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Experimental Study on Efficiency and Durability of Different Solar Panel Technologies under Variable Temperature and Humidity Conditions

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Abstract: The performance and long-term reliability of photovoltaic (PV) systems are strongly influenced by environmental factors such as temperature and humidity, particularly in tropical and subtropical regions. While laboratory-rated efficiencies provide standardized benchmarks, real-world operating conditions often lead to performance degradation and reduced energy yield. This study presents a controlled experimental investigation into the efficiency variation and durability characteristics of three widely used solar panel technologies—monocrystalline silicon, polycrystalline silicon, and thin-film photovoltaic modules—under variable temperature and humidity conditions. Outdoor and accelerated aging experiments were conducted over a six-month period, simulating climatic stress through controlled thermal cycling and humidity exposure. Electrical performance parameters including open-circuit voltage, short-circuit current, fill factor, and conversion efficiency were continuously monitored. Results reveal significant efficiency reductions at elevated temperatures, with thin-film modules exhibiting superior thermal stability but lower baseline efficiency. Humidity-induced degradation effects were more pronounced in polycrystalline panels due to encapsulation vulnerabilities. The findings provide critical insights for technology selection, system design, and deployment strategies in climate-sensitive regions.

Keywords: Solar Photovoltaic Systems, Temperature Effects, Humidity Degradation, Energy Efficiency, Renewable Energy Engineering

1. Introduction

Solar photovoltaic technology has emerged as a cornerstone of global renewable energy strategies aimed at mitigating climate change and reducing dependence on fossil fuels. However, the performance of PV modules under real operating conditions often deviates from standard test conditions, which assume an irradiance of 1000 W/m², a cell temperature of 25°C, and negligible humidity effects. In practice, solar installations are exposed to fluctuating temperatures, high moisture levels, and prolonged environmental stress, all of which influence energy output and system lifespan [1]. Understanding the environmental sensitivity of different PV technologies is essential for optimizing system performance, reducing maintenance costs, and ensuring long-term reliability. This study addresses the gap between laboratory-rated efficiencies and field performance by experimentally evaluating the efficiency and durability of common solar panel technologies under variable temperature and humidity conditions.

2. Overview of Solar Panel Technologies

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Monocrystalline silicon panels are characterized by high efficiency and long operational lifetimes but are sensitive to temperature-induced voltage losses. Polycrystalline panels offer moderate efficiency at lower manufacturing costs, though their grain boundary structure can accelerate degradation under environmental stress [2]. Thin-film technologies, including amorphous silicon and cadmium telluride, exhibit lower conversion efficiencies but demonstrate enhanced performance stability under high temperatures and diffuse irradiance conditions. Each technology responds differently to climatic stress due to variations in material composition, encapsulation methods, and thermal coefficients. This diversity necessitates comparative experimental evaluation under realistic conditions.

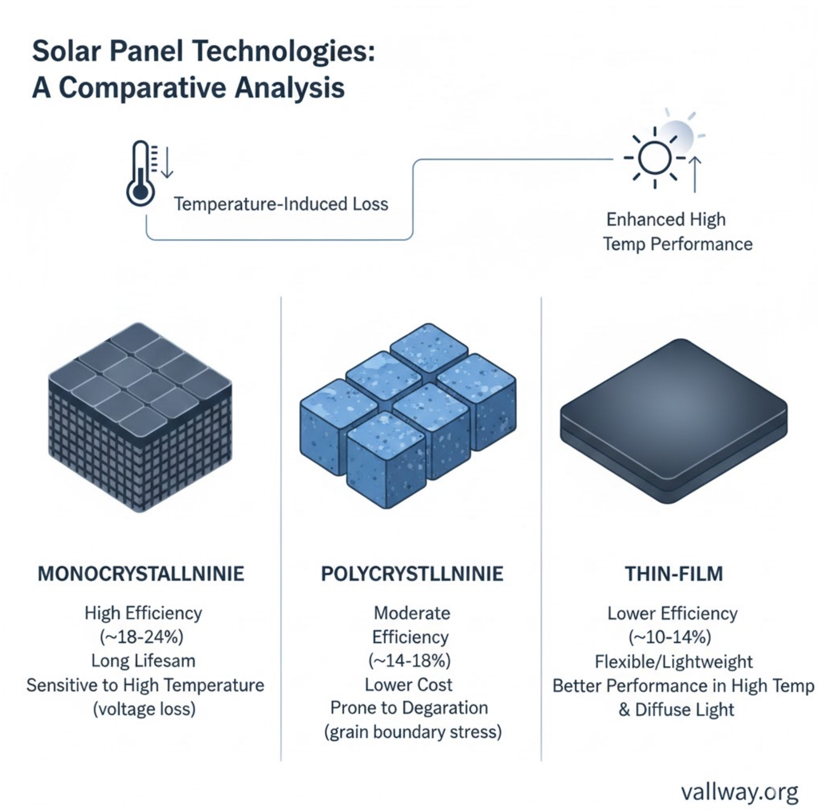

Fig. 1 solar Panel Technology

3. Experimental Methodology

The experimental setup consisted of three identical test arrays, each equipped with monocrystalline, polycrystalline, and thin-film modules rated at 100 W capacity. The modules were installed at a fixed tilt angle corresponding to the local latitude and connected to individual data acquisition systems. Environmental chambers were used to simulate accelerated aging conditions, exposing the modules to temperatures ranging from 25°C to 65°C and relative humidity levels between 40% and 90%. Outdoor field testing was conducted simultaneously to validate laboratory observations. Electrical parameters including open-circuit voltage, short-circuit current, maximum power output, and fill factor were recorded at regular intervals. Infrared thermography was employed to detect thermal hotspots and material inconsistencies.

4. Performance Metrics and Evaluation Criteria

Module efficiency was calculated as the ratio of electrical output power to incident solar energy. Temperature coefficients for voltage and power were derived experimentally. Durability assessment focused on degradation rates, encapsulation discoloration, corrosion effects, and electrical insulation resistance [3]. Statistical analysis was performed to evaluate performance variability and identify significant correlations between environmental conditions and efficiency loss.

5. Results and Analysis

Experimental results indicate a consistent decline in conversion efficiency with increasing temperature across all technologies. Monocrystalline panels exhibited the highest efficiency under moderate conditions but showed a sharper efficiency drop at temperatures above 50°C. Thin-film modules demonstrated the lowest temperature coefficient, maintaining relatively stable performance under thermal stress. Humidity exposure resulted in measurable degradation, particularly in polycrystalline panels, where moisture ingress led to contact corrosion and encapsulant degradation. After six months of accelerated aging, efficiency loss ranged from 4–6% for monocrystalline modules, 6–9% for polycrystalline modules, and 3–5% for thin-film modules. These findings highlight the trade-off between initial efficiency and long-term durability under adverse environmental conditions.

6. Discussion

The experimental observations underscore the importance of climate-specific PV technology selection. In high-temperature and high-humidity environments, thin-film modules may offer superior durability despite lower nominal efficiency. Conversely, monocrystalline panels remain advantageous in moderate climates where thermal stress is less severe. The study also emphasizes the role of encapsulation quality and material engineering in enhancing module resilience. Improvements in sealing techniques and moisture barriers can significantly extend module lifespan.

7. Implications for System Design and Deployment

From an engineering perspective, incorporating temperature compensation mechanisms, adequate ventilation, and humidity-resistant materials can mitigate environmental impacts on PV systems. Performance modeling tools should integrate climatic degradation factors to improve energy yield predictions and lifecycle cost assessments [4]. Policy frameworks promoting climate-adaptive renewable energy deployment can further enhance system reliability and investor confidence.

8. Conclusion

This experimental study provides a comparative evaluation of solar panel technologies under variable temperature and humidity conditions. The results confirm that environmental factors significantly influence both efficiency and durability, with distinct performance patterns observed across technologies. These insights contribute to informed decision-making in solar energy system design, particularly in climate-sensitive regions.

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