Inspection of PV plants using drone-mounted thermography

Plant inspection | Infrared cameras mounted on drones offer a means of detecting instances of equipment malfunction in PV power plants. Claudia Buerhop-Lutz explains some of the faults such an approach can help reveal

In 2014, worldwide 130GWp photovoltaic power plants had been installed. In the coming years, it is expected that the installed capacity of PV will increase further. Considering the availability and safety aspects of PV electric power, the importance of module quality and functionality increases. The demand for appropriate/suitable methods for controlling the quality and functionality of a solar park grows. The requirements for an almost ideal method can be summarised as following:

- No dismantling and no transport of the modules in order to avoid any stress and harm to the modules
- Measuring during operating conditions in order to avoid power loss and accordingly losses in income
- Money- and time-saving
- Reliable and meaningful, with a known uncertainty of measurement
- Fast, best real-time results and data evaluation
- Plain and understandable presentation of the results

In recent years, investors, proprietors and designers of PV plants have begun to appreciate the benefit of infrared (IR) mapping of PV modules and solar parks. Auxiliary carriers, like piloted and unpiloted aerial vehicles, are convenient as they enable easily the inspection from an optimal observation angle and also the fast execution of the inspection. There are several advantages. One is that the inspection is done during real operating conditions, which means real-time imaging with no service interruption. The method is also contact-free, non-destructive, repeatable and fast. Areas that are difficult to reach become accessible. Due to the two-dimensional images, irregularities, such as hotspots in PV modules, are visualised easily using IR-cameras.

The inspection of PV plants is forced by an interest in the quality control of a system; that means the electric output of the generator as well as safety, warranty and ageing aspects. The first one can be done on a plant or string level whereas the second one must be carried out at a module level. Here, monitoring systems on a string level might not have the accuracy required for measurement to detect individual malfunctioning modules within a string. Monitoring every module in a plant individually is fairly new. Processing and evaluating the huge amount of recorded data in connection with local ambient conditions may indicate positions of malfunctioning modules; however, it carries no information about potential module defects.

Since electric and other defects in PV modules lead to changes in temperature distribution, IR cameras are well-suited for searching for faults in installed PV modules [1]. Departures from normally working PV modules are visible in IR images as irregularities in the temperature distribution. These sites of elevated temperature are a strong indication of module defects.

Solar cells, and by extension PV modules, are electric devices that generate heat as well as electric current under working conditions. They convert only a part of the incident solar radiation into electric power; another part is reflected from the surface and the major remaining part absorbed. Therefore solar cells heat up. Component changes, such as manufacturing defects, maltreatment or degradation, may lead to variations of the (electric) material properties and result in malfunctioning and local temperature change, mainly an increase.

The magnitude of this temperature increase is determined by the module parameters, the specific defect characteristics and the actual operating conditions. Defects that can cause temperature increases include unconnected module strings, open substrings, cell fracture, shunted cells, short circuited modules, solder defects and defective bypass diodes [2]. How the temperature increase differs from that of unaffected, sound components, is described later.

Using IR cameras with a two-dimensional detector such local temperature differences or irregularities can be visualised easily. Different defects can be distinguished by typical temperature patterns. Meaningful images require certain measurement conditions, such as an absence of shading, partial shading and all types of reflections, which could lead to misinterpretation. Therefore, optimal measurement conditions require stable weather and include also incident solar irradiation above 400W/m², cloudless sky, no rain and almost no wind. If these meteorological conditions are fulfilled, quasi-stationary heat transfer conditions are realised and local shading by clouds is avoided.

Since IR imaging displays a temperature distribution by measuring the emitted heat radiation of the investigated object, the optical material properties are of importance and have to be taken into account. Here, the emissivity, the reflectivity of the cover glass of a PV module in the IR spectral range of the camera system, is of importance. The glass emissivity at an observation angle perpendicular to the glass surface has a maximum of 82% and decreases strongly for angles above 40° [3], which affects the temperature measurement significantly.

In practice, mobile platforms and aerial vehicles, unpiloted as well as piloted, are useful camera carriers. Besides emissivity, the flight height – the distance between the IR camera and the PV module surface – and the flight speed gain in importance. Former investigations reveal that the radiometric and geometric resolution decrease with increasing distance. This affects the optically measured temperature, too.

A distinction needs to be drawn between large, extended radiating areas and point-like heat sources. The measured temperature for large areas decreases slightly about -0.05K/m or less due to atmospheric absorption. For small heat sources a more significant temperature drop of about -0.25K/m is typical.

This fact is related to the geometric resolution. When the heat source covers less than 5 x 5 pixels, radiation from cooler surroundings affects the corresponding area. As a result the measured temperature appears too low [4]. Frequently the temperature difference between a heated cell and its surrounding is taken as a measure for the gravity of the defect. However, even the temperature difference depends strongly on the distance between IR camera and solar panel. If the distance is too large, the temperature difference may be underestimated. As a consequence severe faults may not be recognised.

Taking advantage of the mobile, aerial measurement system, IR camera plus drone, the measurement can be accelerated. For imaging with a moving camera, motion blurring is the limiting factor. A measure for motion blur can be either the acutance – or sharpness – of the objects or the dislocation of the pixel due to the movement of the drone, and therefore the IR camera. Thus, the dislocation or motion blurring increases with high flight speed or long exposure times or low frame rates. For minimising the lack of definition of object edges, short times or frame rates

Figure 1. Inspection of an installed PV plant using an aerial, unpiloted IR-measurement system consisting of an octocopter with control unit, a fast and high-resolving IR camera and a visual camera for orientation.

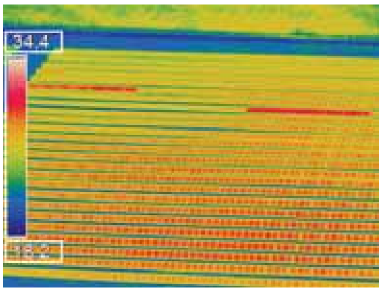


Figure 2: Aerial IR image of an extended solar park, approximately 4MWp, ambient temperature = 15°C, solar irradiance = 420W/m2, showing two irregularly heated module strings that indicates electric disconnection of these strings.

higher than 50-80 Hz are necessary [5].

For inspecting installed PV modules or PV plants aerially, drone-mounted IR imaging systems are used. The measurement system, as shown in Figure 1, consists of an unpiloted drone, a lightweight IR camera, a visible camera and equipment for navigating. For efficient, fast and informative imaging the IR camera needs a high-resolving detector array, a focusing optic (telephoto lens or wide-angle lens) and additionally a high frame rate. A high geometric resolution enhances the ability to visualise temperature differences and therefore the detection of module defects. Various sensors to measure solar irradiation, ambient temperature, wind speed and so on, record conditions for post-processing data evaluation. Navigation systems allow waypoint navigation. That means that the GPS data of the borders of the PV plants are used to mark the routing of the flight across the PV plant. This is a valuable tool to inspect extended solar parks systematically, efficiently, quickly and reliably, so that outstanding modules can be located easily.

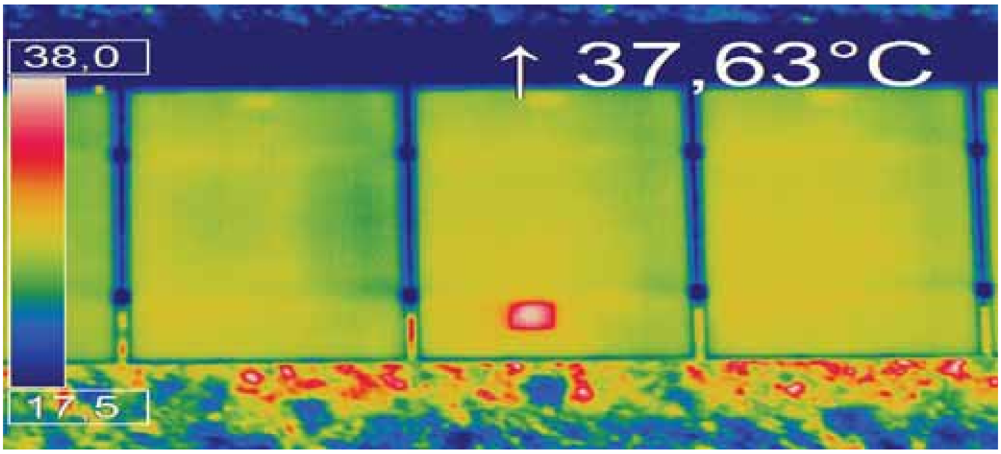
Figure 2 shows a typical IR overview of a PV plant. Temperature gradients across a larger area of the PV plant due to inhomogeneous irradiation or locally differing heat transfer become visible. These phenomena have to be carefully distinguished from optical effects. Singular spots, cells, substrings or module strings with elevated temperatures are a strong indication of faults. This temperature rise is linked on the one hand with heat generation on the other hand with electric losses.

Nevertheless, the solar park of Figure 2 has two irregularly heated, outstanding module strings, marked in the IR image. Presumably, these two module strings are not electrically connected to the inverter. In this case the absorbed solar energy is only converted to heat. For this reason these strings have a higher temperature than their neighbouring modules and are visible in the IR image. Typical temperature differences are 4 to 6K. The most reasonable explanation is that this module string is not connected to the converter or the electric connection is lost. The electric power output is zero. The consequence is a significant power loss.

In the following some module defects and their impact on the module performance are described in detail. Close-ups show more details and enable a deeper investigation of the modules. Different defect types can be distinguished [2]. Figure 3 shows typical examples of two different module defects, but of the defects described below, various types can be distinguished by their characteristic appearance in IR images.

Bypassed module substrings are visible when module failures with a strong impact on the output power are present in PV modules. It is typical for the cells of such a substring to have a homogeneous, elevated temperature of about 4 to 6K above the neighbouring cells and additionally that the corresponding bypass diode is operating and has a higher temperature (approximately 6K). The consequence for the power output of such a module, in the case that one out of four substrings is bypassed, is that the resulting output power is reduced to three-quarters compared to the nominal power of the module.

Cell fracture is one of the most common faults in PV modules. The origins can



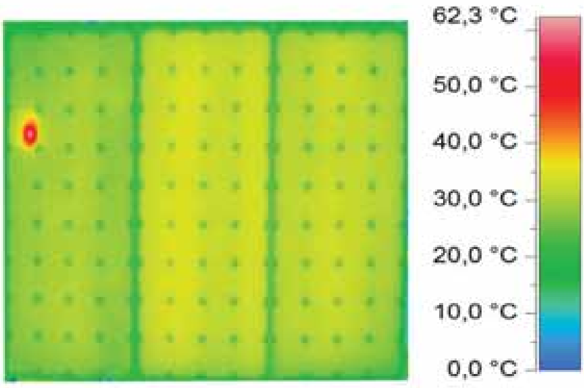


Figure 3: IR images (close-ups) of two typical module defects.
▲Cell defect with homogeneously elevated cell temperature. Temperature = 37.6°C, temperature of good neighbouring cells = 27.5°C, ambient temperature = 14°C, solar irradiance = 410 W/m².
▶Point defect (defective solder joint) with locally raised temperature. T = 62.3°C, temperature of good neighbouring cells = 29.3°C, ambient temperature = 9.3°C, solar irradiance = 760 W/m².

be manifold: manufacturing, transport, installation damage as well as natural lifetime degradation. Fractured cells in PV modules are visible in IR images (see Figure 3, upper image). The temperature difference to the neighbour cells can be high depending on the fracture characteristics, the operating point and the measurement conditions. (For example, we found sample module with ΔT > 100K for distinct cells.) Normally, just the cell with the largest cell fracture shows the temperature increase. Therefore, the resulting module power is determined by the failure characteristics.

Faulty soldering is another frequent failure. Typically, the temperature rises locally at the sites of open or bad solder joints (see Figure 3, lower image). The area is much smaller than the area of a cell and therefore called hotspot. The spot can be at fairly high temperatures. A temperature difference of ΔT > 33K is measured for the example in Figure 3. At higher irradiance on a summer day even higher local temperatures may be reached. This can harm the module, accelerate ageing and reduce the power output because of material degradation. The number of such defects visible depends on the amount of bad solder joints. The impact of defective solder joints on the power output is determined by the number of defects and their electric properties.

Shunted cells result if the front and back contacts of a solar cell are connected electrically. Then the current flows through the low-resistant contact and does not pass the cell. Therefore, the affected solar cell is essentially short-circuited. Since the absorbed energy is not useable, the cell heats up. These shunted cells have a slightly increased temperature, roughly ΔT > 1.5K. In one module several cells can be affected. The influence on the output power is negligible for one shunted cell but for an increasing number of cells the output power can be decreased significantly.

Bypass diodes should prevent modules with defects from damage and excessive power loss. In cases of strong failures, which can reduce the output power drastically and harm or even destroy the module, the bypass diode becomes active. Then, the current flows over the diode and the cells are bypassed. If the bypass diode is stressed too much, it can be damaged too, becoming visible in the IR image.

Quality control benefits

The benefits of IR inspection with unpiloted aerial vehicles for the quality control of PV plants are manifold. Using IR imaging module failures can be differentiated through the visualisation of their typical temperature pattern. It is non-destructive and works without contacting the modules. Thus, the measurements are repeatable. Because they are carried out during normal operating conditions, under solar irradiation, neither energy input for activating the modules externally is necessary, nor are energy and income losses due to service interruptions incurred.

With the drone, optimal measurement parameters are realised. The routing system enables the systematic, fast and reliable examination of a solar park. Short temporal measurement periods can be used efficiently. Outstanding modules are located easily within a solar park taking advantage of the navigation and the two-dimensional IR-imaging. Thus, a 100% check rather than a sample study is possible.

IR imaging with drones is a time-saving inspection method with the potential of giving laypersons an impressive overview of the quality of a solar park as well as experts the data for further analysis and measures. ■

Author

Dr. Claudia Buerhop-Lutz studied material science at the Friedrich-Alexander University of Erlangen-Nürnberg in Germany. Since 2006 she has worked at the Bavarian Center for Applied Energy Research (ZAE Bayern) in Erlangen, Germany, where she is responsible for the outdoor analysis of photovoltaics, pioneering the use of infrared thermography for outdoor analysis of PV modules.

References

[1] Buerhop, C., Jahn, U., Hoyer, U., Lerche, B., and Wittmann, S., "Abschlußbericht der Machbarkeitsstudie zur Überprüfung der Qualität von Photovoltaik-Modulen mittels Infrarot-Aufnahmen", 2007, ZAE Bayern e. V. http://www.zae-bayern.de/das-zae-bayern/publikationen/buecher-manuskripte.html.

[2] Buerhop, C., Schlegel, D., Niess, M., Vodermayer, C., Weißmann, R., and Brabec, C.J., "Reliability of IR-imaging of PV plants under operating conditions", Solar Energy Materials and Solar Cells, 2012. 107(0): p. 154-164, http://www.sciencedirect.com/science/article/pii/S0927024812003741

[3] Buerhop, C., Scheuerpflug, H., and Weißmann, R., "The Role of Infrared Emissivity of Glass on IR imaging of PV Plants", in 26th PVSEC. 2011: Hamburg, Germany. p. 3413-3416.

[4] Buerhop, C. and Scheuerpflug, H., "Field inspection of PV-modules using aerial, drone-mounted thermography", in 29th PVSEC. 2014: Amsterdem, The Netherlands. p. 2975-2979.

[5] Buerhop, C. and Scheuerpflug, H., "Inspecting PV plants using aerial, drone-mounted infrared thermography system", in Third Southern African Solar Energy Conference *SASEC*. 2015: Kruger National Park, South Africa.