Comments to the Chairs:

As requested by the chairman, similarities with previous publications have been removed.

We did not strikethrough the text which has been removed from the manuscript so that it can be seen that the revised version of the paper does not exceed the limit of 6 pages. However, all changes have been marked in red colour.

Changes to the paper as suggested by the reviewers:

Firstly, we would like to thank all reviewers for the help in order to improve the quality of our paper.

While reviewer #2 and reviewer #3 proposed suggestions for minor revisions, reviewer #4 recommended major revisions to our paper. Based on these suggestions, we made the following changes to our paper, summarised as follows:

- Reviewer #2: As suggested by the reviewer, we provide additional data to further and better describe the circumstances of characterising PV panels under harsh outdoor environmental conditions. More precisely, we added a new subsection entitled “Temperature Gradients”. In this new subsection, we analyse in more detail the temperature variations within the same PV panel during characterisation under both, common and harsh outdoor environmental conditions. We are certain that this additional data helps to better understand and clarify the impact of temperatures below zero degree Celsius on IRT imaging techniques.
- Reviewer #3: As recommended by the reviewer, we added more test data. We also extended the discussion on the impacts of harsh outdoor environmental conditions.
- Reviewer #4: As requested by the reviewer, we revised the description of the nature of the problem and why it is challenging to characterise PV panel with the help of IRT imaging techniques under outdoor environmental conditions. We now emphasise more the potential influences of changes in ambient conditions on the correct detection of defects in PV panels. We also revised the description of our method and the meaning of the term “synchronous”. The added subsection “Temperature Gradients” should help to better understand the temperature values shown in Tables I and II and how temperature differences are analysed. We improved the structure of the paper in order to clarify all presented information and hope that, in this way, addressed all the shortcomings mentioned by the reviewer.

In summary, during the past weeks, we made the requested and suggested changes to our paper. In particular, we reduced greatly any similarities with our previous publications and included additional data to describe the importance of our work.

Again, we wish to thank all the reviewers and the chairs for their comments on our work. We are certain that their comments have helped to improve the quality of our paper.

Thermography of Photovoltaic Panels and Defect Detection Under Outdoor Environmental Conditions

Christian Schuss*, Kari Remes*, Kimmo Leppänen[†], Bernd Eichberger[‡], and Tapio Fabritius*

*Optoelectronics and Measurement Techniques (OPEM) Research Unit, University of Oulu, Finland;

email: christian.schuss, kari.remes, tapio.fabritius@oulu.fi

[†]Mettler-Toledo GmbH, SBU AutoChem, Switzerland; email: kimmo.leppanen@mt.com

[‡]Institute of Electronic Sensor Systems, Graz University of Technology, Austria; email: bernd.eichberger@tugraz.at

Abstract—This paper investigates the possibility of detecting defects in photovoltaic (PV) cell and panels under harsh outdoor environmental conditions with the help of synchronized thermography (ST). Infrared (IR) images are obtained under changing solar radiation levels, moderate wind speeds and ambient temperatures below zero degree Celsius with the help of a portable IR-camera. We demonstrate that IR-images obtained under harsh environmental conditions provide the same information as IR-images recorded under common environmental conditions. We elaborate the differences in parameters such as measurement time and region-of-interest (ROI) which need to be adjusted when carrying out measurements under harsh conditions. Our technique allows maintenance staff to carry out measurements, both, during summertime and wintertime, on the site of a PV power plant to identify PV panels with potential defects.

Index Terms—defect, indoor environment, infrared, outdoor environment, photovoltaic cell, photovoltaic panel, solar energy, synchronized thermography.

I. INTRODUCTION

World's energy consumption and carbon dioxide emissions are increasing on a continuous basis [1]. In order to enable a sustainable electricity production for humanity and in order to reduce emissions related to electricity production, more renewable energy resources have to be utilised in near future. Here, research indicates that solar energy is one of the most promising alternatives in particular to substitute non-renewable energy sources such as coal, oil, gas and nuclear power (COGN) [2], [3]. It is worth noting that the circumstances for solar energy production are varying around the globe, making it difficult for society to utilise this renewable energy resources to its full potential.

In principle, the possible output power of photovoltaic (PV) cells depends on the available solar radiation level and the temperature of the PV cell. However, over time, PV cells can lose on output performance due to aging effects and other types of defects for example resulting from environmental impacts such as industrial rain or hail. As a consequence, a defect in one of the PV cells of a PV panel can occur resulting in a loss in output power of the entire panel [4]–[7]. Hence, it is crucial to periodically diagnose PV panels within power plants. If a faulty PV panel is present in a power plant, it should be replaced as soon as possible by the maintenance crew [8].

One way to diagnose the performance of a PV panel is to measure the characteristic Current-Voltage (*I-V*) curve. [9]–

[11]. However, the *I-V* curve only reveals the overall performance under one particular solar radiation level and at one given PV cell temperature. In addition, the ambient conditions have to be recorded at the same time when recording the *I-V* curve of a PV panel for carrying out the complete analyses. At the site of a PV power plant, with large arrays of PV panels, the maintenance crew should be able to carry out measurements quickly to verify if a PV panel needs to be replaced.

Infrared thermal (IRT) imaging techniques have been proposed for rapid diagnostics on the site of the PV power plant [12]. Potential optical measurement techniques such as lock-in thermography (LIT), electroluminescence (EL) imaging, photoluminescence (PL) imaging, synchronized thermography (ST), time-resolved thermography (TRT) and other IRT techniques were developed for the characterisation of photovoltaics under indoor environmental conditions [13]–[19]. Recently, research has been conducted to utilise IRT techniques for the detection of defects in PV panels also under outdoor environmental conditions [20]–[22].

PV panels are expected to withstand various types of environmental conditions such as ice balls (*i.e.* hail) and industrial rain by a protection glass which has a thickness of a few millimetres. However, this protection can make it more difficult for IRT imaging techniques to characterise PV panels accurately. Research indicates the clear need for a thermography method which is capable of detecting defects in PV panels not only during manufacturing, in other words under indoor environmental conditions, but also when PV panels are already installed in the field. Hence, it is of great importance to carry out thermography measurements under outdoor environmental conditions.

In contrast to measurements under indoor environmental conditions, the conditions outdoors cannot be regulated. It is worth noting that IR-imaging cannot just be carried out under perfect weather conditions. If weather conditions are changing frequently, the applied IR-imaging technique should be still capable of producing reliable and accurate data on potential defects in PV panels. Hence, in this work, we concentrate on methods to carry out IR-imaging of PV panels under different types of outdoor environmental conditions. Generally speaking, measurements should be possible during the whole year, both, during summertime and wintertime.

However, research pointed out problems with unstable outdoor environmental conditions. For example, Akram *et al.* reported different results for the detection of defects. Some of the defects identified under indoor environmental conditions were not identified under outdoor environmental conditions [20]. Likewise, Teubner *et al.* showed that the measurement results of IR thermography can be affected by weather conditions. Steady-state conditions (*i.e.* a constant solar radiation level) can help to provide consistent results, but are not always available [21].

In this paper, we extend our analyses presented in [23] related to possible ambient temperatures during measurements. More precisely, we focus on harsh outdoor environmental conditions in which ambient temperatures are below zero degree Celsius. First, we concentrate on the temperature scale of IR-images and, thus, the obtained temperature differences. In our analyses, we compare temperature levels in IR-images recorded under common outdoor environmental conditions with the ones recorded under harsh outdoor environmental conditions. Second, we investigate the impact of different sizes in terms of region-of-interest (ROI) on the potential detection of defects in PV panels.

II. EXPERIMENTAL SETUP AND PROCEDURE

A. Sensitivity to Outdoor Environmental Conditions

As environmental conditions cannot be controlled outdoors, it is important to investigate the impacts of changes in the ambient conditions on the accuracy of measurement results. While environmental conditions such as the available solar radiation and the given ambient temperature can vary throughout the day, the conditions for thermography measurements can also vary over the duration of a year. Depending on the geographical region, the circumstances during summertime (*i.e.* common outdoor environmental conditions) can differ quite significantly from the conditions during wintertime (*i.e.* harsh outdoor environmental conditions).

It is worth noting that the usability and accuracy of thermography measurement technologies in the available literature [20], [21], [23] has been tested only under common outdoor environmental conditions, but not during harsh outdoor environmental conditions. Hence, in this work, we aim to verify potential impacts of harsh outdoor environmental conditions on thermography measurement results. For example, when analysing temperature variations in IR-images, we wish to address the research question if the same methods and algorithms can be applied for analysing IR-images obtained under harsh outdoor conditions as under common environmental conditions.

B. Setup under Outdoor Environmental Conditions

Fig. 1 shows the ST measurement setup on the roof of the University of Oulu in the City of Oulu, Finland. Measurements were conducted on the 2nd of April, 2020, when the ambient temperature was -5.0 °C, and the solar radiation level was frequently varying between 80 and 300 W/m² (horizontal level). A thermal image of the ST measurement setup is shown

Fig. 1: ST measurement setup

Fig. 2: Thermal image of the ST measurement setup

in Fig. 2. As seen in Fig. 2, during the daytime, the sun is capable of heating up the asphalt shingle type roof up to about 16 °C. However, the snow and ice located on the left-hand side of the measurement setup has a temperature which is as low as -8 °C.

Under indoor environmental conditions (*i.e.* in the laboratory), the device under test (DUT) is aligned under a fixed distance (d) from the IR-camera. However, when taking measurements outside, for example for the maintenance crew, it can be challenging to position the IR-camera under a constant d from the DUT and, in this way, to maximise the usage of the resolution of the IR-camera. The width of the IR-image has to be at least as large as the width of the PV panel (w). Fig. 3 shows the available data from the back of the PV panel DSP-5P manufactured by the [lux.pro] solar Corporation which was used within experiments. This type of PV panel was also used in previous research [11], [16], [17], [23].

IR-imaging was started after the DUT reached a constant temperature based on the given outdoor environmental condi-

[lux.pro] solar		
Model		DSP-5P
Maximum Power	(Pmax)	5W $\pm$ 3%
Maximum Power Voltage	(Vmp)	9.00V
Maximum Power Current	(Imp)	0.56A
Open Circuit Voltage	(Voc)	11.25V
Short Circuit Current	(Isc)	0.81A
Nominal Operating Cell Temp.	(NOCT)	-45 to 80°C
Maximum System Voltage		DC600V
Maximum Series Fuse		9A
For field connections, use minimum No. 12 AWG copper wires insulated for a minimum 90°C		
Weight		1.15Kgs
Dimension		176*350*17mm
Standard Test Conditions		
AM=1.5	IRRADIANCE=1000W/m ²	Temp.=25°C
CE ISO9001:2008		

Fig. 3: Data provided by the PV manufacturer

tions. As in [16], [17], [23], [24], an external power supply was used to forward bias the DUT and heat up the PV cells within the panel. If there is any defect present in a PV cell, the defect area of that PV cell does not conduct any current and, thus, will not heat up like the rest of the area of that cell. Moreover, the remaining part (*i.e.* the non-defect area) of the PV cell conducts more current and, as a result, will heat up more. With the help of thermography, IR-images can be recorded that contain temperature variations. When analysing these temperature variations, it is possible to locate cold and hot spots within IR-images indicating potential defects in PV cells [16].

III. EXPERIMENTAL RESULTS

A. Harsh Outdoor Environmental Conditions

As mentioned above, the surrounding temperatures of the PV panel can affect the temperature scale of the IR-image of the PV panel. When IR-imaging is carried out under common outdoor environmental conditions, the temperature scale commonly ranges from about 20 °C to about 60 °C [20], [21], [23]. However, as mentioned above, it is important that thermography allows analysing the performance of PV panels not only during summertime, but also during wintertime. Hence, it needs to be investigated how PV panels can be characterised under harsh outdoor environmental conditions with the help of thermography. Under such types of conditions, ambient temperatures and, thus, the minimum value of the temperature scale can be below 0 °C.

It is worth noting that ambient temperatures below zero degree Celsius can also affect the temperature distribution within PV panels. More precisely, the metal frame which is protecting the PV panel can stay close to the freezing temperature even when the PV panel is forward biased and, thus, the PV cells are heating up. Hence, the temperature variations obtained under harsh outdoor environmental conditions can differ from those ones recorded under common outdoor conditions. The goal of this research was to examine the obtained temperature differences and the possibility of detecting potential defects.

Fig. 4: Thermal image of PV panel 1, data set 1

Fig. 5: Thermal image of PV panel 1, data set 2

IR-imaging was carried out on the 2nd of April, 2020, in the City of Oulu, when the ambient temperature was -5.0 °C and the relative humidity was 72%. The wind speed was 0.8 m/s, while gust speeds were 2.4 m/s. The weather itself was partly cloudy. Figs. 4 and 5 show the obtained IR-images from data set 1 and 2, respectively. In Figs. 4 and 5, we can see a significant difference in the range of the temperature scale in comparison to the temperature scale in previous research. Under common outdoor environmental conditions, the difference between the minimum and the maximum temperature in the IR-image was about 40 °C [23]. However, under harsh environmental conditions, the temperature scale of the measurement setup is less than 25 °C.

B. Measurement Results

The PV panel in the experiments consists of a series connection of 18 PV cells, as shown in Fig. 6. The 18 PV cells are divided into two PV strings of 9 PV cells, string 1 and string 2, respectively. In the IR-image analyses, we focus on the area around the connecting wire collecting the available current from the PV cells. As seen in Fig. 6, for each single

TABLE I: PV panel 1, data set 1 (Fig. 4)

PV string 1			PV string 2		
$\bar{T}_{1,l} = 10.4\text{ }^{\circ}\text{C}$	$\bar{T}_{1,r} = 12.4\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_1 = 2.0\text{ }^{\circ}\text{C} \hat{=} 16.1\%$	$\bar{T}_{1,l} = 13.1\text{ }^{\circ}\text{C}$	$\bar{T}_{1,r} = 11.8\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_1 = 1.3\text{ }^{\circ}\text{C} \hat{=} 11.0\%$
$\bar{T}_{2,l} = 11.9\text{ }^{\circ}\text{C}$	$\bar{T}_{2,r} = 14.6\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_2 = 2.7\text{ }^{\circ}\text{C} \hat{=} 18.5\%$	$\bar{T}_{2,l} = 15.1\text{ }^{\circ}\text{C}$	$\bar{T}_{2,r} = 13.5\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_2 = 1.6\text{ }^{\circ}\text{C} \hat{=} 11.9\%$
$\bar{T}_{3,l} = 12.3\text{ }^{\circ}\text{C}$	$\bar{T}_{3,r} = 15.7\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_3 = 3.4\text{ }^{\circ}\text{C} \hat{=} 21.7\%$	$\bar{T}_{3,l} = 16.4\text{ }^{\circ}\text{C}$	$\bar{T}_{3,r} = 14.2\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_3 = 2.2\text{ }^{\circ}\text{C} \hat{=} 15.5\%$
$\bar{T}_{4,l} = 12.2\text{ }^{\circ}\text{C}$	$\bar{T}_{4,r} = 16.5\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_4 = 4.3\text{ }^{\circ}\text{C} \hat{=} 26.1\%$	$\bar{T}_{4,l} = 17.2\text{ }^{\circ}\text{C}$	$\bar{T}_{4,r} = 14.3\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_4 = 2.9\text{ }^{\circ}\text{C} \hat{=} 20.3\%$
$\bar{T}_{5,l} = 11.6\text{ }^{\circ}\text{C}$	$\bar{T}_{5,r} = 17.7\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_5 = 6.1\text{ }^{\circ}\text{C} \hat{=} 34.5\%$	$\bar{T}_{5,l} = 17.4\text{ }^{\circ}\text{C}$	$\bar{T}_{5,r} = 14.7\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_5 = 2.7\text{ }^{\circ}\text{C} \hat{=} 18.4\%$
$\bar{T}_{6,l} = 11.2\text{ }^{\circ}\text{C}$	$\bar{T}_{6,r} = 18.8\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_6 = 7.6\text{ }^{\circ}\text{C} \hat{=} 40.4\%$	$\bar{T}_{6,l} = 17.4\text{ }^{\circ}\text{C}$	$\bar{T}_{6,r} = 14.9\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_6 = 2.5\text{ }^{\circ}\text{C} \hat{=} 16.8\%$
$\bar{T}_{7,l} = 11.5\text{ }^{\circ}\text{C}$	$\bar{T}_{7,r} = 17.9\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_7 = 6.4\text{ }^{\circ}\text{C} \hat{=} 35.8\%$	$\bar{T}_{7,l} = 16.9\text{ }^{\circ}\text{C}$	$\bar{T}_{7,r} = 14.2\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_7 = 2.7\text{ }^{\circ}\text{C} \hat{=} 19.0\%$
$\bar{T}_{8,l} = 11.6\text{ }^{\circ}\text{C}$	$\bar{T}_{8,r} = 16.0\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_8 = 4.4\text{ }^{\circ}\text{C} \hat{=} 27.5\%$	$\bar{T}_{8,l} = 15.7\text{ }^{\circ}\text{C}$	$\bar{T}_{8,r} = 13.5\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_8 = 2.2\text{ }^{\circ}\text{C} \hat{=} 16.3\%$
$\bar{T}_{9,l} = 10.9\text{ }^{\circ}\text{C}$	$\bar{T}_{9,r} = 13.0\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_9 = 2.1\text{ }^{\circ}\text{C} \hat{=} 16.2\%$	$\bar{T}_{9,l} = 13.7\text{ }^{\circ}\text{C}$	$\bar{T}_{9,r} = 11.7\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_9 = 2.0\text{ }^{\circ}\text{C} \hat{=} 17.1\%$

TABLE II: PV panel 1, data set 2 (Fig. 5)

PV string 1			PV string 2		
$\bar{T}_{1,l} = 8.1\text{ }^{\circ}\text{C}$	$\bar{T}_{1,r} = 10.8\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_1 = 2.7\text{ }^{\circ}\text{C} \hat{=} 25.0\%$	$\bar{T}_{1,l} = 11.8\text{ }^{\circ}\text{C}$	$\bar{T}_{1,r} = 9.4\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_1 = 2.4\text{ }^{\circ}\text{C} \hat{=} 25.5\%$
$\bar{T}_{2,l} = 9.8\text{ }^{\circ}\text{C}$	$\bar{T}_{2,r} = 13.1\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_2 = 3.3\text{ }^{\circ}\text{C} \hat{=} 25.2\%$	$\bar{T}_{2,l} = 13.5\text{ }^{\circ}\text{C}$	$\bar{T}_{2,r} = 11.0\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_2 = 2.5\text{ }^{\circ}\text{C} \hat{=} 22.7\%$
$\bar{T}_{3,l} = 10.2\text{ }^{\circ}\text{C}$	$\bar{T}_{3,r} = 14.4\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_3 = 4.2\text{ }^{\circ}\text{C} \hat{=} 29.2\%$	$\bar{T}_{3,l} = 15.1\text{ }^{\circ}\text{C}$	$\bar{T}_{3,r} = 11.8\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_3 = 3.3\text{ }^{\circ}\text{C} \hat{=} 28.0\%$
$\bar{T}_{4,l} = 10.2\text{ }^{\circ}\text{C}$	$\bar{T}_{4,r} = 15.5\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_4 = 5.3\text{ }^{\circ}\text{C} \hat{=} 34.2\%$	$\bar{T}_{4,l} = 15.9\text{ }^{\circ}\text{C}$	$\bar{T}_{4,r} = 11.9\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_4 = 4.0\text{ }^{\circ}\text{C} \hat{=} 33.6\%$
$\bar{T}_{5,l} = 9.7\text{ }^{\circ}\text{C}$	$\bar{T}_{5,r} = 16.8\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_5 = 7.1\text{ }^{\circ}\text{C} \hat{=} 42.3\%$	$\bar{T}_{5,l} = 16.1\text{ }^{\circ}\text{C}$	$\bar{T}_{5,r} = 12.2\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_5 = 3.9\text{ }^{\circ}\text{C} \hat{=} 32.0\%$
$\bar{T}_{6,l} = 9.3\text{ }^{\circ}\text{C}$	$\bar{T}_{6,r} = 18.1\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_6 = 8.8\text{ }^{\circ}\text{C} \hat{=} 48.6\%$	$\bar{T}_{6,l} = 16.3\text{ }^{\circ}\text{C}$	$\bar{T}_{6,r} = 12.5\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_6 = 3.8\text{ }^{\circ}\text{C} \hat{=} 30.4\%$
$\bar{T}_{7,l} = 9.7\text{ }^{\circ}\text{C}$	$\bar{T}_{7,r} = 17.0\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_7 = 7.3\text{ }^{\circ}\text{C} \hat{=} 42.9\%$	$\bar{T}_{7,l} = 15.5\text{ }^{\circ}\text{C}$	$\bar{T}_{7,r} = 11.7\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_7 = 3.8\text{ }^{\circ}\text{C} \hat{=} 32.5\%$
$\bar{T}_{8,l} = 9.9\text{ }^{\circ}\text{C}$	$\bar{T}_{8,r} = 15.0\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_8 = 5.1\text{ }^{\circ}\text{C} \hat{=} 34.0\%$	$\bar{T}_{8,l} = 14.2\text{ }^{\circ}\text{C}$	$\bar{T}_{8,r} = 10.9\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_8 = 3.3\text{ }^{\circ}\text{C} \hat{=} 30.3\%$
$\bar{T}_{9,l} = 8.9\text{ }^{\circ}\text{C}$	$\bar{T}_{9,r} = 11.8\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_9 = 2.9\text{ }^{\circ}\text{C} \hat{=} 24.6\%$	$\bar{T}_{9,l} = 12.0\text{ }^{\circ}\text{C}$	$\bar{T}_{9,r} = 9.1\text{ }^{\circ}\text{C}$	$ \Delta\bar{T}_9 = 2.9\text{ }^{\circ}\text{C} \hat{=} 31.9\%$

Fig. 6: Schematic of the PV panel (*i.e.* DUT) and ROIs

PV cell, there are two ROIs, one on the left-hand side and one on the right-hand side. The mean temperature ($\bar{T}$) was calculated from each ROI.

In [16], with ST, the DUT had to be forward biased for a specific time, before an IR-image was taken. In [17], we demonstrated that the temperature increase occurs on a continuous basis. Hence, instead of a precise time, a minimum amount of time (t_{min}) can be used after the IR-image of the PV panel can be recorded. After t_{min} , the temperature variations are high enough to distinguish defect areas from non-defect areas and, in this way, locate potential defects in a PV panel. Here, the mean temperature in the ROI on the left-hand side ($\bar{T}_l$) is compared with the mean temperature in the ROI on the right-hand side ($\bar{T}_r$). The difference ($\Delta\bar{T}$) between $\bar{T}_l$ and $\bar{T}_r$ is calculated for each PV cell.

Large values for $\Delta\bar{T}$ can serve as an indicator for potential defects. In this work, we investigated the possibility to detect

potential defects in PV panels under harsh outdoor environmental conditions. Thus, the aim of this work to determine suitable threshold values for $\Delta\bar{T}$. A false detection of defects must be avoided. Tables I and II summarise the temperatures differences obtained from the IR-images seen in Figs. 4 and 5. As a result of our experiments under harsh environmental conditions, we found high values for $\Delta\bar{T}$. Hence, for example for $\Delta\bar{T} \geq 10\%$, every PV cell within the PV panel would be considered to contain a defect.

As a result, a different approach is needed for harsh outdoor environmental conditions. One reason for the high values in $\Delta\bar{T}$ lies in the metal frame for the protection of the PV panel. The metal does not increase much in temperature and remains near the ambient temperature. This is also the case after long heating periods. Thus, temperatures are much higher in the centre of the PV panel than at the outside of the PV panel. As a result, a base value for $\Delta\bar{T}$ needs to be identified which is present throughout the PV panel. One possible way for identifying potential defects is a comparison of $\Delta\bar{T}$ between the PV string 1 and 2, as shown in Fig. 7. The largest difference between the PV cells in the same row is obtained in row (6).

In Fig. 7, data from two measurements is shown. In data set 2, IR-imaging was carried out from a closer distance than in set 1. Hence, the size of the ROI in set 2 is larger than in set 1. The ROI is 25 x 25 px in set 1, while the ROI is 33 x 33 px in set 2. However, even though the size of the ROI is different between the two data sets, the progression of the differences between PV string 1 and 2 in both data sets is similar. In [17], under indoor environmental conditions, we located a defect in PV string 1 in row (6). As seen in Fig. 7,

Fig. 7: Temperature differences between the two PV strings

when comparing the differences between PV string 1 and 2, with 23.1% and 18.2% for the two data sets, this defect can be located in the obtained IR-images under harsh environmental conditions as well.

C. Temperature Gradients

As mentioned above, different threshold values ($\Delta\bar{T}$) have to be used for analysing temperature variations in IR-images obtained under harsh outdoor environmental conditions than under common outdoor environmental conditions. Fig. 8 illustrates the temperature gradient obtained under common conditions [23], while Fig. 9 shows the temperature gradient under harsh conditions (data set 2). When comparing Figs. 8 and 9 with each other, it can be seen that the progression of the two temperature gradients is similar, although the temperature scale in the absolute value is significantly different. The number of data points between Figs. 8 and 9 is different, because the IR-image in Fig. 9 was taken from a closer distance than in Fig. 8.

Due to the metal frame on the outside of the PV panel, under harsh environmental conditions, the areas around the metal frame remain much colder than under common environmental conditions. When concentrating on the ROI, as seen in Fig. 9 and Table II, for PV string 1, $\bar{T}_{5,l} = 9.7^\circ\text{C}$ and $\bar{T}_{5,r} = 16.8^\circ\text{C}$, while for PV string 2, $\bar{T}_{5,l} = 16.1^\circ\text{C}$ and $\bar{T}_{5,r} = 12.2^\circ\text{C}$. In Fig. 8, for PV string 1, $\bar{T}_{5,l} = 44.6^\circ\text{C}$ and $\bar{T}_{5,r} = 47.5^\circ\text{C}$, while for PV string 2, $\bar{T}_{5,l} = 44.5^\circ\text{C}$ and $\bar{T}_{5,r} = 42.2^\circ\text{C}$. The temperature in the centre of the PV panel ($\bar{T}_c$) is for Fig. 8 $\bar{T}_c = 45.1^\circ\text{C}$ and $\bar{T}_c = 14.9^\circ\text{C}$ for Fig. 9, respectively.

The gradients highlight that the temperature variations between the corner and the centre of the PV panel are much more significant under harsh outdoor environmental conditions. As a result, the temperature variation in the ROIs of one PV cell are much greater than under common environmental conditions. These circumstances have to be taken into account when analysing the temperature variations in IR-images obtained under harsh outdoor environmental conditions. Otherwise,

Fig. 8: Temperature gradient under common conditions

Fig. 9: Temperature gradient under harsh conditions

false diagnostics could be made from the IR-images recorded by the maintenance crew.

IV. DISCUSSION

We demonstrated that temperature differences in IR-images obtained under harsh outdoor environmental conditions significantly differ from the ones recorded under common outdoor environmental conditions. Temperatures below zero degree Celsius lead to cold temperatures on the outside of the PV panel where the metal frame is located. As a result, the temperature in a healthy PV cell can vary by 10-30% from the centre of the PV panel to the edge of the PV panel. These circumstances must be taken into account when analysing the temperature differences in IR-images in order to locate potential defects inside the PV panel.

Hence, it is advisable to compare the temperature differences of PV strings with each other. As a result, the temperature differences which are affected by the harsh environmental

conditions can be analysed in a better way. At the side of a PV power plant, for the maintenance crew, it can be difficult to obtain IR-images consistently under the same distance from the DUT. Hence, the size of the ROI can vary. In addition, the given ambient conditions, such as frequent changes in the available irradiation can affect the temperature differences obtained in IR-images. However, in our experiments, we showed that potential defects in PV panel can be still identified under changing and harsh outdoor environmental conditions.

V. CONCLUSION

Portable IR-cameras can be used for recording IR-images on the site of a PV power plant. However, doing so results in different distances between the IR-camera and the DUT. As a result, the size of the ROI is affected. In this paper, we demonstrated the possibility for detecting potential defects with different sizes for the ROI. Furthermore, we showed that defects in PV panels are clearly visible in the obtained temperature variations of recorded IR-images below zero degree Celsius. Temperature gradients in IR-images obtained under harsh outdoor environmental conditions differ from those obtained under common outdoor environmental conditions.

Harsh outdoor environmental conditions can affect the temperature differences recorded in IR-images with the help of thermography. The given circumstances must be taken into account so that a false-positive and false-negative detection of defects can be avoided. The cold temperatures for example at the metal frame protecting the PV panel cause larger variations in terms of temperatures within the DUT. Hence, a different criteria or threshold temperature must be found to locate potential defects. We propose to compare temperature differences in the same row of different PV strings with each other in order to get a better understanding about the magnitude of the temperature differences.

ACKNOWLEDGMENT

Prof. Tapio Fabritius is partially supported by Academy of Finland's FIRI funding (grant no. 320017).

REFERENCES

- [1] Today in Energy. EIA projects world energy consumption will increase 56% by 2040. Vol. July. Available <https://www.eia.gov/todayinenergy/detail.cfm?id=122511> [accessed 16 September 2019], 2013.
- [2] D.P. van Vuuren, N. Nakicenovic, K. Riahi, A. Brew-Hammond, D. Kammen, V. Modi, and K. Smith, "An energy vision: The transformation towards sustainability - interconnected challenges and solutions", *Current Opinion in Environmental Sustainability*, vol. 4, issue: 1, 2012, pp. 18-34.
- [3] S. Mekhilef, R. Saidur, and A. Safari, "A review on solar energy use in industries", *Renewable and Sustainable Energy Reviews*, vol. 15, issue: 4, pp. 1777-1790, 2011.
- [4] S. Hamou, S. Zine, and R. Abdellah, "Efficiency of PV module under real working conditions", *Energy Procedia*, vol. 50, pp. 553-558, 2014.
- [5] G.J.-P. Tevi, M.E. Faye, M. Sene, I. Faye, U. Blieske, A. Seidou Maiga, "Solar Photovoltaic Panels Failures Causing Power Losses: A Review", *7th IEEE International Energy and Sustainability Conference (IESC)*, pp. 1-9, 2018.
- [6] D.C. Jordan, T.J. Silverman, J.H. Wohlgemuth, S.R. Kurtz, and K.T. VanSant, "Photovoltaic failure and degradation modes", *Progress in Photovoltaics: Research and Applications*, vol. 25, issue: 4, pp. 318-326, 2017.
- [7] W.J. Jamil, H.A. Rahman, S. Shaari, S. and Z. Salam, "Performance degradation of photovoltaic power system: Review on mitigation methods", *Renewable and Sustainable Energy Reviews*, vol. 67, pp. 876-891, 2017.
- [8] A. Triki-Lahiani, A.B.B. Abdelghani, and I. Slama-Belkhdja, "Fault detection and monitoring systems for photovoltaic installations: A review", *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 2680-2692, 2018.
- [9] M.G. Villalva, J.R. Gazoli, and E.R. Filho, "Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays", *IEEE Transactions on Power Electronics*, vol. 24, issue: 5, pp. 1198-1208, 2009.
- [10] L. Cristaldi, M. Faifer, M. Rossi, and F. Ponci, "A Simple Photovoltaic Panel Model: Characterization Procedure and Evaluation of the Role of Environmental Measurements", *IEEE Transactions on Instrumentation and Measurement*, vol. 61, issue: 10, pp. 2632-2641, 2012.
- [11] C. Schuss, B. Eichberger, and T. Rahkonen, "Measurement and Verification of Photovoltaic (PV) Simulation Models", *Proceedings of the IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, pp. 188-193, 2013.
- [12] J.A. Tsanakas, L. Ha, and C. Buerhop, "Faults and infrared thermographic diagnosis in operating c-Si photovoltaic modules: A review of research and future challenges", *Renewable and sustainable energy reviews*, vol. 62, pp. 695-709, 2016.
- [13] O. Breitenstein, "Nondestructive local analysis of current-voltage characteristics of solar cells by lock-in thermography", *Solar Energy Materials and Solar Cells*, vol. 95, issue: 10, pp. 2933-2936, 2011.
- [14] O. Breitenstein, "Local efficiency analysis of solar cells based on lock-in thermography", *Solar Energy Materials and Solar Cells*, vol. 107, 2012, pp. 381-389.
- [15] Z. Hameiri, A. Mahboubi Soufiani, M.K. Juhl, L. Jiang, F. Huang, Y.-B. Cheng, H. Kampwerth, J.W. Weber, M.A. Green, and T. Trupke, "Photoluminescence and electroluminescence imaging of perovskite solar cells", *Progress in Photovoltaics: Research and Applications*, vol. 23, issue: 12, pp. 1697-1705, 2015.
- [16] C. Schuss, K. Leppnen, K. Remes, J. Saarela, T. Fabritius, B. Eichberger, and T. Rahkonen, "Detecting Defects in Photovoltaic Cells and Panels and Evaluating the Impact on Output Performances", *IEEE Transactions on Instrumentation and Measurement*, vol. 65, no. 5, pp. 1108-1119, 2016.
- [17] C. Schuss, K. Remes, K. Leppnen, J. Saarela, T. Fabritius, B. Eichberger, and T. Rahkonen, "Detecting Defects in Photovoltaic Panels With the Help of Synchronized Thermography", *IEEE Transactions on Instrumentation and Measurement*, vol. 67, no. 5, pp. 1178-1186, 2018.
- [18] K. Remes and T. Fabritius, "Non-contact Characterization of Flexible Hybrid Electronics by Synchronized Thermography", *IEEE Transaction of Instrumentation and Measurement*, vol. 67, no. 5, pp. 2390-2397, 2019.
- [19] K. Remes, A. Irvanp, and T. Fabritius, "Contactless online characterization of large-area conductive thin films by thermography and induction", *Optics Letters*, vol. 44, no.10, pp. 2574-2577, 2019.
- [20] M.W. Akram, G. Li, Y. Jin, X. Chen, C. Zhu, X. Zhao, M. Aleem, and A. Ahmad, "Improved outdoor thermography and processing of infrared images for defect detection in PV modules", *Solar Energy*, vol. 190, pp. 549-560, 2019.
- [21] J. Teubner, C. Buerhop, T. Pickel, J. Hauch, C. Camus, and C.J. Brabec, "Quantitative assessment of the power loss of silicon PV modules by IR thermography and its dependence on datafiltering criteria", *Progress in Photovoltaics: Research and Applications*, vol. 27, issue: 10, pp. 856-868, 2019.
- [22] G. Cipriani, V. Boscaino, V. Di Dio, F. Cardona, G. Zizzo, and S. Di Caro, S., "Application of Thermographic Techniques for the Detection of Failures on Photovoltaic Modules", *IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe)*, pp. 1-5, 2019.
- [23] C. Schuss, K. Remes, K. Leppänen, J. Saarela, T. Fabritius, B. Eichberger, and T. Rahkonen, "Detecting Defects in Photovoltaic Cells and Panels With the Help of Time-Resolved Thermography Under Outdoor Environmental Conditions", *Proceedings of the IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, pp. 1-6, 2020.
- [24] C. Schuss, K. Remes, K. Leppänen, J. Saarela, T. Fabritius, B. Eichberger, and T. Rahkonen, "Estimating the Impact of Defects in Photovoltaic Cells and Panels", *Proceedings of the IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, pp. 121-126, 2016.