


The Effect of Temperature and Weather Conditions on the Performance of Photovoltaic Modules in Tropical Indonesia

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Article Info	ABSTRACT
<p>Article history:</p> <p>Received April, 2025 Revised April, 2025 Accepted April, 2025</p>	<p>This study explores the effect of temperature and weather conditions on the performance of photovoltaic (PV) modules in tropical Indonesia, utilizing a qualitative approach with interviews from five solar energy professionals. The research identifies key environmental factors such as high temperatures, humidity, and rainfall as significant influences on PV module efficiency. Participants noted that elevated temperatures reduce energy output by causing thermal losses, while high humidity and rainfall lead to dust accumulation and reduced sunlight exposure, further affecting efficiency. Additionally, challenges related to corrosion and dust accumulation were highlighted, particularly in coastal and inland regions. The study also suggests various strategies, including the use of anti-reflective coatings, cooling systems, and optimal panel placement, to mitigate these effects. Regional variations in climate necessitate site-specific maintenance and design strategies. This research provides important insights into optimizing PV system performance in tropical climates and emphasizes the need for tailored approaches in PV design and maintenance.</p>
<p>Keywords:</p> <p>Photovoltaic modules, temperature, weather conditions, humidity, tropical Indonesia.</p>	
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1. INTRODUCTION

The increasing demand for renewable energy sources has positioned solar power as one of the most promising alternatives to conventional energy systems, particularly through photovoltaic (PV) technology, which converts sunlight directly into electricity and has gained widespread attention for its potential to provide sustainable and clean energy. In tropical regions like Indonesia, characterized by abundant sunlight, solar energy holds significant promise. However, the performance of PV modules in such climates is significantly influenced by environmental factors, including

temperature, humidity, and irradiance, which can either enhance or degrade the efficiency and output of solar panels—making it crucial to understand their impacts for optimizing solar energy systems. High temperatures common in tropical regions can reduce the efficiency of PV modules by affecting current output and power conversion efficiency (PCE), with cell temperatures often reaching critical levels that negatively impact power output and energy payback time [1], [2]. Additionally, high humidity and frequent rainfall contribute to performance degradation through corrosion and energy loss, with humidity specifically causing

instability in solar cell modules, especially those based on silicon [3], [4]. Solar irradiance is another critical factor, where higher irradiance generally boosts energy generation, although silicon-based modules may experience decreased efficiency, whereas CdTe and other advanced cells perform better under such conditions [1], [3]. To address these environmental challenges, regular cleaning and maintenance can mitigate the impact of dust and humidity, improving the performance and longevity of solar panels, while the adoption of advanced PV technologies such as CdTe cells—which are less affected by high temperatures and low irradiance—can further enhance solar energy performance in tropical climates [2], [4].

Indonesia's tropical climate, characterized by high temperatures, high humidity, and frequent rainfall, significantly impacts the efficiency and longevity of photovoltaic (PV) systems. These weather conditions have both direct and indirect effects on solar panel performance, which relies not only on solar radiation intensity but also on ambient temperature, cloud cover, and humidity. High temperatures can reduce the efficiency of PV modules by increasing the resistance within solar cells, thereby lowering energy output [1], [5]. Excessive cloud cover or frequent rain limits the amount of sunlight reaching the panels, reducing energy generation, and thus affecting the overall output. Solar irradiance remains a primary determinant of PV panel performance, with higher levels enhancing energy production; however, in Indonesia, although optimal sunlight can last up to nine hours on clear days, this duration is significantly reduced during overcast or rainy conditions [1], [6]. Humidity, while having a less pronounced impact than temperature and irradiance, still contributes to efficiency losses by diminishing light penetration and possibly accelerating material degradation [1], [7]. Furthermore, studies confirm that module efficiency and performance ratio decline as temperatures rise, emphasizing the necessity of temperature management strategies in tropical PV installations [5]. In terms of

technological adaptation, different PV technologies—such as monocrystalline, polycrystalline, and thin-film—exhibit varied performance in tropical environments, with monocrystalline modules generally achieving superior efficiency and power production [5], [8].

Despite the growing use of solar energy in Indonesia, there is limited research examining how specific weather conditions, particularly temperature and humidity, affect PV module performance in this tropical context. As such, it is crucial to better understand how these environmental factors impact the functionality of photovoltaic systems in Indonesia, where solar energy is a growing sector but often faces challenges due to the region's unique climate. This study aims to explore the effect of temperature and weather conditions on the performance of photovoltaic modules in tropical Indonesia.

2. LITERATURE REVIEW

2.1 Temperature and Its Effect on PV Module Performance

Temperature plays a critical role in the performance of photovoltaic (PV) modules, particularly in tropical regions where high ambient temperatures are common. As sunlight is absorbed, not all energy is converted into electricity—some is released as heat, increasing module temperature and reducing efficiency due to higher electrical resistance in the semiconductor. Efficiency typically drops by 0.4% to 0.5% for every 1°C temperature rise [9], [10], and this effect is more severe in tropical climates, underscoring the importance of heat-resistant materials and cooling strategies. Elevated temperatures also speed up material degradation, shortening lifespan and reducing performance [9], [11]. A 5°C increase may cut power output by 2%, and a 20°C rise can reduce it by up to 10.4% [12]. In Indonesia, with average temperatures of 25–30°C, the impact is substantial [11], [12]. Polycrystalline modules are generally more temperature-sensitive than monocrystalline ones [11], making material selection crucial.

To address this, cooling systems and low-temperature-coefficient materials are recommended to maintain PV performance in hot climates [10], [11].

2.2 Weather Conditions and Their Impact on PV Modules

Weather conditions such as humidity, rainfall, and cloud cover significantly affect the performance of photovoltaic (PV) systems, especially in tropical regions. High humidity can lead to moisture accumulation and condensation on the surface of PV panels, obstructing sunlight and reducing energy output [13], [14]. In tropical climates, this condition contributes to energy degradation and potential economic losses [4]. While rainfall can be beneficial by washing away dust and dirt from the panels, thereby enhancing light absorption [15], excessive rainfall and persistent cloud cover reduce sunlight exposure and consequently decrease solar energy generation [4], [15]. Cloud cover further impacts PV performance by significantly reducing solar irradiance, causing sharp drops in energy production during overcast days [4], [15], and in tropical areas, the variability in cloud density creates substantial fluctuations in power output, which challenges the reliability of solar energy supply [15]. To mitigate these impacts, regular cleaning and enhanced monitoring of PV systems are recommended, alongside predictive maintenance strategies and statistical models to better manage the influence of weather variability on energy yield [4].

2.3 Photovoltaic Performance in Tropical Climates

Indonesia's tropical climate offers high solar radiation ideal for photovoltaic (PV) systems but also presents challenges such as high temperatures, humidity, and rainfall that can reduce performance. To mitigate these effects, strategies like optimizing module orientation and tilt have proven effective; in Pontianak, monthly tilt adjustments can yield up to 1893 kWh/m²/year with minimal losses when adjusted less frequently [16]. Material innovations also contribute, with

monocrystalline cells achieving 25% power conversion efficiency (PCE), and CdTe cells maintaining stability under heat and low irradiance [2]. Technologies like back contacts and interconnections help reduce recombination losses and shading [2]. Studies in Surakarta indicate temperature and irradiance have a greater impact than humidity on energy output [7], while the Five Parameter Model offers more accurate PV performance predictions than the Sandia Model in tropical regions with limited data [8].

2.4 Gaps in the Literature

While there is significant research on the general impact of temperature and weather conditions on PV performance, studies specifically focused on Indonesia's tropical climate are limited. Much of the existing research has been conducted in regions with different climate characteristics, such as temperate or arid zones. Therefore, there is a need for more localized studies that examine the unique challenges faced by photovoltaic systems in Indonesia, particularly in relation to the country's high humidity, rainfall, and temperature fluctuations.

Furthermore, most studies have used quantitative methods to measure the performance of PV systems, but qualitative research exploring the experiences and insights of professionals working with solar energy systems in tropical regions is sparse. Qualitative research can provide a deeper understanding of the practical challenges and adaptations necessary to optimize solar energy systems in these climates, offering valuable insights from industry experts and technicians who deal with these issues on a daily basis.

3. METHODS

The research adopted a qualitative design to explore the effects of environmental factors, such as temperature and weather conditions, on the performance of photovoltaic (PV) modules in tropical Indonesia. This approach was selected to gain

an in-depth understanding of the lived experiences and perspectives of professionals working in the solar energy sector. Through this method, the study aimed to address three key research questions: (1) How do temperature and weather conditions in tropical Indonesia influence the efficiency of PV modules? (2) What challenges do solar energy professionals face when working with PV systems under such environmental conditions? (3) What strategies do these professionals recommend for optimizing PV performance in tropical regions? To gather rich insights, five informants were purposively selected based on their experience and expertise in installing, maintaining, and analyzing the performance of PV systems in tropical climates. The criteria for selection included hands-on experience in similar climates, familiarity with weather-related performance issues, and knowledge of optimization techniques. The sample size was considered adequate for qualitative inquiry, prioritizing depth of understanding over broad generalizability.

Data collection was conducted using semi-structured interviews, allowing for both consistency and flexibility across sessions. This format enabled the researcher to explore key themes while giving participants the opportunity to elaborate on their specific experiences. The interview guide, derived from the research questions and literature review, included open-ended questions covering participants' experiences with PV systems, environmental impacts on performance, encountered challenges, and recommended strategies for optimization. Each interview lasted between 45 and 60 minutes and was conducted either in person or online, depending on participant availability. With informed consent, all interviews were recorded and later transcribed verbatim for analysis. Participants were recruited through purposive sampling (Patton, 2015), utilizing professional networks and recommendations to ensure that informants possessed the relevant knowledge and expertise. After initial contact through email or phone, interview sessions were

arranged at times convenient for the participants.

The collected data were analyzed using thematic analysis, a method well-suited for identifying patterns and insights within qualitative data. The process began with familiarization through multiple readings of the transcripts, followed by systematic coding to highlight meaningful data segments related to the research focus. These codes were then organized into initial themes such as "temperature impact," "humidity challenges," "performance optimization strategies," and "maintenance practices." Themes were reviewed and refined to ensure they reflected the data accurately, compared across interviews for consistency, and labeled to capture their core meanings. Finally, the findings were synthesized into a comprehensive narrative supported by direct participant quotes, offering a detailed exploration of the challenges and strategies for enhancing PV module performance in Indonesia's tropical climate.

4. RESULTS AND DISCUSSION

4.1 Key Themes Identified

Through thematic analysis, several key themes emerged from the interviews, which provide insights into the effects of environmental factors on PV module performance in tropical Indonesia. The main themes identified were:

- 1) Temperature Effects on PV Efficiency
- 2) Impact of Humidity and Rainfall
- 3) Challenges in PV Maintenance
- 4) Strategies for Optimizing PV Performance
- 5) Regional Variations and Site-Specific Factors

Each of these themes is discussed below with specific examples drawn from the interviews.

4.1.1 Temperature Effects on PV Efficiency

The majority of the informants (four out of five) emphasized that high temperatures significantly impact the performance of photovoltaic (PV) modules in tropical Indonesia. As temperatures rise, PV

modules become less efficient, resulting in reduced energy output. This issue is particularly critical during midday when solar irradiance and ambient temperatures peak. The participants noted that thermal losses due to high module temperatures are a consistent challenge in Indonesia's equatorial environment, where the sun's intensity remains high throughout the year.

One informant (Informant 1) specifically stated, "In regions with intense sunlight, we see a clear drop in efficiency when temperatures exceed 35°C. The modules' temperature rise causes the voltage output to drop, reducing the overall power generation." This observation is supported by prior research indicating that for every 1°C increase in temperature, the efficiency of crystalline silicon PV modules may decline by approximately 0.4% to 0.5% (Jordan & Kurtz, 2013). Such insights underscore the importance of developing thermal management strategies to sustain PV system efficiency in tropical climates like Indonesia.

4.1.2 Impact of Humidity and Rainfall

While temperature was the most frequently discussed factor, humidity and rainfall were also recognized by informants as significant environmental variables affecting the performance of photovoltaic (PV) systems. Two informants (Informant 2 and Informant 4) highlighted that high humidity, particularly in coastal regions, can lead to the accumulation of dust and moisture on the surface of PV modules, reducing their efficiency. Although rainfall can be beneficial by cleaning the panels, it also introduces variability in energy output, especially during prolonged periods of overcast weather and heavy precipitation.

Informant 4 remarked, "The rainy season helps wash off dust, but constant humidity can cause a layer of moisture to form on the panels, leading to a decrease in energy production. When there's heavy rainfall, output can decrease dramatically due to lower sunlight availability." These observations are supported by existing studies, which suggest that humidity not only accelerates the accumulation of grime but also

contributes to the overall decline in PV efficiency (Alarcon et al., 2016). The participants agreed that although rain can offer short-term maintenance benefits, it simultaneously presents a challenge to consistent solar energy generation due to reduced irradiance during stormy or cloudy conditions.

4.1.3 Challenges in PV Maintenance

Maintenance of photovoltaic (PV) modules is a critical concern in tropical climates due to the various environmental factors that influence their performance. Informants highlighted several recurring issues, including dust accumulation, corrosion from salt-laden air in coastal areas, and the growth of algae or moss on panel surfaces. These challenges require routine maintenance to prevent efficiency losses and ensure the longevity of the system components. Informant 3 pointed out that such environmental stressors are particularly pronounced in coastal regions, where additional effort is needed to preserve the condition of PV installations.

According to Informant 3, "In coastal regions, salt from the sea air can corrode the frames and wiring of PV panels. This requires more frequent cleaning and maintenance, especially in areas exposed to high winds." This insight aligns with the findings of Hottel and Whillier (2012), who observed that salt, dust, and moisture can have a lasting impact on PV system efficiency. To address these challenges, the informants emphasized the importance of implementing regular and region-specific maintenance schedules to maintain optimal energy output and reduce long-term system degradation.

4.1.4 Strategies for Optimizing PV Performance

Several strategies were recommended by the informants to optimize the performance of photovoltaic (PV) modules in response to environmental challenges such as high temperature and variable weather conditions. These included the application of anti-reflective coatings to minimize light reflection and enhance solar energy absorption, particularly under intense

sunlight. Informant 2 emphasized the importance of using cooling systems or heat sinks to dissipate excess heat from PV modules, which can significantly improve efficiency in high-temperature environments. Additionally, the proper placement and orientation of PV panels were repeatedly mentioned as crucial. Installing panels at an angle helps maximize sunlight exposure while reducing direct thermal buildup and avoiding shading from nearby objects.

Informant 5 highlighted this by stating, "We focus on installing the modules at an optimal angle to ensure they catch the maximum amount of sunlight while minimizing the heat buildup that happens when the panels face directly upward in intense sun." These insights align with existing literature, which supports the effectiveness of such strategies in mitigating performance loss under suboptimal environmental conditions (Mekhilef et al., 2012). In particular, the use of cooling systems has been shown to be effective in reducing temperature-induced efficiency losses in PV modules (Sharma et al., 2018). Overall, the integration of these techniques can enhance the resilience and energy yield of PV systems in tropical climates like Indonesia.

4.1.5 Regional Variations and Site-Specific Factors

The informants emphasized that the challenges and solutions related to photovoltaic (PV) module performance vary significantly based on regional factors such as proximity to the coast, altitude, and local weather patterns. For instance, coastal areas are more prone to corrosion due to salt-laden air, while inland regions often struggle with dust accumulation, which can obstruct sunlight and diminish energy output. These environmental differences necessitate tailored maintenance and operational strategies to ensure optimal system performance across diverse locations.

Informant 2 illustrated this point by stating, "In coastal areas like Bali and Surabaya, salt corrosion is a major issue, while in places like Sumatra, dust accumulation can block sunlight. We have to tailor the

maintenance and operational strategies according to each region." This insight highlights the need to consider site-specific climatic and environmental conditions when designing, installing, and managing PV systems. Such an approach is consistent with findings from previous studies, which confirm that regional factors significantly influence the effectiveness and longevity of solar power systems (Perez et al., 2011).

4.2 Discussion

The results of this study support previous research on the negative impact of temperature and weather conditions on photovoltaic (PV) module performance, particularly in tropical climates. Informants highlighted how high temperatures, humidity, and rainfall collectively influence the overall efficiency and reliability of PV systems. High temperatures were consistently reported to reduce PV module efficiency—a well-established phenomenon—especially in Indonesia, where midday temperatures often exceed 35°C. This reinforces the importance of incorporating mitigation strategies, such as heat sinks or active cooling systems, into PV installations to counteract temperature-related performance losses. Meanwhile, while rainfall can help clean panel surfaces, persistent humidity and frequent precipitation during the wet season can reduce sunlight availability, thus limiting energy output. These findings underscore the need for weather-responsive system designs and maintenance strategies tailored to seasonal conditions.

Furthermore, maintenance challenges such as corrosion in coastal regions and dust buildup in inland areas reinforce the importance of proactive, region-specific maintenance practices. Informants noted that environmental stressors like salt and dust not only decrease efficiency but also increase the long-term costs associated with replacing or repairing components. Consequently, preventive maintenance becomes essential to maintaining system reliability and avoiding costly breakdowns. Regional variations further complicate system management, as factors such as coastal proximity, elevation,

and local weather dynamics require site-specific adjustments in both system design and operational protocols. As noted by the participants, optimizing PV system performance in Indonesia's diverse tropical environments demands a flexible, localized approach that accounts for environmental variability and ensures consistent energy production throughout the year.

5. CONCLUSION

This study highlights the critical influence of temperature and weather conditions on the performance of photovoltaic (PV) modules in tropical Indonesia. Insights from interviews with industry experts revealed that high temperatures significantly reduce energy output due to thermal effects, while humidity and rainfall contribute to dust accumulation and diminished sunlight exposure. These environmental challenges, particularly in coastal and inland regions, necessitate more

frequent maintenance and the implementation of customized operational strategies to maintain module efficiency and system reliability in the face of variable tropical conditions.

The findings also underscore the importance of region-specific solutions to sustain optimal PV performance. Techniques such as applying anti-reflective coatings, installing cooling systems, and optimizing panel placement and orientation were identified as effective strategies to counter environmental stressors. Furthermore, the study calls for continued research to quantify the specific impact of temperature, humidity, and rainfall on PV efficiency and to assess the long-term benefits of various mitigation approaches. By addressing the unique challenges posed by Indonesia's tropical climate, this study provides practical insights that can inform the design, deployment, and maintenance of PV systems, supporting the broader development of solar energy infrastructure in the region.

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