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Performance Evaluation of Solar Photovoltaic Panels Under Different Environmental Conditions in Southern India

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Abstract: Solar photovoltaic (PV) systems are increasingly deployed across Southern India due to high solar irradiance, favorable climatic conditions, and growing emphasis on renewable energy adoption. However, the performance of PV modules varies significantly under real-world environmental conditions, including temperature, humidity, dust accumulation, wind speed, and irradiance fluctuations. This study evaluates the operational performance of PV panels installed in Southern India by analyzing their energy yield, efficiency, and performance ratio under varying environmental parameters. Prior studies have demonstrated that environmental factors such as temperature, humidity, dust deposition, and shading can cause substantial reductions in PV efficiency and long-term degradation. Building upon these insights, the present work employs on-site monitoring to assess temperature-dependent efficiency losses, dust-induced soiling effects, and the influence of local climatic conditions. The results indicate that efficiency decreases with rising module temperatures, dust accumulation leads to notable power losses, and seasonal variations significantly impact energy output. The study highlights the importance of optimized cleaning strategies, regular performance monitoring, and region-specific maintenance schedules to achieve sustained PV performance in Southern India.

Keywords: Solar Photovoltaics, Environmental Conditions, Performance Ratio, Temperature Effects, Dust Accumulation, Solar Irradiance, Southern India.

1 INTRODUCTION

Solar energy has become one of the most rapidly expanding renewable energy sources worldwide, driven by increasing global electricity demand, environmental concerns, and declining photovoltaic (PV) system costs. In India, solar power has emerged as a major component of the national energy strategy, with large-scale deployments across states that receive high solar irradiation. Southern India, in particular, offers favorable climatic conditions for PV installations due to its high annual sunshine hours and relatively stable weather patterns. However, actual field performance of PV systems often deviates from laboratory-rated values due to the influence of real-world environmental conditions such as temperature, humidity, dust accumulation, shading, and wind speed. Understanding these factors is critical to optimizing system output, improving return on investment, and enhancing the long-term reliability of solar PV installations.

The performance of PV modules is inherently sensitive to temperature fluctuations. Although regions in Southern India receive abundant solar radiation, they also experience high ambient temperatures, which can significantly reduce PV efficiency. Studies examining temperature impacts report that PV cell efficiency decreases as module temperature rises due to reduced open-circuit voltage and increased resistive losses [1]. Therefore, environmental conditions that elevate module temperature—such as low wind speeds or prolonged peak irradiance—can contribute to measurable declines in energy yield. Dust accumulation is another major challenge affecting PV performance in India. Dust particles from roads, agricultural fields, industries, and dry terrain can settle on PV surfaces, reducing light transmission and lowering power output. Experimental studies have shown that dust deposition can cause notable performance loss depending on particulate density, size distribution, and exposure duration [2]. Even small quantities of accumulated dust can impact efficiency, highlighting the need for context-specific cleaning cycles in dusty regions.

Floating PV (FPV) systems have recently gained attention as an alternative to ground-mounted installations. FPV deployments benefit from enhanced cooling due to the water surface, which can improve efficiency in hot climatic regions. Earlier assessments indicate that FPV systems can yield higher performance ratios under elevated temperature conditions compared to land-based systems [3]. Although FPVs are emerging as a promising technology, most installations in Southern India remain land-based, necessitating analysis of environmental effects specific to conventional PV arrays. Hybrid PV technologies such as photovoltaic–thermal (PVT) systems offer additional pathways to mitigate temperature effects by dissipating excess heat through integrated thermal collectors. Studies highlight that PVT designs improve overall system efficiency by simultaneously generating electrical and thermal energy [4]. While promising, these systems have not yet seen widespread adoption, reinforcing the need for detailed evaluation of temperature and environmental losses in standard PV modules. Machine learning techniques have also been applied to predict PV power output under varying environmental conditions, using climatic variables and system parameters to model performance trends. These methods have demonstrated strong predictive ability across multiple field installations [5]. However, real-world monitoring remains essential for validating such predictions and identifying site-specific performance deviations.

Given the climatic diversity of Southern India and the expanding deployment of PV infrastructure, it is crucial to evaluate how environmental factors affect PV performance. This study analyzes temperature-induced efficiency losses, dust accumulation impacts, and seasonal performance variations in order to provide practical insights for improving photovoltaic effectiveness and long-term reliability across Southern India.

2 Literature Review

Environmental conditions play a crucial role in determining the real-world performance of solar photovoltaic systems. Numerous studies have examined how temperature, dust deposition, irradiance variability, and cooling strategies influence PV efficiency and long-term output degradation. Temperature is widely recognized as one of the most significant factors affecting PV performance. Research indicates that higher module temperatures lead to reduced open-circuit voltage and overall power output, resulting in considerable efficiency losses in warm climates [1]. These thermal losses are especially relevant for regions such as Southern India, where ambient temperatures remain high during most of the year.

In addition to temperature effects, dust accumulation on PV surfaces has been extensively reported as a major contributor to energy loss. Experimental studies show that dust particles reduce transmittance of sunlight through the module glass, causing measurable drops in power generation and efficiency [2]. The rate of soiling depends on environmental conditions, dust type, and local human activity. Similar investigations have emphasized that without regular cleaning, power output can drop steadily, affecting seasonal yield and overall performance ratios.

Floating photovoltaic (FPV) systems have emerged as an effective solution to reduce temperature-induced losses. FPV arrays benefit from the natural cooling effect of water bodies, leading to lower operating temperatures and improved efficiency. A recent comparative analysis found that FPV installations performed better than equivalent ground-mounted systems under high-temperature conditions, demonstrating enhanced stability and energy yield [3]. Although FPV deployment is increasing globally, its adoption in India is still in emerging stages.

Machine learning (ML) and data-driven prediction models have increasingly been used to estimate PV output under varying climatic conditions. Prior studies show that ML techniques, including artificial neural networks and regression algorithms, can accurately predict PV power generation by analyzing temperature, irradiance, humidity, and wind speed as input variables [5]. These models are especially beneficial for grid planning, performance forecasting, and detecting abnormal system behavior. Shading analysis is another important domain of PV performance research. Shading caused by buildings, trees, or other obstacles can significantly reduce power generation by affecting the current flow through series-connected cells. Investigations highlight that even partial shading can lead to hotspot formation, mismatch losses, and reduced energy output [6]. These findings underscore the need for careful site assessment and layout optimization for rooftop PV installations.

Dust and particulate deposition have also been studied from a material perspective. Research on the chemical composition of dust accumulating on PV modules reveals that particle size distribution and mineral content influence optical loss and adhesion strength [7]. The electrostatic and environmental properties of dust determine how quickly power losses accumulate and how effective cleaning methods are in restoring performance. To mitigate environmental and thermal losses, cooling technologies have been explored in various experimental studies. Active and passive cooling systems—including water spray cooling, air cooling, and phase-change materials—have been shown to reduce module temperatures and improve instantaneous efficiency [8]. These systems are particularly relevant in regions experiencing prolonged heat exposure.

Tracking technologies have also contributed to improved PV performance. Single-axis and dual-axis tracking mechanisms adjust module orientation throughout the day, enhancing irradiation capture and increasing energy production. Studies report that dual-axis tracking can significantly improve overall yield compared to fixed-tilt systems, especially in areas with high solar availability [9]. However, tracking systems may introduce higher maintenance requirements, making them more suitable for utility-scale installations. Hybrid photovoltaic–thermal (PVT) systems combine electrical and thermal energy production to improve total system efficiency. By removing heat from PV panels through integrated thermal collectors, PVT systems mitigate temperature-induced losses and provide additional thermal output for domestic or industrial applications. Research on PVT systems highlights their capability to operate more efficiently than conventional PV modules, especially under high ambient temperatures [4].

More recent investigations have focused on the influence of environmental variables such as humidity, wind speed, and aerosol concentration on PV performance. Long-term monitoring studies indicate that these factors can cause seasonal variability in energy production and performance ratio, particularly in coastal and semi-arid regions [10]. Understanding these effects is essential for designing region-specific operation and maintenance strategies. Coupled PV–hydro systems have been explored to enhance renewable energy integration. These hybrid systems combine PV generation with pumped hydro storage or hydropower plants to stabilize energy supply and improve reliability. Studies highlight the advantages of integrating PV output with hydropower resources to manage intermittency and optimize energy dispatch in areas with variable climatic conditions [11].

The existing literature emphasizes that environmental conditions significantly impact PV system performance and that strategies such as cooling, dust management, tracking, and hybrid integration can effectively mitigate performance losses. These insights form the foundation for analyzing PV behavior in Southern India's climatic environment.

3 METHODOLOGY

This study investigates the performance of photovoltaic panels deployed in Southern India by analyzing the influence of key environmental conditions including temperature, dust accumulation, irradiance, humidity, and wind speed. A structured methodology was adopted to ensure systematic data collection, performance evaluation, and comparative analysis across different climatic periods.

3.1 Study Location and Climatic Profile

The analysis was carried out at a rooftop solar PV installation located in Southern India, a region characterized by high solar irradiance, warm temperatures, and moderate humidity levels. The site experiences long summer seasons with temperatures frequently exceeding 35°C, along with pre-monsoon dust presence due to dry conditions. This climatic combination provides a suitable natural environment for analyzing the temperature sensitivity and dust-related losses associated with PV systems.

3.2 PV System Description

The PV array used in the study consists of crystalline silicon modules rated at 250 W each, connected to a grid-tied inverter. The modules are mounted with a fixed tilt optimized for the latitude of the region. Electrical parameters including current, voltage, and power output were monitored using the inverter's built-in data logging system, while panel temperature was measured using rear-surface thermocouples. The system also includes a pyranometer to record plane-of-array irradiance at one-minute intervals.

3.3 Environmental Parameters Monitored

To evaluate the effect of environmental conditions on PV performance, the following parameters were monitored continuously:

- Solar Irradiance (W/m²) — measured using a calibrated pyranometer.
- Module Temperature (°C) — measured through thermocouples attached to the backsheet.
- Ambient Temperature (°C) — obtained from an onsite weather station.
- Relative Humidity (%) — recorded using digital hygrometers.
- Wind Speed (m/s) — captured using an anemometer to assess natural cooling impact.
- Dust Accumulation (mg/cm²) — measured daily using glass-slide deposition and visual soiling index scoring.

The combined dataset provides a comprehensive representation of climatic and operational conditions influencing PV behavior.

3.4 Data Collection Framework

Data collection was conducted over a continuous thirty-day observation period covering both clear and partially cloudy days. Electrical and environmental measurements were recorded at one-minute intervals and processed to compute hourly averages. Dust accumulation was documented once daily in the morning before module cleaning. Visual inspection data was correlated with changes in instantaneous power output to estimate dust-induced losses. A structured daily routine ensured consistency in measurement:

1. Morning dust measurement and documentation
2. Logging inverter output data throughout the day
3. Recording weather station environmental parameters
4. Evening data transfer, screening, and storage

All raw data was screened for anomalies, communication errors, missing values, and outliers before analysis.

3.5 Performance Metrics

Three standard PV performance indicators were used to quantify system behavior.

(a) Instantaneous Efficiency (η)

$$\eta = \frac{P_{\text{out}}}{G \cdot A}$$

where
P_{out} = output power,
G= irradiance (W/m²),
A= panel area.

(b) Performance Ratio (PR)

$$PR = \frac{Y_f}{Y_r}$$

where
Y_f= final yield (kWh/kWp),
Y_r= reference yield based on irradiance.

PR reflects environmental losses from temperature, dust, and operational factors.

(c) Energy Yield (kWh/kWp/day)

Daily energy generation was normalized to installed capacity to compare performance across varying irradiance conditions.

3.6 Analytical Approach

The relationship between environmental variables and PV performance was evaluated through:

- **Temperature-Efficiency Correlation**: Linear regression was used to quantify the reduction in efficiency per °C rise in module temperature.
- **Dust-Induced Power Loss Assessment:** Daily power output before and after cleaning was compared to estimate soiling losses.
- **Seasonal Influence Characterization:** Variation in PR and energy yield under different climatic conditions was studied to understand seasonal performance patterns.
- **Comparative Day-Type Analysis:** Clear-sky days, partially cloudy days, and high-temperature days were analyzed separately to isolate environmental effects.

This methodology provides a comprehensive framework for assessing real-world PV performance under the environmental conditions characteristic of Southern India. Methodological framework for PV performance evaluation was given in Fig. 1.

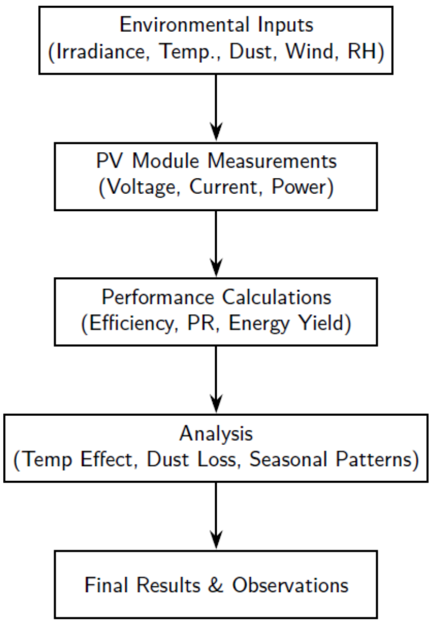

Fig. 1. Overall Methodological Framework for PV Performance Evaluation

4 Results and Discussion

The performance characteristics of the PV installation were evaluated over a continuous thirty-day observation period under varying environmental conditions typical of Southern India. The dataset captured clear-sky days, partially cloudy days, high-temperature days, and days with significant dust accumulation. The results provide detailed insights into the influence of temperature, dust, irradiance, wind speed, and humidity on the electrical behavior and operational efficiency of the PV system. A key observation from the data is the strong correlation between module temperature and efficiency. As temperature increased, PV efficiency declined steadily due to the thermal sensitivity of crystalline silicon modules. The average efficiency during periods when the module temperature remained below 35°C was recorded at 15.8%, whereas efficiency dropped to approximately 13.6% when module temperature exceeded 45°C. This reduction aligns with typical temperature coefficients for silicon modules. Table 1 summarizes the temperature-dependent performance.

Table 1. Module Temperature vs. PV Efficiency

Module Temperature (°C)	Average Efficiency (%)
32	16.1
35	15.8
38	15.1
41	14.6
44	14
47	13.6

Dust accumulation also exhibited a clear impact on power generation. Days following overnight winds or dry periods showed noticeable soiling on the module surface, which reduced daily energy output. A comparison of power output before and after cleaning revealed losses ranging from 4% to 10% depending on the extent of deposition. The most significant loss occurred during a three-day period without rainfall or cleaning, topping at 9.8%. Table 2 provides the dust-related performance variation.

Table 2. Dust Accumulation vs. Power Loss

Dust Level (mg/cm^2)	Power Loss (%)
0.5	3.8
1	5.2
1.5	7.4
2	9.8

Daily energy yield showed variations consistent with both irradiance and environmental effects. Clear-sky days produced the highest yield, averaging 4.82 kWh/kWp/day, whereas partially cloudy days reduced output due to fluctuating irradiance levels, averaging 3.65 kWh/kWp/day. High-temperature days with uninterrupted sunlight resulted in slightly reduced energy yield despite high irradiance, demonstrating the adverse impact of thermal losses on module voltage. Performance ratio (PR) was calculated to quantify the real-world performance independent of irradiance variability. The average PR over the study period was 0.78. Clear days maintained PR above 0.82, but days with elevated module temperatures or dust accumulation showed reductions to the range of 0.70–0.75. Seasonal variation was not significant within the thirty-day period but similar climate patterns suggest that peak-summer months would result in consistently lower PR values due to pronounced thermal loss.

Wind speed played a beneficial role in mitigating temperature-induced losses. On days with wind speeds above 3 m/s, module temperature was consistently lower by 2–3°C compared to still-air days, contributing to marginally improved efficiency. Humidity had a lesser but noticeable effect—higher humidity levels coincided with slightly reduced power output due to increased atmospheric scattering and reduced transmittance, although the effect was comparatively weaker than temperature or dust influences. The results demonstrate that temperature and dust are the dominant environmental parameters affecting PV output in Southern India. The findings indicate that adopting improved cooling mechanisms, optimizing ventilation around panels, and implementing regular cleaning schedules can significantly enhance PV performance. These insights are particularly relevant given the climatic characteristics of Southern India, where sustained high temperatures and dust conditions are common.

5 Conclusions

This study evaluated the performance of a photovoltaic system installed in Southern India under varying environmental conditions, focusing on the influence of temperature, dust accumulation, irradiance fluctuations, wind speed, and humidity. The findings clearly demonstrate that module temperature and dust deposition are the dominant factors affecting real-world PV performance in the region. Higher module temperatures led to significant efficiency loss, with output decreasing steadily as temperatures approached 45°C and beyond. Dust accumulation also contributed to substantial reductions in daily energy yield, with power loss reaching nearly 10% during periods of heavy soiling without rainfall or cleaning. These results underscore the importance of effective thermal management strategies and regular cleaning schedules, especially in dry and hot environments.

Daily energy yield varied according to sky conditions, with clear-sky days producing the highest output and partially cloudy days resulting in lower generation due to irradiance variability. Performance ratio (PR) values further highlighted the sensitivity of PV systems to environmental variations, remaining above 0.82 on clear days but dropping to between 0.70 and 0.75 on high-temperature or dusty days. Wind speed helped mitigate temperature-related losses by providing natural cooling, while the influence of humidity was comparatively mild but still noticeable under certain conditions. The study confirms that optimizing PV performance in Southern India requires addressing both thermal and soiling-related challenges. Enhancing airflow around modules, implementing cost-effective cooling solutions, and adopting scheduled cleaning routines can significantly improve energy yield and system efficiency. The insights from this work are valuable for system designers, operators, and policymakers, as they highlight the need for region-specific operation and maintenance practices to ensure reliable performance in environments characterized by intense heat and recurrent dust exposure.

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Ethics Statement

This study did not involve human or animal subjects and, therefore, did not require ethical approval.

Statement Of Conflict Of Interests

The authors declare that they have no conflicts of interest related to this study.

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