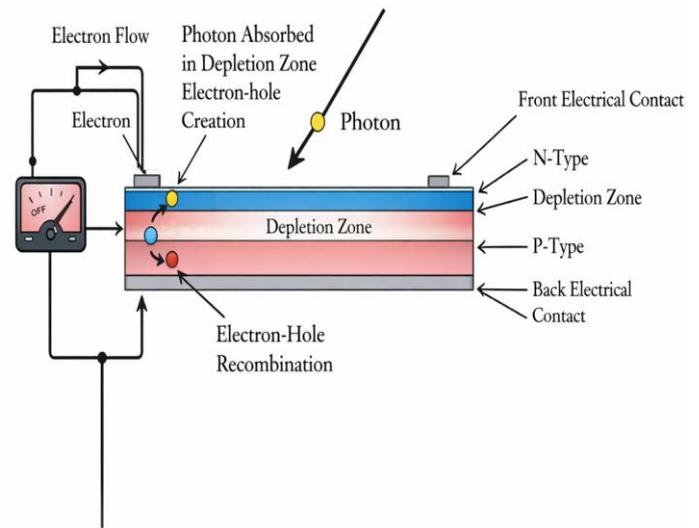


Figure 2 Solar radiation geometry illustrating declination angle, hour angle, and solar zenith angle. The declination angle represents the angular position of the sun relative to the Earth's equatorial plane and varies seasonally. The hour angle defines the sun's apparent movement across the sky due to Earth's rotation. The solar zenith angle determines the effective irradiance

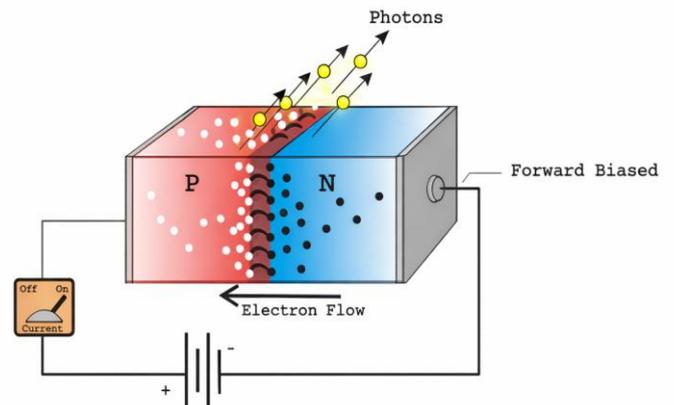
intensity incident on the PV module surface. Recent studies have emphasized the role of air mass (AM) ratio in PV performance analysis. Higher air mass values increase atmospheric attenuation, reducing irradiance intensity and altering spectral distribution [8]. Mono-crystalline modules generally demonstrate improved spectral response under high air mass conditions compared to poly-crystalline modules due to superior carrier collection efficiency [9].

### III. Fundamental Principles of Photovoltaic Energy Conversion

Photovoltaic energy conversion is based on the photovoltaic effect occurring in semiconductor p-n junctions. When photons with energy greater than the semiconductor bandgap are absorbed, electron-hole pairs are generated within the depletion region [10].



### How an LED Works



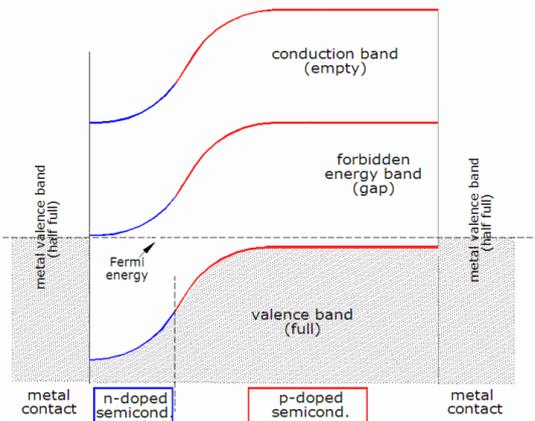


Figure 3 Structure of a p-n junction solar cell and photovoltaic effect.

The built-in electric field across the depletion region separates charge carriers, producing a photocurrent when an external circuit is connected. The output voltage is governed by the separation of quasi-Fermi levels for electrons and holes under illumination. Carrier recombination mechanisms and bandgap energy play a critical role in determining conversion efficiency, particularly under elevated temperature conditions [11].

#### IV. Electrical Modeling of Photovoltaic Cells

The electrical behavior of a photovoltaic cell is commonly represented using the single-diode equivalent circuit model, which balances modeling accuracy and computational simplicity [12].

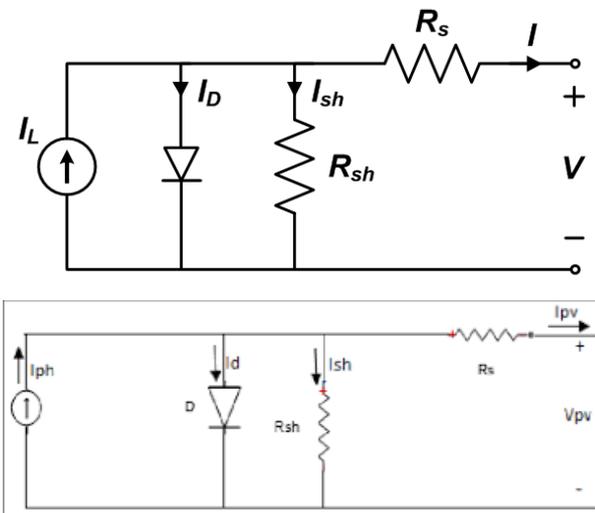


Figure 4 Equivalent circuit model of a photovoltaic cell. The output current-voltage relationship is given by:

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

where  $I_{ph}$  is the photocurrent,  $I_0$  is the diode saturation current, and  $R_s$ ,  $R_{sh}$  represent series and shunt resistances, respectively. Recent analytical studies show that series resistance significantly affects fill factor and

maximum power output degradation in commercial PV modules [13].

#### V. Crystal Structure and Material Properties of Silicon Solar Cells

Mono-crystalline silicon solar cells are fabricated from a single continuous crystal lattice, resulting in minimal grain boundaries and reduced recombination losses. This structural uniformity enhances carrier mobility and efficiency [14]. In contrast, poly-crystalline silicon cells consist of multiple grains separated by grain boundaries, which act as recombination centers and increase resistive losses [15].

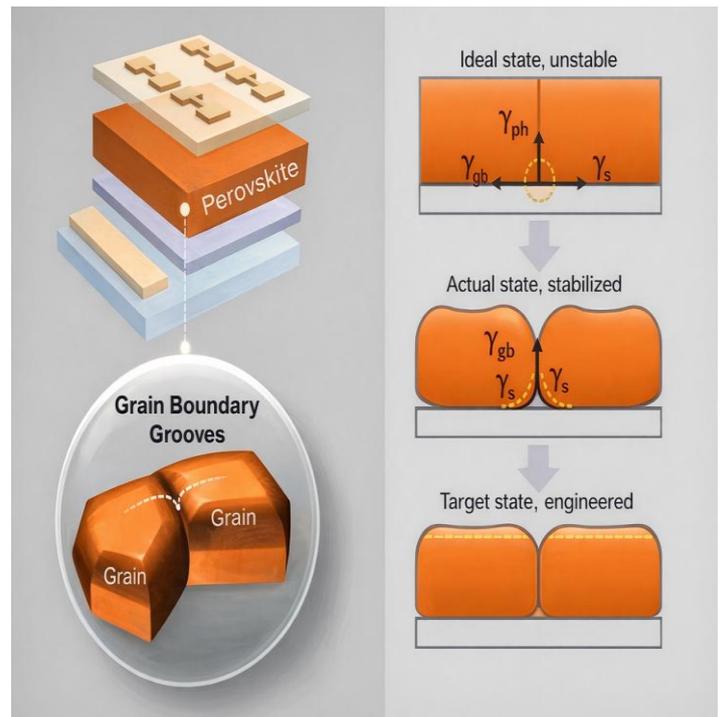
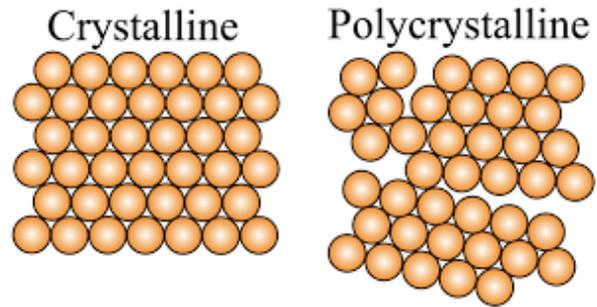


Figure 5 Crystal structure comparison of mono-crystalline and poly-crystalline silicon solar cells.

Recent comparative studies confirm that mono-crystalline modules outperform poly-crystalline modules under low-irradiance and high-temperature operating conditions [16].

#### VI. Effect of Solar Irradiance on Module Performance

Solar irradiance primarily influences the short-circuit current of PV modules. As irradiance increases, photon

flux increases, resulting in a nearly linear rise in photocurrent [17]. In contrast, open-circuit voltage exhibits a logarithmic dependence on irradiance.

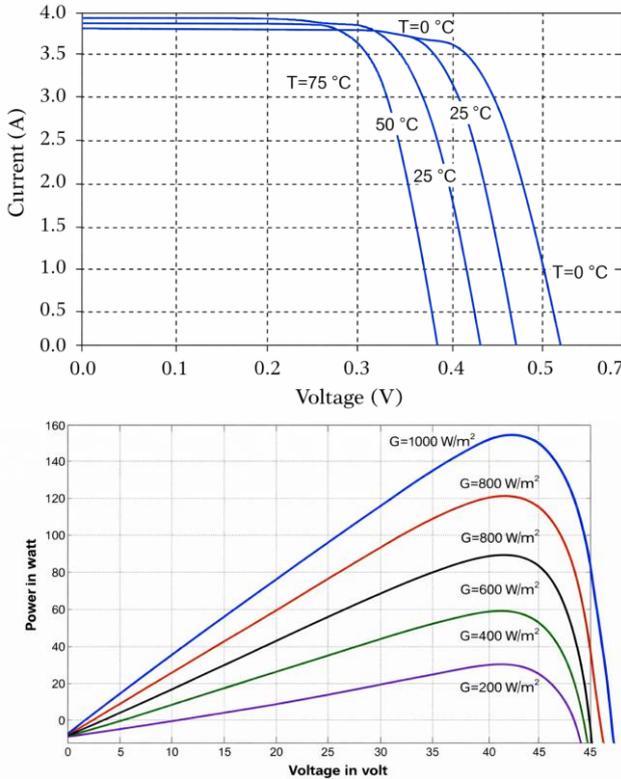


Figure 6 Influence of solar irradiance variation on PV module characteristics. Mono-crystalline modules generally maintain higher efficiency under low-irradiance conditions, making them suitable for regions with high diffuse radiation components.

### VII. Temperature Dependence of PV Module Characteristics

Operating temperature has a significant impact on PV module performance. An increase in temperature reduces open-circuit voltage due to bandgap narrowing, resulting in decreased power output [18].

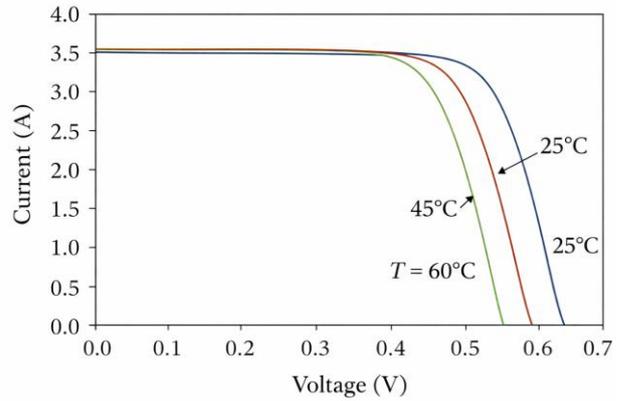
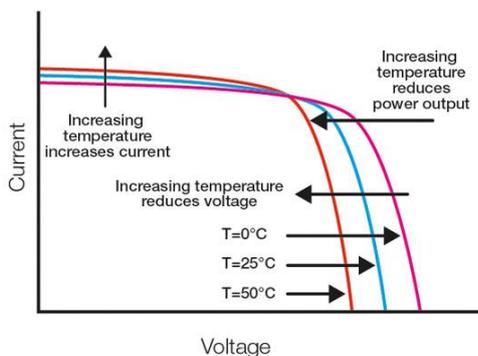


Figure 7 Temperature effect on PV module electrical characteristics.

Mono-crystalline modules exhibit lower negative temperature coefficients compared to poly-crystalline modules, making them preferable for hot climatic regions [19].

### Loss Mechanisms in Silicon Photovoltaic Modules

Losses in PV modules include optical losses, electrical losses, and thermal losses. Optical losses arise from surface reflection and shading, while electrical losses originate from series resistance, shunt leakage, and carrier recombination [20].

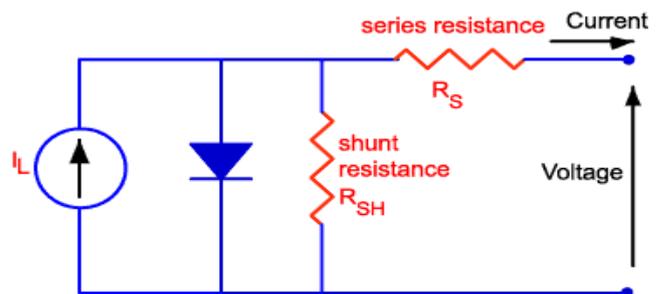
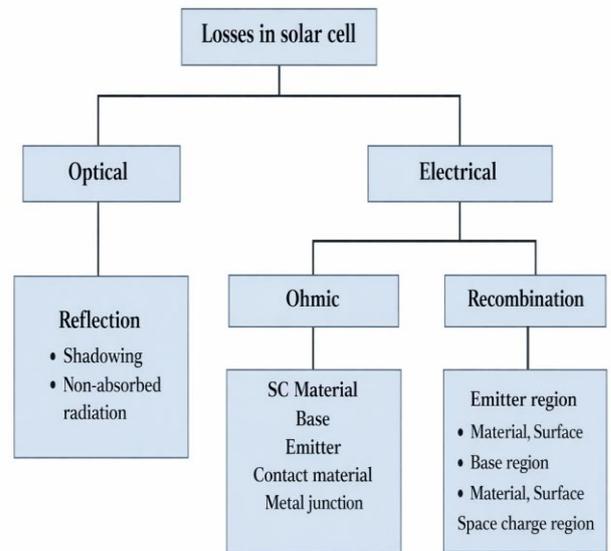


Figure 8 Major loss mechanisms in silicon photovoltaic modules.

### Mathematical Formulation of Performance Parameters

Key performance indices such as fill factor and efficiency are defined as:

$$FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}}$$
$$\eta = \frac{P_{max}}{G \times A}$$

where  $G$  is incident irradiance and  $A$  is module area. Mono-crystalline modules generally exhibit higher fill factor due to lower internal resistive losses [21].

### Long-Term Degradation and Reliability Considerations

Photovoltaic modules experience gradual performance degradation due to environmental stress factors such as thermal cycling, UV exposure, and humidity ingress [22]. Mono-crystalline modules generally demonstrate better long-term stability owing to superior material quality, while poly-crystalline modules may exhibit higher degradation rates under harsh conditions [23].

### Performance Ratio and Energy Yield Perspective

Performance ratio (PR) provides a realistic measure of PV system effectiveness by accounting for all system losses. Studies show that mono-crystalline modules achieve higher PR values compared to poly-crystalline modules under similar operating conditions [24].

## VIII. Conclusion

This paper presented a comprehensive performance characterization and comparative evaluation of mono-crystalline and poly-crystalline silicon solar modules. The analysis covered solar radiation modeling, photovoltaic conversion principles, electrical modeling, material properties, environmental influences, and long-term performance considerations. The results indicate that mono-crystalline modules offer superior efficiency, thermal stability, and low-irradiance performance, while poly-crystalline modules remain a cost-effective option for large-scale installations. The findings provide a strong theoretical foundation for experimental validation and future photovoltaic research.

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