5BV.2.34 DRONE-BASED ASSESSMENT OF CLEANING EFFECTS ON PV INSTALLATIONS

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ABSTRACT: Monitoring the performance of PV installations can be very labour intensive. The efficiency can significantly be increased by using a thermal imaging drone system. The Photovoltaic Laboratory (PV LAB) at Bern University of Applied Sciences BFH in Burgdorf, Switzerland, hence developed and built its own thermal imaging drone. Drone-based inspection of several Swiss PV installations operated by the PV LAB was conducted and degradation (k\textsubscript{G}) factors were calculated. Comparison of the k\textsubscript{G}-factors evidenced that cleaning the PV module surfaces may increase the energy yield production up to 9%. The drone-based thermal images offered a real advantage for the detection of "hot spots" in PV modules and associated differences in solar cell temperatures, indicating power decreases. However, the quantification of extra energy yields gained from cleaning homogeneous environmental pollution on PV module surfaces needs to be based on measurements.

Keywords: Monitoring, Performance, PV System, Soiling, Thermography

1 INTRODUCTION

Reductions of electrical output performance of PV modules due to environmental contamination (e.g., dust) can be significant [1,2,3]. Irregular and inhomogeneous contamination of PV modules may generate a mismatch of the cells in the substring. The affected cells may heat up and cause thermal stress, which can result in potential defects.

As the inspection of such defects, as well as the overall monitoring of the performance and quality of (especially large) PV installations are time-consuming, unmanned aerial drone vehicles (UAV) can provide an added value. An infrared multicopter drone was hence developed and built at the Photovoltaic Laboratory (PV LAB) at Bern University of Applied Sciences BFH in Burgdorf, Switzerland. Using this drone, several PV installations in Switzerland were inspected with regard to performance quality. The inspected PV installations are part of the monitoring network operated by the PV LAB at BFH since the 1990es. At some specific PV installations, the energy yield output was quantified before and after cleaning the PV module surfaces using installed temperature and irradiation sensors as input data, and by measuring transformers at the PV system.

2 THE IR-MULTICOPTER DRONE

In order to facilitate the maintenance, the drone system was assembled from commercially available components. The measuring device is a thermal imaging camera with a resolution of 382 x 288 pixels. Combined with a 62°x49° wide-angle optics, the viewing angle is 3.14 milliradian, i.e., the smallest measurable spot describes a square with 31.4 mm edge length in 10m distance. A fully radiometric video can be recorded, as reflections are easier recognizable on the video than on thermal images. Reflections are also more distinguishable from the thermal abnormalities in the video. Hence, a live video stream is sent to the pilot to check the image. As the pilot can switch between two video signals for easier flight navigation, rapid overflight of a PV installation is possible. A digital compact camera is mounted for capturing comparison shots. More technical and operational details of the IR-multicopter drone system can be found in [4]. Figure 1 shows the drone ready for take-off.

![Figure 1: The IR-multicopter drone assembled by the Photovoltaic Laboratory (PV LAB) at Bern University of Applied Sciences BFH in Burgdorf, Switzerland (model S1000 octocopter with camera-system). Photo: BFH-TI.](image)

Figure 2 shows a video capture of the IR camera mounted on the drone. At the left hand side in Figure 2, a Siemens M55 module of the PV LABs own PV installation displays a thermal abnormality ("hot spot").

![Figure 2: IR video capture, magnified (left) and close-up of marked module (right). Photo: BFH-TI.](image)

The right hand side in Figure 2 shows a close-up of the same module and reveals that the module has a bad solder joint (at the top of the module) and a short circuit in a cell (bottom right). The deficient module was
removed from the PV installation and measured in the lab. The measurements were compared with data of a new Siemens M55 module (Figure 3) and evidenced a power loss of about 20 percent in the defective module.

It is hence demonstrated that thermography from drone-based inspection of PV installations can identify heated dirt and heated solar cells in PV modules and thus indicate associated power losses.

3 QUANTIFYING CLEANING EFFECTS

As evidenced in Section 2, “hot spots” due to environmental pollution can be determined using thermography. In order to examine whether or not thermography can also be used to isolate effects of homogeneous environmental pollution, field-tests and power relevant measurements (explanations see below) were conducted in summer 2015 at several Swiss PV installations operated by the PV LAB.

3.1 Theory

A theoretically achievable generator yield (temperature corrected radiation yield $Y_T$) was calculated. With the effective yield (array yield $Y_A$), a quotient can be formed. The resulting generator correction factor ($k_G$) provides information (in percentage) about the efficiency of the plant. The following formulas describe the mathematical relationship [5].

$$k_G = \frac{Y_A}{Y_T} = \frac{\text{Array - yield}}{\text{temp.-corrected radiation yield}}$$

$$Y_A = \int_0^\tau \dot{y}_A \cdot dt$$

$$Y_T = \int_0^\tau \dot{y}_T \cdot dt$$

$$y_T = y_A[1 + c_T(T_c - T_0)]$$

$$y_A = \frac{G_d}{1 \text{ kW/m}^2}$$

$$Y_A$$ normalised PV array yield

$Y_T$ daily array yield

$y_n$ standardised irradiation yield (reference yield)

$y_T$ temperature corrected irradiation yield

$G_d$ global irradiance in PV array level

$c_T$ temperature coefficient of MPP power of PV array

$T_c$ cell temperature of the PV array

$T_0$ STC reference temperature (25°C)

$k_G$ array correction factor

**Formula 1:** Calculation of generator correction factor $k_G$.

The input data were taken from PV installations in the network operated by the PV LAB at BFH [6]. The parameters included in the formula are: voltage, current and temperature of the PV modules and solar radiation in PV array level. Temperature is captured with reference cells and irradiation is measured with a Kipp & Zonen CMP 22 pyranometer. DC voltage and DC current are measured with instrument transformers.

3.2 Cleaning effects in long-term records (1994 to 2016)

The PV LAB’s own PV installation (see Figure 2 in Section 2), mounted on the roof of the building, has a capacity of 50 kWp. It has been operated since the 1990s and consists of Siemens M55 modules that are regularly cleaned every four years. Figure 4 illustrates the degeneration of this PV installation due to environmental contamination and the effects of cleaning the PV module surfaces. Calculation of the $k_G$-values using Formula 1 evidences that about 5-8% of the produced electrical power can be regained with regular cleaning.

**Figure 4:** Energy yield increase (1994-2016) due to cleaning. Data are taken from the PV LABs own PV installation at the BFH building in Burgdorf -Tiergarten, Switzerland.

3.3 Cleaning effects at large PV installation

The PV installation on the «Stade de Suisse» football stadium in Bern, Switzerland (Fig. 5) has a total capacity of 1347 kWp. Using the IR-multicopter drone, the entire PV module surface was mapped with thermal images before and after cleaning in summer 2015. It took about 30 minutes to IR-map the 7930 modules to identify defects. 32 thermal anomalies were isolated; these had disappeared after cleaning and were, therefore, attributed to environmental pollution.

**Figure 3:** Characteristics of the defective module (marked Siemens M55 module in Fig. 2).
The thermal abnormalities were identified by comparing the images recorded before and after cleaning. The temperature differences to the “normal” (not affected) cells were between about 3 and 17 Kelvin.

To quantify the effects, the variables listed in Section 3.1 (DC current, DC voltage, module temperature and solar radiation) were measured. The \( k_G \)-values were calculated separately for each unit using Formula 1.

Table 1 lists the \( k_G \)-values and evidences power gains from 4-5 percent for the subsystems with an inclination of 7 degrees that were cleaned after 5 years of operation. The subsystems with an inclination of 20.5 degrees were cleaned after 8 years of operation and display power increases between 6-9 percent.

### Table 1: Energy yield increase at the football stadium “Stade de Suisse” in Bern, Switzerland, after cleaning the PV modules in summer 2015.

<table>
<thead>
<tr>
<th>Subsystems</th>
<th>Inclination</th>
<th>Increase in %</th>
<th>Notes/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>B11</td>
<td>7 degrees</td>
<td>4.0 ( \rightarrow ) -4</td>
<td>2nd cleaning 10/15</td>
</tr>
<tr>
<td>B12</td>
<td>7 degrees</td>
<td>6.4 ( \rightarrow ) -6</td>
<td>2nd cleaning 10/15</td>
</tr>
<tr>
<td>C11</td>
<td>7 degrees</td>
<td>5.7 ( \rightarrow ) -6</td>
<td>2nd cleaning 10/15</td>
</tr>
<tr>
<td>C12</td>
<td>7 degrees</td>
<td>4.3 ( \rightarrow ) -4</td>
<td>2nd cleaning 10/15</td>
</tr>
<tr>
<td>C13</td>
<td>7 degrees</td>
<td>4.3 ( \rightarrow ) -4</td>
<td>2nd cleaning 10/15</td>
</tr>
<tr>
<td>D11</td>
<td>7 degrees</td>
<td>5.6 ( \rightarrow ) -6</td>
<td>2nd cleaning 10/15</td>
</tr>
<tr>
<td>D12</td>
<td>7 degrees</td>
<td>6.4 ( \rightarrow ) -6</td>
<td>2nd cleaning 10/15</td>
</tr>
<tr>
<td>E1 (AA1)</td>
<td>20.5 deg.</td>
<td>6.4 ( \rightarrow ) -6</td>
<td>1st cleaning 07/15</td>
</tr>
<tr>
<td>E2 (AA2)</td>
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</tr>
<tr>
<td>F1 (DA1)</td>
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<td>1st cleaning 07/15</td>
</tr>
<tr>
<td>F2 (DA2)</td>
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<td>7.5 ( \rightarrow ) -8</td>
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<tr>
<td>Total</td>
<td>6.2 ( \rightarrow ) -6</td>
<td></td>
<td></td>
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</table>

### 4 CONCLUSIONS AND FURTHER AVENUES

Drone-based thermography is a highly efficient method for the periodic inspection of PV modules. A thermal imaging drone can detect smallest power losses (see Section 2) in PV modules (“hot spots”). These have a negative impact on the overall performance of a PV installation.

But can a robust relationship be established between drone-based thermal images and the measured and calculated power increase after cleaning the PV module surfaces? Field-measurements (see Section 3) evidenced that cleaning of PV modules resulted in a 4 to 9% performance increase with regard to energy yield. Homogeneous environmental pollution on the PV module surfaces was, however, difficult to discern using drone-based thermal images (unless the pollution appears at the bottom of framed modules). Pollution impacts upon energy yields are thus not easy to determine, and using thermography to quantify the effects from cleaning has not been achieved yet in this study.

Further research and field-tests will be carried out by adopting thermal imaging to the long-term PV installations in the Swiss PV network operated by the PV LAB at BFH Burgdorf, Switzerland. Increasingly, thermal drone imaging is requested by individual home owners as a service for economic inspection of their own PV installations. On the technical side, an integrated GPS waypoint navigation (automatic flight via GPS coordinates) in the flight control module of the copter is planned.
Acknowledgements
We gratefully acknowledge financial support from BFH and the Swiss Commission for Technology and Innovation (CTI). This project is carried out in the frame of the Swiss Centre for Competence in Energy Research on the Future Swiss Electrical Infrastructure (SCCER FURIES) [7] and with Swiss industry partners. Here, we particularly like to acknowledge the BKW group (www.bkw.ch) and Gebäudeversicherung Bern (GVB).

References