

A Review of Solar Panel Efficiency in Different Weather Condition

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Abstract

Solar photovoltaic (PV) systems are now widely recognized as an important response to the growing demand for cleaner energy. Yet their performance is never constant. Day by day, and sometimes even hour by hour, output changes because weather conditions directly affect sunlight levels, surface temperature of the modules, and even the cleanliness of the panels. In this review, I bring together findings from earlier studies as well as simple field observations to show how efficiency shifts under three common situations: clear skies, cloudy weather, and periods of rain. On bright sunny days, panels naturally produce the most power, but very high heat can cause a gradual drop in efficiency—often around 0.3 to 0.5% for every degree Celsius above the test standard. Under cloudy skies the output usually falls, sometimes by 20% and in heavier conditions even up to 60%. Rainy days cut irradiance as well, though rainwater also cools the panels and helps clean away dust, which may partly balance the loss. These patterns suggest that designers and users should not only think about maximum output but also about local weather variability. Choosing the right tilt, keeping modules clean, and combining systems with storage can improve stability over the long term.

Keywords

Solar Panels, Photovoltaic Efficiency, Weather Conditions, Cloudy Days, Renewable Energy, Temperature Effects

1. Introduction

The rising global demand for energy, coupled with the urgent need to reduce greenhouse gas emissions, has accelerated the shift toward renewable energy sources. Among the various alternatives, solar photovoltaic (PV) technology has emerged as one of the most widely adopted and promising solutions due to its scalability, declining costs, and minimal environmental footprint. According to the International Energy Agency, solar PV accounted for nearly one-third of newly installed renewable capacity worldwide in 2022, reflecting its central role in the global transition toward clean energy [1]. Despite these advantages, the efficiency of solar panels is not fixed; it is highly sensitive to external environmental factors, particularly weather conditions.

Solar panels generate electricity by converting sunlight into electrical energy through the photovoltaic effect. While laboratory-rated efficiencies provide useful benchmarks, real-world conditions often deviate significantly from standard test environments. Factors such as solar irradiance, temperature, humidity, and atmospheric scattering strongly influence the actual energy yield. For instance, panels in hot, tropical regions may produce less energy than panels in cooler climates under similar irradiance levels, as excessive heat reduces voltage output. Likewise, variations in cloud density or rainfall can alter irradiance patterns, producing unpredictable fluctuations in system performance. These challenges highlight the importance of understanding how different weather conditions affect solar panel efficiency in practical applications.

Several studies have sought to quantify the influence of weather on solar performance. Research in Europe and North America has demonstrated that cloudy conditions can reduce efficiency by 20-60%, depending on cloud thickness and duration [2]. In equatorial regions such as Southeast Asia, frequent rainfall has been found to lower irradiance but also cool the panel surface, sometimes improving efficiency compared to hot, dry conditions. These findings suggest that weather impacts on PV performance are complex and region-specific, requiring both theoretical modeling and long-term field measurements for accurate assessment.

The purpose of this paper is to provide a comprehensive review of solar panel efficiency under varying weather conditions, with a particular focus on sunny, cloudy, and rainy environments. By synthesizing data from published research and incorporating simple field measurements, this review aims to:

- Quantify the differences in panel output under diverse weather scenarios.
- Examine the underlying physical mechanisms, including irradiance scattering, temperature effects, and panel cooling.
- Offer practical recommendations for system installation, maintenance, and energy planning in regions with variable weather patterns.

This review contributes to the growing body of knowledge on solar PV performance by consolidating findings from multiple climatic zones and highlighting practical strategies to mitigate weather-related inefficiencies. The results are

expected to assist engineers, policymakers, and energy planners in optimizing solar energy deployment, particularly in regions where weather variability poses a significant challenge to reliable energy generation.

2. Literature Review

2.1 Fundamentals of Solar Panel Efficiency

The efficiency of solar photovoltaic (PV) modules is defined as the ratio of electrical power output to the solar irradiance incident on the module's surface. This conversion efficiency is influenced by multiple factors including cell material, surface temperature, spectral distribution of sunlight, and the angle of incidence [3]. Crystalline silicon cells dominate the commercial market due to their maturity and relatively high efficiency, typically ranging between 15% and 22%. Thin-film technologies, such as cadmium telluride (CdTe) and copper indium gallium selenide (CIGS), provide lower efficiencies but offer advantages in manufacturing cost and flexibility (Best et al., 2019). More recently, perovskite-based solar cells have demonstrated remarkable improvements in laboratory conditions, although their long-term stability under outdoor weather remains a critical challenge.

While cell material sets the upper bound for efficiency, real-world performance is largely dictated by environmental conditions. Standard test conditions (STC), defined as 1000 W/m² irradiance, 25°C cell temperature, and an air mass of 1.5, rarely represent outdoor environments. Deviations from these conditions explain why actual panel output often falls short of laboratory ratings. As such, understanding weather influences is essential for predicting the practical yield of solar installations.

2.2 Performance under Sunny Conditions

Clear skies provide the highest levels of direct irradiance, typically ranging from 800 to 1000 W/m² depending on location and season. Numerous studies confirm that panels achieve near-maximum output during such conditions, although the relationship is not linear due to thermal effects. Skoplaki and Palyvos reported that crystalline silicon modules experience a 0.4-0.5% drop in efficiency for every 1°C rise in temperature above 25°C [4]. Similar findings were observed by Radziemska, who emphasized the strong negative correlation between module temperature and open-circuit voltage [5].

In hot regions, therefore, sunny conditions can paradoxically reduce efficiency despite high irradiance. Mitigation strategies such as ventilation, heat sinks, or water-cooling systems have been proposed, though these solutions add to system costs. Tracking systems, which adjust the orientation of panels to maximize exposure, have also been shown to increase yield by up to 25% compared with fixed systems under clear skies.

2.3 Performance under Cloudy Conditions

Clouds reduce direct irradiance but increase diffuse radiation. This dual effect makes their impact on panel efficiency complex. On one hand, heavy cloud cover significantly lowers energy yield, with Gueymard estimating reductions of 20-60% depending on thickness and persistence [6]. On the other hand, partial cloudiness may enhance irradiance intermittently through the so-called "cloud edge effect," where scattered sunlight produces momentary spikes in output above clear-sky levels [7].

Research in Germany and the United Kingdom, where cloud cover is frequent, indicates that annual PV output can still remain economically viable despite reduced peak efficiency. For example, Aste observed that diffuse light under cloudy skies can maintain stable performance across panel surfaces, reducing shading mismatch losses. These findings suggest that cloudy climates, while less optimal than sunny ones, do not necessarily preclude the widespread adoption of solar energy, provided system design and financial models account for variability [8].

2.4 Performance under Rainy Conditions

Rain is often considered detrimental because it coincides with dense cloud coverage and reduced irradiance. However, recent studies suggest a more nuanced effect. Few researchers conducted field measurements in Malaysia and found that rainy days still sustained 30-50% of the output generated on sunny days. This was largely attributed to the cooling effect of rainfall, which lowered module surface temperature and improved voltage output [9].

Furthermore, rainfall performs a secondary but important role in cleaning dust and particulate matter from panels. It was also demonstrated that dust accumulation can reduce PV efficiency by 10-25% in arid climates, and natural rainfall substantially mitigates these losses. Consequently, in humid tropical regions with frequent rain, panels may maintain better long-term efficiency compared to arid regions where dust deposition is severe and cleaning is costly [10].

2.5 Long-Term Climatic Effects

Beyond daily weather fluctuations, long-term climatic factors also shape solar efficiency. Seasonal variations in solar angle and day length determine cumulative irradiance. For instance, PV systems in northern Europe achieve higher output per installed kilowatt during summer months, while winter contributions are significantly lower [11]. Conversely, equatorial regions experience relatively stable irradiance throughout the year but face challenges from frequent monsoons and high humidity.

Studies also emphasize the role of microclimates. Urban heat islands, characterized by elevated ambient temperatures, can worsen efficiency losses in metropolitan areas. Similarly, coastal environments may expose panels to salt corrosion, further reducing long-term performance unless protective coatings are applied.

2.6 Research Gaps

Although extensive research exists, several limitations remain. First, many studies are site-specific and may not be generalizable across different climatic zones. Second, most experimental datasets span only months or a few years, whereas PV systems are expected to operate for 20-30 years. Third, the combined effects of multiple weather variables—such as simultaneous high humidity, cloud cover, and heat—remain insufficiently quantified. Lastly, integration of weather-dependent performance data into smart grid forecasting models is still underdeveloped. Addressing these gaps is critical for enhancing reliability and scalability of solar energy systems worldwide.

3. Methodology

3.1 Research Approach

This paper adopts a review-based methodology combined with supportive field observations. The primary aim is not to introduce new experimental data, but to consolidate and critically evaluate existing knowledge regarding the influence of weather conditions on solar panel efficiency. By synthesizing findings from peer-reviewed journals, technical reports, and regional case studies, the study develops a comparative framework that highlights how sunny, cloudy, and rainy conditions affect PV performance across different climatic zones. Limited field measurements conducted in Malaysia were also considered to complement published results, ensuring that both global and regional perspectives are represented.

3.2 Literature Selection

A structured search was conducted using major academic databases such as Scopus, IEEE Xplore, ScienceDirect, and SpringerLink. Keywords included “solar panel efficiency,” “photovoltaic performance,” “weather conditions,” “cloudy days,” and “rainfall effect on PV.” Articles published between 2000 and 2023 were prioritized to capture both foundational studies and recent advancements in technology. In total, over 120 articles were screened, of which approximately 40 were selected for detailed analysis based on their methodological rigor, geographical diversity, and relevance to weather-related performance. To avoid bias, studies covering different technologies—monocrystalline silicon, polycrystalline silicon, thin film, and emerging perovskite cells—were included.

3.3 Comparative Framework

The selected literature was categorized according to three dominant weather conditions: sunny, cloudy, and rainy. For each category, reported efficiency changes, underlying mechanisms, and mitigation strategies were extracted and tabulated. Quantitative results, such as percentage drops in efficiency under cloud cover, were compared across multiple regions to identify common trends and regional deviations. For example, European studies often emphasized diffuse radiation effects during overcast skies, while Southeast Asian research highlighted the dual role of rainfall in both reducing irradiance and cooling panels.

Where available, numerical ranges were cross-validated. For instance, Gueymard reported a 20-60% reduction in efficiency under cloudy skies, while Juan, Yue Hai and Jan documented instances of transient output gains due to cloud-edge effects. Such variations were noted and discussed in terms of methodological differences and local conditions.

3.4 Field Measurements

To complement secondary data, simple field observations were carried out in Penang, Malaysia, between June and September 2023. A set of 300 W monocrystalline panels was installed on a fixed south-facing rooftop with a tilt angle of 15°. Panel output was monitored using a digital multimeter and irradiance was measured with a pyranometer. Temperature sensors were also placed on the panel surface to record thermal variations. Data were collected over 45 days covering sunny, cloudy, and rainy conditions, and daily averages were calculated to minimize the effect of short-term fluctuations.

The field observations were not designed to replace large-scale experimental datasets, but rather to serve as illustrative examples that validate patterns reported in the literature. For instance, efficiency losses on cloudy days were found to range between 35% and 50% relative to clear skies, which aligned closely with reported values in previous studies. Rainy days produced lower absolute output but maintained approximately 40% of clear-sky yield, confirming the partial compensatory effect of surface cooling.

3.5 Data Synthesis and Analysis

Collected data from the literature and field observations were synthesized through qualitative and semi-quantitative analysis. Rather than conducting a meta-analysis with strict statistical weighting, the approach emphasized comparative interpretation. The goal was to highlight consistent patterns across diverse studies and identify discrepancies warranting further research. Tables and charts were developed to summarize efficiency ranges under different weather conditions,

and narrative discussion was used to link these results to underlying physical principles such as irradiance scattering and temperature effects.

3.6 Limitations

The methodology has certain limitations. First, the field observations were restricted in both duration and scope, and cannot fully capture seasonal or annual variability. Second, published studies differ in terms of measurement protocols, panel types, and site conditions, making direct comparison challenging. Lastly, the focus on three weather categories—sunny, cloudy, and rainy—simplifies the wide spectrum of atmospheric conditions such as haze, snow, or mixed weather. Nevertheless, the chosen framework provides a structured basis for evaluating the dominant weather effects most relevant to tropical and temperate regions.

4. Results and Discussion

4.1 Overview of Findings

The review of existing literature combined with field observations reveals that solar panel efficiency varies significantly under different weather conditions. While sunny days provide the highest irradiance, efficiency is negatively influenced by elevated surface temperatures. Cloudy days cause substantial reductions in irradiance but occasionally enhance output momentarily through diffuse scattering effects. Rainy days result in further irradiance decline but simultaneously reduce panel temperature and clean accumulated dust, offering a mixed impact on performance. These findings suggest that no single weather condition determines overall system effectiveness; instead, efficiency is shaped by a balance of irradiance intensity, temperature, and environmental interactions.

4.2 Performance under Sunny Conditions

Results consistently show that panels reach their highest daily output during sunny conditions, with irradiance levels averaging between 850 and 1000 W/m². The field data from Penang indicated an average daily efficiency of 17.8% for monocrystalline panels during clear days, which closely matches performance reported in previous studies [12].

However, elevated module temperatures were observed to reduce output efficiency despite high irradiance. Surface temperature readings reached as high as 58°C during midday, resulting in efficiency losses of approximately 8-10% compared to morning values. This aligns with the widely reported temperature coefficient of -0.4% to -0.5% per °C rise above 25°C. Therefore, in hot climates, sunny conditions are not always synonymous with peak efficiency.

Mitigation strategies such as passive ventilation gaps beneath panels, heat-dissipating materials, and evaporative cooling have shown potential in reducing temperature-induced losses [13]. In high-latitude countries with cooler ambient conditions, however, sunny days typically lead to both maximum irradiance and favorable operating temperatures, thereby producing consistently high efficiency.

4.3 Performance under Cloudy Conditions

Cloud cover reduces direct irradiance sharply, with literature reporting efficiency reductions between 20% and 60% depending on cloud thickness and density. Field measurements in Penang demonstrated average efficiency declines of 37% on overcast days compared to sunny conditions. Nevertheless, the effect of clouds is not uniformly negative.

The “cloud-edge effect,” documented by the above researchers, was also observed in several field sessions, where irradiance briefly spiked above clear-sky levels as sunlight scattered around cloud edges. During these moments, power output exceeded baseline levels by up to 5%, although the effect lasted only a few minutes. While this phenomenon cannot compensate for the broader reduction caused by clouds, it demonstrates the complex interaction between irradiance and atmospheric scattering.

Another positive aspect of cloudy conditions is the increase in diffuse radiation. Diffuse light, though weaker than direct irradiance, spreads more evenly across the panel surface, reducing the mismatch losses often caused by partial shading in direct sunlight. Aste emphasized that in countries like the United Kingdom, where cloudy weather dominates, diffuse radiation ensures more stable performance across the day, even if total output is lower. This suggests that in temperate climates with frequent clouds, solar installations remain viable provided energy yield expectations are realistically adjusted.

4.4 Performance under Rainy Conditions

Rainy conditions combine reduced irradiance with beneficial cooling effects. In Penang, rainy days produced an average of 42% of the daily output achieved during sunny days. While this represents a significant drop in absolute energy generation, the surface temperature of panels dropped by up to 12°C compared to clear-sky values, improving instantaneous efficiency per unit irradiance. This observation supports the findings of Tan and his friends, who reported similar compensatory cooling effects in tropical Malaysia.

Rain also plays an important role in maintaining long-term performance by cleaning accumulated dust and particulate matter from the panel surface. In regions such as the Middle East and North Africa, dust accumulation has been shown to decrease efficiency by 10-25%. Natural rainfall mitigates this issue, reducing the need for manual cleaning and

lowering maintenance costs. Thus, while rainy weather reduces short-term yield, it indirectly contributes to more stable long-term system performance.

Interestingly, the combination of heavy rainfall and diffuse irradiance also produces relatively stable voltage output. This is because cooler temperatures enhance open-circuit voltage, partially offsetting the reduction in current caused by weaker irradiance. These dynamics highlight the complex trade-offs associated with rainy weather.

4.5 Comparative Analysis of Weather Impacts

The synthesis of results from literature and field observations allows for a comparative assessment of weather conditions (Table 1).

Table 1. Comparative effects of weather conditions on solar panel efficiency

Weather Condition	Irradiance Effect	Temperature Effect	Net Efficiency Impact	Additional Notes
Sunny	High irradiance (850-1000 W/m ²)	Elevated surface temp reduces efficiency by 8-10%	High output but not peak efficiency in hot climates	Cooling/ventilation improves yield
Cloudy	Reduced irradiance (20-60% loss)	Moderate surface temps	Lower total output but diffuse light improves stability	Occasional “cloud-edge effect” boosts output
Rainy	Very low irradiance	Significant cooling improves voltage	40-50% of sunny-day yield	Natural cleaning effect enhances long-term performance

According to Table 1, this comparative analysis highlights that sunny days provide the highest output but are limited by temperature-related losses. Cloudy conditions reduce yield but maintain operational stability. Rainy conditions reduce irradiance further but provide compensatory benefits in terms of cooling and maintenance.

4.6 Practical Implications

The findings have direct implications for system design and planning. In hot climates, panel orientation and ventilation should be optimized to minimize temperature-induced efficiency losses. In regions with frequent cloud cover, energy storage systems become critical to ensure reliability during periods of reduced output. Hybrid systems that combine solar with wind or hydropower can also mitigate weather-related fluctuations. In tropical regions with frequent rainfall, natural cleaning should be considered an asset, reducing maintenance costs over time.

These insights are particularly valuable for policymakers and investors. For instance, energy yield projections in feasibility studies should integrate realistic weather-based performance data rather than relying solely on STC ratings. Grid operators must also account for variability in solar output when planning dispatch and reserve capacity.

4.7 Limitations of Findings

While the results provide useful insights, several limitations must be acknowledged. The field measurements in Penang were limited to a short timeframe and a small number of panels, which may not capture broader climatic trends. Literature data, though extensive, is often site-specific and varies in methodology, making direct comparisons challenging. Furthermore, other weather phenomena such as haze, fog, and snow were not addressed in this study, though they can significantly impact PV efficiency in certain regions.

5. Conclusion and Future Perspectives

The review has examined how solar panel efficiency varies under three major weather conditions-sunny, cloudy, and rainy-drawing evidence from both published literature and supportive field observations in Malaysia. The findings confirm that while solar photovoltaic systems perform optimally under clear skies, their performance is not entirely compromised under less favorable conditions. On cloudy days, although efficiency drops significantly, ranging from 20% to 60%, the contribution of diffuse radiation allows continued operation, ensuring that PV systems still provide partial energy output. Rainy days reduce irradiance further, yet cooling effects and panel cleaning from precipitation moderate thermal and dust-related losses, resulting in an average of 30-40% retained efficiency compared with clear-sky operation.

This nuanced understanding has several implications. First, solar PV technology should not be dismissed as unreliable in regions with frequent cloud cover or high rainfall. Instead, system planners should recognize that partial generation continues even under challenging conditions. This highlights the importance of integrating storage systems and grid connections to stabilize supply. Second, appropriate siting and maintenance strategies, such as selecting optimal tilt angles, using anti-reflective coatings, and ensuring regular cleaning, can mitigate some of the performance losses

associated with adverse weather. In tropical regions, rainfall may even play a beneficial role in reducing surface dust accumulation, counteracting one of the persistent issues in long-term PV deployment.

From a technological standpoint, innovations in solar cell design are critical to improving all-weather efficiency. Emerging technologies such as bifacial modules, tandem cells, and perovskite-silicon hybrids demonstrate promising resilience to diffuse and low-light conditions. Likewise, advances in smart inverters and maximum power point tracking (MPPT) algorithms can adapt dynamically to fluctuating irradiance, enhancing system stability during transient weather events. Future research should focus not only on material science but also on system-level optimization, including predictive weather modeling and hybrid energy integration with wind or biomass to complement PV variability.

Despite the valuable insights gained, this study also recognizes its limitations. The literature reviewed spans diverse regions, panel types, and methodologies, which introduces variability that cannot be fully reconciled. The field observations, while useful for validation, were limited in scope and duration, capturing only short-term conditions within a tropical environment. Expanding such observations to cover seasonal cycles and diverse climates would provide a more comprehensive understanding.

Looking forward, the future of solar energy will depend not only on efficiency under ideal conditions but also on resilience under real-world variability. As global energy transitions accelerate, the ability of PV systems to operate across a wide range of weather patterns will be a decisive factor in their large-scale adoption. Policymakers, engineers, and researchers must collaborate to ensure that installation standards, maintenance practices, and technological innovations collectively address weather-related challenges. By doing so, solar power can move beyond its dependence on clear skies and establish itself as a stable, reliable pillar of sustainable energy systems worldwide.

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