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Identification of early operational defects in photovoltaic modules: A case study of a 24.9 MWp solar PV system in Sumatra, Indonesia

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ABSTRACT

This study investigates early operational defects in a 24.9 MWp solar PV system located in Sumatra, Indonesia, within its first two years of operation. The primary objective is to identify key issues affecting performance, reliability, and energy output. Field observations revealed several critical defects, with hotspot formation being the most dominant issue. Hotspots, caused by partial shading, cell mismatches, or module damage, result in excessive localized heating, leading to material degradation and significant power losses. Additional defects included glass cracking (282 cases), primarily linked to hotspots and mechanical impacts, and 350 cases of junction box failures due to improper sealing, which pose long-term risks of moisture ingress and diode malfunction. Instances of foggy or discolored glass (delamination) were also identified, reducing light transmission and overall efficiency. Shading from external objects and self-shading between PV arrays exacerbated these problems. The study highlights that half-cut modules outperform full-cell modules in mitigating hotspot risks due to their lower current per cell and enhanced bypass diode configuration. Reducing the number of modules per string further minimizes hotspot severity. Recommendations include regular maintenance, shading mitigation strategies, and optimized system design to enhance performance and reliability. These findings provide valuable insights for improving large-scale PV system durability in real-world conditions.

1. Introduction

The adoption of solar photovoltaic (PV) technology as a sustainable energy solution has grown rapidly worldwide, particularly in regions with abundant solar resources [1]. In Indonesia, the deployment of large-scale PV systems plays a critical role in achieving renewable energy targets and reducing dependence on fossil fuels [2,3]. However, maintaining optimal performance and reliability of PV systems remains a challenge, especially during the initial years of operation. Early operational defects, such as hotspots [4,5], glass cracking [6], and junction box failures, can significantly reduce energy output, accelerate module degradation, and increase operational costs. Understanding the nature and causes of these defects is essential to ensure system longevity and maximize return on investment.

Several studies have reported on the performance of large-scale PV systems [7,8]. Most works evaluated the effects of irradiance, temperature, and shading on modules and inverters, enabling the identification of failures and optimization of maintenance strategies. Validated across six PV plants in southern Italy, the models achieved a power production prediction accuracy of 4.1 %. They effectively detect inverter and string-related downtimes while distinguishing shading issues (causing up to 5 % energy loss) from component failures. Additionally, aerial infrared imaging validated the models, demonstrating their ability to link thermal anomalies to underperformance and predict annual deterioration rates in PV plants. Another study [9]introduces an artificial neural network tool to quantify power losses in photovoltaic (PV) modules caused by soiling and partial shading. The approach uses visible spectrum RGB images and environmental data to predict individual modules' performance. The method involves three stages: segmentation of module regions using RCNN and supervised learning, resizing these regions for uniform processing, and performance prediction through a custom CNN model. The tool categorizes power loss into percentiles, achieving over 73 % accuracy across eight percentiles. Compared to existing methods, it delivers comparable results with reduced computational cost, offering a practical solution for PV system maintenance.

Partial shading in photovoltaic (PV) systems causes non-uniform illumination, leading to electrical mismatch and uneven temperature

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distribution, which impacts power output and long-term reliability. The thermal shade impact factor is introduced to estimate temperature gradients under varying shading conditions [10]. It indicated that a factor below −1 amplifies temperature gradients when bypass diodes activate, while factors above −1 show higher gradients in inactive states. Shingled solar modules offer higher efficiency but exhibit greater power losses and higher local heating risks under partial shading compared to conventional modules. A reported study [11], using equivalent circuit modeling and experimental verification, highlights that risks from reverse biases in shaded shingles can be mitigated through module-level power electronics or additional bypass diodes.

A study analyzed the mechanical strength of PV cells under mechanical loading using a 3D FE model and XFEM [6]. A 10 % reduction in elastic modulus reduced failure load by 70 %. Thinner silicon modules (0.1 mm) cracked at lower loads (<2400 Pa), and isotropic silicon failed 12 % earlier than anisotropic silicon. Half-cell PV modules experienced lower stresses, with cracks initiating at higher loads and stopping at cell boundaries.

Bayrak et al. [12]conducted an in-depth analysis of the electrical performance and thermodynamic behavior of 75 W photovoltaic (PV) panels under varying shading conditions and ratios. Their research focused on understanding the impact of shading on key parameters such as cell temperature, overall heat loss coefficient, and fill factor. The study employed an experimental setup to evaluate three distinct shading scenarios: cellular, horizontal, and vertical shading, each at different shading percentages. The findings revealed that shading has a substantial effect on both energy and exergy efficiencies, with horizontal shading demonstrating the most detrimental impact. At a 100 % shading rate, power losses were recorded as 69.92 % for cellular shading, 66.93 % for vertical shading, and 99.98 % for horizontal shading. Additionally, the study assessed the role of fill factor, illustrating its significant influence on the overall efficiency of the system.

Islam et al. [13]reported the performance degradation of solar photovoltaic (PV) systems under Malaysia's tropical climate over extended 10-year periods. Using visual inspections, I-V curve measurements, and thermal imaging, the research examines aging mechanisms and degradation rates of PV modules. Annual degradation rates for UMPSA modules were 0.3 % for Vo, 0.23 % for Is, 0.81 % for Pmax, and 0.35 % for FF, while Pasir Mas modules exhibited higher rates. Monocrystalline panels degraded by 6.48 %, while polycrystalline panels showed 12.76 %.

Previous work by Bai et al. [14], introduces a method for simulating photovoltaic (PV) system outputs under partial shading or mismatch conditions. Using a five-parameter equivalent circuit, the method derives I-V characteristics of PV modules or arrays from manufacturer data. It incorporates a calculation algorithm with multiple subsection functions to model complex shading scenarios and determines bypass diode states for accurate simulation of multi-peak characteristics. Experimental results validate the method's accuracy by comparing simulated and actual I-V and P-V curves under various conditions. This approach effectively predicts PV system performance under real-world conditions, aiding in performance optimization and reliability assessment.

Sumatra Island is one of the largest islands in Indonesia, traversed by the equator. Therefore, the implementation of solar power plants (PLTS) has good prospects in this area. However, empirical studies on solar power plants in Sumatra are still limited [15,16]. This study will complement the existing information on solar power plants in the region. While most previous studies have broadly examined PV module defects, limited research focuses specifically on early operational defects in large-scale installations, particularly in tropical climates like Sumatra. This study addresses this gap by analyzing defect occurrence within the first two years of operation.

The primary objective of this study is to identify and analyze early operational defects in a 24.9 MWp solar PV system located in Sumatra, Indonesia, during its first two years of operation. This research aims to categorize and quantify the types of defects observed, including hotspot effects, glass cracking, junction box failures, and foggy or discolored glass, to understand their impact on system performance. A key focus is on evaluating the influence of hotspot formation, which causes power dissipation, localized temperature rise, and material degradation, leading to long-term system inefficiencies. This work is expected to have important implications for developers, maintenance teams, and policymakers. Identifying early defects allows for practical maintenance, minimizing downtime, and maximizing energy production. The first two years of operation of PV systems are critical for detecting early-stage defects.

Additionally, this study investigates the role of module configuration, specifically comparing half-cut modules and full-cell modules, in mitigating the effects of hotspots and power losses. The effect of string design, particularly the number of modules per string, is also analyzed to assess how it influences hotspot severity and overall power output. Furthermore, the research examines the impact of shading, both from surrounding objects such as trees, buildings, and poles, and from self-shading between PV arrays, as a contributing factor to early defects. Ultimately, this study provides recommendations for improving system design, monitoring practices, and maintenance strategies to enhance the reliability, performance, and longevity of large-scale PV systems operating in tropical environments like Indonesia.

This study identifies and analyzes module defects. Although these defects may lead to decreased energy output, the research does not intend to assess the overall energy performance of photovoltaic (PV) systems. Rather, it aims to comprehend the characteristics and origins of module defects and their effects on the long-term reliability of PV systems. The findings from this analysis offer important information for enhancing module quality and installation practices.

2. Method

This study investigates defects and abnormalities in photovoltaic (PV) modules deployed at eight PV systems located in Bengkalis, Sumatra, Indonesia, with a combined total capacity of 24.9 MWp. The geographical coordinates of the site are 0°34′30″N and 101°26′17″E; situated in a tropical region with high solar irradiation levels, making it a suitable location for PV energy generation. One of the PV system sites is presented in Fig. 1, using Google Maps to provide an overview of the location and its layout.

The study was conducted in August 2024, focusing on PV systems that had been in operation for less than two years. The justification for selecting a two-year operational period aligns with various large-scale PV system studies referenced in the literature [17,18]. The relatively short operational period ensures that the observed defects primarily stem from early operational factors, rather than prolonged wear and tear. The eight PV systems are referred to as System 1 through System 8, with their respective installed capacities summarized in Table 1. This classification helps streamline the analysis and comparison of the systems.

Each of these systems utilizes the SANKELUX SLX-390-72M type of PV module, manufactured by PT. Sankeindo, one of Indonesia's leading producers of PV modules. The choice of this module reflects the growing adoption of locally manufactured PV technologies in Indonesia, supported by government policies encouraging domestic production. The technical specifications of the SANKELUX SLX-390-72M module, as detailed in Table 2, serve as a reference for assessing the performance and identifying any deviations from the expected operational parameters.

The PV systems are installed in a ground-mounted configuration, where the modules are connected in series to form strings. Each string comprises 30 modules connected in series, ensuring a stable and efficient energy output. This configuration was designed to operate within the maximum voltage and current values specified by the module's manufacturer. During field observations, the operating voltage (Vmp)

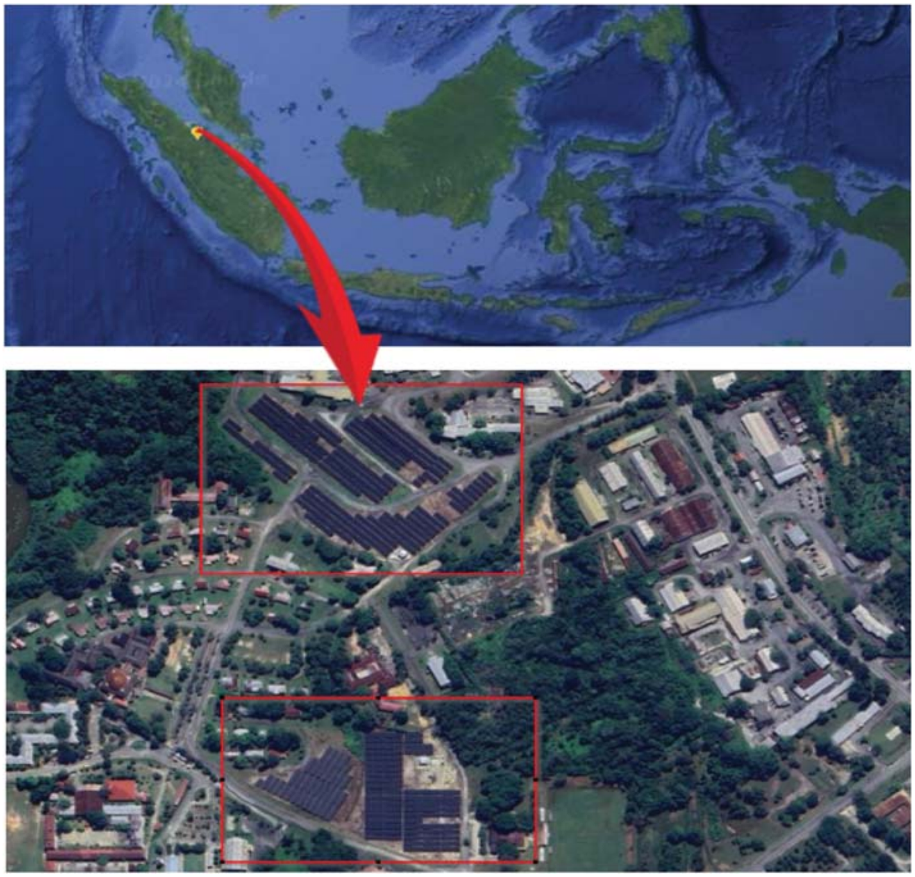

Fig. 1. PV system site location on google maps.

Table 1
PV systems and their capacities.

No.	Denoted PV System	PV System Capacity (MWp)	Number of Modules	Number of Inverter
1	PV System 1	3.70	9480	15
2	PV System 2	3.95	10,140	16
3	PV System 3	3.15	8100	13
4	PV System 4	2.20	5640	9
5	PV System 5	4.20	10,980	17
6	PV System 6	3.20	8280	13
7	PV System 7	2.50	6420	10
8	PV System 8	2.00	5100	8
	Total	24.90	64,140	101

Table 2
Technical specifications of the PV module.

Parameter	Value
Brand dan Type	SANKELUX SLX- 390-72 M
Power Max	390 Wp
Vpm	41.5 V
Ipm	9.4 A
Voc	48.74 V
Isc	9.87 A
Max System Voltage	1500 V
Maximum Series Fuse Rating	10 A
Standard Test	STC (Irradiance 1000 W/mÂ^2)
Product tolerances	+3 %

and operating current (Imp) were monitored and compared against the module's technical specifications to identify potential irregularities.

The observations focused on identifying abnormalities in the power output of specific module strings. A string was considered abnormal when the power output displayed by the inverter was significantly lower than the theoretical values calculated for the string under the given environmental conditions. These abnormalities were further investigated to determine the presence of module defects. The defects identified included glass breakage, hotspot development, and junction box (JB) abnormalities such as swelling, detachment, or improper sealing. These defects were selected based on their potential to significantly impact the performance and reliability of the PV systems. The categorization of defects helps in systematically analyzing their causes and their implications for system performance.

The methodology combined visual inspections with direct measurements to gather comprehensive data on module performance and defects. Visual inspections were conducted to identify visible defects such as cracks, discoloration, delamination, and junction box issues. These inspections were carried out systematically across all eight PV systems, with each module in the strings under investigation being carefully examined.

For more in-depth analysis, specific modules suspected of having defects were subjected to detailed measurements. Electrical parameters, including the open-circuit voltage (Voc) and short-circuit current (Isc), were measured using calibrated testing equipment. These parameters were compared with the module specifications to confirm the presence of abnormalities.

In addition, thermal imaging was employed to detect hotspots, which often indicate underlying issues such as soldering defects or cell degradation. Module surface temperatures were recorded to assess the impact of hotspots on overall module performance. Thermal imaging is a non-invasive and efficient method for identifying hotspots and temperature anomalies, which are early indicators of module defects such as cell degradation and junction box failures.

The identification process focused on strings exhibiting significant deviations from expected power output levels. These deviations were determined by comparing the power output recorded by the inverters with theoretical values calculated using the module specifications, solar irradiance levels, and ambient temperature. Modules within underperforming strings were individually assessed to identify and classify the defects causing the performance drop.

The data collected from the visual inspections and measurements were analyzed to determine the prevalence and impact of each type of defect. Patterns and trends were identified, such as the correlation between certain defects and module performance degradation. These findings are presented and discussed in the subsequent sections of this paper, with an emphasis on practical recommendations for mitigating defects in PV installations.

2.1. Hotspot analysis

The presence of hotspots indicates damage that can vary in severity, ranging from mild heat buildup to significant structural failure. To mitigate hotspots, it is essential to implement preventive maintenance measures such as regular cleaning, shading analysis, and infrared thermographic inspections to detect early signs of uneven heating. Additionally, ensuring proper system design, including bypass diode protection and avoiding mismatched or defective modules, can help minimize the risk of hotspots and extend the lifespan of PV systems.

When a solar cell is shaded, it cannot produce current as it normally would. Instead, it acts as a resistance within the circuit, absorbing energy from the other unshaded cells. The resulting temperature rise (hotspot) occurs due to excessive power dissipation in the form of heat.

The equation for the power dissipated in a solar cell that behaves as a resistance can be expressed as:

$$P = I^2 R \tag{1}$$

Where:

- P = Power dissipated (in Watts)
- I = Current flowing through the solar cell (in Amperes)
- R = Resistance of the shaded or damaged cell (in Ohms)

If the resistance R increases (due to shading or damage), the dissipated power P will also increase, causing the temperature of the cell to rise.

In a photovoltaic module, the power generated by a healthy cell follows the basic power equation:

$$P = V\,I \tag{2}$$

Where:

- P = Power generated by the cell (in Watts)
- V = Voltage produced by the solar cell (in Volts)
- I = Current produced by the solar cell (in Amperes)

However, when a solar cell is shaded or damaged, its current II decreases. Since the current of the entire module must remain constant in a series connection, the energy from the unshaded cells is absorbed by the shaded cell. This leads to power dissipation, which causes the hotspot effect.

The temperature rise due to power dissipation in a shaded cell can be estimated using the principles of heat conduction and thermodynamics. The equation relating power dissipation to temperature rise is:

$$\Delta T = \frac{P}{hA} \tag{3}$$

Where:

- ΔT = Temperature rise (in Kelvin or degrees Celsius)
- P = Power dissipated (in Watts)
- h = Heat transfer coefficient (in W/m^2K)
- A = Affected surface area (in m^2)

It is important to note that this study focuses solely on the identification and analysis of module defects. While module defects can contribute to reduced energy output, this study does not aim to evaluate the overall energy performance of the PV systems. Instead, the focus is on understanding the nature and causes of module defects and their implications for the long-term reliability of PV systems. The results of this analysis provide valuable insights into improving module quality and system installation practices.

3. Result and discussion

The defects observed in PV modules in this study are categorized into several types based on their visual and structural characteristics. These include glass cracking, which compromises the module's structural integrity; junction box swelling or bulging, which often indicates internal overheating or component failure; and improper sealing of the junction box, which can lead to moisture ingress and electrical issues. Additionally, some modules exhibited foggy or discolored glass, which can reduce light transmission and overall module efficiency. Another common issue observed was shading caused by external objects, such as trees, dust accumulation, or nearby structures, which obstruct sunlight, thereby reducing energy output. Various other visual defects, such as surface contamination, scratches, or delamination, were also recorded. The observations were conducted under clear sky conditions to ensure that the identified defects were not influenced by adverse weather or insufficient sunlight, allowing for accurate assessment of module performance and fault identification.

The results of the observations indicate that within the first two years of operation, out of a total of 64,400 installed PV modules, approximately 678 modules exhibited operational abnormalities caused by various defects previously mentioned. These defects, such as glass cracking, junction box issues, foggy glass, and shading, contributed to the suboptimal performance of the affected modules. The observed failure rate, approximately 1.05 %, highlights the importance of early monitoring and maintenance to ensure the reliability and longevity of PV systems. Identifying and addressing these defects promptly can minimize energy losses, prevent further deterioration, and improve the overall efficiency of the PV system. This analysis underscores the need for regular inspections, as well as the implementation of quality control measures during both the manufacturing and installation phases, to mitigate such early-stage defects.

The following are the results and discussion that address the findings of the observations based on the defect categories.

a PV Modules Glass Breakage

Based on the observations, 282 cases of glass breakage were identified, evenly distributed across all strings. The primary cause of glass cracking is linked to interconnected events, with hotspot formation being the most significant contributor. This is characterized by signs such as burnt ribbons, burnt backsheet, diode failures within the junction box leading to elevated temperatures, and sudden temperature fluctuations caused by transitions from hot to rainy weather, which eventually result in glass fractures. Fig. 2 shows a sample photograph of glass cracking on the front side and its impact on the ribbon, which appears burnt from the front to the back side, caused by a hotspot.

In addition, some PV module cracks were found to be caused by the impact of heavy falling objects, as evidenced by the analysis of distinct breakage patterns on the glass surface.

Glass breakage often begins with excessive heat and the formation of hotspots on specific sections of the PV modules that are vulnerable to

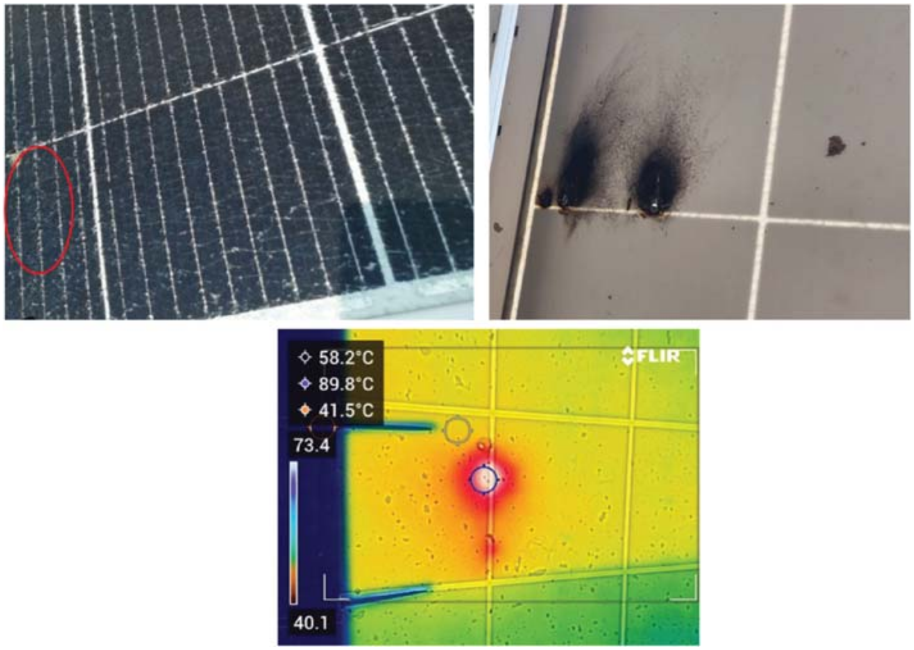

Fig. 2. Glass cracking and ribbon burnt caused by hotspot.

damage. This sequence of events occurs repeatedly and cumulatively, accelerating the degradation process. While hotspots and mechanical impacts are dominant factors, other potential causes cannot be ruled out, such as lightning induction, high air humidity, and fluctuating ambient temperatures. These multiple factors underscore the complexity of PV module defects and highlight the importance of comprehensive monitoring and preventive measures to address early-stage failures.

b Junction Box Swelling or Bulging

Field observations revealed 42 PV modules with junction boxes exhibiting swelling or bulging. In general, this issue is caused by elevated temperatures resulting from a shorted bypass diode inside the junction box. Measurements taken using a thermal imaging camera (Fig. 3) showed that the temperature of the problematic junction boxes reached as high as 82 °C or above, indicating abnormal heating conditions.

In cases where the swelling was observed, it was also noted that a series of solar cells connected to the shorted diode experienced temperature increases. This condition suggests a direct correlation between shorted diodes and localized overheating in the affected cells. Fig. 4 highlights the PV module cells associated with shorted diodes, where the thermal imaging clearly demonstrates elevated temperatures.

This phenomenon has a significant impact on the performance of the PV module. The overheating caused by the shorted diodes results in partial shading effects and energy losses within the module. Over time, this reduces the overall power output of the string to which the affected module belongs, diminishing system efficiency and reliability.

Addressing junction box swelling requires timely detection and replacement of faulty diodes or modules to prevent further damage, improve system performance, and ensure the longevity of the PV system. Regular monitoring using thermal imaging technology is essential for identifying and mitigating such issues early.

c Other Damages to the Junction Box

Field observations identified approximately 350 cases of improperly installed junction boxes, distributed across all eight PV systems. These cases are believed to be caused primarily by installation errors or imperfections during the assembly process. Many instances were observed where the junction boxes were either left open or not properly sealed.

While in the short term this issue may not have a significant impact on the performance of the PV system, it poses a considerable risk over the long term. Improperly sealed junction boxes increase the likelihood of moisture ingress, which can lead to corrosion of internal components

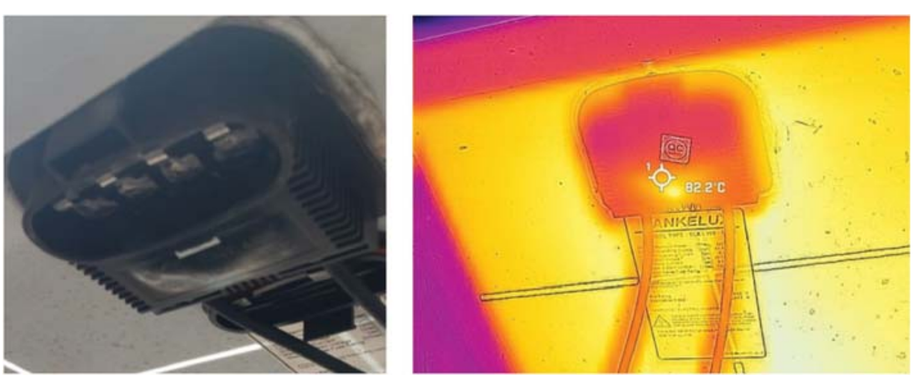

Fig. 3. Sample photograph of junction box swelling.

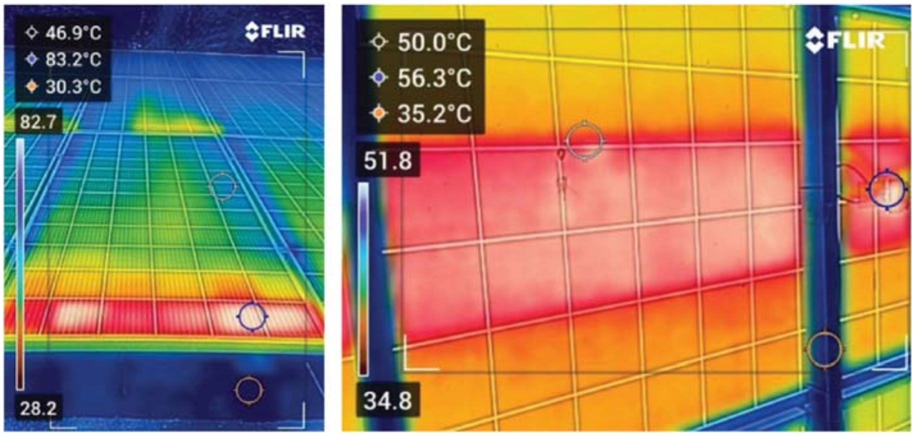

Fig. 4. Higher temperatures observed in cells with shorted diodes.

and short circuits in the diodes within the box. Over time, these problems can result in reduced module efficiency, operational failures, and even safety hazards such as overheating or electrical fires.

The findings highlight the importance of ensuring proper installation and sealing of junction boxes to maintain the reliability, longevity, and safety of PV systems. Regular inspections and maintenance are recommended to promptly detect and rectify such issues before they escalate into more severe damage.

d Dust, Soiling and Other Dirt.

The PV system installation, which is ground-mounted, is located in an open area surrounded by vacant land and trees. Such environmental conditions make the system susceptible to dust, soil, and other dirt unintentionally adhering to the surface of the PV modules. This issue is observed across nearly the entire system, though with varying degrees of severity.

The presence of dust or dirt on the module surface acts as a barrier, partially blocking sunlight from reaching specific cells in the PV modules. The types of airborne particles, which can be a source of dirt on solar panels, are a distinct research area discussed in various references [19,20].This partial shading reduces the module's ability to generate power, leading to a decline in overall system performance. Fig. 5 shows examples of unexpected objects, dust, and dirt accumulated on the PV modules.

Furthermore, the accumulation of dust on the module surface causes localized temperature increases in affected cells due to reduced energy conversion efficiency. This condition exacerbates the hotspot effect, as the covered cells are unable to dissipate heat effectively. Thermal imaging measurements clearly demonstrate elevated cell temperatures in areas covered by dust or dirt. Fig. 6 shows an example of thermal imaging where a noticeable temperature rise is observed in dust-affected cells.

The impact of dust and soiling on PV systems is significant and requires regular maintenance and cleaning to ensure optimal energy output. Without proper cleaning, the performance degradation may accumulate over time, leading to permanent damage to the cells and further reducing the system's efficiency. Implementing scheduled cleaning practices and exploring self-cleaning solutions, such as anti-soiling coatings or automated cleaning systems, can help mitigate this problem in dusty environments. Additional studies on the effects of nonuniform PV soiling have been presented in previous works, as referenced in Refs. [9,21,22].

e Shading from Surrounding Objects

Field observations revealed several PV modules and areas that, at certain times of the day, were obstructed by shadows from surrounding objects. These objects included trees, electric poles, and buildings located near the edge of the PV system installation, which were taller than the system itself (Fig. 7).

Additionally, shading caused by the PV system itself on neighboring PV arrays was also identified, particularly during low solar altitude in the early morning or late afternoon (Fig. 8). This phenomenon occurs when shadows are cast by one part of the system onto adjacent modules, creating partial shading conditions. Although this shading is relatively short-lived, it can significantly impact the overall performance and energy output of the PV system by reducing efficiency and introducing power losses.

To mitigate these issues, proper initial system design and planning are crucial. Factors such as module spacing, system orientation, and consideration of surrounding structures must be carefully evaluated during the design phase to minimize shading risks. Addressing shading challenges early can help optimize system performance, ensuring

Fig. 5. Unexpected soil and dirt on the PV Module.

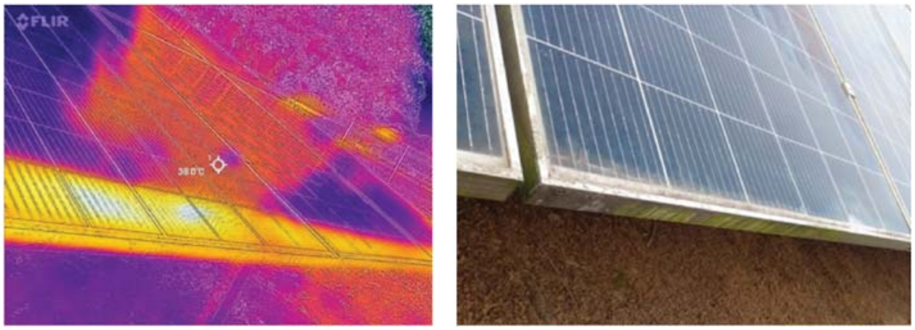

Fig. 6. Temperature rise caused by soiling.

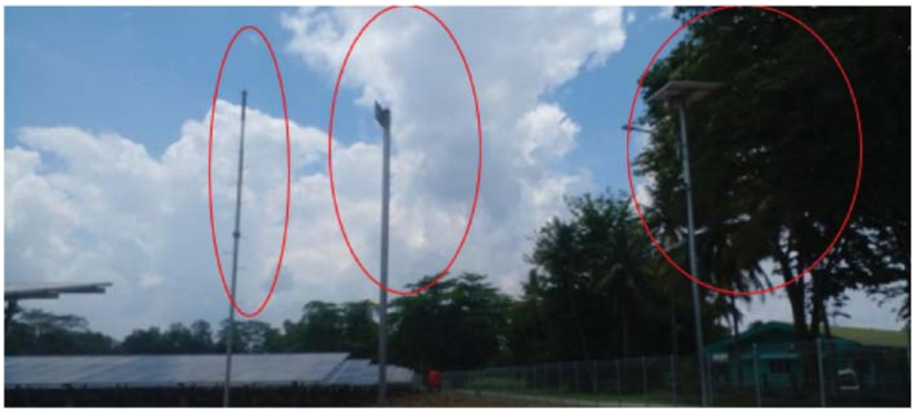

Fig. 7. Potential shading caused by surrounding objects on the PV system.

Fig. 8. Shading caused by the PV system itself.

consistent and efficient energy generation throughout the day. Studies on the effects of shading on the performance of PV systems in various locations have been presented in previous works, as referenced in Refs. [23–25].

f Foggy or Discolored Glass

Field observations also identified approximately 7 cases where the glass of PV modules exhibited fogging or discoloration, often in the form of delamination (Fig. 9). This condition is believed to occur as a result of glass cracking in the PV modules, which may stem from various causes, such as hotspot formation or impact from falling objects, as previously discussed.

Foggy or discolored glass significantly impacts the optical transparency of the module, reducing the amount of sunlight that penetrates the glass to reach the solar cells. This results in a decline in module efficiency and energy output over time. Delamination, a form of material separation within the PV module layers, can worsen due to moisture ingress, temperature fluctuations, and the natural degradation of materials. Once initiated, delamination accelerates further deterioration, particularly under prolonged exposure to harsh environmental conditions, such as high humidity, heavy rainfall, and extreme temperature variations.

These issues underscore the importance of quality control during manufacturing to ensure robust glass and encapsulation materials are used. Additionally, regular monitoring and maintenance of PV systems are necessary to detect early signs of fogging, discoloration, or delamination. Prompt identification and replacement of defective modules can prevent further losses and ensure the long-term reliability and efficiency of the PV system.

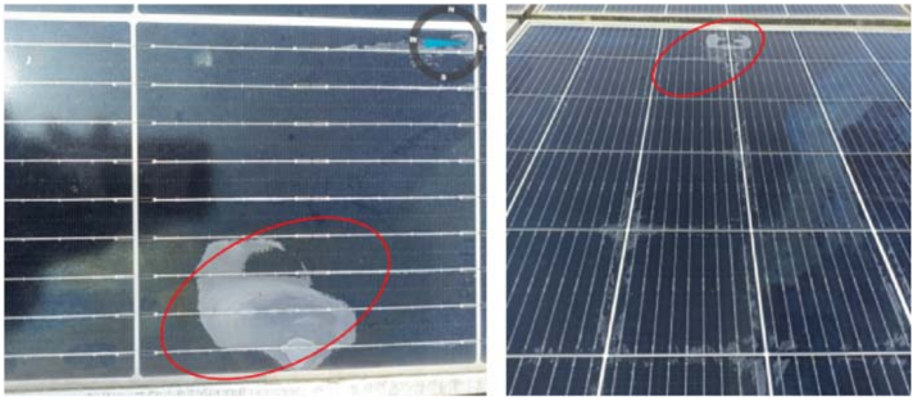

Fig. 9. Delamination of PV module glass.

g Other Observations

Observations were also conducted on various aspects related to the operation of the PV system, including the grounding system, cable connections, electrical insulation, and inverter temperature. No significant damage or abnormalities were detected across the entire system during the inspection.

However, regular monitoring and periodic maintenance are essential to ensure the PV system continues to operate optimally. Proper grounding is critical to protect the system against electrical surges and lightning strikes, which could lead to equipment failure or safety hazards. Similarly, ensuring that cable connections are secure and free of corrosion is important for minimizing energy losses and preventing electrical faults.

Electrical insulation integrity must also be maintained to prevent leakage currents or short circuits, which could reduce system reliability and efficiency. Additionally, monitoring inverter temperature is crucial, as excessive heat can impact inverter performance and lifespan. Inverters are the heart of the PV system, and maintaining their temperature within safe operating limits ensures stable energy conversion and overall system reliability.

While no issues were found during this observation, ongoing monitoring is necessary to detect potential problems early, allowing for timely corrective actions. Implementing a preventive maintenance schedule will help ensure the long-term durability, safety, and efficiency of the PV system.

Early operational defects in PV systems can have significant long-term implications on reliability and financial performance. Defects, as discussed, can accelerate module degradation, reduce energy production, and increase maintenance costs. These issues may lead to reduced system efficiency, higher operational expenditures, and potential revenue losses for PV plant operators. Therefore, proactive maintenance strategies are crucial in mitigating these defects early, ensuring sustained performance, and maximizing the financial return.

3.1. Hotspots in photovoltaic modules

From the overall observations, it is evident that the dominant issue identified in the PV system is related to the hotspot effect on the modules. Hotspots, or localized overheating, are one of the most common issues affecting photovoltaic (PV) modules. They occur when there is a difference in illumination among individual solar cells within a module. A hotspot is characterized by a temperature imbalance, where one or more cells exhibit a significantly higher temperature compared to the surrounding cells.

This localized high temperature reduces the module's power output by disrupting the uniform flow of current and accelerates the material degradation process in affected areas. In essence, hotspots occur when a solar panel starts dissipating energy instead of generating it. Under such conditions, the impacted solar cells behave as if they are consuming energy, turning into resistive loads rather than energy producers.

The formation of hotspots is often caused by partial shading, dirt accumulation, manufacturing defects, or internal micro-cracks within the cells. For example, when one part of the module is shaded by an object, such as a tree branch or building, the affected cells resist the current generated by the unshaded cells, leading to localized heating.

Hotspots are particularly problematic because they tend to be unstable and can become more intense over time. If left unaddressed, they can lead to further module degradation, such as burnt ribbons, discolored glass, or delamination. Ultimately, the increasing severity of hotspots can cause the overall performance of the PV panel to deteriorate or, in extreme cases, result in irreversible failure of the module.

It obviously seen that from equations (1) and (2), when a solar cell becomes shaded, it not only reduces the overall performance of the PV module but also absorbs energy from other cells, leading to localized power dissipation and a significant temperature rise. If left unaddressed, this hotspot effect can accelerate material degradation, reduce the module's lifespan, and even result in permanent damage to the PV system.

From the temperature rise in Equation (3), it is understood that the increase in temperature in a cell affected by a hotspot is directly proportional to the dissipated power and inversely proportional to the shaded area and the efficiency of heat transfer. Therefore, the factors influencing ΔT are as follows:

- Continuous or Permanent Shading: Persistent shading on the module significantly increases the likelihood of hotspots, as the cell cannot recover or dissipate the heat effectively.
- Number of Modules in a String: A higher number of modules in series can increase the current passing through the shaded cell, intensifying power dissipation and heat buildup.
- Type of Cell Connection in the Module: The configuration of the solar cells, such as half-cut cells or full-cell modules, influences the module's ability to minimize the effects of shading. Half-cut cell modules typically reduce power loss and heating compared to full-cell modules.
- Shaded Panel Area: The extent of the shading on the module surface directly affects the amount of power dissipated. A larger shaded area reduces current mismatch, whereas small localized shading may intensify the hotspot effect.
- Heat Transfer Coefficient: The efficiency of heat transfer away from the affected area determines how quickly the hotspot temperature rises. Poor heat dissipation exacerbates the temperature increase, leading to accelerated module degradation.

When a PV system consists of multiple strings, each comprising 30 solar modules with a specification of 390 Wp, a maximum voltage (Vmp) of 41.5 V, and a maximum current (Imp) of 9.4 A connected in series, significant impacts on the string's performance occur when one module is shaded. These effects particularly influence the current flow and the potential for hotspot formation. With 30 modules connected in series as PV system above the total string voltage is 30 x 41.5 = 1245 V, while string current is 9.4 A, means the total power will be 11,733 Watt. If one shaded module produces a reduced current (e.g., 4 A), the total string power drops significantly because current in a series connection is limited by the weakest module. The string power will be remaining 1245 x 4 = 4980 Watt, means $\Delta P = 11{,}700 - 4980 = 6720\ W$

The shaded module behaves like a resistive load, absorbing energy from the unshaded modules in the form of heat. This condition can trigger the hotspot effect, where the temperature of the shaded module rises significantly. If left unchecked, this excessive heating can cause permanent damage to the module.

When a module is fully shaded and cannot generate current but is still forced to conduct the current from other modules, it absorbs energy from the circuit, resulting in heat generation. The power dissipated as heat in the shaded module can be calculated using equation (1). As the internal resistance of the shaded module increases, the power dissipation also increases, leading to greater heat generation. The higher the heat, the greater the risk of irreversible damage, particularly if the shading persists for a prolonged period.

Shading on a single module within a string of 30 modules significantly reduces the string's total power output and introduces the risk of hotspot formation. Hotspots not only degrade the affected module but can also compromise the long-term performance and reliability of the entire PV system. Proper system design, shading analysis, and the use of bypass diodes are critical to mitigating these issues and ensuring the system operates efficiently under varying conditions.

3.1.1. *The effect of the number of modules in a string*

To explain the reduction of hotspot risk by decreasing the number of modules in a single string, we can observe the differences in total voltage, string current, and heat dissipation in the shaded module. If the number of modules in a string is reduced from 30 to 20, the total string voltage will also decrease proportionally.The total voltage of the string with 20 modules compared to the string with 30 modules is 20/30, means by reducing the number of modules in a single string from 30 to 20, the total string voltage decreases to 2/3 of its original value. This reduction in string voltage helps mitigate the risk of hotspots because the overall power dissipation in the shaded module is reduced. Lower voltage and current flowing through the string decrease the energy absorption by the shaded module, thereby minimizing heat generation and reducing the likelihood of permanent damage. This approach emphasizes the importance of string configuration optimization to balance power generation efficiency and minimize hotspot risks in photovoltaic systems.

When the total string voltage decreases (due to fewer modules in the string), the inverter may reduce the current to adjust for the lower input voltage. Suppose the current decreases from I_{30} *to* I_{20} when the number of modules is reduced from 30 to 20, where the power dissipation (heat) in the shaded module of a string with 20 modules is 4/9 of the heat generated in a string with 30 modules.

By reducing the number of modules in a single string from 30 to 20, the following effects are observed:

1. The total string voltage decreases to 2/3 of the original voltage.
2. The heat dissipation in the shaded module decreases to 4/9 of the previous value.

Mathematically, this demonstrates that reducing the number of modules in a string can significantly reduce the risk of hotspots in shaded modules, as the power dissipation in the affected module is also reduced. This optimization helps improve the overall reliability and longevity of the photovoltaic system.

3.1.2. *Type of Cell Connection in modules (half-cut module vs full-cell module)*

Half-cut modules are generally more resistant to hotspot effects compared to full-cell modules. This is due to better heat distribution, lower current per cell, and a more effective bypass diode configuration. These features make half-cut modules a more reliable option in conditions where shading may occur, reducing the risk of hotspot damage and maintaining more stable performance.The differences between half-cut and full-cell modules in terms of current, voltage, and heat generation can be explained using several equations related to current flow, power dissipation, and heat (hotspot) generation when shading occurs on a solar module.

With the same power capacity, both half-cut and full-cell modules have the same total voltage, but the current per cell is different. When shading occurs on one cell, the shaded cell behaves like a resistance, causing power dissipation in the form of heat (hotspot). The power dissipated due to resistance can be calculated using. It can be mathematically proved that a half-cut module generates only one-quarter (1/4) of the heat compared to a full-cell module under the same shading conditions.

When a cell is shaded, bypass diodes allow current to bypass the affected area. The configuration of bypass diodes differs between full-cell and half-cut modules, leading to differences in power Half-cut modules are significantly more resistant to hotspot effects and power loss due to shading compared to full-cell modules. Their lower current per cell reduces heat dissipation in shaded conditions, and their enhanced bypass diode configuration minimizes power losses. This makes half-cut modules a more efficient and reliable choice, particularly in environments where shading is likely to occur.

4. Conclusion and recommendation

The dominant defect observed in the 24.9 MWp Solar PV System in Sumatra, Indonesia, was hotspot formation. This defect is primarily caused by partial shading, cell mismatches, and module damage. Hotspots lead to excessive localized heating, which accelerates material degradation, reduces power output, and poses the risk of permanent module failure. Additionally, glass cracking (282 cases) was identified as a significant issue, often linked to hotspots and mechanical impacts, compromising module integrity.

The study also found 350 cases of improperly installed junction boxes, where loose sealing and improper installation increase the risk of moisture ingress, corrosion, and electrical faults over time. Furthermore, foggy or discolored glass caused by delamination was observed, reducing light transmission and module efficiency. Shading, both from surrounding objects such as trees, poles, and buildings and from self-shading between PV arrays, was found to exacerbate these problems. Through analysis, it was shown that half-cut modules perform better than full-cell modules in mitigating hotspot effects due to their lower current per cell and improved bypass diode configuration, reducing heat dissipation and power losses. Additionally, reducing the number of modules in a string effectively lowers string voltage and current, thereby minimizing the severity of hotspots.

To ensure the long-term performance, reliability, and efficiency of PV systems, several actions are recommended. First, regular monitoring and preventive maintenance are essential to detect and address defects such as hotspots, glass cracking, and junction box faults at an early stage. Implementing shading mitigation strategies is crucial, including proper module layout, periodic shading analysis, and environmental management (e.g., trimming trees or removing obstructions). The use of half-cut modules is strongly recommended, as they offer better resilience against shading and significantly reduce hotspot risks due to their enhanced electrical configuration.

Moreover, optimizing the string configuration by reducing the number of modules per string can help lower total voltage and current, mitigating heat dissipation in shaded modules. To further minimize early operational defects, rigorous quality control measures must be implemented during the manufacturing, installation, and commissioning phases. Finally, adopting advanced monitoring technologies, such as infrared thermography and real-time data analysis, will enable the timely identification of defects and ensure the system operates at its full potential. These measures will collectively enhance the system's performance, extend its operational lifespan, and improve the overall return on investment for solar PV projects.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The author is an Editorial Board Member/Editor-in-Chief/Associate Editor/Guest Editor for this journal and was not involved in the editorial review or the decision to publish this article.

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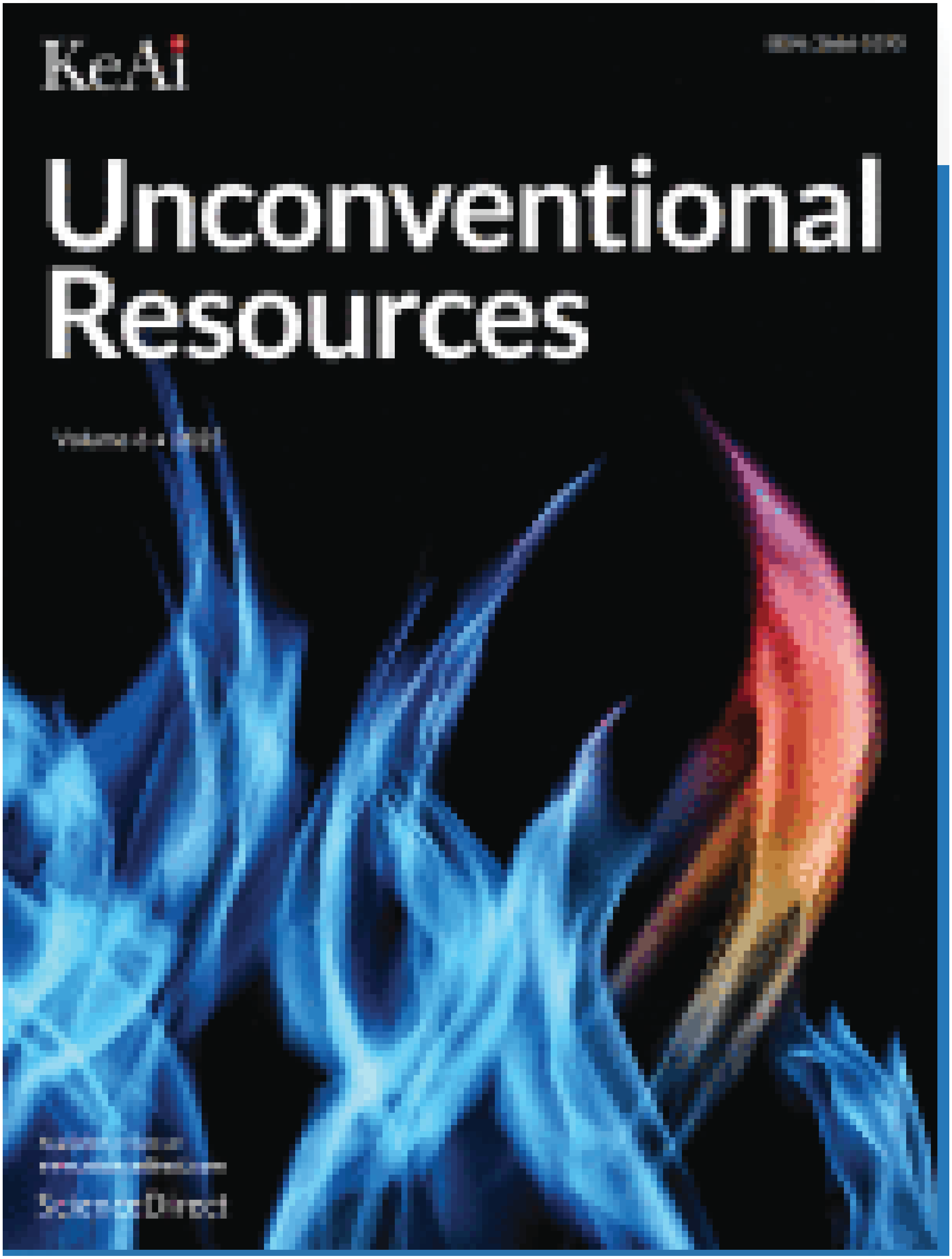
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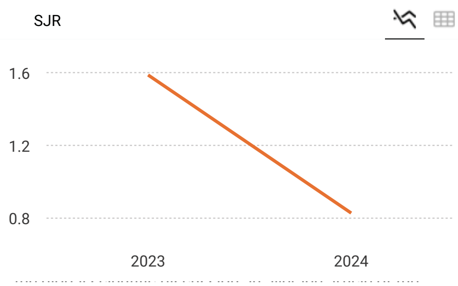
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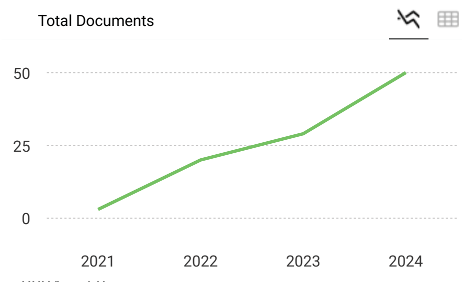
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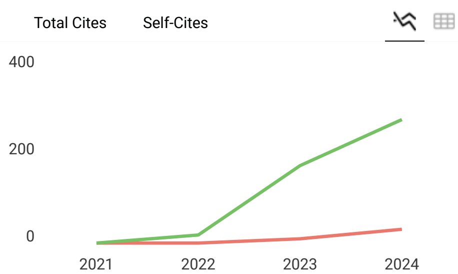
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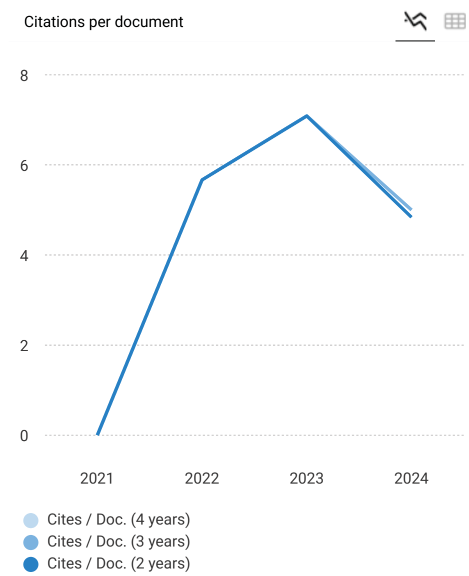
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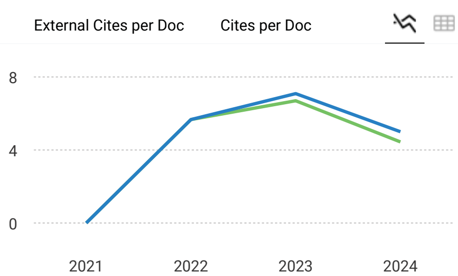
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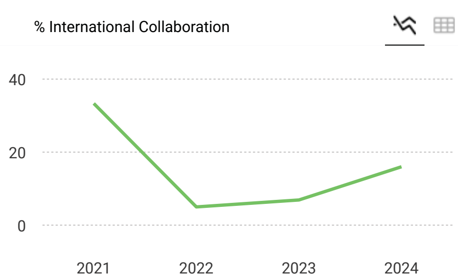
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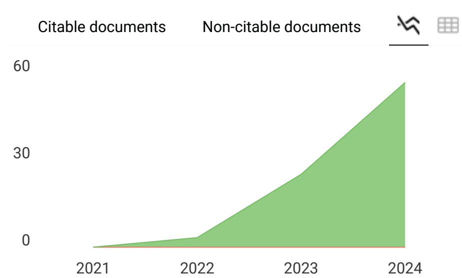
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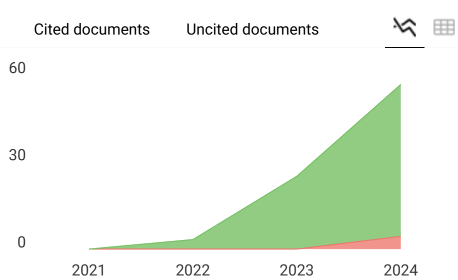
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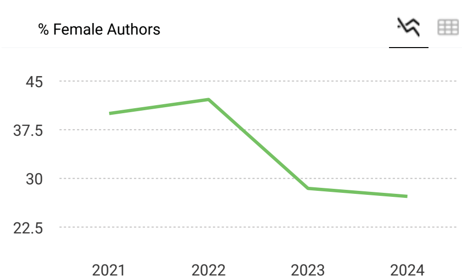
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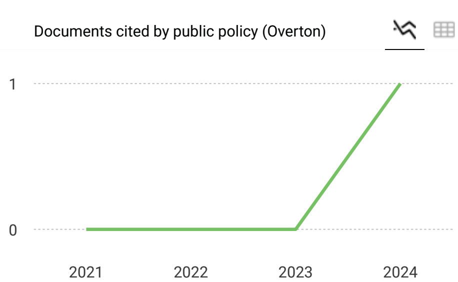
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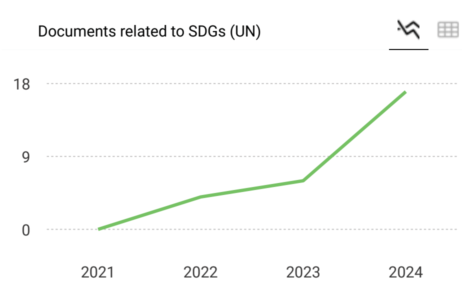
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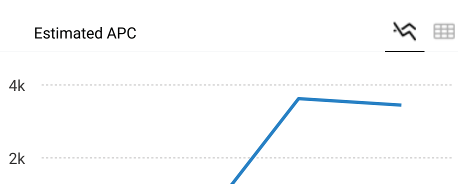
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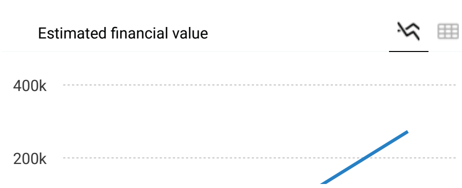
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