Light Unmanned Aerial Vehicles (UAVs) for Cooperative Inspection of PV Plants

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Abstract—After a fast photovoltaic (PV) expansion in the past decade supported by many governments in Europe, in this postincentive era, one of the most significant open issues in the PV sector is to find appropriate inspection methods to evaluate real PV plant performance and failures. In this context, PV modules are surely the key components affecting the overall system performance; therefore, there is a main concern about the occurrence of any kind of failure in PV modules. This paper aims to propose a novel concept for monitoring PV plants by using light unmanned aerial vehicles (UAVs) or systems (UASs) during their operation and maintenance. The main objectives of this study are to explore and evaluate the use of different UAV technologies and to propose a reliable, cost-effective, and time-saving method for the inspection of PV plants. In this research, different UAVs were employed to inspect a PV array field. For this purpose, some thermal imaging cameras and a visual camera were chosen as monitoring tools to suitably scan PV modules. The first results show that the procedure of utilizing UAV was effective in the detection of different failures of PV modules. Moreover, such a process was much faster and cost effective than traditional methods.

Index Terms—Photovoltaic (PV) module, PV system control and monitoring, thermal imaging camera, unmanned aerial vehicle (UAV).

I. Introduction

NOWADAYS, renewable energy is known as an alternative and sustainable energy that can help to conserve fossil fuels for future generations. In fact, renewable energy can be created by natural sources, which means that they are abundant and there is no need to be concerned about their depletion and replacement in the future. Developed countries have been widely investing in sustainable and alternative energy to make the world full of green and clean energy. Scientists have predicted that mankind will need an additional 30 TW of energy by the mid-21st century, and only the support of photovoltaic (PV) energy promises to meet this challenging target, since solar energy is free and always widely available, even on cloudy days [1].

Solar energy has many advantages: It is environmentally friendly, has decentralized installation, has a long life, requires low maintenance and is noise-free, clean, and light weight.

Nevertheless, PV energy is limited due to intermittent power, low-energy density, high startup costs, location, and climate condition dependence. However, a deep investigation concerning the degradation effects in PV modules is quite essential to guarantee the performance and reliability of PV systems [2], [3].

The past decade has seen the rapid development of civil unmanned aerial systems (UASs), also known as remotely piloted aircrafts, to cooperate in monitoring applications such as power transmission line inspection, disaster relief, precision farming, gas and oil pipeline monitoring, weather reconnaissance, pollution and environmental monitoring, port and off shoreline security, arctic ice monitoring, and land mine and forest fire detection. Nevertheless, initially, most of the applications of unmanned aerial vehicles (UAVs) were for military purposes [4].

The aim of this paper is to propose and give a preliminary validation of a cost-effective and rapid monitoring method suitable to inspect PV field array defects by using UAVs. In this light, a family of light UAVs has been employed and tested to detect the common visible, and not visible, failures in solar panels also utilizing a thermal camera. PV array field monitoring by UAVs has many advantages, such as low cost and large area coverage, precise imagery, fast detection, high flexibility, unmanned and easy operations, the ability to operate in harsh environments, and sensible time reduction, which means that a large PV plant can be inspected in a short time to find defects and react with early solutions [5].

This paper is structured in six sections. Section I introduces our proposal about a novel inspection method for PV module monitoring. Section II discusses about the effects of the environmental conditions on the performance of PV modules and the classification of common defects and failure modes. Section III presents traditional inspection methods for PV panel monitoring. Section IV strives to show various aspects of the proposed UAV applications and great potential in the inspection of PV modules. Finally, in Sections V and VI, the experimental investigation is described with geo-referenced captured images taken by the UAVs, drawing some conclusions related to the proposed method.

II. Common Defects and Failure Modes in PV Modules

Weather conditions surely affect the PV system performance over time, and various defects can occur in the PV modules even in the short term. Solar irradiation and temperature are the main stress factors that can degrade PV modules. Other weather and environmental conditions—such as, for example, wind, salt,

hail, snow, dust, and many corrosive gases—can indirectly have an effect in increasing and decreasing these two main factors.

The best performance of PV modules can be obtained at a standard temperature (25 °C). Hence, any excess in PV module temperature can affect the standard performance [6]. Temperature stress can accelerate the chemical degradation of the panels [5], [7]. Therefore, it can lead to creating defects in the PV modules, and eventually the performance of PV systems may decline in a short time [8]. Based on the aforementioned environmental conditions, even in the thin-film solar cell recent development, many defects can appear in PV modules. Therefore, it is useful to first classify the PV module defects to find out an early solution.

According to the investigations, most visible failures appear in the PV modules due to the polymers' defects such as delamination, bubbles, cracking, or yellowing [9]. Discoloration, oxidation, and corrosion of connectors' defects can also affect the PV modules' electrical characteristics, but their inspection is quite easy by visual observation. Other phenomena such as *snail trails*, shading, hot spots, microcracks, and cell breakage defects can have the highest influences on the performance of the PV modules as discussed later on. These kinds of failures can, in fact, be better detected using also thermal and infrared cameras.

Yellowing and browning can appear in PV modules due to dry heat (e.g., due to desert climate), high UV radiations, and humidity. Moreover, it can occur because of insufficient adhesion between cells and glass material. However, this creates an obstacle between solar cells and sunlight, which leads to compromising PV modules' voltage output.

The corrosion will occur in PV modules' glass and metal because of the combination of gasses and humidity. Snow and wind can produce a higher static load; hence, they can break PV modules' glass due to the mechanical load for dynamic and static reasons. In the desert climate for example, sand, wind, and dust significantly decrease the performance of PV modules [5], [10]. Furthermore, glass breakage can be caused by bumps.

Adherence loss among PV modules' layers usually causes delamination. Typically, it happens between cells and front glass or between polymeric encapsulant and cells. This defect can increase reflection, and the water can then penetrate into the module itself. Nevertheless, a delamination defect in the borders of the PV module causes both electrical and installation risks and likely transmittance losses [11].

On the other hand, bubble defect is more similar to delamination, while adherence losses occur only in some areas of PV modules due to chemical reactions. Generally, bubble defects occur in the backside and not in the front side of the PV module. In fact, a bulk in the back cover or polymeric encapsulant prevents the dissipation of heat from the solar cells [12].

In recent years, manufacturers have produced thin solar cells, and the thicknesses of absorber layers have reached values around 100 μm or even less. Moreover, it should be mentioned that the area of the solar cells has been increased to 210 mm^2 [13]. These changes can make the solar cells more sensitive and fragile during shipment and installation. Microcrack defects can appear as some different color lines on both sides of the PV
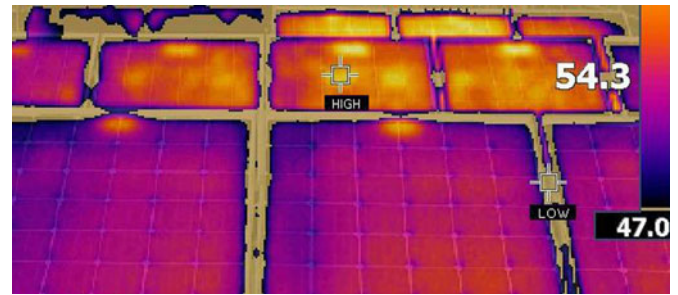

Fig. 1.   Thermal image of different PV modules: healthy ones (1st row), affected by hot-spot phenomena (2nd row) and those with a complete overheated surface (3rd row).
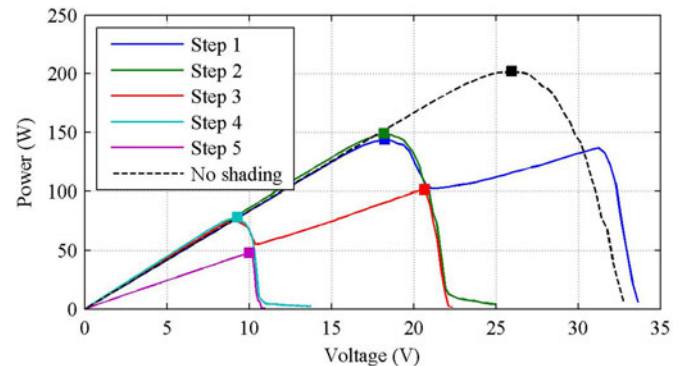

Fig. 2.   *P–V* characteristic of multiple diagonal steps shadowing effects on the same module (from [15]).

module, and they can be detected only using special devices such as thermal and infrared cameras or by the optical method. This failure causes a decline in solar cell consistency and it could also lead to an increase in the carrier recombination path. In addition, the cracks' effect compromises energy conversion, and it seriously affects the current generation due to isolation properties.

Antireflective coating is used in PV modules so that maximum sunlight can reach to the modules. The antireflective coating is subjected to solar radiation; hence, its color may change. In this regard, the characteristics of antireflective coating changes the sun reaching mechanism to the solar cell which is reduced. However, the main reason of this failure is oxidation and it can lead to adherence loss between the glass and the solar cell; thus, the voltage can accelerate oxidation on the antireflective coating.

One of most significant defects is the hot-spot failure, which is defined as an area on the PV module with higher temperature, as shown in Fig. 1. The hot spot can damage the solar cell and other components of the PV system. Typically, the reasons of the hot-spot defect include mismatch of solar cells, partial shadowing, or any failure in the interconnection between the solar cells [14].

When the solar cells are subjected to shadowing, they may operate reversely as loads, as shown in Fig. 2. Therefore, in this case, the solar cells consume energy instead of generating it [15]. In addition, sufficient protection can prevent hot spots
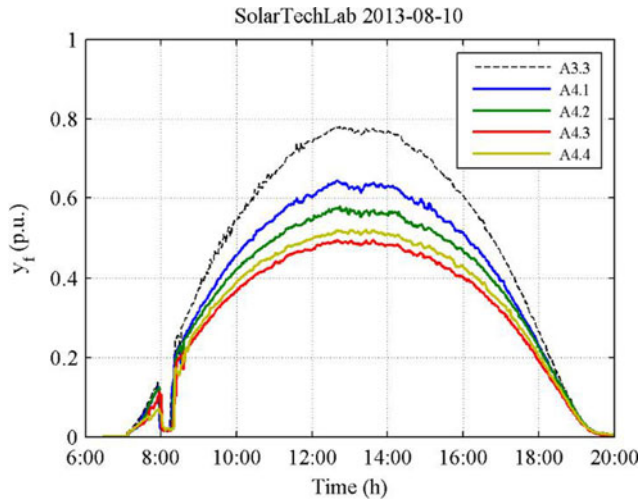
Fig. 3. PV modules performance evaluation: A4.1 to A4.4 modules are affected by snail trails; A3.3 is a healthy module.

from appearing when partial shadowing is present on the PV modules. Bypass diodes can also be used in the connections to avoid overheating and hot spots. They limit the reverse voltage and thereby temperature reduction in the PV modules.

Sometimes the hot spot can occur due to the shunt resistance. This shunt resistance can appear because of a shortcut or an error in interconnections in the solar cell, which may happen during the manufacturing process. Once a solar cell generates lower currents than other solar cells, a mismatch occurs among the modules. Hot spots can easily be detected by thermal cameras.

Finally, the PV modules can be subjected to a defect known as the *snail trail* phenomenon. The snail trail impact emerges on the PV modules' edge because of both environmental conditions and manufacturing process. They appear as dark and small lines or solar cell discoloration on the PV modules. Furthermore, snail trails can occur if the PV cell is produced as thin thickness, and in this case, it cannot compromise efficiency too much [16].

Experimental tests show that the performance of PV modules affected by snail trails decreases by more than 20% if compared with a healthy module as shown in Fig. 3, where the instantaneous final yield y_f is reported

$$y_f = \frac{P(t)}{P_R} \tag{1}$$

where $P(t)$ is the instantaneous power, and P_R is the rated power.

III. COMMON DETECTION METHODS

Generally, the failures in PV systems can be classified into two categories: those related to the overall PV system and those concerning single PV modules. The choice of suitable inspection methods is critical to detect any fault in the PV modules in particular. Moreover, early failure detection plays a significant role in maintaining the performance of PV modules over time. In fact, it can prevent extending failures to other nondefective modules. Hence, the rapid recognition of module defects can

keep the PV system performances high. Nevertheless, most of the detection methods either for PV systems or for PV modules are quite expensive; in fact, the use of many sensors or the employment of inspectors for monitoring is generally not cost-efficient and acceptable for large PV fields. Regardless of economical aspects, the data collection and processing procedure usually takes time, and its complexity increases with the PV system size.

Thus, in the future, we can expect a growing attention to investigation on reliable and cost-effective methods for PV module monitoring. Nowadays, there are different inspection methods for PV modules, some of which are presented below.

A. Visual Detection

Typically, inspection by sight is the first method of evaluation of failures of PV modules. In this method, cracks, yellowing, misalignment, delaminations, bubbles, snail trails, and brunt cells can often be observed. After this step, the experts can make a decision about further inspection and actions to be taken.

B. Photovoltaic Parameters' Measurement

Defects in PV modules can be found by measuring the output under standard test conditions (STC—temperature: 25 °C, radiation: 1000 W/m^2, AM 1.5). The measurement test can be performed either outdoor, under sunlight radiation, or indoor, using solar simulators. Although the environmental condition can be better controlled indoor, the measurement is less significant in terms of actual conditions, since temperature will usually be above STC [17], [18].

C. Using Infrared and Thermal Cameras

Thermal and infrared cameras can be used to detect high-temperature regions on the PV module surface. Therefore, a thermographic technique can be employed to detect defects in PV modules, such as for example hot spots by using high-resolution thermal or infrared cameras in the PV array field [19], [20]. Of course, for correct identification of the failure, modules showing anomalies must also be inspected visually and tested electrically. In the following, a *cooperative monitoring* approach using photo and thermal cameras is presented, in order to combine both visual inspection and thermal analysis in an automated procedure for large PV field monitoring.

IV. UNMANNED AERIAL VEHICLE

Recent advances in the aerial industry technology, sensors, technical cameras, and control systems have made it possible to employ UAVs in inspecting and monitoring large areas [21]. Therefore, the identification of suitable UAV characteristics requires specific investigations and studies for possible and appropriate application in various fields.

Currently, UAVs are used basically for monitoring power transmission line [22], disaster relief, wildlife, gas and oil pipelines, weather reconnaissance, pollution and environmental monitoring, port and off-shore line security, arctic ice, land mine, forest fire detection, and even in civil applications.

However, the advantages of UAVs in comparison with manned aircraft monitoring are their intrinsic safety (e.g., no risk for the pilot in dangerous remote missions), low weight, and cost-effectiveness; moreover, large amounts of data can be collected by various sensors and cameras, and several other monitoring applications can be implemented [23], [24]. Since UAVs can carry various detectors, sensors, and cameras to inspect defects on the monitored systems, the main objective of this study is to determine the possibility of applying UAVs to monitor visible and invisible defects on the PV modules in a small or huge field area by photo- and thermal-camera devices [25].

In fact, there are many advantages of using UAVs for this cooperative monitoring of PV fields: Since the PV modules' lifetime depends on proper monitoring and inspection, precise information of module degradation is critical in PV systems to reduce the financial risk.

A. System Description

With respect to the UAV regulation achievements, in order to properly operate with UAS technology in this sector, it is important to emphasize that the peculiarities of the considered activities request the grant of proper Permit to Fly to be able to operate in real field operations. For this reason, the platforms considered here are the ones manufactured by Nimbus, an Italian SME active in the UAV design and production, since in the past few years, it has already received multiple Permits to Fly from the Italian Civil Aviation Certification Authority. In fact, the novel-patented UAV platforms represent, in this light, the first case in Italy in the category of the so-called *light UAV* and promise to open up new market opportunities in PV plant performance monitoring. Moreover, according to the certification prescriptions, the construction characteristics of these technologies make them harmless in terms of materials, geometry, and kinetic energy of impact.

In this investigation, two different UASs have been employed to inspect the PV modules' conditions: Nimbus EosXi UAV (see Fig. 4) for a first analysis and Nimbus PLP6 (see Fig. 5) for an in-depth analysis and detailed information about the plant. Both of them can be classified in the *light UAS* segment. In fact, the use of UAVs can reduce the monitoring cost much more than the other methods. Inspection by this method will be fast and it can save monitoring time. Therefore, this method can be appropriate for small and large PV array fields to find out PV modules' degradation and other failures. However, the early recognition of defects can prevent extending PV modules' degradation and wasting energy. The key aspects of UAV application in PV module monitoring include flexibility, fast detection of a large PV array field, and cost-effectiveness.

The characteristics and main features of Nimbus EosXi UAV and Nimbus PLP6 are compared in Table I, in terms of the cruise speed, endurance, and main operational constraints.

However, it should be mentioned that UAVs cannot operate alone in PV module monitoring; they require *ad hoc* sensors onboard to be used as inspection tools. Therefore, it is suggested to use appropriate cameras to detect different PV module failures

Fig. 4. Nimbus EosXi UAV platform.

Fig. 5. Nimbus PLP6 during PV monitoring operation.

TABLE I
UAV FEATURES

Items	NIMBUS EOSXI	NIMBUS PLP6
Cruise Speed	13–17 kts	0–15 kts
Operational range	5 Km	0.5 Km
Max Altitude	500 ft	150–200 ft
Flight Endurance	<3 h	0.25–0.5 h
Weight	64 Kg	3.3 Kg
Height	3 m	0.3 m
Length	5 m	(Ø) 0.8 m
Wing span	6 m	NA
Propulsion	Gasoline engine	Electric Power

in production plants. Another useful feature both for thermal imaging and for visual captures is the tagging of images with GPS data. This helps to localize faulty modules easily in large areas.
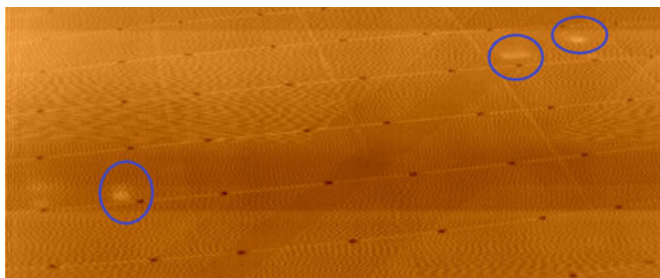
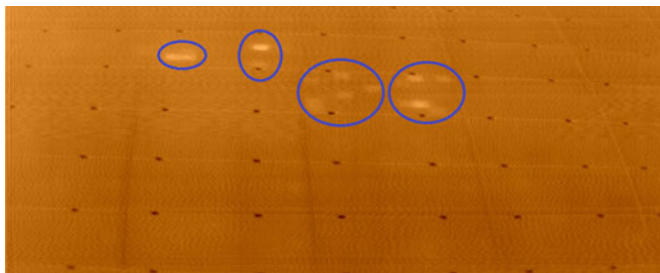Fig. 6.   Different hot areas captured by a thermal camera.

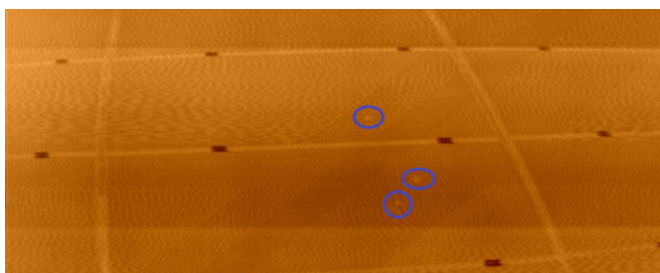Fig. 7.   Sample "patchwork pattern" detected in the monitored plant.

Fig. 8.   Example of single hot spots in PV modules.

Fig. 9.   Picture captured by a Nikon1-v1 camera with inlet detail of a particular shock-defect.

V. ANALYSIS AND RESULTS

In this paper, different kinds of sensors have been used in a first trial campaign to detect PV module failures, namely a thermal camera (MicroCAM 640 by Thermoteknix Systems Ltd.) and an HD photocamera (Nikon1-v1), which were mounted on the Nimbus EosXi and Nimbus PLP6 platforms to capture precise pictures and videos of PV panel defects, both in the visible and infrared ranges. Thermal imaging cameras show themselves to be reliable and fast tools for PV module evaluation. Using thermal cameras in PV module inspection has more advantages than using other monitoring devices. In fact, thermal cameras can be used to scan PV modules during their normal operation with no need of system shutdown. Moreover, thermal cameras on UAVs can scan a large PV array field within a short time frame. However, a visual inspection can be used to correct identification of the failure. The use of UAVs allows us to analyze large areas in a short time, where there is both thermal imaging and visual imaging.

The PV system under analysis is in the north of Italy and its power is 200 kW with 810 polycrystalline silicon modules installed on a shelter. The PV plant is connected to the medium-voltage grid by means of 27 inverters and a single transformer.

First of all, a preliminary analysis was made using the bigger Nimbus EosXi UAV platform for an overall view of the plant. Figs. 6–8 have been captured by a MicroCAM 640 thermal camera.

As shown in Fig. 6, some defective points have been detected in different areas of the PV field. Depending on their shape and location, these hot spots and hot areas can highlight different faults. Usually, if an entire module is warmer than usual, as partially shown in Fig. 1 (taken by a Fluke Ti 25 thermal camera), then some interconnection problems can be envisaged. On the other hand, if single cells or strings of cells are showing up as a hot spot or a warmer "patchwork pattern," as shown in Fig. 7, the reason can usually be found either in defective bypass diodes, internal short-circuits, or in a cell mismatch, as well as due to snail trails phenomenon. Sometimes, shadowing and cracks in cells show up as hot spots (see Fig. 8) or polygonal patches in the thermal image. The temperature rise of a cell (or part of it) indicates a defective cell or shadowing.
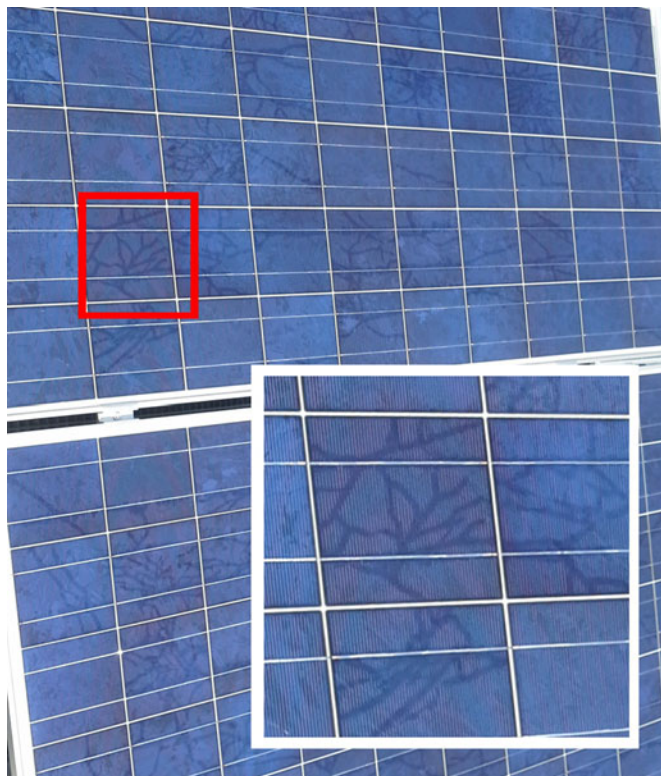
Fig. 10.   Picture captured by a Nikon camera with a module affected by *snail trails*.

However, the distance between the PV array and the UAV in this case did not allow the accurate identification of additional information on the type of problem that was causing the overheating of some cells. The use of the second type of UAV allows us to get closer to the shelter and, consequently, to the modules. In this case, we performed a second analysis using a different sensor, namely a camera in the visible range. Figs. 9 and 10 show some of the results obtained. First picture shows that the defect detected by the thermal analysis is because of breaking of the glass (a mechanical shock). The second picture shows the snail trail phenomenon.

In order to give some estimate of the system cost, according to our preliminary test analysis, using the light UAS described in Section III-A, it is possible to reach an optimal quality-price ratio if three or four small plants are located in the same area, or on the contrary, a unique big plant is inspected in a single day. The described system was targeted for a plant size of around 0.2–1 MW, and some scale effect can be envisaged in terms of logistic costs [26]. However, since the operating cost of such vehicles is very low, when compared with traditional aircrafts or helicopters, the overall system cost can be evaluated by less than 5% of the average annual maintenance cost for the cited plant size, but the potential benefits resulting from the inspection can multiply the value with respect to the initial expenditure for the monitoring system.

VI. Conclusion

Solar modules are the key components in a PV plant system, and they play a fundamental role in the conversion of solar radiation and related energy output performance. Even if the solar energy cost is decreasing due to investment in thin-film technology and other developments, it is still high if compared with other sources in many countries. However, in the near future, the cost and efficiency of PV systems can be optimized by appropriate monitoring and maintenance activities both for small- and large-sized plants. In this context, the monitoring with related technological solutions can have a significant impact to obtain the best performance and solutions from the installed capacity.

In this paper, a novel monitoring concept using light UAVs is proposed to detect different kinds of PV modules' failures. In this regard, the current investigation was conducted to determine the real feasibility of UAS technology in PV array field inspection and evaluate data captured by different sensors mounted onboard. In future work, a methodology to automatically correlate specific sensor data with the defects in PV modules' will be investigated in order to obtain fast and reliable results, which are especially useful for large-sized PV plant activities such as performance analysis, operation and maintenance, and revamping.

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