Comprehensive Analysis of Solar Photovoltaic System Defects and Inspection Techniques in Tropical Environments Using Thermal UAV: Study Case in Marang, Terengganu

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Abstract. Solar power plays a key role in sustainable energy development. However, tropical climates pose challenges such as high temperatures and humidity, requiring a deep understanding of PV system defects. This study uses unmanned aerial vehicle thermographic inspection techniques to assess defects in solar farms in Marang, Terengganu, aiming to improve solar energy reliability in tropical environments. Results show that Bypass Diode issues are the most common defect, making up 75.70% of occurrences, indicating a critical area for remediation. Clusters of Thermal Anomalies (CTA) defects follow at 13.20%, necessitating detailed examination of abnormal thermal patterns. Faulty Interconnections are less frequent at 1.90%, highlighting the need for proper electrical connections. Hot spots and Overheating Component defects account for 8.70% and 0.40% respectively, pointing to localized overheating and potential malfunctions. The study also examines the correlation between solar irradiance patterns and PV defects, with irradiance levels ranging from 700.6 W/m² to 1073.1 W/m², showing how sunlight intensity fluctuations impact PV system performance. This analysis helps prioritize resources and develop targeted maintenance strategies, enhancing the reliability and performance of solar energy systems in tropical climates. The findings offer practical insights for advancing renewable energy infrastructure in tropical regions, promoting the sustainable adoption of solar energy worldwide.

1 Introduction

Considering the current situation of global climate change and the increasing need for sustainable energy sources, solar energy plays a major role in the transition towards a more resilient and sustainable energy landscape.

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In particular, photovoltaic (PV) systems have attracted a lot of attention because of their direct conversion of sunshine into power, which provides a clean and renewable substitute

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for fossil fuels. Every component, especially the PV panels, must operate and remain intact for any solar PV system to run as effectively and efficiently as possible (1). Numerous operational and environmental strains are placed on these panels, which over time could lead in malfunctions and a decrease in performance (2). However, there is a lack of comprehensive understanding regarding how extreme tropical climate conditions impact the durability and performance of solar PV systems, particularly in terms of defect formation and degradation. Thermographic inspection seems to be an essential part of a solar PV system's toolkit of maintenance and monitoring processes. This non-destructive inspection technique (3) uses thermal imaging from Unmanned Aerial Vehicles (UAVs) to detect and visualize thermal anomalies across PV panels, indicating structural defects or irregularities that may occur (4). This preventive maintenance can also enhance the overall reliability and performance of solar installations by enabling the early detection of defects and issues such as hot spots, cell cracks, and delamination (5).

The primary aim of this research is to investigate solar PV defects and challenges in Marang, Terengganu, focusing on the growing importance of solar energy in addressing energy security and climate change mitigation goals. Despite Malaysia's abundant solar resources and the government's push for renewable energy, the unique tropical climate characterized by extreme weather, high humidity, and elevated temperatures poses challenges for the durability and performance of solar photovoltaic (PV) systems (6). Using thermographic inspection techniques, this study aims to evaluate the types and frequency of defects found in solar PV panels through systematic inspections and UAV thermal imaging surveys conducted across 29 zone flights at solar farm sites in Marang. Additionally, the study seeks to analyse the relationship between solar irradiance patterns and the occurrence of PV defects, providing insights into the factors contributing to performance degradation.

2 Methodology

In Marang, Terengganu, the overall methodology of solar mapping (Figure 1) takes a comprehensive approach that includes describing the study area, using advanced and specialized equipment like solar radiometers and UAV for data collection, creating a detailed flight plan, and carrying out data collection tasks like aerial thermographic inspection and irradiance data collection. Upon the data collection, in-depth analysis is carried out to identify relationships between solar radiation irradiance levels measured by solar radiometers with the time and thermal anomalies depicted in aerial thermographic images with the zone flights. This research guide decision-making processes aimed at optimizing solar PV system efficiency and reliability for the production of sustainable energy.

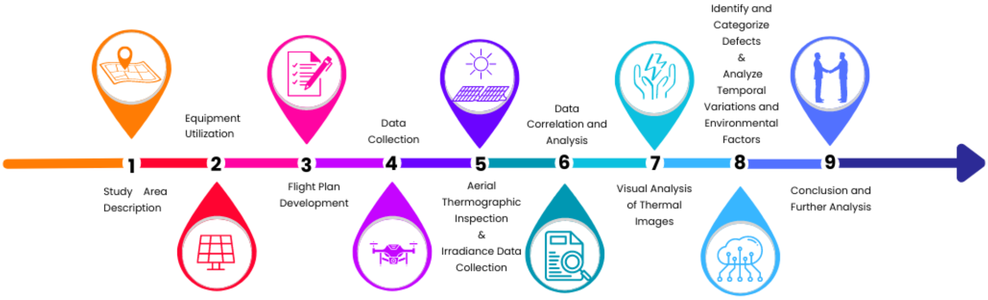

Fig. 1. Overall methodology of the solar PV inspection

2.1 Study Area

Fig. 2 shows the study area, which includes a solar farm situated in Marang, Terengganu, Malaysia. This area has the coverage of 270 hectares. Marang is located in the northeastern part of Peninsular Malaysia and has a tropical climate marked by elevated temperatures, humidity, and ample sunlight, which makes it a perfect place for generating solar energy. Photovoltaic (PV) panels, distributed across various zones within the site, compose the solar farm. Each zone corresponds to a certain part of the installation.

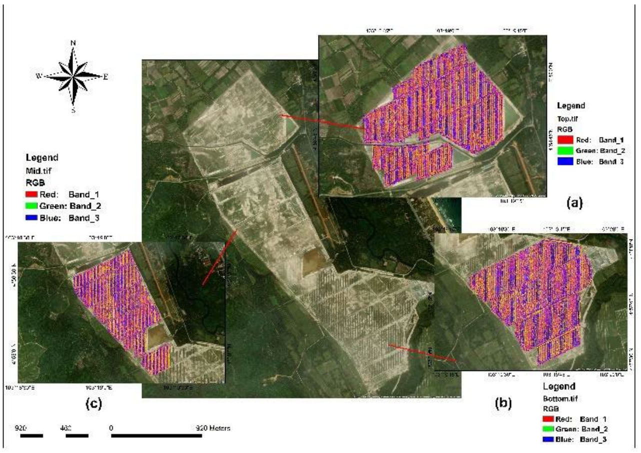

Fig. 2. Study Area

2.2 Equipment Used

The DJI H20T and DJI Mavic 3 Enterprise Thermal (M3T) are two different methods of thermal examination, each with unique advantages and uses. The H20T (Fig. 3a), equipped with a multi-sensor payload that includes a radiometric thermal sensor, provides adaptability and advanced capabilities that are well-suited for intricate situations. This device's high-resolution radiometric video-capturing capability makes it an excellent choice for real-time monitoring and in-depth analysis. Conversely, the M3T drone incorporates a thermal camera directly into its design, resulting in a more efficient and user-friendly solution. Although its primary purpose is to capture radiometric still images, it performs exceptionally well in routine inspections when the analysis conducted after the flight is of utmost importance. At some point, the choices between these two payloads depend on the specific requirements of the inspection task, with the H20T being well-suited for more demanding scenarios and the M3T offering a direct and fast option for routine inspections. The DJI Mavic M3T is an advanced unmanned aerial vehicle (UAV) designed primarily for thermographic inspection applications and boasts advanced thermal imaging capabilities. Fig. 3b depicts the M3T, equipped with a high-resolution thermal camera that records detailed thermal images of solar PV panels from an aerial perspective. We utilise the DJI Mavic M3T drone to expedite and comprehensively inspect the solar farm, enabling rapid collection and processing of data across vast areas. The UAV's compact and effective design, nimbleness, and integrated thermal imaging equipment make it very appropriate for acquiring thermal data from the PV panels in various regions of the solar installation.

A solar radiometer placed inside the solar farm during the mission is used to gather irradiance data over the course of two days in addition to airborne thermographic assessment. The solar radiometer (Fig. 3c) gauges solar irradiance levels and gives PV panel owners real-time information on how much sunlight they receive each day. In order to determine the correlation between solar radiation exposure and the occurrence of PV defects, the acquired data on irradiance is being correlated with the results obtained from thermal imaging. For a comprehensive analysis, only data points with solar irradiance readings equal to or exceeding 600 W/m2 are use. Examining the temporal fluctuations in irradiance levels and thermal anomalies seen in the thermal images allows us to understand how environmental elements, such as sunlight intensity, affect the development and severity of PV panel faults.

(a) (b) (c)

Fig. 3. Equipment used for the case study

Table 1 below presents flight parameters tailored for ground-mounted fixed solar modules inspections utilizing the DJI H20T and M3T thermal imaging setups, each equipped with DJI Pilot 2 software. For the H20T configuration, at GSDs of 3, 5.5, and <8 cm/pixel, flight altitudes range from 34 to 90 meters, achieving estimated areas covered per flight of 4.8 to 30 hectares, with overlap ratios of 63/44. Similar to that, the M3T configuration, with the same GSDs, shows heights between 23 and 61 metres, covering 8.6 to 43 hectares every trip while keeping overlap ratios between 75 and 45. Effective data collection for these parameters guarantees thorough thermal assessments of ground-mounted solar arrays for various resolution requirements.

Table 1. Flight settings specifically designed for mounted fixed solar module inspections with the DJI H20T and M3T thermal imaging systems.

Inspection Level: Mounted Fixed Solar Modules with 180 degrees panel tilted	**GSD (cm/pixel)**	**Overlap (%)**	**Altitude (m)**	**Estimated Area/Flight (ha)**
H20T + DJI Pilot 2	3	63/44	34	4.8
	5.5	63/44	62	15
	<8	63/44	90	30
M3T + DJI Pilot 2	3	75/45	23	8.6

	5.5	75/45	42	27
	<8	75/45	61	43

2.3 Equipment Used

After collecting data and conducting an aerial survey, we visually examine the thermal photos to identify and classify any flaws in the solar PV panels. We use thermal properties and the appearance of thermographic anomalies suggestive of flaws like hot spots, cell splits, delamination, and soiling to identify and categorize them. Qualitative and quantitative evaluations of the thermal images, in addition to the visual inspection, can determine the degree and severity of each type of fault. High-resolution thermal pictures enable a highly comprehensive inspection of individual PV panels, while also simplifying the precise identification and characterisation of faults across the solar farm. Visual analysis reveals patterns and trends in defect occurrence, providing crucial insights into the underlying causes and mechanisms of PV panel deterioration. A visual inspection precedes further sophisticated diagnostic studies and maintenance procedures aimed at maximizing the performance and dependability of the solar PV system.

As part of our comprehensive inspection, we are assessing defective solar PV panels over 29 zone flights, or 270 hectares of the research area. Each zone presents specific requirements and challenges, necessitating the whole thermal inspection for the ease of troubleshooting of the solar PV infrastructure. Our team of experts performs comprehensive evaluations, identifying problems and formulating effective solutions specific to each zone's needs. Our extensive network ensures that solar PV panels operate smoothly and as efficiently as possible, beginning with verification and troubleshooting and concluding with rectification and maintenance. By attentively analysing issues and developing prompt, efficient fixes, we remain committed to eco-friendly operations and sustainable energy production in a variety of contexts.

3 Results and analysis

We ensured the precision of the boundary data during the UAV-based thermographic examination by utilizing high-resolution thermal cameras and precise flight planning. We outfitted the UAVs, such as the DJI H20T and DJI Mavic 3 Enterprise Thermal (M3T), with enhanced thermal imaging capabilities to capture detailed thermal photographs of the solar PV panels. We specifically design the border in cyan to enhance image quality, resolution, and coverage, thereby ensuring a comprehensive assessment of the entire solar farm. This strategy permitted the accurate detection and localization of problems, giving reliable data for maintenance and optimisation plans by utilising UAVs over the boundary (Fig. 4).

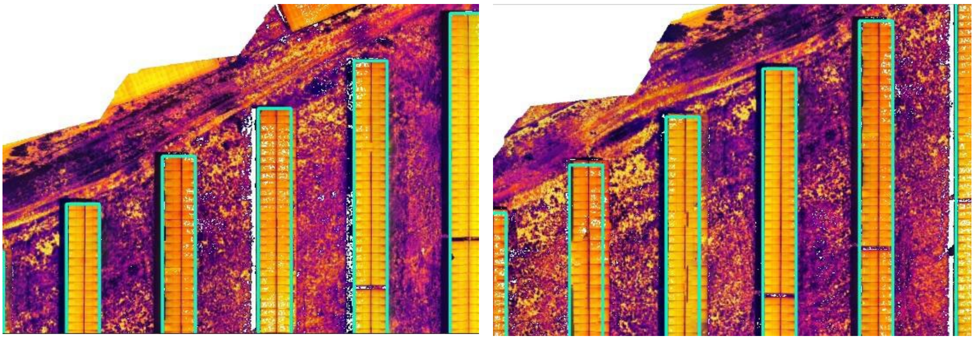

Fig. 4. Accuracy of the boundary with the thermal data

The thermal images acquired offer visual depictions of the solar PV panels, emphasising temperature fluctuations over the surface. We display the imageries in a specific folder, arranging them based on the flight plan and zones to facilitate systematic examination and analysis. Then, irradiance data obtained through a solar radiometer, been analyzed as time-series datasets spanning a three-day period. The files record the amount of sunshine received by the PV panels during the observation period, offering information on daily and time-related changes in solar radiation exposure. We identify and classify the deficiencies of the solar PV panels through a comprehensive visual assessment of the thermal images. We detect and categorize thermal abnormalities, such as areas of high temperature, cell fractures, layer separation, and dirt accumulation, based on their visual and thermal properties. The study includes both qualitative evaluations, such as detecting the existence and placement of flaws, and quantitative evaluations, such as measuring temperature variations and the seriousness of problems. High-resolution thermal imaging allows for meticulous examination of individual PV panels, enabling precise identification and analysis of problems throughout the entire solar farm.

A thermographic inspection of 216,832 solar PV panels in Marang, Terengganu, was carried out using unmanned aerial vehicles (UAVs). Out of the total, 216,370 panels were found to be in good condition, showing that the majority of the panels are in a healthy state. The inspection identified the following particular errors in 462 malfunctioning panels: 352 panels had problems with bypass diodes, 59 panels showed anomalies in cluster of thermal anomalies (CTA), 9 panels had incorrect interconnections, 40 panels displayed hot spots, and 2 panels had components that overheated. This indicates that the entire system is well-maintained and functioning effectively, with only a minor component requiring upkeep and repair. The study conducted UAV-based thermographic inspections to identify the health condition and particular flaws of solar PV panels in Marang, Terengganu. Table 2. summarises the findings.

Table 2. Health status and specific defects of solar PV panels in Marang, Terengganu, identified through UAV-based thermographic inspections

Condition of panels	**Quantity of panels**
Total Panels	216832
Healthy Panels	216370
Unhealthy Panels	
a) Bypass Diode	352

b) CTA	59
c) Faulty Interconnections	9
d) Hot spots	40
e) Overheating Component	2

The graph in Fig. 5 shows the findings of five distinct thermographic fault types as recorded by the 29 zone flights in the Marang Area. The graph provides a comprehensive analysis of different fault types in different zones, along with valuable quantitative data on their distribution patterns. Bypass diodes are the most common type of system error, with 352 incidences detected across all zones. There are eight or more occurrences in each of the following zones: 5, 10, 21, 22, 24, 25, and 27. There are a total of 59 panels of CTA (Clusters of Thermal Anomalies) faults, with Zones 24 and 29 being particularly notable, with 9 and 5 occurrences, respectively. Faulty interconnections, which have occurred a total of nine times, are rather uncommon. Among all the zones, Zone 24 has the highest number of incidents, with three occurrences. Zones 5, 10, and 24 contain the majority of the 40 hot spots. Each of these zones has eight or more instances of hot spots. In contrast, overheating component failures are relatively rare, with only two instances observed across all zones. Zone 24 consistently displays a high frequency of occurrences across several fault types, indicating that it may necessitate targeted maintenance or corrective actions. In contrast, some areas exhibit reduced frequencies or the complete absence of specific fault types, indicating greater resistance to those particular problems. This comprehensive quantitative analysis enables the identification of zones with higher risk levels, allowing resources to be prioritized for targeted interventions. As a result, it helps create more efficient fault management systems.

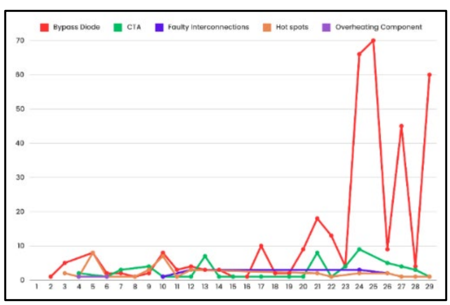

Fig. 5. Thermographic Defect Occurrences in Marang Area

In addition to the panel values for the 29 zone flights, we can determine the percentages of the types of defects that have occurred in the solar farm located in Marang, Terengganu. Looking at the different types of faults in Fig. 6 can help you understand how they are spread out and how important they are in the 29 zone flights that were done in the Marang Area. Bypass diode difficulties, accounting for a significant majority at 75.70%, are the most common problems detected. The significant proportion underscores the potential widespread occurrence of bypass diode malfunctions in the examined area, underscoring a critical issue that necessitates investigation and remediation efforts. Clusters of Thermal Anomalies (CTA) defects occur less frequently, but they still account for a significant amount, 13.20%. These anomalies highlight specific places with typical temperature patterns, necessitating a thorough analysis to identify the problems. However, improper linkages account for only 1.90% of reported problems. Hot spots, with a percentage of 8.70% of defects, signal localized overheating concerns that require prompt attention to prevent equipment damage or safety hazards. Lastly, Overheating Component defects, though rare at

0.40%, indicate potential equipment malfunctions or inefficiencies, underscoring the need for proactive maintenance. By systematically analysing these defect types and their respective percentages, stakeholders can prioritize resources and interventions effectively to mitigate risks and optimize the operational reliability of the Marang Area infrastructure.

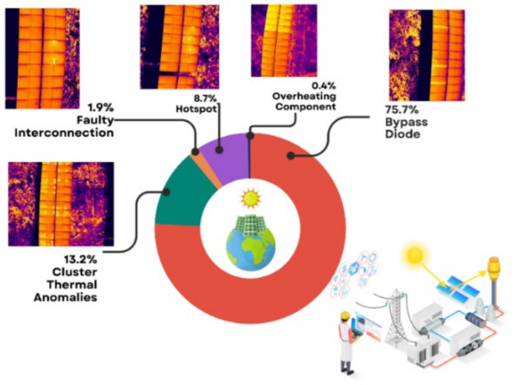

Fig. 6. Percentage of Thermographic Defect Occurrences

We displayed the irradiance data as a graph to create time-series plots that depicted the levels of solar irradiance from morning to evening during the observation period. The graphs depict fluctuations in solar radiation levels over the course of a day and under various environmental conditions. Identifying patterns or deviations: We examine the irradiance graphs to identify any trends or irregularities in solar radiation exposure. The study analyzes trends such as hourly fluctuations, weather variations, and abnormalities in irradiance levels to gain insight into how they affect PV panel performance and defect development. Anomalies, such as sudden spikes in irradiance, may indicate environmental disturbances or operational issues requiring further investigation. By conducting comprehensive analysis of both thermal images and irradiance data, insights can be gained into the health and performance of the solar PV system in Marang, Terengganu, Malaysia. This analysis serves as a crucial step in identifying and addressing defects, optimizing system efficiency, and ensuring the long-term reliability of the solar installation.

During the three-day thermal inspection at the Marang solar farm (Fig. 7), precise monitoring of solar irradiance levels using a solar power metre provided useful insights into the temporal variations of sunshine exposure. At 11:54 on Day 1, the irradiance levels started at a significantly high value of around 750.9 W/m². Throughout the day, the levels of irradiance gradually declined, ranging from 877.3 W/m² at 15:30 to 943 W/m² at 14:30. Although there was a progressive decrease, there were small changes in the amount of radiation received during the day, which could suggest occasional cloud cover or meteorological changes impacting the intensity of sunlight. However, Day 2 saw more fluctuations in the irradiance levels. At 12:49, the irradiance value spiked to 1073.1 W/m² before decreasing to 865.5 W/m² by 16:16. These fluctuations can be due to the varying cloud cover or atmospheric conditions impacting light penetration, which can directly influence the efficiency and performance of solar PV panels, affecting energy generation and output stability. In contrast to the previous days, Day 3 began with noticeably lower irradiance levels, with readings starting at approximately 700.6 W/m² at 11.15. The irradiance remained consistently low throughout the day, with a fluctuating pattern marked by substantial variations. During the time period from 15:30 to 13:58, the irradiance levels varied between 807.6 W/m² and 1027.5 W/m². We can attribute the unpredictable variations to the swift alterations in weather conditions, cloud cover, or other environmental elements that impact the amount of sunlight received.

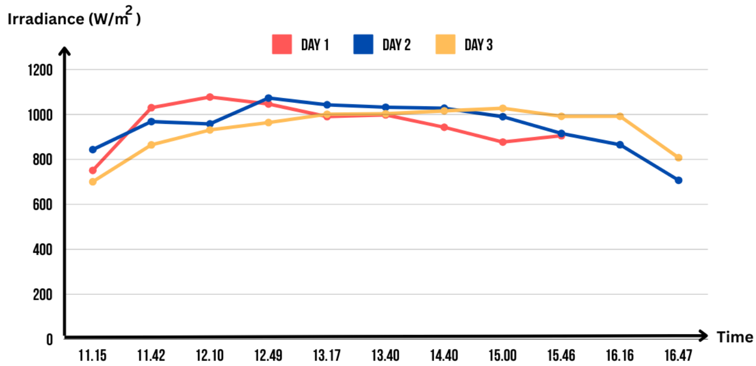

Fig. 7. Irradiance level over the time for the three days

Understanding these fluctuations is crucial for optimising the performance of solar photovoltaic (PV) systems, as they have a direct impact on the amount of energy produced and the reliability of the system. Operators can implement the maintenance and optimization strategies by conducting a comprehensive analysis of solar irradiance data over time and correlating it with other factors, such as thermal imaging results, in order to maximize energy production, improve system reliability, and ensure the long-term sustainability of the solar photovoltaic installation in Marang.

4 Conclusion

In summary, by utilising the effectiveness of UAV technology, the case study carried out in the Marang, Terengganu region can thoroughly assess the five different types of thermographic flaws in solar PV panels, saving time, money, and labour. Through the use of RTK GPS drones, the team was able to gather precise and accurate geographical data in a shorter amount of time three days that included both thermal and RGB imageries. This allowed for improved maintenance planning, accurate problem location. The utilisation of UAVs can significantly expedite the inspection process, allowing for rapid coverage of a wide area of solar farm sites that would have been time-consuming and labour-intensive with conventional methods. With only two people, scope and mission were driven by the increasing emphasis on solar energy adoption in addressing global climate change challenges and Malaysia's commitment to advancing renewable energy technologies. Two people per team required for operation, manpower costs were minimised without compromising the quality or comprehensiveness of the survey. The inspection and mission were driven by the increasing importance of solar energy adoption in addressing global climate change challenges and Malaysia's commitment to advancing renewable energy technologies.

The tropical climate of Marang, which presents unique problems such as high temperatures and humidity, can have a considerable impact on the performance and durability of solar photovoltaic (PV) systems. To address these concerns, a comprehensive study was carried out to determine the prevalence and types of defects in the region's solar farms, to investigate the relationship between solar irradiance patterns and PV faults, and to analyse the effectiveness of thermographic examination as a diagnostic tool. The study employed systematic inspections and UAV based thermal imaging surveys across various solar farm sites in Marang. The data collected from these surveys was analyzed to provide insights and recommendations for optimizing PV system performance and maintenance in tropical climates. On the recommendation of RTK GPS drone coordinate ID, the study emphasizes the importance of precise geospatial data for accurate defect localization and efficient maintenance planning. Implementing RTK GPS technology in UAV inspections enhances the accuracy of coordinate data, thereby improving the reliability of defect detection and mapping. This integration allows for more precise monitoring and targeted interventions, ultimately contributing to the optimal performance and longevity of solar PV systems.

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The authors declare no conflict of interest.

References

1. Farahmand MZ, Nazari ME, Shamlou S, Shafie-Khah M. The simultaneous impacts of seasonal weather and solar conditions on pv panels electrical characteristics. Energies (Basel). 2021 Feb 1;14(4).
2. Al Mahdi H, Leahy PG, Alghoul M, Morrison AP. A Review of Photovoltaic Module Failure and Degradation Mechanisms: Causes and Detection Techniques. Solar. 2024 Jan 9;4(1):43–82.
3. Akay SS, Özcan O, Özcan O, Yetemen Ö. Efficiency analysis of solar farms by UAV-based thermal monitoring. Engineering Science and Technology, an International Journal. 2024 May 1;53.
4. Aghaei M, Bellezza Quater P, Grimaccia F, Leva S, Musetta M. Unmanned Aerial Vehicles in Photovoltaic Systems Monitoring Applications. European Photovoltaic Solar Energy Conference and Exhibition. 2014 Sep.
5. Balasubramani G, Thangavelu V, Chinnusamy M, Subramaniam U, Padmanaban S, Mihet-Popa L. Infrared thermography based defects testing of solar photovoltaic panel with fuzzy rule-based evaluation. Energies (Basel). 2020 Mar 2;16(3).
6. Karim H, Mohd Noh F, Noordin IN. Solar Panel Defect Detection using Convolutional Neural Network (CNN). Progress in Engineering Application and Technology. 2023;4(1):345–52.