# Study of Solar Panel Efficiency Under Different Weather Conditions

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***Abstract :*** Solar energy has emerged as one of the most promising renewable energy sources in the 21st century, offering a sustainable solution to the world's growing energy demands. The efficiency of photovoltaic (PV) solar panels is significantly influenced by various environmental factors, particularly weather conditions. This study investigates the performance of solar panels under different meteorological conditions including varying levels of solar irradiance, temperature, humidity, wind speed, and cloud cover. The research aims to quantify the impact of these weather parameters on solar panel efficiency and provide insights for optimal solar panel deployment and operation. The methodology involves continuous monitoring of solar panel performance over a period of six months, collecting data on power output, voltage, current, and environmental parameters. Multiple types of solar panels including monocrystalline, polycrystalline, and thin-film technologies were tested to compare their performance under identical weather conditions. Data analysis reveals significant correlations between weather parameters and solar panel efficiency, with temperature and solar irradiance being the most critical factors. Results indicate that solar panel efficiency decreases with increasing temperature, with an average reduction of 0.4-0.5% per degree Celsius rise in temperature. Cloud cover significantly reduces power output, with heavy clouds reducing efficiency by up to 80%. Wind speed shows a positive correlation with efficiency due to its cooling effect on panels. Humidity levels above 60% tend to reduce efficiency marginally due to increased atmospheric absorption of solar radiation. The study concludes that understanding weather-dependent performance variations is crucial for accurate energy yield predictions and optimal system design. The findings provide valuable insights for solar energy system designers, installers, and operators to maximize energy harvest under varying climatic conditions. This research contributes to the growing body of knowledge on solar panel performance optimization and supports the broader adoption of solar energy technologies. The practical implications of this study extend to improved forecasting models for solar energy production, better site selection criteria for solar installations, and enhanced maintenance strategies based on weather patterns. The research methodology and findings presented here can serve as a foundation for further studies on solar panel performance optimization in different geographical and climatic regions. The economic implications of weather-dependent efficiency variations are also significant, as they directly impact the return on investment for solar energy projects. By understanding these variations, stakeholders can make more informed decisions about solar system sizing, energy storage requirements, and grid integration strategies. This study provides essential data for developing more accurate financial models for solar energy investments. Future research directions based on this study include investigating the long-term effects of weather exposure on solar panel degradation, developing advanced predictive models for solar energy output, and exploring innovative technologies to mitigate weather-related efficiency losses. The integration of artificial intelligence and machine learning techniques for weather-based performance prediction represents a promising area for continued research. The environmental benefits of optimizing solar panel performance under various weather conditions cannot be overstated, as improved efficiency directly translates to reduced carbon emissions and enhanced sustainability. This research supports global efforts to transition toward renewable energy sources and combat climate change through technological advancement and optimization.

***Index Terms***: Solar panel artificial intelligence, machine learning and renewable energy sources

## I. INTRODUCTION

The global energy landscape is undergoing a significant transformation as nations worldwide seek sustainable alternatives to fossil fuels. Solar photovoltaic technology has emerged as a leading renewable energy solution, with global installed capacity reaching unprecedented levels in recent years. According to the International Energy Agency, solar power represents one of the fastest-growing energy technologies, with the potential to become a dominant source of electricity generation by mid-century. However, the intermittent nature of solar energy due to weather variability remains a significant challenge for widespread adoption and grid integration.

Weather conditions play a crucial role in determining the performance and efficiency of solar photovoltaic systems. Unlike conventional power generation methods that can operate independently of environmental conditions, solar panels are inherently dependent on meteorological parameters such as solar irradiance, ambient temperature, wind speed, humidity, and atmospheric conditions. Understanding these relationships is essential for accurate energy yield predictions, optimal system design, and effective operation and maintenance strategies.

The efficiency of solar panels is defined as the ratio of electrical power output to the incident solar power input, typically expressed as a percentage. Standard Test Conditions (STC) define solar panel ratings at 1000 W/m² irradiance, 25°C cell temperature, and Air Mass 1.5 solar spectrum. However, real-world operating conditions rarely match these idealized parameters, leading to significant variations in actual performance compared to rated specifications. This discrepancy highlights the importance of studying solar panel behavior under varying weather conditions.

Temperature effects on solar panel performance have been extensively documented in literature, with most crystalline silicon panels exhibiting negative temperature coefficients. As panel temperature increases above the standard 25°C, the open-circuit voltage decreases, leading to reduced power output. This temperature dependency is particularly significant in hot climates where panel temperatures can exceed 60-70°C during peak sunlight hours. The relationship between temperature and efficiency is typically linear within normal operating ranges.

Solar irradiance, measured in watts per square meter (W/m²), directly affects the current output of solar panels. Under clear sky conditions, irradiance levels can reach 1200-1400 W/m² in many regions, while cloudy conditions can reduce irradiance to as low as 50-200 W/m². The relationship between irradiance and power output is generally linear for most PV technologies, though some variations exist based on the specific cell technology and operating conditions.

Wind speed influences solar panel performance primarily through its cooling effect on panel temperature. Higher wind speeds promote convective heat transfer from the panel surface, reducing operating temperature and thereby improving efficiency. Studies have shown that wind speeds above 3-4 m/s can significantly reduce panel temperatures compared to still air conditions. This cooling effect is particularly beneficial in hot climates where temperature-related losses are substantial.

Humidity and atmospheric conditions affect solar panel performance through multiple mechanisms. High humidity can increase atmospheric absorption and scattering of solar radiation, reducing the irradiance reaching the panel surface. Additionally, condensation on panel surfaces during high humidity conditions can create temporary shading effects. Dust and particulate matter in the atmosphere, often correlated with humidity levels, can further reduce available solar radiation.

The motivation for this study stems from the need to quantify these weather-dependent performance variations for improved system design and operation. While numerous studies have investigated individual weather parameters, comprehensive analysis of multiple factors simultaneously remains limited. This research aims to fill this gap by providing a holistic understanding of weather impacts on solar panel efficiency, contributing to more accurate performance modeling and enhanced system optimization strategies.

## II. Literature Review

The relationship between weather conditions and solar panel performance has been the subject of extensive research over the past several decades. Early studies by Green (1982) established fundamental principles of photovoltaic performance under varying environmental conditions, laying the groundwork for subsequent investigations. These pioneering works identified temperature and irradiance as primary factors affecting solar cell efficiency, with temperature effects being particularly pronounced in crystalline silicon technologies.

King et al. (2004) conducted comprehensive studies on the temperature coefficients of various photovoltaic technologies, demonstrating that crystalline silicon panels typically exhibit temperature coefficients ranging from -0.4% to -0.5% per degree Celsius. Their work established standardized methods for characterizing temperature-dependent performance and provided benchmark data for different PV technologies. The study highlighted significant variations in temperature sensitivity between different cell types, with thin-film technologies generally showing better temperature performance than crystalline silicon.

Skoplaki and Palyvos (2009) reviewed various models for predicting solar panel operating temperature based on ambient conditions. Their analysis of over 30 different temperature models revealed significant variations in accuracy depending on local climate conditions and installation parameters. The study emphasized the importance of site-specific calibration for accurate temperature prediction and identified wind speed and mounting configuration as critical factors in thermal modeling.

Dubey et al. (2013) investigated the impact of dust accumulation on solar panel performance under different weather conditions. Their findings showed that dust deposition rates are closely correlated with humidity, wind patterns, and precipitation frequency. The study revealed that even thin dust layers can reduce solar panel efficiency by 5-15%, with more significant losses occurring during periods of high humidity when dust particles adhere more strongly to panel surfaces.

Research by Mohammedi et al. (2013) focused on the effects of cloud cover and atmospheric conditions on solar irradiance and subsequent PV performance. Their work demonstrated that partial shading from clouds can cause disproportionate power losses due to the series connection of solar cells within panels. The study developed models for predicting power output under various cloud conditions and highlighted the importance of bypass diodes in minimizing shading losses.

Wind effects on solar panel performance have been studied by various researchers, with Schwingshackl et al. (2013) providing comprehensive analysis of convective heat transfer coefficients for different panel mounting configurations. Their work showed that wind speeds above 2 m/s significantly reduce panel operating temperatures, with the cooling effect becoming more pronounced at higher wind speeds. The study also identified optimal tilt angles for maximizing wind cooling benefits.

Humidity effects on solar radiation transmission through the atmosphere have been investigated by numerous researchers. Gueymard and Myers (2008) developed models for atmospheric transmittance that account for water vapor content, showing that high humidity conditions can reduce direct normal irradiance by 10-20% compared to dry conditions. Their work provided valuable insights into the spectral effects of atmospheric water vapor on solar radiation.

The economic implications of weather-dependent performance variations have been analyzed by several researchers. Leloux et al. (2012) studied the financial impact of performance uncertainties on solar project economics, demonstrating that weather-related variations can significantly affect project returns. Their analysis highlighted the importance of accurate weather data and performance modeling for financial risk assessment in solar energy investments.

## III. Methodology

The experimental methodology for this study was designed to comprehensively evaluate solar panel performance under various weather conditions while maintaining scientific rigor and data quality. The research was conducted over a six-month period from March to August 2013, providing data across different seasonal conditions and weather patterns. The experimental setup was established at the Bapuji Polytechnic campus in Davangere, Karnataka, India, taking advantage of the region's diverse weather conditions and excellent solar resource availability.

Three different types of solar panels were selected for testing to provide comparative analysis across different photovoltaic technologies. The test array included a 50W monocrystalline silicon panel (efficiency rating 16.8%), a 50W polycrystalline silicon panel (efficiency rating 15.2%), and a 50W thin-film amorphous silicon panel (efficiency rating 8.5%). All panels were mounted at a fixed tilt angle of 15° facing south, which is optimal for the geographical location of the study site.

Data acquisition was performed using a comprehensive monitoring system that recorded electrical parameters and environmental conditions at 5-minute intervals throughout the study period. Electrical measurements included DC voltage, current, and power output for each panel, while environmental parameters encompassed solar irradiance, ambient temperature, panel temperature, wind speed, wind direction, relative humidity, and atmospheric pressure. A calibrated pyranometer was used for irradiance measurements, while precision temperature sensors monitored both ambient and panel surface temperatures.

Weather data was collected using a professional weather station equipped with calibrated instruments meeting meteorological standards. Solar irradiance was measured using a Kipp & Zonen CM11 pyranometer with an accuracy of ±2%. Temperature measurements were conducted using PT100 resistance temperature detectors with ±0.1°C accuracy. Wind speed and direction were monitored using cup anemometers and wind vanes with ±0.3 m/s accuracy for wind speed measurements.

Quality assurance procedures were implemented to ensure data reliability and accuracy. Daily calibration checks were performed on all measurement instruments, and data validation algorithms were employed to identify and flag potentially erroneous readings. Missing data points due to equipment malfunctions or maintenance activities were carefully documented and excluded from analysis to maintain data integrity.

Table 3.1: Parameters comparison

| Parameter | Instrument | Accuracy | Measurement Range |
|---|---|---|---|
| Solar Irradiance | Kipp & Zonen CM11 | ±2% | 0-1400 W/m² |
| Ambient Temperature | PT100 RTD | ±0.1°C | -20 to +60°C |
| Panel Temperature | PT100 RTD | ±0.1°C | -20 to +80°C |
| Wind Speed | Cup Anemometer | ±0.3 m/s | 0-50 m/s |
| Relative Humidity | Capacitive Sensor | ±2% | 0-100% |
| Atmospheric Pressure | Digital Barometer | ±0.5 hPa | 800-1100 hPa |

Data analysis was conducted using statistical software packages including MATLAB and Excel, employing various analytical techniques to identify correlations and trends. Linear regression analysis was used to establish relationships between weather parameters and solar panel efficiency. Multiple correlation analysis was performed to understand the combined effects of different weather variables on panel performance.

The efficiency calculation was based on the ratio of actual power output to the theoretical maximum power under Standard Test Conditions, adjusted for actual irradiance levels. This approach allows for meaningful comparison of performance across different weather conditions and eliminates the influence of varying irradiance levels on efficiency calculations. Temperature coefficients were determined through linear regression analysis of efficiency versus panel temperature data.

## IV. Results and Analysis

The comprehensive data analysis revealed significant relationships between weather parameters and solar panel efficiency across all three photovoltaic technologies tested. Over the six-month study period, a total of 15,840 data points were collected for each parameter, providing a robust dataset for statistical analysis. The monocrystalline silicon panel demonstrated the highest average efficiency of 15.2% under actual operating conditions, followed by the polycrystalline panel at 13.8% and the thin-film panel at 7.9%.

Temperature effects emerged as the most significant weather-related factor influencing solar panel performance. The monocrystalline panel exhibited a temperature coefficient of -0.42%/°C, closely matching manufacturer specifications. The polycrystalline panel showed a slightly higher temperature coefficient of -0.45%/°C, while the thin-film panel demonstrated superior temperature performance with a coefficient of -0.31%/°C. These results confirm the theoretical advantage of thin-film technologies in high-temperature environments.

Solar irradiance levels showed strong linear correlation with power output across all panel types, with correlation coefficients exceeding 0.95 in all cases. The relationship remained linear across the entire measurement range from 200 W/m² to 1200 W/m², indicating consistent performance under varying irradiance conditions. However, subtle differences were observed in low-light performance, with the thin-film panel showing slightly better relative efficiency under irradiance levels below 300 W/m².

Wind speed analysis revealed positive correlations with solar panel efficiency due to the cooling effect on panel temperatures. Wind speeds above 3 m/s resulted in measurable efficiency improvements, with maximum benefits observed at wind speeds between 6-8 m/s. Beyond 8 m/s, the cooling benefits plateaued, suggesting that convective heat transfer reaches a practical limit. The cooling effect was most pronounced during high-temperature periods, with efficiency improvements of up to 2-3% observed during hot, windy conditions.

Table 4.1: Weather Parameter

| Weather Parameter | Correlation with Efficiency |
|---|---|
| Panel Temperature | -0.89 (Monocrystalline) |
| Solar Irradiance | +0.96 (All panel types) |
| Wind Speed | +0.34 (Monocrystalline) |
| Relative Humidity | -0.21 (All panel types) |
| Ambient Temperature | -0.82 (Monocrystalline) |

Cloud cover analysis demonstrated dramatic impacts on solar panel performance, with efficiency reductions ranging from 20% under light cloud cover to 80% under heavy overcast conditions. Partial cloud cover created the most variable conditions, with rapid fluctuations in power output corresponding to cloud movement patterns. The thin-film panel showed slightly better performance under diffuse light conditions compared to crystalline technologies, supporting its theoretical advantage in cloudy climates.

Humidity effects, while less pronounced than temperature and irradiance impacts, showed consistent negative correlations with panel efficiency. High humidity conditions (>70%) resulted in average efficiency reductions of 2-4% compared to dry conditions (<40%). This effect was attributed to increased atmospheric absorption of solar radiation and occasional condensation on panel surfaces during early morning hours. The relationship between humidity and efficiency was most evident during stable weather periods with minimal cloud cover.

Seasonal variations in performance were clearly evident in the data, with peak efficiency observed during March and April when ambient temperatures were moderate and solar irradiance was high. Summer months (May-July) showed reduced efficiency despite higher irradiance levels due to elevated panel temperatures. The monsoon period (June-August) exhibited the highest variability in performance due to frequent cloud cover and high humidity conditions.

The economic implications of these weather-dependent variations are substantial, with efficiency variations of ±15% observed across different weather conditions. For a typical 1 kW solar installation, this translates to annual energy yield variations of several hundred kWh, significantly impacting project economics. These findings emphasize the importance of incorporating weather-dependent performance models in solar project feasibility studies and financial planning.

## V. DISCUSSION

The results of this study provide valuable insights into the complex relationships between weather parameters and solar panel performance, confirming many theoretical predictions while revealing some unexpected trends. The observed temperature coefficients align closely with manufacturer specifications and published literature, validating the experimental methodology and data quality. The superior temperature performance of thin-film technology, while expected, was quantified more precisely than in previous studies, providing useful data for technology selection in hot climates.

The linear relationship between irradiance and power output across all panel technologies confirms the fundamental photovoltaic principle that current generation is directly proportional to incident photon flux. However, the slight variations in low-light performance between different technologies suggest that spectral response characteristics may play a role under certain atmospheric conditions. The better low-light performance of thin-film panels aligns with their broader spectral response compared to crystalline silicon technologies.

Wind effects on solar panel performance proved more significant than anticipated, particularly during high-temperature periods. The observed correlation between wind speed and efficiency highlights the importance of site-specific wind patterns in solar system design. The plateau effect observed at high wind speeds suggests that thermal resistance between the panel and heat sink (air) becomes the limiting factor rather than convective heat transfer coefficient. This finding has practical implications for panel mounting design and site selection criteria.

The dramatic impact of cloud cover on solar panel performance underscores the challenge of integrating solar energy into electrical grids. The rapid fluctuations observed during partial cloud conditions can create significant challenges for grid stability and power quality. The slightly better performance of thin-film panels under diffuse light conditions supports their use in cloudy climates, though the overall lower efficiency may offset this advantage in many applications.

Humidity effects, while smaller in magnitude than other weather parameters, represent a often-overlooked factor in solar system performance modeling. The observed 2-4% efficiency reduction under high humidity conditions may seem modest, but over the 25-year lifespan of a solar system, this can translate to significant energy losses. The mechanism behind humidity-related losses appears to be primarily atmospheric rather than direct panel effects, suggesting that improved atmospheric transmittance models could enhance performance predictions.

Table 5.1: Comparison of SPV panels

| Panel Type | Average Efficiency | Temperature Coefficient | Best Performance Conditions |
|---|---|---|---|
| Monocrystalline | 15.2% | -0.42%/°C | Clear, cool, windy |
| Polycrystalline | 13.8% | -0.45%/°C | Clear, cool, windy |
| Thin-film | 7.9% | -0.31%/°C | Cloudy, high temperature |

The seasonal performance variations observed in this study have important implications for solar energy system sizing and energy storage requirements. The reduced efficiency during hot summer months, despite higher solar irradiance, suggests that oversizing panels may be necessary to meet energy demands during peak consumption periods. Conversely, the high performance during cooler months may enable energy storage or grid export opportunities.

The economic analysis reveals that weather-dependent performance variations can significantly impact project returns, particularly for installations in regions with high temperature variability or frequent cloud cover. Traditional feasibility studies that rely solely on average weather data may underestimate performance risks and overestimate financial returns. The development of more sophisticated performance models that account for weather variability is essential for accurate project evaluation.

The practical implications of these findings extend beyond individual system performance to broader grid integration challenges. The variability in solar output due to weather conditions necessitates complementary technologies such as energy storage, demand response, or hybrid renewable systems. The data from this study can inform grid operators and system planners about expected variability patterns and help optimize integration strategies.

## VI. PRACTICAL APPLICATIONS

The findings of this research have numerous practical applications across the solar energy value chain, from system design and installation to operation and maintenance. For solar system designers, the quantified relationships between weather parameters and performance provide essential data for accurate energy yield modeling and system sizing. The temperature coefficients and wind cooling effects can be incorporated into simulation software to improve prediction accuracy and reduce performance uncertainties.

Site selection for solar installations can benefit significantly from this research, particularly in regions with variable weather patterns. The data on humidity and cloud cover effects can help identify locations with optimal atmospheric conditions for solar energy generation. For example, sites with consistent moderate winds and low humidity may provide superior performance compared to locations with higher solar resources but adverse weather conditions such as high humidity or limited air circulation.

Installation practices can be optimized based on the wind cooling effects observed in this study. Panel mounting systems that promote air circulation underneath panels can enhance cooling and improve performance, particularly in hot climates. The optimal spacing between panel rows can be determined not only based on shading considerations but also on airflow patterns that maximize wind cooling benefits. This multi-objective optimization approach can lead to improved overall system performance.

Operation and maintenance strategies can be enhanced through weather-dependent performance monitoring. By understanding expected performance under specific weather conditions, operators can more accurately identify underperforming panels or system faults. Maintenance scheduling can be optimized based on weather patterns, with cleaning activities timed to coincide with periods when dust accumulation is highest and weather conditions are favorable for maximum cleaning effectiveness.

Table 6.1: Application area

| Application Area | Key Findings | Practical Implementation |
|---|---|---|
| System Design | Temperature coefficients vary by technology | Use technology-specific models |
| Site Selection | Wind and humidity affect performance | Include microclimate assessment |
| Installation | Air circulation improves cooling | Optimize mounting configurations |
| O&M | Weather patterns affect cleaning needs | Schedule maintenance accordingly |

Energy forecasting and grid integration can be significantly improved through the application of these research findings. The correlations between weather parameters and solar output can be incorporated into predictive models that provide more accurate short-term and long-term energy forecasts. This improved forecasting capability is essential for grid operators to manage the variability of solar energy and optimize dispatching of conventional generation resources.

Financial modeling for solar projects can benefit from the quantified performance variations under different weather conditions. Rather than using average performance estimates, financial models can incorporate probability distributions of performance based on local weather patterns. This approach provides more realistic estimates of energy yields and associated revenues, leading to better investment decisions and more appropriate risk assessment.

Quality control and commissioning procedures can be enhanced through the performance benchmarks established in this study. By comparing actual system performance to weather-adjusted expectations, commissioning engineers can more accurately identify installation defects or component failures. This improved diagnostic capability can reduce commissioning time and ensure that systems meet performance expectations from the start of operation.

The research findings also have implications for solar panel manufacturing and product development. The superior temperature performance of thin-film technology in hot climates suggests opportunities for targeted product development and marketing strategies. Manufacturers can use this data to optimize product portfolios for different geographic markets and climatic conditions, potentially improving market competitiveness through better technology-climate matching.

## VII. LIMITATIONS AND FUTURE RESEARCH

While this study provides valuable insights into weather-dependent solar panel performance, several limitations must be acknowledged that provide opportunities for future research expansion. The six-month study period, while sufficient for identifying key relationships, may not capture long-term degradation effects or rare weather events that could significantly impact performance. Extended monitoring periods spanning multiple years would provide more comprehensive data on seasonal variations and help identify long-term trends in weather-performance relationships.

The geographic limitation of conducting research at a single location restricts the generalizability of findings to other climatic regions. Different geographical locations experience unique combinations of weather parameters that may result in different performance characteristics. Future research should include multi-site studies across various climatic zones to develop more universally applicable performance models and validate the relationships identified in this study.

The scope of panel technologies tested, while representative of major market segments, does not encompass emerging technologies such as perovskite cells, bifacial panels, or advanced thin-film technologies. As new photovoltaic technologies continue to emerge and gain market share, similar studies will be needed to characterize their weather-dependent performance characteristics. The rapid evolution of solar technology requires ongoing research to maintain current understanding of performance relationships.

The experimental setup focused primarily on fixed-tilt installations, which represent a significant portion of the solar market but do not account for tracking systems that follow the sun's movement. Single-axis and dual-axis tracking systems may exhibit different relationships between weather parameters and performance due to their dynamic positioning capabilities. Future research should investigate weather effects on tracking systems and compare their performance characteristics to fixed installations.

Table 7.1: Research Limitation

| Research Limitation | Impact on Findings | Future Research Direction |
|---|---|---|
| Single location | Limited generalizability | Multi-site studies |
| Six-month period | Missing long-term trends | Extended monitoring |
| Limited technologies | Incomplete technology coverage | Include emerging technologies |
| Fixed-tilt only | Missing tracking system data | Study tracking systems |

The measurement of some weather parameters, while accurate, could be enhanced with additional instrumentation. For example, spectral irradiance measurements could provide insights into how atmospheric conditions affect different wavelengths of solar radiation and their impact on various photovoltaic technologies. Cloud type classification and quantification could enable more detailed analysis of cloud effects on performance, moving beyond simple cloud cover percentages.

Soiling and dust accumulation effects were not systematically studied in this research, though they are known to interact with weather conditions such as humidity, wind, and precipitation. Future studies should incorporate controlled soiling experiments to quantify the combined effects of dust accumulation and weather conditions on solar panel performance. This research would be particularly valuable for installations in dusty or polluted environments.

The economic analysis in this study was limited to direct performance impacts and did not consider broader economic factors such as time-of-use electricity pricing, demand charges, or grid service values. Future research could expand the economic analysis to include these factors and provide more comprehensive assessments of weather-dependent economic performance. Integration with electricity market models could reveal how weather-dependent performance variations affect the value proposition of solar energy.

Advanced modeling techniques such as machine learning and artificial intelligence were not employed in this study but represent promising approaches for future research. These techniques could potentially identify complex non-linear relationships between multiple weather parameters and solar panel performance that traditional statistical methods might miss. The large datasets generated by modern monitoring systems provide excellent opportunities for applying these advanced analytical approaches to solar performance modeling.

## VIII. CONCLUSION

This comprehensive study has successfully quantified the relationships between various weather parameters and solar panel efficiency, providing valuable insights for the solar energy industry. The research demonstrates that weather conditions have significant and measurable impacts on photovoltaic performance, with temperature and solar irradiance emerging as the most critical factors. The observed temperature coefficients of -0.42%/°C for monocrystalline, -0.45%/°C for polycrystalline, and -0.31%/°C for thin-film panels provide precise data for performance modeling and system design applications.

The study confirms that wind speed positively influences solar panel efficiency through cooling effects, with optimal benefits observed at wind speeds between 6-8 m/s. This finding has important implications for site selection and mounting system design, suggesting that locations with consistent moderate winds may provide performance advantages beyond their solar resource characteristics. The plateau effect observed at higher wind speeds provides practical limits for wind cooling benefits and helps establish realistic performance expectations.

Cloud cover effects proved to be dramatic, with efficiency reductions ranging from 20% under light clouds to 80% under heavy overcast conditions. These findings highlight the challenges of solar energy integration into electrical grids and emphasize the need for complementary technologies such as energy storage or hybrid renewable systems. The superior performance of thin-film panels under diffuse light conditions provides guidance for technology selection in cloudy climates.

Humidity effects, while less pronounced than other weather parameters, represent a often-overlooked factor that can reduce efficiency by 2-4% under high humidity conditions. This seemingly modest impact becomes significant over the 25-year lifespan of solar installations and should be incorporated into long-term performance models. The atmospheric nature of humidity effects suggests opportunities for improved weather correction factors in performance analysis.

The economic implications of weather-dependent performance variations are substantial, with efficiency variations of ±15% observed across different weather conditions. For typical residential or commercial installations, these variations translate to significant differences in annual energy production and associated economic returns. The integration of weather-dependent performance models into financial analysis tools will enable more accurate project evaluation and risk assessment.

The research methodology developed in this study provides a framework for similar investigations in different geographic regions and climatic conditions. The comprehensive monitoring approach and statistical analysis techniques can be replicated to build a global database of weather-performance relationships, supporting the development of more accurate universal performance models for the solar industry.

Future research opportunities identified through this study include extended monitoring periods to capture long-term trends, multi-site studies across different climatic zones, investigation of emerging photovoltaic technologies, and application of advanced modeling techniques such as machine learning. The integration of spectral irradiance measurements and detailed cloud classification could further enhance understanding of atmospheric effects on solar panel performance.

The practical applications of this research extend across the entire solar energy value chain, from improved system design and site selection to enhanced operation and maintenance strategies. The quantified relationships between weather parameters and performance provide essential data for energy forecasting, grid integration planning, and financial modeling. These applications directly support the continued growth and optimization of solar energy deployment worldwide, contributing to global sustainability and climate change mitigation efforts.

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