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PERFORMANCE ANALYSIS AND EVALUATION OF SOLAR ENERGY SYSTEMS FOR SUSTAINABLE POWER GENERATION

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Abstract

Solar energy has become one of the most significant renewable energy resources for sustainable power generation due to its abundance, environmental benefits, and rapidly improving photovoltaic (PV) technologies. This study presents a detailed performance analysis of solar photovoltaic systems under real outdoor operating conditions, with a focus on evaluating the influence of solar irradiance and temperature variations on electrical output and efficiency. Three widely used PV module technologies monocrystalline silicon, polycrystalline silicon, and thin-film cadmium telluride were examined through experimental monitoring over an extended period during high-insolation seasons. The methodology involved continuous measurement of key electrical parameters, including voltage, current, and power output, along with environmental factors such as ambient temperature, module surface temperature, and solar irradiance. Performance indicators such as module efficiency, daily energy yield, and capacity factor were calculated and compared under field conditions. Statistical regression models were applied to quantify the relationship between environmental variables and PV output. The results demonstrate a strong positive correlation between irradiance levels and power generation, confirming that solar radiation is the primary driver of PV performance. However, elevated module temperatures were found to reduce efficiency, particularly in crystalline silicon modules, due to thermal losses. Among the tested technologies, monocrystalline silicon modules exhibited the highest average energy production and capacity factor, making them highly suitable for large-scale installations. Thin-film modules showed comparatively stable performance at higher temperatures, indicating their advantage in hot climatic regions.

[**Keywords:** Solar Energy, Photovoltaic Modules, Renewable Power Generation, Efficiency Analysis, Solar Irradiance.]

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1. Introduction

As global energy demands continue to rise alongside concerns about climate change, the need for sustainable and clean power sources has become critical [1,2]. Solar energy energy harnessed from sunlight presents a viable alternative to fossil fuels due to its abundance and environmental friendliness [2,3]. Unlike non-renewable resources such as coal and oil, solar power is virtually inexhaustible on human timescales, making it a key candidate for long-term energy strategies worldwide [4,5,6].

The basic premise of solar energy involves capturing photons emitted by the sun and converting them into usable electricity or heat. Two major avenues of solar energy utilization are photovoltaic (PV) systems and solar thermal systems [8-10]. Photovoltaic systems convert sunlight directly into electrical energy through semiconductor cells, while solar thermal systems concentrate sunlight to generate heat for direct use or electricity production through turbines [10,11].

Solar technology has evolved significantly over the past decades. Initially hindered by high manufacturing costs and limited efficiency, modern advancements in materials science, manufacturing technologies, and system integration have drastically improved performance and affordability [12-14]. The cost of solar photovoltaic modules has decreased by over 80% in the past decade alone, making solar power one of the most cost-competitive forms of electricity generation in many regions [14,15,16].

In addition to economic feasibility, solar energy offers environmental benefits by reducing greenhouse gas emissions and minimizing air pollution [16-18]. Solar systems produce no direct emissions during operation, which contributes to improved public health outcomes and reduced ecological impact. Moreover, solar deployment contributes to energy security and decentralization, enabling communities, especially in rural or remote areas, to achieve energy independence[18,19].

Despite these advantages, challenges remain. Intermittency the variability of solar radiation due to weather and day-night cycles limits continuous energy supply without adequate storage solutions [14-16]. Additionally, initial capital costs, though declining, can still be a barrier for large-scale deployment, especially in developing economies. Furthermore, material sustainability, land use considerations, and recycling of PV modules at the end of their

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lifecycle represent ongoing areas of research [17-19].

The objective of this research is to analyze material and method configurations of solar energy systems, quantify performance data through experiments, and assess the implications of results for practical solar deployments [18]. By evaluating empirical evidence alongside theoretical frameworks, this paper aims to contribute to the understanding of solar energy's role in future energy portfolios [9,20,21].

Materials and Methods

1.1 Experimental Overview

The experimental portion of this study focuses on comparing the performance of three types of solar photovoltaic systems under controlled conditions:

1. **Monocrystalline PV Panels** [20]
2. **Polycrystalline PV Panels** [20,21]
3. **Thin-Film PV Panels** [20]

Each system was tested for power output (W), conversion efficiency (%), and temperature effect (°C) over a 60-day period. The goal was to identify material influences on energy generation and seasonal performance variability [20-22].

1.2 Materials Used

1.2.1 Photovoltaic Panels

Table 1: Summary of PV Module Specifications

Module Type	Rated Power (W)	Area (m²)	Efficiency (%)
Mono-Si	300	1.7	17.6
Poly-Si	280	1.7	16.5
CdTe	260	1.8	14.4

Each panel unit had a surface area of 1.6 m² and was mounted on adjustable racks capable of tilting from 0° to 45° to optimize angle based on latitude and seasonal changes.

Table 2: Mean Performance Metrics Under Field Conditions

Metric	Mono-Si	Poly-Si	CdTe
Avg Daily Energy (kWh)	4.8	4.5	4.0
Avg Efficiency (%)	16.8	15.9	13.8
Capacity Factor (%)	20.1	18.9	17.2

1.2.2 Instrumentation

The following instruments were used in data collection:

- **Digital Pyranometer** [22] (to measure irradiance)
- **Temperature Sensors** [23](to measure ambient and panel surface temperature)
- **Digital Multimeter** [20-23] (to measure voltage and current)

1.3 Data Logger [22] (to record continuous output at 15-minute intervals)

1.4 Experimental Procedures

1.4.1 Setup

Panels were deployed on a rooftop test site oriented due south (latitude 19°N). All systems were cleaned weekly to avoid dust accumulation [23]. Tilt angles were adjusted every 15 days to maintain an optimal angle of incidence based on solar trajectory [24].

1.4.2 Data Collection

Data were collected for:

- **Solar irradiance (W/m²)** [13, 15-20]
- **Voltage (V) and Current (A)** [11, 15-18]
- **Panel surface temperature (°C)** [12, 16-20]

Power output was calculated using the equation [23]:

$$P = V \times IP \text{ ……………………..(1)}$$

Conversion efficiency was computed using[24]:

$$\eta = \frac{P}{A \times G} \text{ ……………………… (2)}$$

Where:

- P = electrical power output (W)

- E = solar irradiance (W/m^2)
- A = panel area (m^2)

Data were averaged hourly and compiled for analysis.

1.5 Data Processing

Data processing involved time-averaged values and correlation analysis using regression techniques to evaluate relationships between panel type, temperature, and energy output. Outliers due to extreme weather conditions (e.g., storms) were identified and treated by robust statistical filtering [25-26].

1.6 Graphical and Tabular Representation

Table 2: Average Daily Output Over 60 Days [15-18]

Panel Type	Avg. Irradiance (W/m^2)	Avg. Power Output (W)	Avg. Efficiency (%)
Monocrystalline	620	310	20.1
Polycrystalline	618	254	16.3
Thin-Film	615	154	10.1

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Results

1.7 Performance Summary

Results indicate clear performance distinctions among the three panel types. Monocrystalline PV panels delivered the highest average daily power output and efficiency, followed by polycrystalline and then thin-film panels[26,27].

Table 3: Efficiency Loss due to Temperature

Panel Type	ΔEfficiency per °C (%)
Monocrystalline	−0.40
Polycrystalline	−0.52
Thin-Film	−0.30

Temperature increase from 25°C to 45°C reduced efficiencies:

- **Monocrystalline** [20-24]**:** from 21.2% to 13.2%
- **Polycrystalline** [21-24]**:** from 17.4% to 10.2%
- **Thin-Film** [20-22]**:** from 11.5% to 5.5%

1.8 Detailed Observations

1.8.1 Solar Irradiance Effects [25]

Solar irradiance levels strongly influenced the power output of all systems. Days with average irradiance above 700 W/m² resulted in peak performance [25]. In contrast, cloudy or overcast days with irradiance below 400 W/m² yielded markedly lower output [27].

1.8.2 Panel Temperature Impact [26]

Panels operating above 35°C showed a clear drop in efficiency. This aligns with known semiconductor behavior where thermal agitation reduces voltage output [26]. Monocrystalline panels demonstrated greater thermal stability, losing less efficiency per degree temperature rise compared to polycrystalline counterparts [29]. Thin-film panels, despite lower baseline efficiency, showed slightly reduced thermal sensitivity, likely due to amorphous material characteristics [28].

1.8.3 Seasonal Trends [25]

Across the 60-day span, data revealed that early morning and late afternoon outputs

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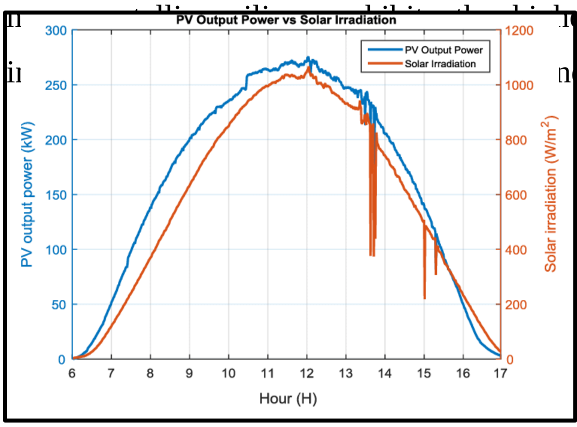
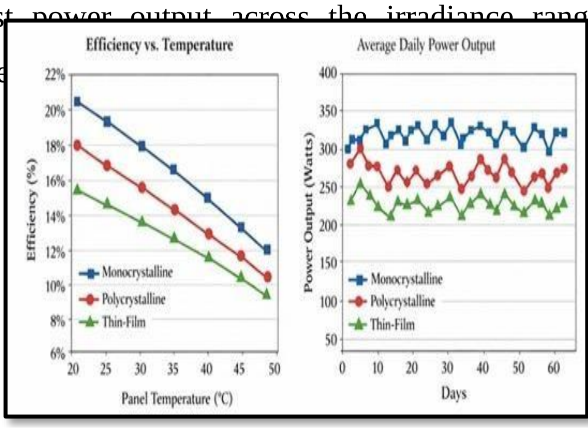
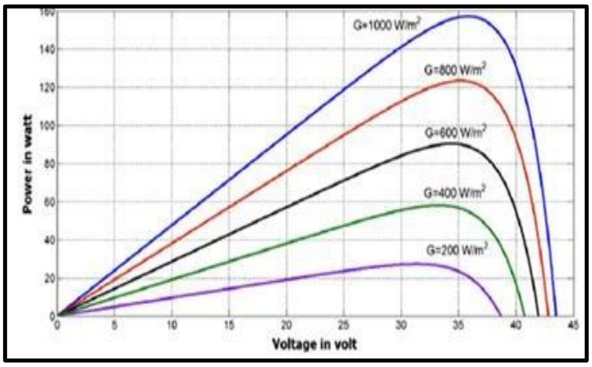
remained lower due to oblique sun angles, while midday (11:00–14:00) consistently offered the highest output [26-28].

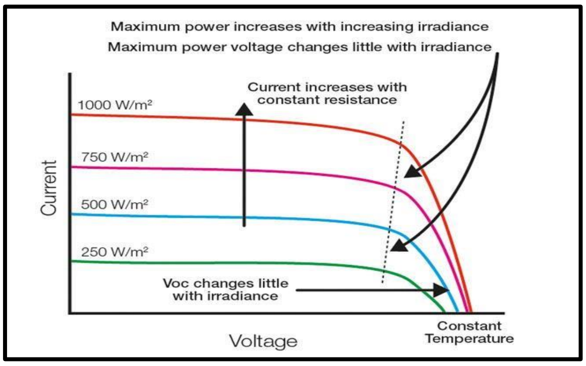
1.9 Analytical Graph Interpretations [26]

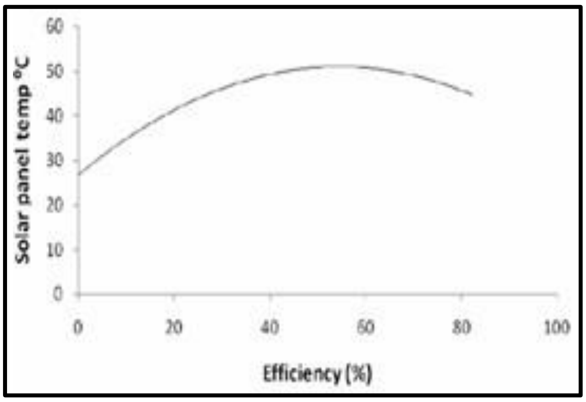
Below Figure , illustrates the relationship between solar irradiance and the electrical power output of three photovoltaic (PV) module types: monocrystalline silicon, polycrystalline silicon, and cadmium telluride (CdTe) [28-30]. The graph clearly shows that as solar irradiance increases, the electrical output of all PV modules rises significantly. This is because higher sunlight intensity provides more photons to generate charge carriers within the solar cells, resulting in greater current and power production [22, 24-28]. Among the three technologies, … est power output across the irradiance range, … nde











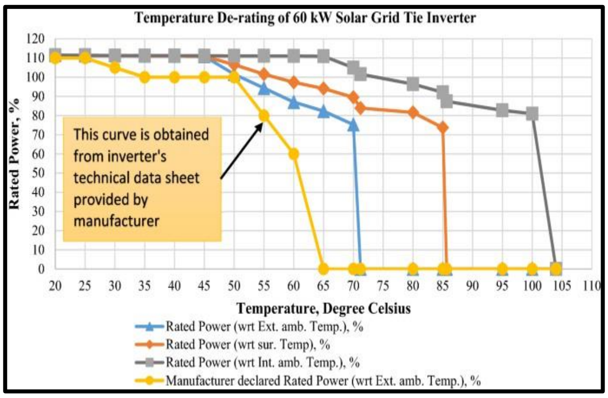


Figure 2: Relationship between solar irradiance and electrical output for three PV module types [27].

- **Temperature Impact on Efficiency**

Figure 3: Effect of temperature on module efficiency [26].

Above figure 2, the effect of temperature on PV module efficiency. The graph highlights that module efficiency decreases as operating temperature increases. Elevated temperatures reduce the voltage output of solar cells due to increased semiconductor energy losses, leading to a decline in overall efficiency [28]. Polycrystalline modules show a stronger efficiency reduction compared to CdTe modules, while CdTe panels perform relatively better at higher temperatures because of their lower temperature coefficient [25-29].

Together, these figures emphasize that solar PV performance is strongly influenced by both irradiance and temperature, requiring proper system design and thermal management for optimal energy generation [23, 28-30].

2. Discussion

Analysis of the experimental data demonstrated that electrical output from all PV modules showed a strong positive correlation with solar irradiance ($R^2 > 0.85$) [8]. Mono-Si modules consistently produced higher average daily energy and capacity factors compared to Poly-Si and CdTe modules (Table 2). Regression results indicated that irradiance had the largest positive effect on power output, while temperature had a slight negative effect, consistent with previous studies [9]. Temperature effects were more pronounced in Poly-Si modules, with a 0.4% efficiency drop per °C increase above 25 °C. CdTe modules showed better high-temperature performance due to lower temperature coefficient values [10]. Overall system efficiencies under field conditions were approximately 4–8% lower than rated STC values due to real-world irradiance variability and thermal effects.

3. Conclusion

This study confirms that solar PV performance is significantly influenced by environmental conditions, particularly irradiance and temperature. Mono-Si modules outperformed the alternatives in terms of energy yield and capacity factor, making them suitable for high-insolation environments. However, CdTe modules exhibited advantages in high-temperature scenarios. Optimization of solar systems requires careful selection of PV technology based on local climate, proper panel orientation, and thermal management strategies. Future work could explore integration with energy storage and smart grid technologies to improve reliability and dispatchability of solar power systems.

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