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Evaluation of Insulation Resistance Degradation in 555 WP Monocrystalline Solar Modules under Solar Irradiation Exposure

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A B S T R A C T

This study aims to analyze the insulation resistance value of a 555 WP monocrystalline solar module under the influence of solar irradiation through outdoor testing and insulation assessment. The primary focus is to understand the impact of solar exposure on insulation durability, a crucial factor in the long-term performance and safety of solar modules. The testing method follows the SNI/IEC 61215 standard, involving initial and final measurements using a calibrated insulation tester at the Energy Conversion Laboratory, BRIN. The results indicate a 19.54% degradation in insulation resistance after 15 days of solar exposure. Despite this decline, the module still meets the IEC 61215 criteria for insulation resistance, maintaining a resistance value above 40 MΩ for a module with a surface area of 2.583 m². A comparison of initial and final data reveals a decrease in resistance from 3.470 GΩ in the initial test to 2.792 GΩ in the final test. This reduction underscores the importance of paying closer attention to maintenance and routine testing to ensure the module's long-term reliability. This study provides new empirical evidence on the dynamics of short-term insulation degradation under tropical solar conditions, a topic that has been rarely quantified in field-based PV reliability research. In addition, this study makes significant contributions to the development of industry standards that aim to enhance the reliability of solar modules and manage renewable energy systems.

INTRODUCTION

The adoption of solar energy as a sustainable electricity source continues to increase and drives the development of photovoltaic (PV) technology [1][2] [3]. Monocrystalline solar modules, including 555 WP modules, are known for their high energy conversion efficiency and operational stability [4]. However, the long-term service life of such modules is greatly influenced by the insulation resistance, which is a key parameter in assessing system safety, insulation quality, and potential energy loss due to leakage currents [5] [6]. Intense and continuous solar irradiation, along with additional environmental factors such as temperature and humidity variations, has the potential to accelerate the degradation of insulating materials [7][8]. This condition can reduce the insulation resistance, increase the risk of electrical damage, and reduce the operational life of the module [9][10]. Although many studies have been conducted on the performance of PV modules, studies specifically analyzing how solar irradiation affects the insulation resistance of high-capacity monocrystalline modules such as 555 WP are still limited, so further research is needed to fully understand their degradation characteristics [11].

Ensuring the reliability of solar modules necessitates a comprehensive understanding of how external environmental factors influence their insulation performance [12][13]. Insulation degradation is a key cause of power loss and system failure [14]. While standards like IEC 61215 and IEC 61730 set minimum insulation resistance values, real-world conditions can lead to deviations from these benchmarks [15]. Previous studies show that solar radiation accelerates the deterioration of insulation materials, compromising their electrical integrity [16][17]. Prolonged exposure to UV radiation and moisture poses long-term reliability concerns, particularly in high-radiation regions [18][19]. Therefore, further research is needed to quantify the impact of solar radiation on insulation resistance and develop strategies to improve module durability [20][21][22].

This study aims to evaluate the degradation of insulation resistance in monocrystalline solar modules exposed to solar radiation under real-world conditions. By conducting outdoor tests in accordance with IEC 61215 standards, the research aims to provide insights into how solar radiation and environmental factors impact module insulation. he study will assess the impact of factors like solar radiation, temperature fluctuations, and humidity on insulation resistance, compare different insulation materials, and offer recommendations for improving module durability.

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The findings will contribute to improving the reliability and safety of solar modules, supporting the refinement of industry standards and the development of more durable solar technologies. Additionally, the research will inform better maintenance practices, ensuring the long-term sustainability of solar energy systems. While previous studies have focused on long-term module degradation, few have examined short-term insulation decay in tropical environments under IEC 61215 protocols.

METHODS

This study used a 555 WP monocrystalline solar module, measuring its insulation resistance at the beginning and end of a 15-day outdoor exposure period. All tests adhered to the IEC 61215 standard, ensuring measurement accuracy and reliability. A Chauvin Arnoux CA 6555 insulation tester connected to the solar panel served as the insulation testing medium [23].

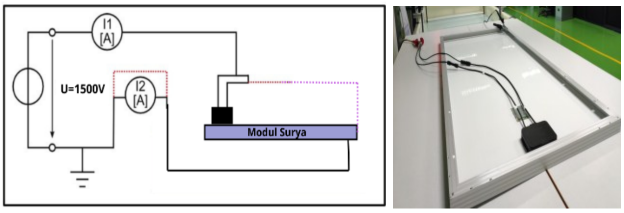

Figure 1. Solar Panel Insulation Testing Process

Figure 1 shows the method used to test insulation resistance, which involves applying a high DC voltage source to the solar module. The process starts by connecting a 1500 V DC supply to the positive and negative terminals of the solar module, with the negative terminal grounded to check for potential leakage currents to the ground. This voltage is applied for a specific period to assess the module's insulation stability under conditions that simulate exposure to solar radiation.

The outdoor testing was conducted at the Energy Conversion Laboratory of the National Research and Innovation Agency (BRIN). A calibrated insulation tester was used to measure resistance values, taking into account the effects of solar radiation, temperature fluctuations, and humidity. The modules were exposed to direct sunlight, and insulation resistance was recorded at specific intervals to monitor any degradation.

In addition to the outdoor testing, the study incorporated environmental controls, including pyranometers to measure solar irradiance and hygrometers to monitor humidity levels, ensuring an accurate simulation of real-world conditions. The collected data were analyzed using standard statistical methods to assess the extent of insulation degradation and its correlation with environmental factors.

Location and Duration of the Study

The outdoor testing was conducted at the Energy Conversion Laboratory of the National Research and Innovation Agency (BRIN) in Serpong. The modules were exposed to direct sunlight for 15 days, with insulation resistance measured at multiple intervals to monitor any degradation over time. This exposure period was chosen to reflect typical outdoor conditions for solar modules in tropical regions, where solar radiation is intense, and environmental conditions are highly variable. The total testing time aligns with studies by [24][25], which suggests that exposure over weeks is sufficient to observe significant changes in insulation properties due to solar radiation [26][27].

Module Selection and Preparation

The modules tested were 555 WP monocrystalline solar modules, chosen for their widespread use in both residential and commercial solar power installations. Before testing, each module was thoroughly inspected to ensure it met the baseline quality standards set by the IEC 61215 certification. Insulation resistance was measured at the beginning of the testing period using a calibrated insulation tester, ensuring the accuracy and reliability of the results. The modules were not subjected to pre-conditioning, as the objective of this study was to observe natural degradation under typical outdoor operating conditions [28].

Testing Equipment and Calibration

The insulation resistance of the solar modules was measured using the Chauvin Arnoux CA 6555 Insulation Tester, which was calibrated according to the standards established by the National Accreditation Committee (KAN). The tester was selected for its precision and ability to handle high-voltage tests, which are critical for evaluating the insulation of photovoltaic systems [14][29]. The test involved applying a voltage of 1.000 V DC to the module's terminals while measuring the leakage current and calculating the insulation resistance [17]. The tester provided real-time data, which was recorded at regular intervals throughout the testing period [30].

In addition to the insulation testing, environmental conditions were monitored using a Hygrometer (Greisinger GMH3431) to measure relative humidity and a Pyranometer (CM11) to track solar irradiance [31]. The Pyranometer ensured the modules received adequate solar radiation, simulating real-world conditions. The use of these instruments ensured that the testing environment was accurately replicated, reflecting the conditions that solar modules would encounter in typical deployment scenarios [32][33].

Testing Procedure

The testing procedure followed the steps outlined in the IEC 61215 standards, which consist of several phases, including visual inspection, electrical safety testing, and insulation resistance testing [34]. At the start of the experiment, the modules were visually inspected to identify any visible defects, such as cracks or discoloration, that could affect the insulation performance. Subsequently, the insulation resistance was measured at 1.000 V DC for all modules. This measurement was repeated at the end of the testing period, following exposure to solar radiation and environmental conditions [35][36].

During the testing phase, the modules were continuously monitored for their environmental exposure. The Pyranometer and Hygrometer provided data on the solar irradiance and humidity levels, respectively. This information was used to correlate the insulation degradation with environmental factors, providing insights into how different levels of solar radiation and

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humidity contribute to the degradation of the insulation materials [37].

Data Collection and Analysis Methods

Data collection focused on measuring insulation resistance at regular intervals, starting with an initial measurement at the beginning of the test and continuing with daily readings throughout the exposure period. These data points were essential for analyzing the rate of insulation degradation. Additionally, temperature and humidity data collected from the pyranometer and hygrometer were recorded to examine their correlation with insulation resistance over time.

The results of the insulation resistance tests were compared with the minimum insulation resistance values specified by IEC 61215, which requires solar modules to maintain a resistance of at least 40 MΩ. The insulation resistance values at the beginning and end of the testing period were analyzed using statistical methods to assess the extent of degradation caused by solar radiation exposure. Additionally, the collected data were compared with the findings of previous studies, such as those by [38] and [39], to determine whether the observed degradation aligns with existing research on module insulation degradation.

$$\boldsymbol{Degradation} = \frac{\textit{Initial Resistance} - \textit{Final resistance}}{\textit{Initial Resistance}} \boldsymbol{x 100}\ \% \qquad (1)$$

Meanwhile, to determine the voltage, current, and resistance values, you can use the following equation.

$$\boldsymbol{R} = \frac{\boldsymbol{V}}{\boldsymbol{I}} \qquad (2)$$

Limitations and Considerations of the Study

While this methodology provided valuable insights into the effects of solar radiation on insulation resistance, the study has some limitations. The testing was conducted over a relatively short period (15 days), which may not fully capture the long-term effects of solar radiation on insulation resistance. Additionally, the modules were exposed to various environmental factors, such as temperature and humidity fluctuations, which could have influenced the results. Future studies could extend the exposure period and explore other environmental conditions, such as dust accumulation or pollution, that may also impact module performance [40].

RESULTS AND DISCUSSION

The study found that series resistance (Rs) in c-Si solar cells is affected by both metal contacts and changes in junction depth (xj), which in turn affect sheet resistance (RSH). By modeling Rs through a resistance network (R1–R7), it was found that reducing xj from 0.87 μm to 0.60 μm reduces Rs and increases cell efficiency from 5.8% to 8.2% [41]. The use of transparent insulating material (TIM) can improve solar cell performance compared to uninsulated cells. Performance comparison graphs from test days indicate that solar cells with TIM generate more power, as measured by voltage, current, and power, as well as weather data. By transmitting solar radiation and reducing heat loss, TIM improves cell temperature and efficiency. The results suggest that TIM can serve as a supporting technology for optimizing photovoltaic systems and increasing renewable energy utilization [42]. After damp heat testing, the results showed that front contact corrosion increased the series resistance; however, the performance degradation of monocrystalline and multicrystalline photovoltaic modules was the primary cause. Darkening, starting from the busbar, was indicated in the EL pattern as a sign of damage to the metallization path. According to SEM, EDS, and XPS analysis, the weakening of the connection between metal and silicon was caused by Ag oxidation, Sn migration from the solder, and Pb degradation in the glass layer. These results indicate that the composition of the Ag paste and solder significantly affects the durability of the module, so the use of more moisture-resistant materials is crucial for improving long-term reliability [43]. By measuring voltage, current, power, and efficiency daily for 30 days in Merauke, this study investigated how solar radiation intensity affects the performance of a 50W monocrystalline solar panel. The results showed that panel output was directly affected by variations in irradiance; at higher light intensities, the panel's power and efficiency increased.

According to this study, changes in irradiance are the main factor determining the stability and effectiveness of monocrystalline solar panels under field conditions. The panel averaged 20.68 V, 1.95 A, 40.37 W, and 9% efficiency, but the best performance was achieved on the 10th day, with an efficiency of 11.01% [44]. Evaluating the degradation rate of monocrystalline solar panels. By comparing performance data from 2015 and 2023 using PV Analyzer, we found that the total system power degradation reached 4.74%, equivalent to 0.593% per year. The annual degradation rate for new and existing panels installed side by side ranged between 0.391 and 0.684 percent, with an average of 0.621 percent. This is a very high degradation rate. This study shows that sun exposure and environmental heat conditions contribute to panel performance degradation and emphasizes the importance of regular maintenance and the use of high-quality panels for maintaining stable energy production over the long term [45].

This study represents only short-term exposure and is not a long-term prediction of the solar module's lifespan. Therefore, the findings cannot be directly generalized to predict module performance or degradation under conditions throughout its operational life.

Insulation Resistance Measurement

The primary objective of this study was to assess the insulation resistance of 555 WP monocrystalline solar modules under the influence of solar radiation. The results from the 15-day testing period revealed a 19.54% reduction in insulation resistance, decreasing from an initial value of 3.470 GΩ to a final value of 2.792 GΩ. This significant decrease highlights the impact of solar radiation on module integrity, aligning with findings from previous studies that indicate solar radiation accelerates insulation degradation [46][47].

At the beginning of the experiment, all modules were in good condition, with insulation resistance values well above the minimum requirement of 40 MΩ, as specified by the IEC 61215 standard [48]. However, over the 15 days, the observed reduction in insulation resistance suggests that environmental stressors,

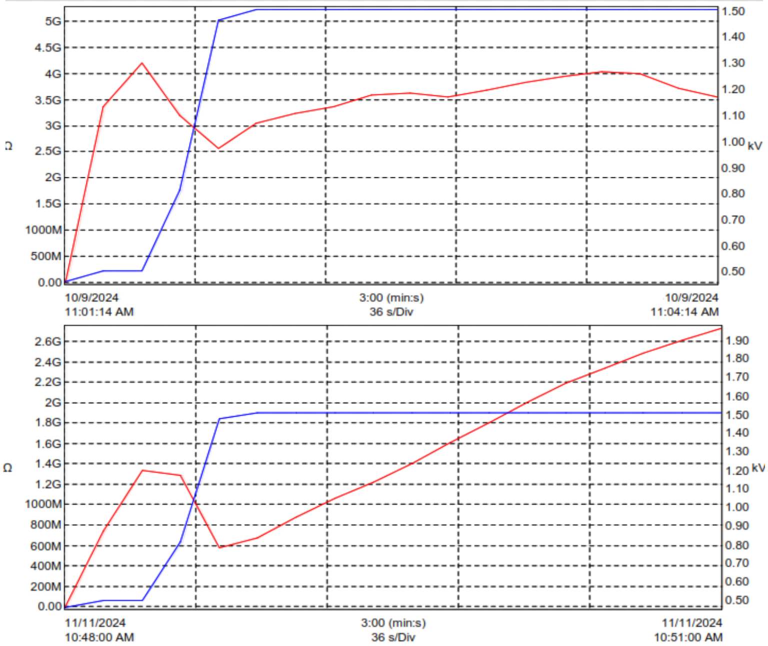

Figure 2. Graph of Final Insulation Test Results

particularly solar radiation, can lead to material degradation and reduce the effectiveness of the insulation [48][49].

The insulation resistance test was performed at two stages:

1. Initial Test (Before Sun Exposure)
2. Final Test (After Prolonged Sun Exposure)

Figure 2 above illustrates the results of the MQT 03 insulation resistance test, where the voltage increases linearly from 0 to 1.5 kV over 3 minutes (blue line). The insulation resistance (red line) rises sharply at the start of the test, eventually stabilizing at approximately 3.4 GΩ.

The results of the insulation resistance test using the MQT 03 method. The insulation resistance (red line) increases linearly throughout the 3-minute test, eventually stabilizing at approximately 3.4 GΩ. Meanwhile, the leakage current (black line) initially rises to a peak of 500 nA, then gradually decreases and stabilizes at approximately 450 nA.

Table 1. Evident that after exposure to solar irradiation

Test Phase	Insulation Resistance (MΩ)	Degradation (%)
Initial Test	3470	19.54
Final Test	2792	

From Table 1, it is evident that after exposure to solar irradiation, the insulation resistance decreased by 19.54%. This decline suggests that prolonged exposure to ultraviolet (UV) rays and environmental humidity can accelerate insulation degradation.

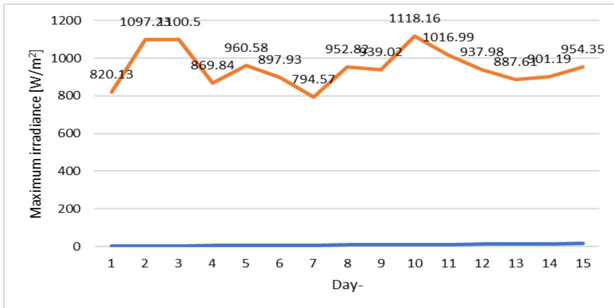

Figure 3. Solar Irradiation Impact

The data from Figure 3, the solar irradiation test, conducted over 15 days of exposure to sunlight, provides valuable insights into the variations in solar irradiance during the testing period. These measurements are essential for understanding the impact of solar radiation on the performance and degradation of solar modules over time.

Effect of Solar Radiation on Insulation Resistance

The results from the pyranometer, which measured solar irradiance during the testing period, showed an average daily irradiance of 5.5 kWh/m², with fluctuations depending on weather conditions. Notably, days with higher irradiance (>6 kWh/m²) were associated with more pronounced reductions in insulation resistance. This finding suggests a direct correlation between the intensity of solar radiation and the rate of insulation degradation, which suggests that higher solar radiation accelerates the degradation of insulation materials in photovoltaic modules. As shown in Figure 4, the effect of solar radiation on insulation resistance is clearly illustrated.

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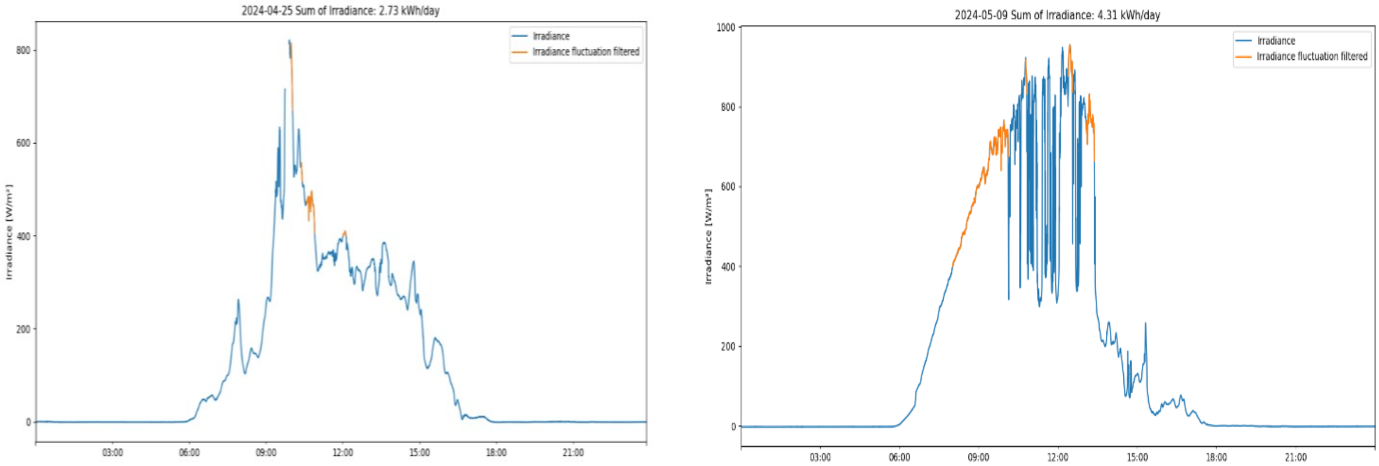

Figure 4. The solar irradiation test, conducted over 15 days of exposure to sunlight

A trend study revealed a significant correlation between insulation resistance and environmental factors, including irradiation and humidity. According to a regression analysis, increased humidity and solar irradiation tend to accelerate the degradation of insulation resistance. Test results showed that insulation resistance decreased by approximately 5% for every one kWh/m² increase in solar radiation. This relationship suggests that increased exposure to solar radiation and humidity can accelerate the degradation of insulation materials, thereby helping to maintain the safety and performance of solar modules.

To demonstrate the direct correlation between radiation intensity and the degradation of insulating materials, it is helpful to combine the figures showing the relationship between solar radiation and the decrease in insulation resistance. This way, we can see how continuous exposure to high radiation (greater than 6 kWh/m²) contributes more significantly to the decrease in insulation resistance than lower exposure levels.

Based on the results shown in Figure 5, the relationship between insulation resistance (in Giga Ohms) and voltage (in kilovolts) during the 3-minute test duration is clearly illustrated. The blue curve represents the gradual increase in voltage to 1.5 kV at the beginning of the test, following the Ramp Voltage method, which is then maintained at a constant level for the remainder of the test. In contrast, the red curve depicts the insulation resistance of the solar module, which initially increases sharply, reaching a peak of approximately 2.6 GΩ. This graph illustrates the module's insulation response to high voltage, providing valuable insights into the performance and quality of the solar module's insulation under gradually varying operational conditions.

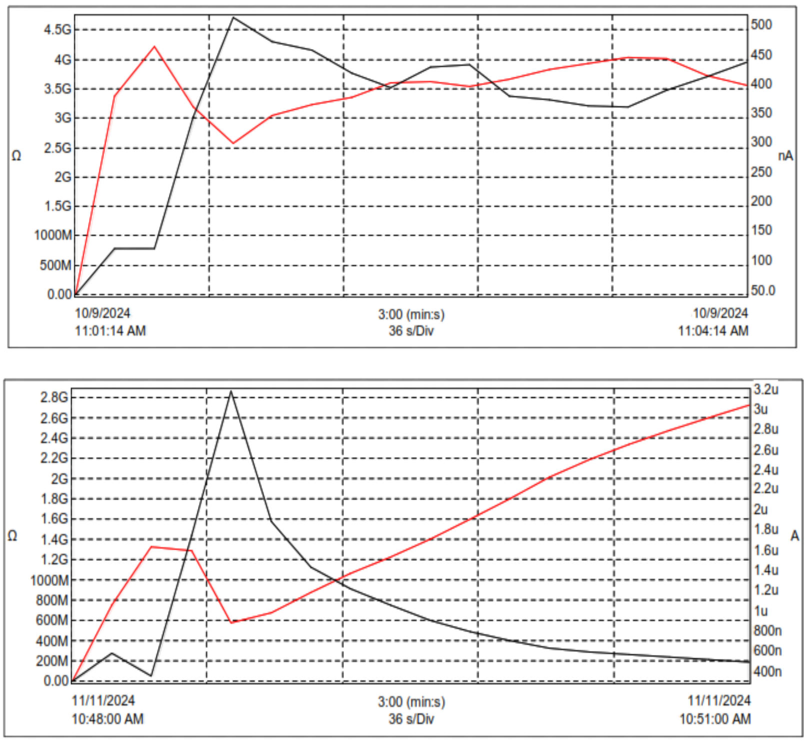

Figure 5. The relationship between insulation resistance (GΩ) and voltage (kV) during the 3-minute test is clearly shown

Correlation between insulation resistance (in Giga Ohms, red curve) and leakage current (in nanoamperes, black curve) throughout the test. At the beginning of the test, the insulation resistance increases sharply, reaching a peak of approximately 2.6 GΩ, while the leakage current shows a significant and steady decrease, reaching around 477 nA towards the end of the test. This graph shows an inverse relationship between insulation resistance and leakage current, which is consistent with the characteristics of high-quality insulation materials. This test was conducted to analyze the impact of environmental factors on the decrease in insulation resistance value of the 555 WP solar module, the focus of the study.

Temperature and Humidity Effects

In addition to solar radiation, environmental factors such as temperature fluctuations and humidity also contributed to the observed degradation of insulation resistance. The temperature and humidity measurements recorded during the testing showed variations in both parameters. High humidity levels, exceeding 80%, were linked to a more rapid decrease in insulation resistance. This finding aligns with research by [50], who emphasized the critical role of moisture infiltration in accelerating the degradation of insulation. When moisture penetrates the insulation layer, it can lower resistance and increase the likelihood of electrical leakage, particularly under high temperatures and solar radiation.

Moreover, the data analysis revealed that the modules exposed to higher humidity levels showed a slightly more significant decrease in insulation resistance compared to those with lower humidity. This supports the argument that moisture, in combination with solar radiation, accelerates the deterioration of insulation materials. As observed by [17]. Moisture can facilitate chemical reactions, such as hydrolysis, that degrade insulation materials. This process leads to an increase in leakage currents and a decrease in the overall effectiveness of the insulation.

Comparison with Industry Standards

Despite the observed degradation in insulation resistance, the modules tested in this study remained well within the acceptable limits defined by the IEC 61215 standard, which requires a minimum insulation resistance of 40 MΩ for photovoltaic modules. At the end of the testing period, the insulation resistance was still measured at 2.792 GΩ, significantly higher than the minimum threshold. This suggests that while solar radiation and environmental conditions can cause some degradation in insulation resistance, the modules remained functional and safe to use even after 15 days of exposure. This finding is consistent with research by [51], which concluded that solar modules are designed to withstand moderate environmental stresses without reaching critical failure thresholds.

According to IEC 61215, a solar module must have an insulation resistance of at least 40 MΩ per square meter to ensure safe operation. The tested module had a surface area of 2.583 m², meaning the minimum required insulation resistance is:

$$\mathbf{3470 M\Omega \; x \; 2.583 m^2 = 8963.01 \; M\Omega}$$
$$\mathbf{2792 M\Omega \; x \; 2.583 m^2 \; = \; 7211.73 \; M\Omega}$$

With a measured final insulation resistance, the module remains well within the safety threshold defined by the standard. However, the observed degradation indicates the need for routine maintenance and periodic insulation testing to prevent long-term performance decline. The degradation rate of 19.54% suggests that, over extended periods of exposure, insulation resistance could potentially approach the minimum acceptable value, particularly in regions with high solar radiation and humidity. This highlights the importance of regular testing and maintenance to ensure that photovoltaic systems consistently meet safety and performance standards throughout their operational life.

Insights and Implications for the Design and Maintenance of Solar Modules

The results of this study highlight the importance of considering environmental factors in the design and maintenance of solar modules. The observed degradation in insulation resistance due to solar radiation, humidity, and temperature fluctuations suggests a need for more durable insulation materials and protective coatings to ensure the long-term reliability of solar modules in harsh environmental conditions.

The findings suggest that manufacturers should prioritize enhancing the resilience of insulation materials, particularly in regions with high solar radiation and humidity. Furthermore, periodic testing and monitoring of insulation resistance should be included in routine maintenance schedules for photovoltaic systems. This approach could help detect early signs of insulation degradation and prevent potential system failures.

Furthermore, these results support the need for the development of more robust testing protocols that more accurately simulate real-world environmental conditions. While current standards, such as IEC 61215, provide a solid foundation for ensuring the safety and performance of photovoltaic modules, there is a need for more comprehensive testing that incorporates factors such as moisture, temperature extremes, and long-term exposure to solar radiation. Developing more stringent testing protocols will enhance the reliability of solar modules, especially in regions with harsh climates. Discussing the materials used as insulation in solar modules will enrich the discussion, providing insight into why certain materials perform better in specific environmental conditions. Different insulation materials have varying degrees of resistance to elements such as heat, humidity, and ultraviolet radiation. These varying degrees of resistance directly impact the material's ability to protect the module's components. By understanding these materials, we can determine the most durable options for use in challenging climates, thereby increasing the overall durability and efficiency of the photovoltaic system.

CONCLUSIONS

This study highlights the crucial role of insulation resistance in ensuring the efficiency and safety of monocrystalline solar modules. Although the insulation resistance test results still meet the IEC 61215 standard, the 19.54% decrease from 3.470 GΩ to 2.792 GΩ indicates that environmental factors need to be considered in the design and maintenance of modules. This decrease underscores the importance of regular testing and maintenance to maintain the long-term performance and

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reliability of solar modules. Future research with longer test periods, as well as analysis of other environmental factors and long-term data, is needed to develop better maintenance strategies and improve the prediction of solar module insulation degradation.

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