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Solar Photovoltaic Hotspot Inspection Using Unmanned Aerial Vehicle Thermal Images at a Solar Field in South India

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Abstract: The sun is an abundant source of energy, and solar energy has been at the forefront of the renewable energy sector for years. A way to convert it into electricity is by the use of solar cells. Multiple solar cells, connected to each other, create solar panels, which in their turn, are connected in a solar string, and they create solar farms. These structures are extremely efficient in electricity production, but also, cells are fragile in nature and delicate to environmental conditions, which is the reason why some of them show discrepancies and are called defective. In this research, a thermal camera mounted on a drone has been used for the first time in the solar farm operating conditions of India in order to capture images of the solar field and investigate solar panels for defective cells and create an orthomosaic image of the entire area. This procedure next year will be established on an international scale as a best practice example for commercialization, providing effortless photovoltaic monitoring and maintenance planning. For this process, an open source software WebODM has been used, and the entire field was digitized so as to identify the location of defective panels in the field. This software was the base in order to provide and analyze a digital twin of the studied area and the included photovoltaic panels. The defects on solar cells were identified with the use of thermal bands, which record and point out their temperature of them, whereas anomalies in the detected temperature in defective solar cells were captured using thermal electromagnetic waves, and these areas are mentioned as hotspots. In this research, a total number of 232.934 solar panels were identified, and 2481 defective solar panels were automatically indicated. The majority of the defects were due to manufacturing failure and normal aging, but also due to persistent shadowing and soiling from aerosols and especially dust transport, as well as from extreme weather conditions, including hail. The originality of this study relies on the application of the proposed under development technology to the specific conditions of India, including high photovoltaic panels wear rates due to extreme aerosol loads (India presents one of the highest aerosol levels worldwide) and the monsoon effects. The ability to autonomously monitor solar farms in such conditions has a strong energy and economic benefit for production management and for long-term optimization purposes.

Keywords: IR-imaging; drone; hotspot; thermal imaging; photovoltaic; solar cells; Unmanned Aerial Vehicles

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1. Introduction

One of the biggest problems that modern societies are facing is climate change. In our days, it is more important than ever to find eco-friendly and renewable energy sources in order to restrict carbon emissions and hold global temperature increases [1]. In December 2015, the Paris Agreement set out an international framework for a global treaty on climate change, with a main long-term target to set national and global strategies that will reduce emissions and will limit the planet's average temperature increase to 1.5 °C. Therefore, for the powering of a future and for an eco-friendlier world, renewable energy sources, such as solar and wind, became top of the list of sustainable alternatives with incredible potential and efficiency.

The sun radiates about 1.74 × 1017 W to the earth's surface, and this, in about one hour, provides more than enough energy to meet the global energy needs. The only limitation of solar power is our ability to turn it into electricity in an efficient way, and one promising solution is photovoltaics (PVs). PVs convert sunlight into electricity using semiconducting materials that absorb photons and generate electrons. This process is known as the photoelectric effect [2].

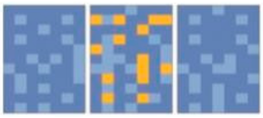
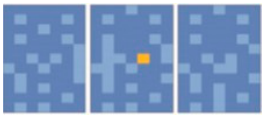
However, PV panels are dealing with problems that their outdoor position is causing them. Many environmental factors such as wind, salt, snow, and dust can affect the efficiency of the PV module by causing a significant decrease in their generation and other malfunctions such as corrosion and short circuit. Moreover, there is a possibility of a single PV cell overheating in cases when its connector is damaged, or there is a reverse bias effect. These scenarios could lead to a significant temperature increase in the cell since all the energy is forced to circulate only to a small part of it. Therefore, in order to secure the great performance of the PV systems, frequent inspections for possible damage as well as proper maintenance and immediate repair of any faults are essential [3].

A single solar cell produces about half a volt of electricity and up to about eight amps depending on the cell type, so cells are connected in series to create what is called a series string in order to increase their voltage. The voltage of the series string is simply the sum of the half-volt cells. The series string is laminated to the backing material, sealed in a weatherproof plastic coating, and covered by a glass on top, often with an aluminum frame around the edges. This assembly is called the photovoltaic module. It is also referred to as a solar panel. In a high short circuit PV cell string, a defective cell with a low circuit can cause reverse bias, which can lead to a drastic increase in temperature and to hotspotting, which is one of the most common defects that cells are dealing with [4].

A PV fault that, in this study, is preferred to be mentioned as a defect can be disrupted as everything is different in the performance of a PV module from the expected, and the reasons why PV failure may vary [5,6]. A detected defect basically defines a part of the unit that, compared to a perfect one, exhibits some malfunction which is not necessarily due to factors such as a safety issue or loss of performance as in a failure. Some commonly known defects that PVs deal with are mismatches which are caused by the association of cells with not identical physical properties or operating under different conditions between them, cracks which is a very common defect, and they can have different formations, directions and sizes, discolorations from internal factors such as lousy quality polymers, hot temperatures and humidity, soiling which refers to the concentration of dirt on their epiphany, delamination of their bonds through time, and finally snail tracks or trails which are black or brown lines of discoloration on the cell surface which appear after months or years of performance of the solar panel.

PV modules are inspected using various techniques, and defective solar cells are pointing through these procedures. The most common PV inspection techniques are visual inspection, I-V (current-voltage) measurement testing, which is applied in order to extract the characteristic I-V curve of a particular PV module, electroluminescence imaging, infrared thermography, which uses thermal cameras to capture the heat radiation of the cells and convert it into electrical signals (the pattern of how a defective panel looks from a thermal camera is shown in Table 1), and UAVs (Unnamed Aerial Vehicles) manned with cameras which allows the detection of extended areas, the collection of data in higher speed, and the assessment of difficult to reach installations and locations.

Table 1. Pattern of thermal image of defective panels.

Pattern	Description	Possible Error	Possible Cause
	One module regularly warmer than others	Nonfunctioning module	Module disconnected
	Warmer of a module by line (string)	One cell string short-circuited	Bypass diode defective internal short circuit
	Single random cells considerably warmer	The module is short-circuited	All bypass diodes defective
	One cell considerably warmer	-	Overshadowing defective cells
	Part of cell considerably warmer	Cell rupture	Outside mechanical influence
	Spot heating	Cell crack	Overshadowing due to bird droppings or maybe construction error

The first significant check that PV modules should successfully pass is the visual inspection. This technique's common detectable defects are soiling, cracks, discolorations, delamination, and snail trails. The I-V curves that are produced from I-V measurements later may point to an abnormality in PV operating standards, such as interferences related to the various possible weather conditions and the existence of some defects, such as delamination, mismatches, defective bypass diodes, and others. The final analysis is based on the comparison between the I-V curve that is created from the inspected modules and a reference curve that is considered perfect. However, this technique does not provide the exact location of defects in panels, and an I-V curve profile of a defective module may not reveal all the potential defects.

Solar PV modules are designed to absorb sunlight and use that energy in order to generate electrical current. Therefore, based on the principle of reciprocity, the electrical current that has been produced in the semiconductor material leads to the emission of photons, and this is a process that is called "electroluminescence". Electroluminescence inspection on PV modules is a technique that is widely used, and it consists of applying a direct current to a module and measuring the resultant photoemission using an infrared camera. At the final output, damaged zones, caused by a variety of possible defects, appear as dark areas, whereas intact zones appear bright and clear. For the performance of the electroluminescence imagery, dark environments are required. This technique is an excellent method for detecting cracks that appear as dark lines, but a major drawback is that for inspections, the photovoltaic installations cannot be in operation, and in addition, it requires high energy consumption and provides only a qualitative diagnosis.

Thermal imaging, also known as infrared thermography, provides images in raster form where pixels contain temperature signatures. In thermal cameras, the most significant factor is the detector's array, and there exist two types of them. The first type is the thermal or uncooled detectors, whose operation is based on the detection of a change in the temperature of the object under examination through the absorption of electromagnetic radiation, and the second type are quantum or cooled detectors, which convert directly into an electrical signal the incoming photons; they are more complex, but they have a higher sensitivity and response speed. In PVs, infrared inspection is mainly used as micro bolometric detectors, which are subject to the thermal detectors category. There exist two ways that measurements from thermal detectors can be performed. The first way is called quantitative, whereas the second is called qualitative. In a quantitative way, exact temperature values of a component are obtained, whereas the qualitative way compares the temperature of similar components in order to extract defections. The factors that affect I.R. thermography results can be divided into three main categories: the procedural, the technical, which are mainly related to the equipment and the practices that are used, and the environmental factors. Above all, the advantages of I.R. thermography vary, and they include capabilities such as non-destruction of the inspection areas, the ability of large areas scanning with PV plants at maximum power production state, fast data acquisition, and low cost.

The use of UAVs manned with cameras is the most efficient way in big-scale operations, and they can save time and human resources. Aerial cameras can perform visual and thermal inspections, and especially in extended photovoltaic plants, they are extremely efficient since they can save up to 85% of the time spent performing thermographic inspections in these areas. However, there exists a list of significant conditions that are required for efficacious PV inspections with the use of UAVs. In the case of RGB (Red, Green, and Blue) images, aerial photographs must be taken vertically, with a desired tilt of less than 3°, while for specific purposes, oblique photos can also be used. Another important factor that contributes to the quality of RGB visual inspections is the environmental conditions that prevail in each area, as they can contribute drastically to the final result. For thermal inspections, the used thermal camera should be sensitive in the 8–14μm band, with a recommended thermal sensitivity below 0.08 K to detect slight temperature differences. Sufficient solar irradiance is necessary to ensure enough thermal contrast; a stable value between 500 W/m^2 and 700 W/m^2 is suggested. Regarding the placement of the thermal camera on the flying vehicle, it is recommended that the viewing angle with respect to the direction perpendicular to the surface of the units be between 5 and 60 degrees for better recording of the results. Moreover, two of the most critical factors that must be considered in UAV inspections are the flight height and the camera resolution. Moreover, in order to prevent shadow effects and reflections on the surface of the PV module from the UAV, the best recommended hours for carrying out measurements are early in the morning or in the evening, which also allows better differentiating of characteristic temperatures on I.R. captures. It is also important to ensure the stability of the flight and the non-contribution of external factors affecting the temperature of the units; for this reason, the airflows should be seriously considered and eliminated.

UAVs have become an increasingly crucial tool in the delivery of products, services, and technologies related to a variety of industries—including renewables and specifically solar energy. At the same time, UAVs are able to provide an invaluable asset to solar professionals, giving the opportunity to reduce costs and accelerate the time-consuming process of analyzing and estimating PV panel performance. From UAV mapping to aerial infrared surveys and photovoltaic (PV) inspections, UAVs have become an invaluable tool in the industry. In past years, many research groups tried to identify "hotspots" on solar panels using UAVs [7–9]. Taking advantage of near-infrared technology, it was feasible to detect problems that had previously been undetected—from corroded connections and partial module shading to uneven power losses, mismatched voltage, and defective bypass diodes. In this direction, it was a valuable tool to enable solar installers to easily identify defects impacting solar panel performance, such as malfunctioning of bypass diodes and hotter cells, shading issues, and exposure to dirt or dust.

In October 2018, one of India's largest solar power providers, Adani Solar, announced a project to use UAVs to identify defects on solar panels. Utilizing data analytics, the UAVs enabled the detection of hotspots and other defects on 200 MW of photovoltaic systems, providing insight into the efficiency of the solar energy systems. Initiatives such as this demonstrate the potential advantages of utilizing UAVs for solar panel inspections. In summary, UAVs in the solar industry are making continual progress, and with improvements in technology, UAVs are becoming an increasingly viable option for solar professionals in both developed and developing countries. From identifying "hotspots" on solar panels and mapping solar farms to inspecting facilities for thermal bridging and corrosion, UAVs are providing the possibility to reduce costs and improve performance in the solar energy industry. Among all the uses of thermal cameras, either hand-held or mounted on a UAV, has been considered the best, time-efficient way to investigate large solar panels. However, it has its restriction about the time of the day when the survey has to be conducted. From the above, it is pointed to the importance of regular and adequate inspections to detect defects and also the most productive and profitable methods for this purpose. Objectives of the current research are the implementation of an aerial thermal survey of the solar farm, which is our study area, the creation of a vector shape file of the solar park and panel name as the details provided by the client, the identification of the hotspots in the PV panels, and finally the generation of a report with panel name, hotspot, and its temperature on it.

The research project is divided into two parts: pre-inspection and post-inspection. During the pre-inspection stage, a pre-flight survey is conducted to determine the location of solar PV panels in the solar field. Following the pre-flight survey, the UAV is deployed in the field to collect thermographic images of the solar PV panel array. During the post-inspection stage, the thermal images are analyzed to identify and locate thermal hotspots. The results from the post-inspection stage are then used to identify possible areas of concern and actionable maintenance topics for the solar PV panels. This research project is designed to help improve the monitoring of solar energy systems and provide actionable feedback for preventative maintenance of solar panel arrays. The results from this project can be used to identify and reduce thermal losses in solar panel installations, resulting in increased efficiency and reliability. Section 2 represents the study area and the data collection process that had been followed, the technical details, and the methodology that was used. Section 3 refers to the results of the analysis, and finally, Section 4 provides the conclusions with the summary of this research, as well as the future aspirations.

2. Materials and Methods

2.1. Study Area and Data Collection

It is clear that one of the most significant open issues in the PV sector is finding appropriate inspection methods to evaluate actual PV plant performance and failures [10]. There are many methods to inspect PV modules during an online operation, but the most popular include visual inspections and thermal and infrared cameras [11]. In addition, extended photovoltaic systems require special maintenance and close monitoring, frequent and rigorous inspections, as well as preventive checks. Drone mounted IR-imaging is one exciting technique for the inspection of large-scale PV modules, which in combination with specialized computer software, could provide essential information about the cell defects and their temperature differentiations [12,13]. In cases such as this, using aerial vehicles, new parameters must be considered, such as the geographical region and the latitude and longitude of the area, which can influence the temperature evaluations [14,15].

Although some procedures are proven to be insufficient to detect specific problems and determine the reliability and durability of PV modules, flight infrared thermography with the use of remote-controlled drones is a time-saving and efficient tool for inspecting a large number of installed PV modules or difficult to reach PV-plants, such as in rooftop installations [16]. One of the characteristics of thermal infrared imaging is that the larger the distance between the sensor and the target, the lower the measured temperature of the object; therefore, local detection rules were applied to automatically detect defective panels using an array's mean power and standard deviation range [17].

In addition, one of the most critical points in PV inspections is that differing defects can be diagnosed by characteristic temperature differences [12], and significant temperature abnormalities such as high-temperature spots, the so-called hotspots, and high-temperature areas can be recognized with the use of specialized pipelines [18]. Thermal and visual imagery taken by UAVs [7,19], voltage-based hotspot detection methods [20], artificial intelligence systems [21], automation techniques [22–25], RGB images [26], and monitoring techniques based on infrared analysis of PV modules are some non-intrusive inspection methods that provide information of possible detects by correlating and analyzing the thermal behavior of the modules with the overall operating condition of the solar panels [27].

In this research, the study area was a Solar field of 55 MW in the Southern part of India, situated on Arakkan Ittery Rd, Moongiltholuvu, Tamil Nadu State of India. The geographic coordinates of the study area are 10°46′37.5″N 77°13′58.8″E. The whole solar park was divided into six blocks with five blocks of 10 MW power and 5 MW power. The aerial survey of the park was conducted in the last week of February 2021, and the aerial orthomosaic of the solar park is shown in Figure 1a. To capture the solar park with a thermal camera mounted on an Unmanned Aerial Vehicle (UAV), sixteen flight paths were required. The flight of the drones was kept during the daytime so that the panels could be charged at 25, and the operational condition and the temperature of excellent and defective cells could be noted down with the help of the thermal camera mounted on the drone. The sixteen batches covering the area of the park are shown in Figure 1b.

As RGB and thermal cameras both were mounted on the drone, we obtained the lens images. These images were then brought back to the lab to identify hotspots and make the vector shape file of the solar park. The park consists of six blocks of solar panels, where five blocks have a 10 MW power generation capacity, whereas one has a power generation capacity of 5 MW. These six blocks have 3.757 solar tables, where each table is divided into two parts: the upper part with 31 solar panels and the lower part with 31 solar panels. There was a total of 232.934 solar panels. Along with these, the AutoCAD files of all six blocks were taken from the client, which has the terminology for each solar panel. The defective solar panel could be operated and checked directly from the control room once its name was known.

2.2. Drone Flying Planning

In general, drone flight planning is a multi-dimensional process in which all factors affecting a flight must be included, such as defining specific parameters related to flight specifications, the pattern to be followed, the altitude at which the flight will be made, the image or video captures and the characteristics they wish to include, as well as environmental and weather factors and conditions such as temperature, weather patterns, and light intensity. All these factors contribute to the successful completion of the mission and the correct collection of data and information. A drone flight plan is a detailed design where basic instructions are combined to achieve the mission and guide the drone properly. These instructions include information such as the coordinates of the space, the speed of the vehicle, the geographical characteristics of the area, the altitude, and the direction of movement while taking into account the weight and other characteristics of the camera that will be manned in the system.

It is important, before the mission, to determine the flight path of the drone using a series of all the important characteristics of the study area, such as the longitude, the latitude, and the altitude that will be used as input information that will automatically navigate the aircraft. In addition, the velocity of the drone during flight needs to be set, which is recommended to be slow and consistent throughout the flight plan since these are the ideal conditions for mapping. In case of an enhanced zoom is required over a particular location, then the drone hovers over the exact location. Moreover, it is important to study the overlaps, which are the common areas between two adjacent photos. Higher overlap means more images, and thus more processing time will be required. The minimum overlap between images should be kept as 65% to obtain the best quality results. However, in cases such as vegetation, uneven terrain, etc., it is advised to increase the value by 80%. The overlaps are divided into two types, the side laps, which refer to the percentage of overlaps between sides of the images, and the front laps, which refer to the percentage of overlaps between the top and bottom of the images.

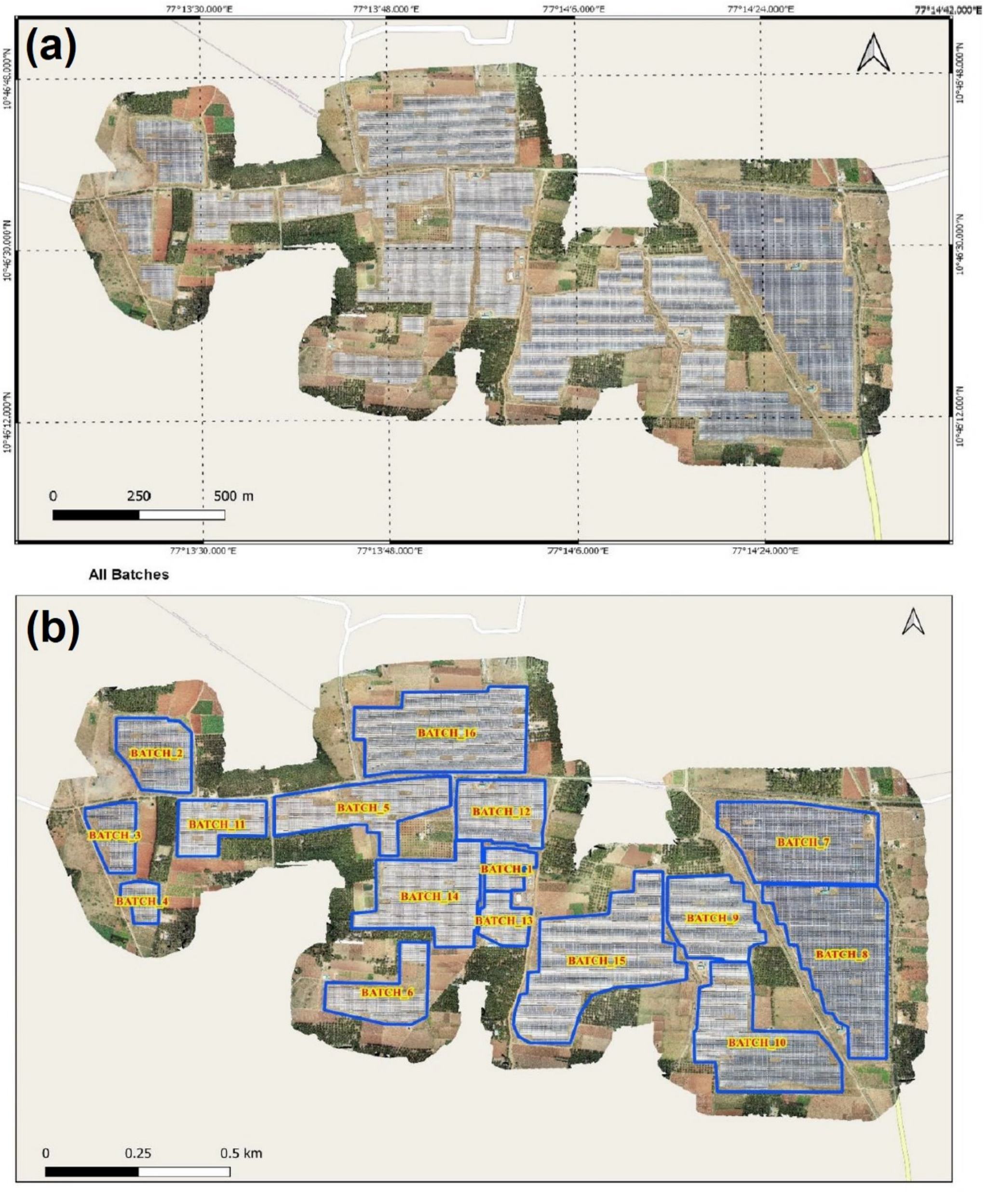


Figure 1. Aerial image of the solar field (**a**) and drone flight pattern (**b**).

It is also critical to define flight paths that are divided into two types: so-called "zone paths" and "waypoint paths". Grid runs, as their name suggests, follow a grid pattern. Their preferred use is in mapping missions that aim to collect imagery for processing into 2D and 3D data products (Figure 2). On the other hand, the paths of waypoints follow an undefined pattern that results from the unique characteristics of each area of interest where the flight takes place and are used for linear missions designed which are designed for investigations, project progress monitoring, security issues, etc.

Figure 2. Grid Path Pattern, Images: Drone Deploy.

According to the thermal survey, the key points to be considered are that the study area needs to be outlined with a polygon, overlaps should be kept at 80% for the front and 20% for the side, capturing an image at equal time intervals is recommended instead of capturing at equal distance, altitude of flight should be kept between 130–140 feet, and the long edge of the solar table should be kept parallel with the long edge of the image.

The size of a solar panel on the field was found to be 1 m in width and 2 m in length, and it has 6 solar cells in width and 12 solar cells in length. Therefore, the size of a solar cell is 166 $\times$ 166 mm. In order to capture a defective solar cell, the ground sampling distance should be kept at 15 cm/pixel, where Ground Sampling Distance (GSD) is defined as the interval between the center point of two neighboring pixels, and it can be calculated using Formula (1).

Ground Sampling Distance (GSD):

$$\text{GSD} = \frac{\text{Flight height} * \text{Sensor width}}{\text{Focal length of Camer}} \tag{1}$$

2.3. Methodology

The methodology of this research followed some specific steps. The first step of the process was to collect data and then sort the data according to the block-wise; after conducting this process, the whole data was divided into six parts as per the blocks. The creation of the vector shape file was conducted after taking the data. The RGB orthomosaic was used to make the vector shape file of the solar panels. Once shape files are created, then the captured images are imported, considering their location data from metadata. This helps to locate the photos precisely in the position they were taken at the park. Lastly, a hotspot was identified on each image manually, and it was marked on the shape file. The marked panels were then shown in the form of a table with defective panels' names written on them.

The process of the creation of the rectangular shape file of the panels was conducted in open sources GIS software known as Quantum GIS. According to the method that was followed, the top left corner of each table was marked as a point shape file with a timestamp as metadata in it. Once points were marked, their X and Y position was input as an attribute using the Field Calculator option in the processing toolbox. The output of this vector shape file is stored in the form of a list also to use in PyQGIS in later stages. Moreover, a parent solar table with all 62 solar panels was made using the grid option in the processing toolbox; the length and breadth of each solar panel are 2 m and 1 m, respectively. This step makes a solar table with 31 panels on top and 31 panels on the bottom, and then after is treated as the solar base table for the whole farm. The coordinates of the top left corner of this solar table are also noted down since it will further act as a base for another solar table. Finally, the relative X and Y distance of the solar table with parent tables was calculated. The parent table vector shape file was translated for all tables using the PyQGIS tool. In this tool, the offset distance in the X and Y direction was given as input from a list having the offset distance in both directions. The input layer is kept as the parent table shape file. The whole process can be shown in the form of a flowchart, as shown in Figure 3. Moreover, each table was named according to the guidelines that were provided. To quote each table uniquely, six different fields need to be filled, which are shown in Figure 4.

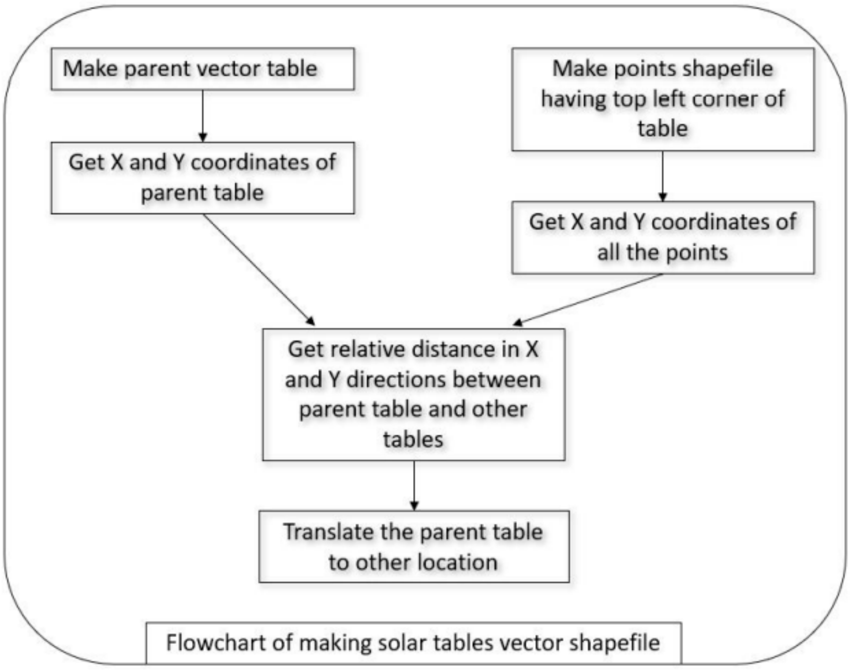


Figure 3. Flowchart of making solar tables vector shape file.

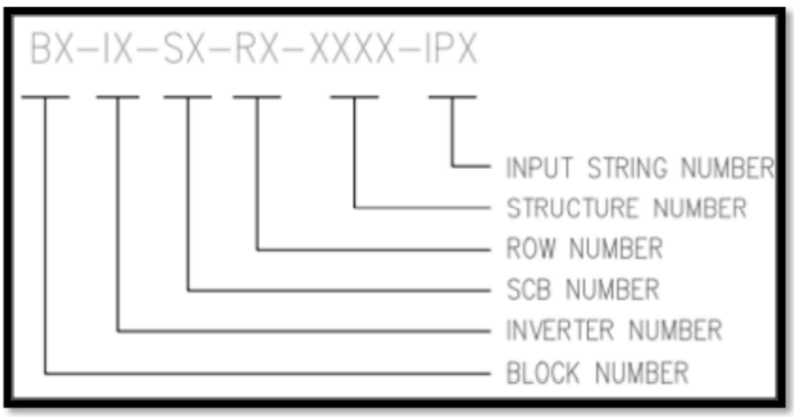


Figure 4. Table nomenclature. The six different fields that need to be filled in order to quote each table uniquely according to the required guidelines.

The second task was to import the images captured from the drone. For this import, geotagged image options from the processing toolbox were used. To run this tool, the folder's location having the images needs to be given as input. It automatically fetches the 34 coordinates of the photos from the metadata file and places a point shape file on that location. The geotagged image photo points are shown in Figure 5.

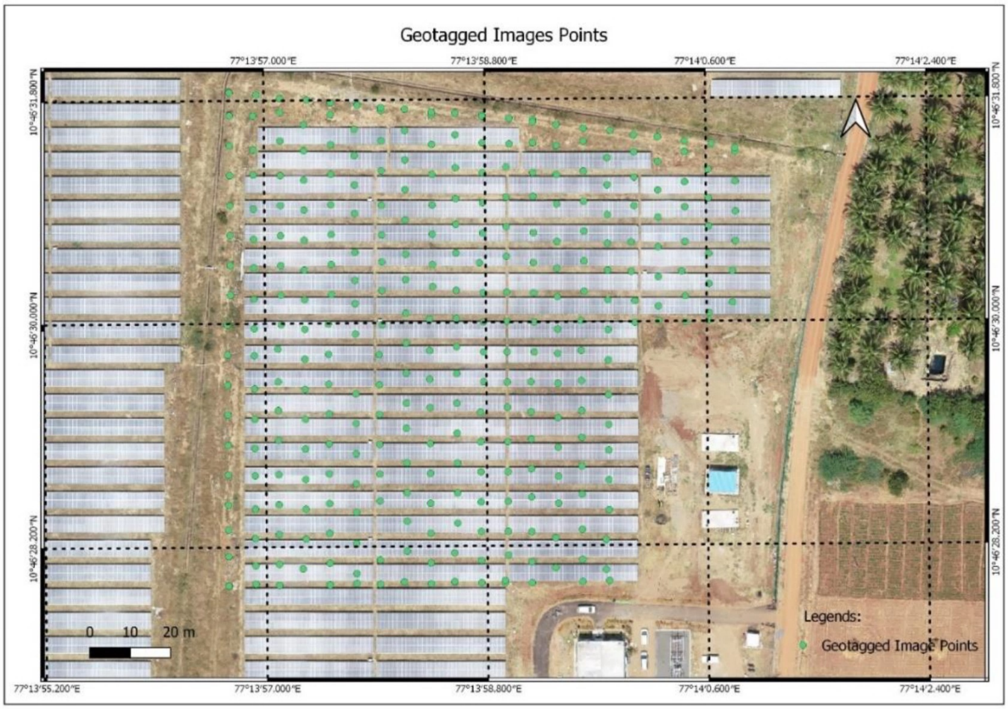


Figure 5. Geotagged image photo points.

Finally, once all the solar tables and geotagged images were located on the canvas, each photo was investigated one by one, and hotspots were found. Once a hotspot is seen in a photo, its position is found, and that hotspot is traced and marked on the solar table. As an example, Figure 6 represents a photo named "DJI_0002_R", and it can be visually inspected that it has six hotspots in it. The shape and the location of these hotspots and hot areas can imply different defects. Usually, if single cells are showing up as hotspots or warmer "patches", the reason can be found in many possible failures, such as defective bypass diodes, cell mismatches, snail trails, internal short-circuit, as well as environmental conditions, such as shadowing and cracks. The temperature rise of a cell or a part of it, in any case, implies some kind of defection or shadowing [7]. Moreover, the combination of solar cell cracks and the increase in temperature or the shading ratio can likely lead to hotspots [28].

Hotspots are one of the most typical and significant failures on a PV module, and they can damage not only the solar cell but also other components of the system. Solar cells in a PV module are connected in series. If one of the cells, or just a part of it, produces less current, the exceeding current produced by the other cells forces it into reverse bias. Thus, power is dissipated and transferred into heat. To avoid a solar cell from being reverse biased beyond its breakdown voltage, bypass diodes embedded in PV modules and short circuit less current-producing cell strings. The reason for less carrier production can vary from shading to cracked or short-circuited cells. Therefore, a hotspot is actually not a degradation itself but an effect occurring due to the presence of other degradation modes [29].

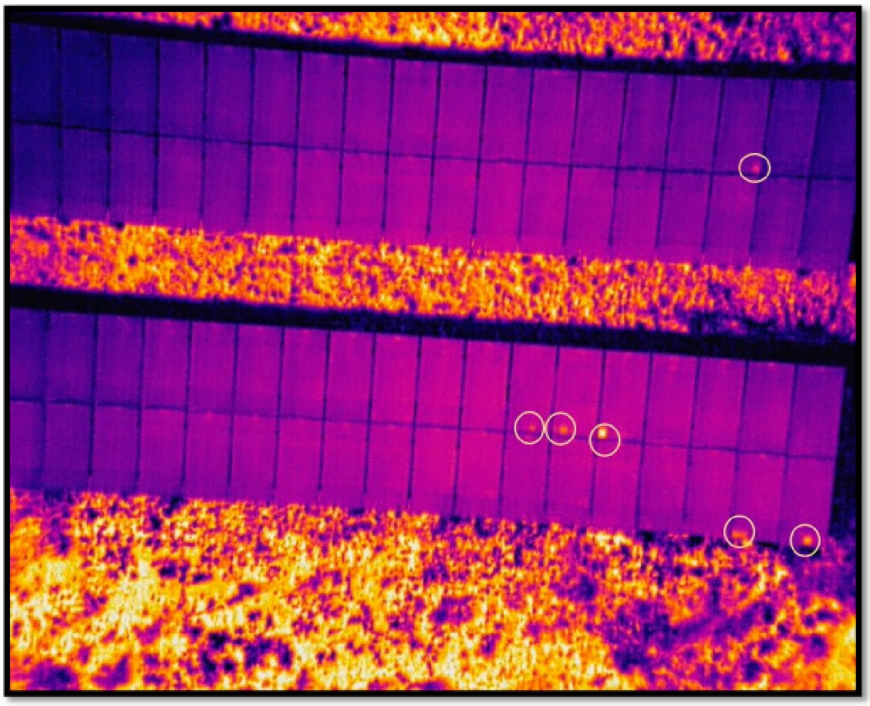


Figure 6. Thermal Image "DJI_0002_R". An example of a visual display of the six hotspots that were detected in this photo.

The reasons for hotspot detection, as already mentioned, lie either in technical issues or environmental conditions [30,31]. The shading that affects PV cells and leads to hotspot creation can be caused by bird droppings, leaves, and dust, which suspend the cells' function and prevent the current generated from other cells. As a result, the cell diode operates in reverse bias mode, the cell is heating, and hotspots are created [32,33]. Of course, there are many other reasons that can lead to the creation of hotspots, such as cracked cells or solder bond failures and corrosion [34]. Now according to the geographical location of the image, these defects were mapped on the solar table as shown in Figure 7a,b. Figure 8 shows the temperature for each hotspot that was identified earlier. From SP01 to SP06, hotspots have temperatures in the range from 39.6 °C to 42.9 °C for this case, whereas for the location of good panels, the temperature is 2 °C lower. Likewise, hotspots are identified and mapped for each thermal photo.

The method applied in this paper in order to find the cause of solar photovoltaic hotspots was the combination of a local search approach and a thermal imaging system. We applied a zonal statistical analysis of the thermal image to investigate the potential causes of the hotspots detected [35]. This method is not a new one proposed in this paper, but it is a combination of existing thermal imaging technologies, data analytical approaches, and in situ measurements to detect and analyze solar photovoltaic hotspots. This method has been described in several papers [36,37] and, for the first time, was optimized and tested for Indian conditions, including monsoon and long-range dust transport effects. As a result, based on previous methods [35–37], the whole idea was upgraded by including the automation of the process in order to form a holistic solar PV monitoring system for efficient maintenance management and decision-making tool (panels issues and macroscopic analysis). This method was tested for the first time in India, characterized by complex climatological conditions (i.e., high solar potential but also high atmospheric instability with various aerosol sources (fires, dust, air pollution), monsoon effects, and intense urbanization that requires rapid conversion into smart cities where one of the main pillars is the UAV exploitation.

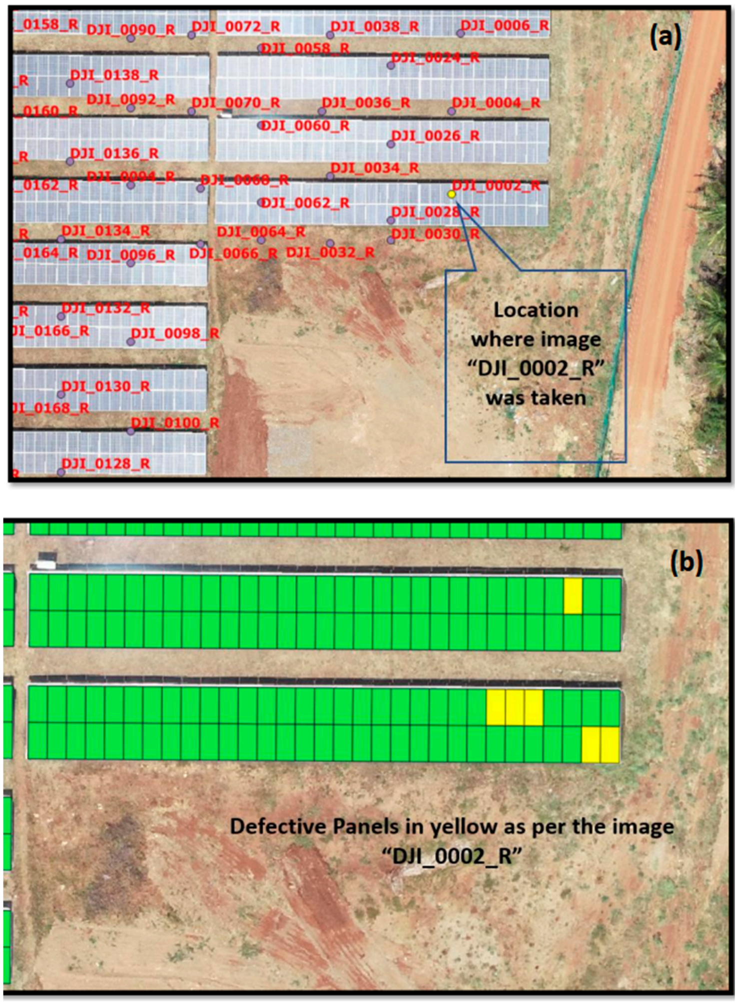


Figure 7. Location of thermal image (**a**) and defective panels in sample thermal image (**b**).

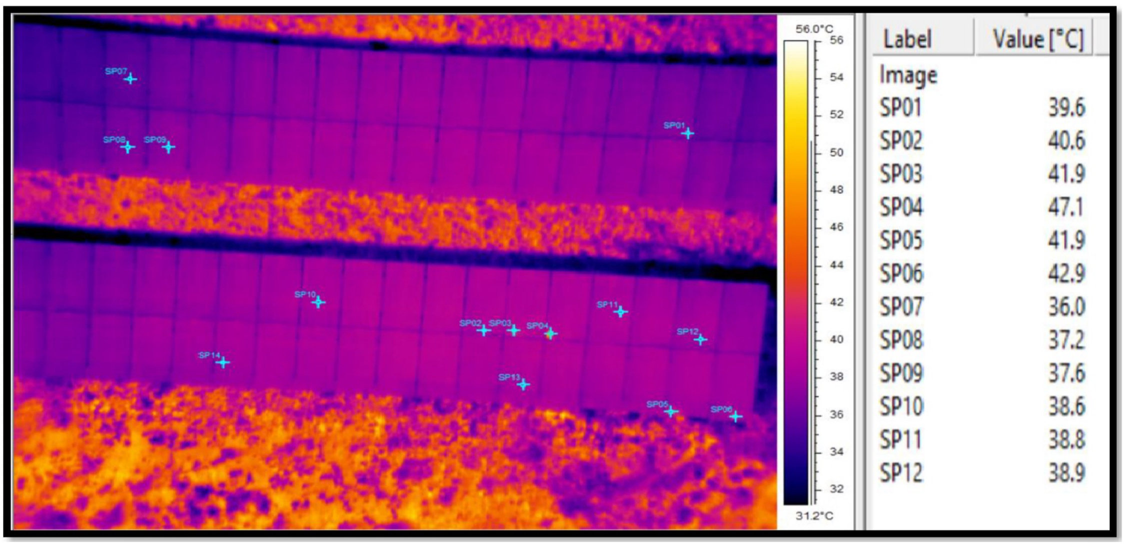


Figure 8. Temperature of hotspots of the thermal image.

In order to validate the methodology used for the detection of defective photovoltaic cells, a number of statistical techniques were utilized, including the following:

(1) Correlation Analysis: The correlation between the thermal images and the ground measurements obtained from the solar field was calculated in order to determine whether there was a direct relationship between the two. The measure of correlation was Pearson's correlation coefficient, r-value. This determined the strength of any linear relationship between two variables, in this case, the temperatures obtained from the UAV images and the ground measurements.

(2) Regression Analysis: The data obtained from the thermal imaging was compared with the ground measurements by applying linear regression analysis. This provided an indication of how accurate the model was in predicting the temperatures obtained from the images. The measure of accuracy was the coefficient of determination (R-squared).

(3) Temperature Difference Analysis: The difference between the thermal satellite images and the ground measurements was calculated in order to evaluate the accuracy of the UAV images obtained. This indicated whether there were any areas of significant thermal variability that could help to identify the presence of defective photovoltaic cells.

(4) *t*-Test: The *t*-test was used to compare the mean temperatures of the photovoltaic cells in order to determine if any differences between the two groups (hot and cold cells) were statistically significant. These statistical techniques were used to determine the accuracy of the methodology used for the detection of defective photovoltaic cells and help to validate the results.

(5) Error analysis: Error analysis is used to determine the accuracy of the results obtained and to identify the possible sources of errors. In this case, the root mean square error was used to compare the temperatures of the inspected photovoltaic cells in the thermal images and the actual temperatures in the solar field. This was used to determine the accuracy of the system in detecting defective photovoltaic cells.

(6) Anomaly detection: Anomaly detection is used to identify abnormal occurrences in a dataset that can indicate the presence of a fault. In this case, a one-class support vector machine was used to detect any abnormal temperature readings from the thermal images. This was used to detect defective photovoltaic cells.

3. Results

By the completion of the data gathering and the analysis process, the shape file of the table with names for each block was generated. The results for all six blocks and the total number of defective solar panels in each one are shown in Table 2. The map of the defective solar panels is also made and displayed for each block (an example for Block 1 is given in Figure 9a,b). A total number of 2481 defective solar panels were found.

Table 2. Defects in each block.

Blocks	Total Number of Tables	Total Number of Solar Panels	Total Number of Defective Panels
Block 1	684	42,408	832
Block 2	684	42,408	607
Block 3	684	42,408	416
Block 4	683	42,346	361
Block 5	679	42,098	93
Block 6	342	21,204	174

Figure 10 also displays the statistical graphic analysis of the number of panels in its block versus the number of defective panels in the corresponding block. Moreover, the temperature of the hotspot and cells neighboring to it, of all defective cells, were identified to do the temperature analysis of the field, which is shown in Table 3. Figure 11 represents the boxplot of the temperature of hotspots, their neighboring cells, and the difference between both.

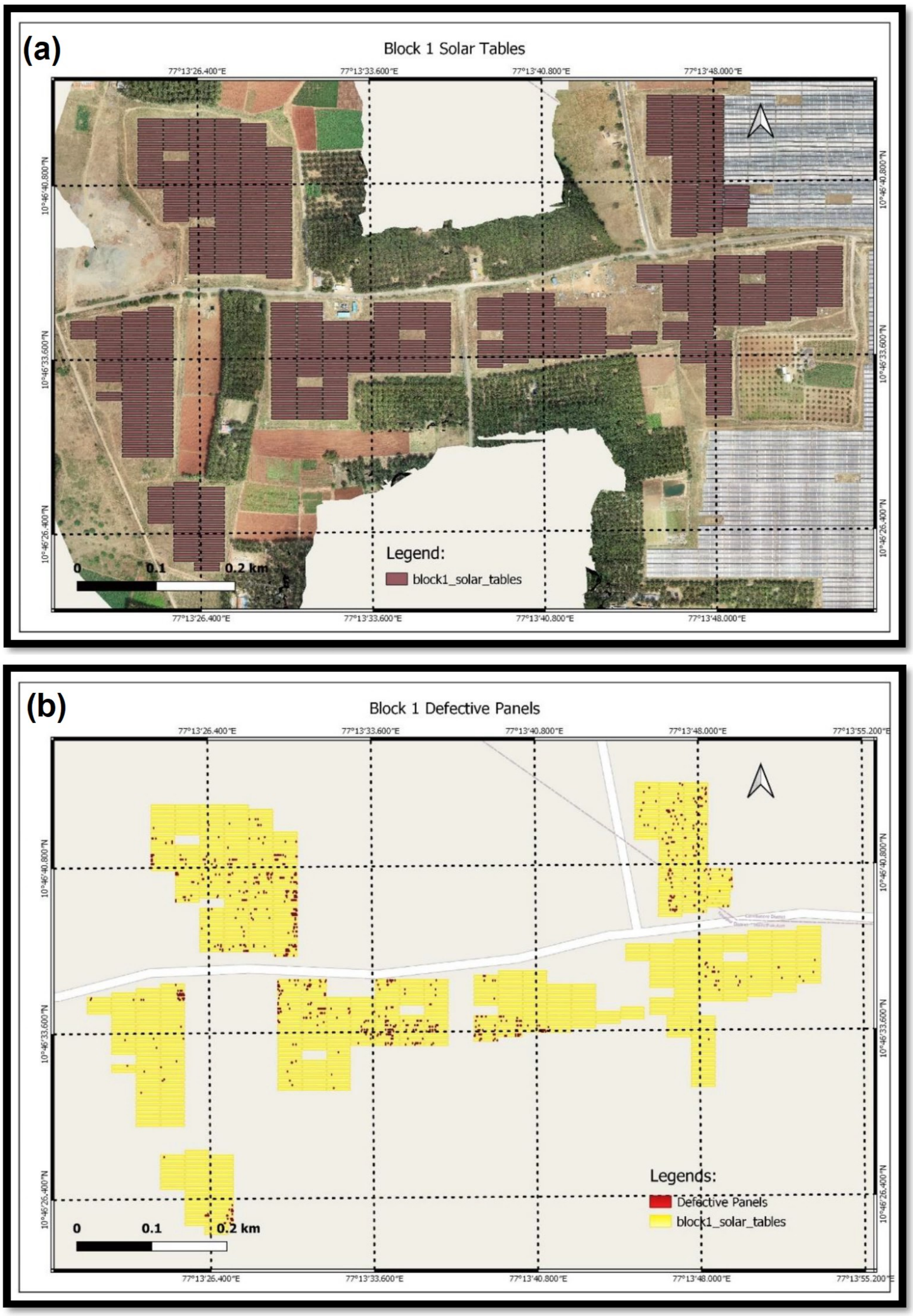


Figure 9. Block 1 solar tables (**a**) and defective panels in the same block (**b**).

Table 3. Temperature statistics of hotspots.

	Hotspot Temp.	Neighbor Temp.	Difference
Minimum	37.4	24.9	3
Quartile1	46.7	32.175	12.8
Median	54.15	35.1	17.7
Quartile2	64.7	38.9	27.7
Maximum	150	66.6	111.4
Mean	58.92	36.04	22.88
Range	112.6	41.7	108.4

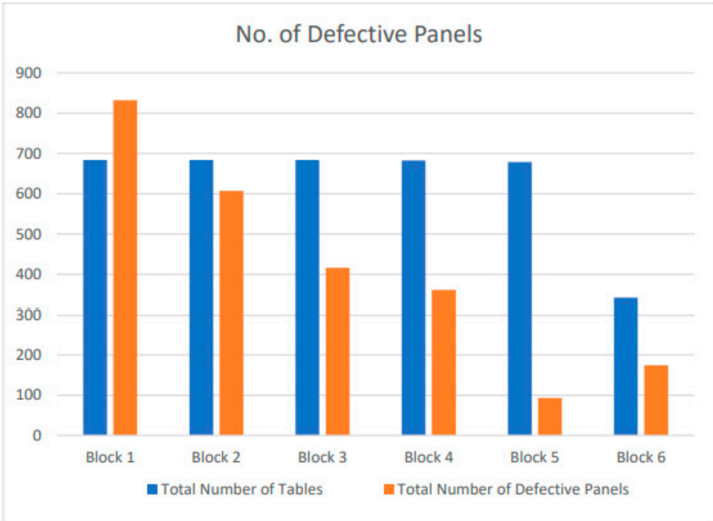


Figure 10. No. of defective panels. The statistical graphic analysis of the number of panels in its block versus the number of defective panels in the corresponding block.

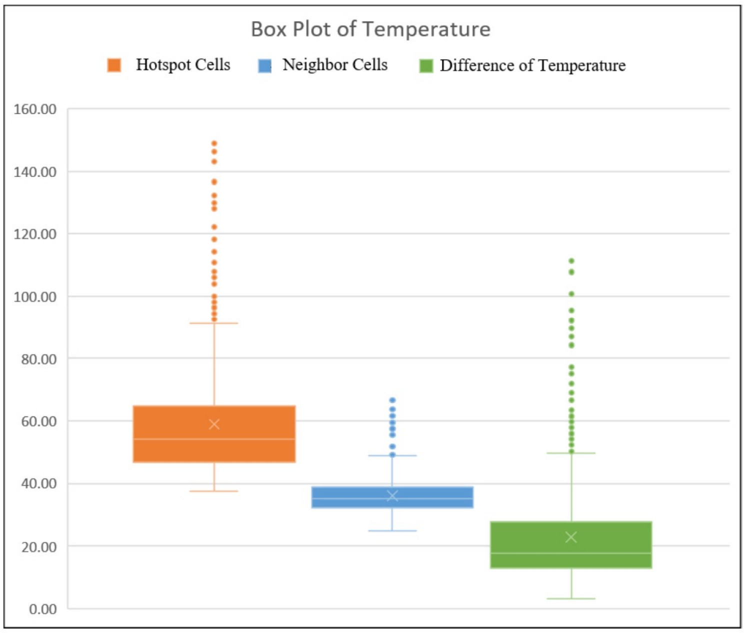


Figure 11. The boxplot of the temperature of hotspots, their neighboring cells, and differences between both. The bottom line of its box represents the first quartile, the medium line represents the second, and the top line the third. The outliers appear outside the maximum of its box.

As from the above statistics, it can be concluded that the difference between quartile 3 and quartile 1 is least in neighboring cells, which shows that the cells are good when their temperature is between 32 °C and 39 °C. The minimum of the hotspot temperature is greater than the median value of the temperature of good cells. In addition, the statistics show that the difference in median values of hotspot temperature and its neighboring cells is 20 °C, and the quartile band is very narrower in neighboring cells while it is broad for defective cells. The values that are above the outliers in neighbor cells are the values where the whole panel is defective. The outliers in hotspots indicate the cells which are physically damaged as their temperature is more, and cells that are in the quartile range in hotspots are majorly due to shadow, soiling, and due to shade of trees. Finally, some of the reasons for the defects in panels are relevant to the growth of trees, bird droppings, and shadows, such as shown in Figure 12.

This study provides a valuable addition to the existing body of knowledge on the benefits of leveraging UAV thermal imaging to inspect solar PV hotspots. Its findings suggest that UAV thermal imaging can more quickly and accurately identify potential hotspots in solar fields than manually conducted visual inspections, reducing the amount of time and sources of errors associated with manual inspections. This finding is in line with similar studies conducted by other authors [10,38]. Furthermore, this study demonstrates the applicability of UAV thermal imaging to solar fields in the Indian context, where urban and industrial settings often require more detailed imagery than other settings.

This research suggests that UAV thermal imaging is a useful tool for monitoring the condition of photovoltaic panels in a solar field. Furthermore, the results of this study support the importance of using such tools in order to ensure the quality control of photovoltaic systems and to identify and address potential hotspot issues as soon as possible. Additionally, the findings of this study show that UAV thermal imaging can significantly reduce the time and complexity of inspection, which can ultimately reduce the cost of maintaining photovoltaic panels by eliminating the need for manual labor. Therefore, this study contributes to the existing body of knowledge by providing a novel approach to monitoring and maintaining photovoltaic panels that can help reduce costs and improve the accuracy of quality control inspections.

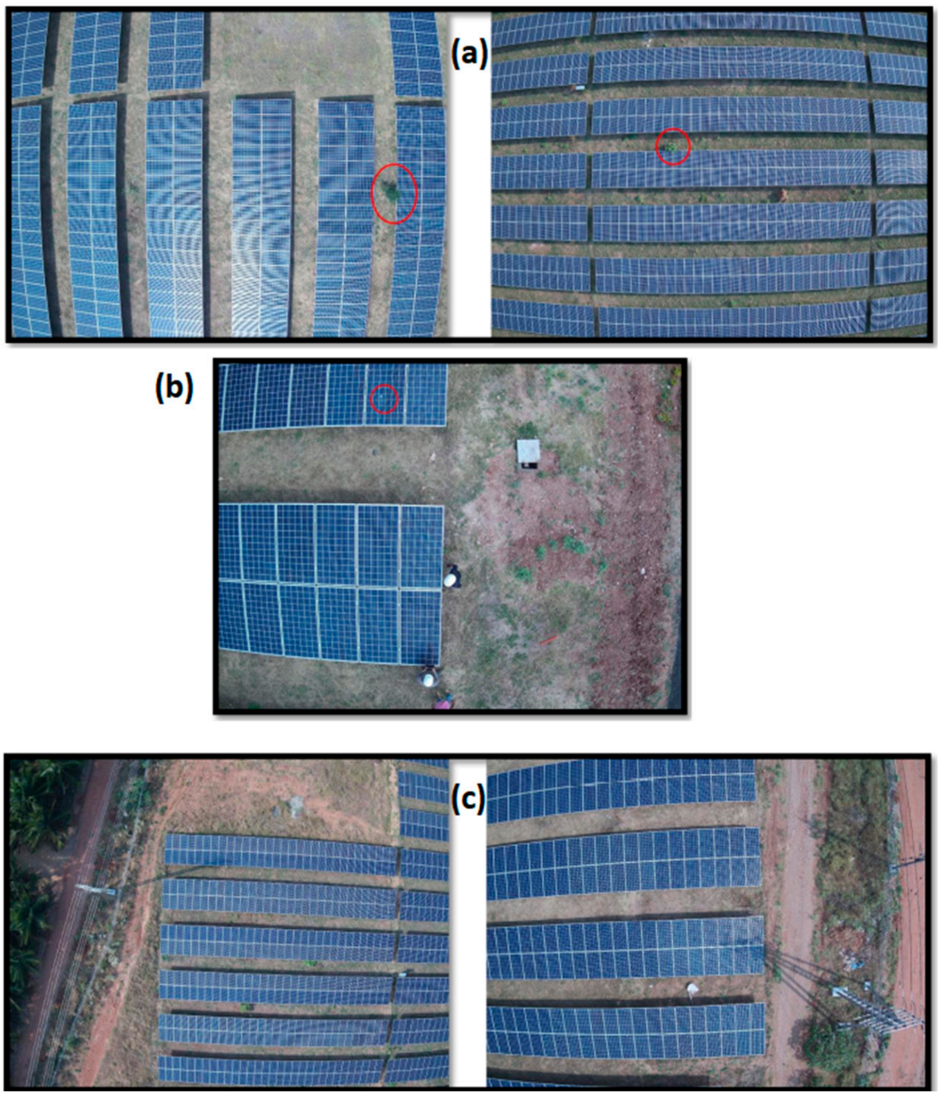


Figure 12. Some of the reasons detected for defective panels are related to external factors, such as the growing of plants (**a**), bird droppings (**b**), and shadows (**c**).

4. Summary and Conclusions

As is already mentioned in the literature and the experimental results from previous research, the mechanism which combines UAVs and thermal cameras for the detection of defective cells in solar panels is a very efficient and profitable way in the process of the inspection of the photovoltaic system. In the current research, a solar field of 55 MW, situated in the Tamil Nadu State of India, was selected as the study area of the project. PyQGIS was used for the digitization of the solar table and solar panels, and each table was named as per a set nomenclature. The drone images were imported and geotagged to locate the panels accurately, and the hotspots identified for the entire area were listed. Finally, the temperature analysis shows that most of the cells have minor defects such as soiling, shadow, and growth of plants.

The main results obtained in this study could be summarized as follows:

- drone thermal images can be used to effectively inspect solar photovoltaic hotspots at a solar field in South India
- thermal images are capable of identifying with great accuracy the locations of the hotspots
- a full mapping of the hotspots with an accuracy of up to 97% was provided through the analysis of image visualization algorithms such as RGB, NIR, and Thermal Index yield.

All the above points to the utility and the efficiency of UVAs in the maintenance and surveillance of PV systems, a method that is cheaper and faster in comparison to traditional ones, and it also enables early detection of hotspots in order to prevent extended damage to the system.

If highly overlapping images can be acquired at the time of the surveying, it is possible in the future to automate the above process completely. The defects, along with their kind, can also be identified, and empirical equations can be made to obtain the panels' temperature by using the DN values of the red, green, and blue bands. Methods such as YOLO V5 Machine Learning can be used to find out the images have hotspots in them, and the identification of the spatial location of hotspots using drone location and image metadata is another goal in the conscious development of the detection and analysis process of defective cells. YOLO V5 can be applied to Solar Photovoltaic Hotspot Inspection by utilizing object detection methods such as anchor boxes, object tracking, and object segmentation. Anchor boxes can be used to detect and classify objects of interest within the thermal images, such as damaged solar panels, cracks, and other areas of concern. Object tracking can be used to identify the position and area of these objects over a period of time. Lastly, object segmentation can be utilized to trace objects against their backdrop, allowing for improved accuracy and providing a more informative inspection of potential hotspots. Utilizing YOLOv5, not only can relevant hotspots be located, but through the inclusion of thermal imagery, temperatures of these areas can also be ascertained. This can further provide clues concerning what kind of damage or defect the image is depicting, enabling effective and efficient solar photovoltaic inspection.

Since, overall, powering a green, more sustainable world is a challenge for the present and future generations, solar energy is considered one of the most promising solutions for this concept, and it is important to extend the potential of photovoltaic technology in mega-cities with rooftop panel PVs. Rooftop solar PVs are constantly increasing their popularity, and they are becoming one of the most preferred options for not only businesses but also many homeowners. The continuous evolution of this alternative and renewable form of electrical power creates the necessity for the economic and functional study of such systems in order to ensure their maximum performance. According to this, the future plans of the above analysis are to include these structures in its research, where shadowing is more intense and accessibility more difficult, in order to extract profitable and efficient detection solutions in rooftop-placed PVs.

The importance of this research lies in the fact that it utilizes thermal imaging of an Unmanned Aerial Vehicle (UAV) to inspect a solar field in South India. This research is novel in its use of UAVs and thermal imaging technology to detect faults and inefficiencies in solar photovoltaic hotspots. It is also the first research to propose and evaluate the performance of a fully automated, UAV-based system for solar PV hotspot inspection. The use of UAVs and thermal imaging offers unique advantages and opportunities in solar PV hotspot inspection, such as the ability to detect hard-to-find faults, extended area coverage, and reduced inspection time. The results of this study suggest that using UAVs for thermal imaging can be a valuable tool for the maintenance and surveillance of photovoltaic systems. This method is faster and cheaper than traditional techniques and enables early detection of hotspots in order to prevent catastrophic damage. The limitations of this study are mainly related to the lack of thermographic knowledge and its application to photovoltaic plants.

Future work should include further studies focused on the validation of the analysis techniques used in this study and other techniques for accurate hotspot identification. Additionally, a study of hotspot evolution and temperature spread over time would provide valuable insight for further photovoltaic plant maintenance and operations. The next step of this study will be a follow-up work in which the observational results will be classified and analyzed by exploiting computer vision techniques (e.g., pattern recognition, similarity forecast, etc.) for on-the-fly decision-making and early warning without human consideration and image post-analysis.

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Abbreviations

The following abbreviations are used in this manuscript:

AutoCAD	Computer Aided Design program
GIS	Geographic Information System
GSD	Ground Sampling Distance
PV	Photovoltaic
PyQGIS	Python Quantum Geographic Information System
UAV	Unnamed Aerial Vehicle
WebODM	Web Open Drone Map
YOLO	You Only Look Once

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