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Inequalities in Photovoltaics Modules Reliability: From Packaging to PV Installation Site

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Abstract

In recent years, the determination of the reliability of photovoltaic (PV) modules has been of ubiquitous interest to the PV industry. Therefore, this work reports on the reliability and degradation mechanism of 186 PV modules from packaging to installation stage. The paper shows that no cracks or hotspots affecting the PV modules before the packaging stage, while a minor reduction in the output power was observed at $\pm 0.3\%$. The same PV modules were delivered using standard practice, and no further precautions were considered. Electroluminescent (EL) images of all PV modules were taken at the PV installation site, and it was discovered that 2.2% evolved cracks. Depending on the crack size, the estimated output power losses under standard test conditions varied from 0.53% to 1.43%. Furthermore, the PV modules were thermally inspected six months after being installed. It was found that hotspots developed in all the cracked PV modules, and their temperature increased from 10°C to 20°C. In addition, a potential induced degradation (PID) test was performed on the cracked PV modules and compared with a crack-free module. It was found that PID affected the modules with cracks more than the crack-free module.

Keywords: Solar cells; cracks, electroluminescence, performance analysis, potential induced degradation.

12 **1. Introduction**

13 One of the most valuable attributes of solar cell technology is its high stability, with operational
14 lifetimes of over 30 years. Nevertheless, there are numerous degradation mechanisms, and
15 these collectively reduce the module output power over time. One of the main degradation
16 mechanisms is called potential-induced-degradation (PID) [1, 2]. For many photovoltaic (PV)
17 systems, PID is one of the leading causes of module degradation and is caused by voltage and
18 the interaction of this stress factor with temperature and humidity. Recent studies prove that
19 PID could develop due to pre-existing cracks or hotspots developed in the PV modules during
20 their manufacturing and packaging/shipment procedures. Therefore, according to the current
21 IEC/TS60904-13 [3], PV modules are advised to be inspected using an electroluminescence
22 (EL) imaging setup or at least thermally when they arrive at the PV site before they are
23 mounted/installed.

24 Several stages are passing during the production of PV modules. However, it was demonstrated
25 that cracks could develop during the assembly of solar cells into full-scale PV modules [4]. PV
26 cracks could be as small as micro-level or inactive/breakdown areas in the solar cells (Figure.
27 1) [5]. In contrast, there is no published information regarding the output power losses of the
28 PV modules before and after being transported to the PV installation site.

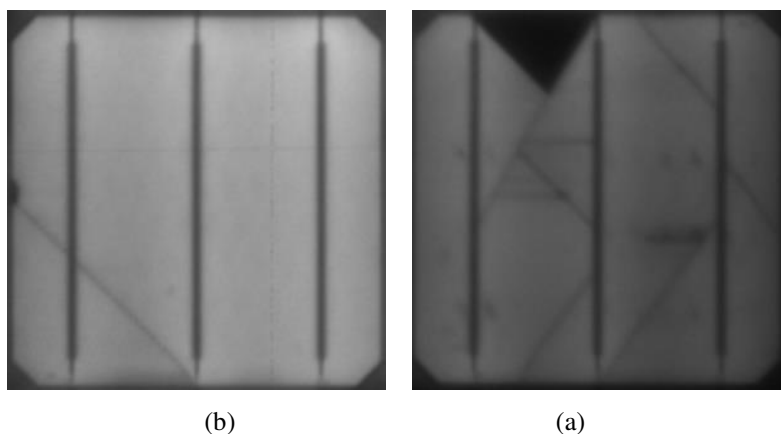


Figure 1. Solar cells affected by cracks or structural defects. (a) Micro-crack, (b) micro-cracks and breakdown area (represented by the black area) [5].

29 In a recent study, [6], a PV module subjected to a reverse bias of 160 V was shown to exhibit
30 severe PID, leading to the formation of hotspots which appeared on the modules. This study
31 showed that the PID resulted in a reduction of the current density and the open-circuit voltage.
32 Improved testing has been the focus of much recent research; for example, in [7], the authors
33 have presented an approach to examining different types of cracks in bifacial passivated emitter
34 rear contact (PERC) solar cells.

35 Other researchers [8, 9] have reported that cracks in solar cells can accelerate the PID effect
36 due to the localized heat caused by the cracks. This work was supported by studies conducted
37 using electroluminescence (EL) imaging before and after PID testing. This affirmed that cracks
38 could lead to hotspots in the solar cells, and as a result, PID is expected, yet there were no
39 discussions on the type/size of cracks and their anticipated impact on PID.

40 To prevent PID or cracks in solar cell level, an optimization for the antireflection coating
41 (ARC) must be determined [10-12]. These recent studies show that the thin silicon dioxide
42 (SiO_2) ARC layer combined with n-type and p-type solar cells can reduce the number of solar
43 cells that experience PID. However, this coating layer cannot prevent cracks and structural
44 defects, resulting in a PID for that solar cell.

45 At a PV module level, comprising 30 or more solar cells connected in strings, every component
46 in the PV must be PID resistant [13, 14], including the encapsulants, absorption layers, and
47 preferably the glass, as small leakage currents can cause ion migration. In addition, there are
48 currently no mitigation techniques developed to overcome cracking in solar cells. In contrast,
49 since 2015, there have been a number of attempts to create suitable devices to mitigate PV
50 hotspots, such as those implemented using power electronics circuits [15-17]. These devices
51 are executed to replace previously commonly used bypass diodes alliance with PV modules.
52 However, they are not yet commercially available or at least experimented with large scale PV
53 systems.

54 Therefore, these mismatched conditions affecting PV modules will likely lead to significant
55 output power losses and levelized degradation rates. Consequently, it is important to investigate
56 whether cracks can develop before the PV modules are installed at the PV site. This
57 interpretation would also give us an unknown upshot on the reality of the PV production and
58 packaging/shipment process overall. Accordingly, this paper demonstrates the results of
59 examining the output power losses, hotspots, cracking modes, and PID of 186 PV modules as
60 soon as they are assembled during the PV manufacturing process and at the PV installation
61 site.

62 This paper is organized as follows: Section 2 comprises the sample preparation, the description
63 of the EL testing setup, and output power loss estimation before the packaging/shipment phase.
64 Section 3 presents the results of the examined PV modules after being arrived at the PV
65 installation site. Section 4 shows the PID testing of the PV modules, whilst the conclusions of
66 the complete study are presented in Section 5.

67 **2. Samples Preparation and Experimental Procedure: Before Shipment/Packaging**

68 **2.1 PV Manufacturing Process**

69 The solar cells production/fabrication line is shown in Figures. 2(a) and 2(b) with over 300
70 cells/day pipeline production capacity. The manufactured solar cells are crystalline silicon (c-
71 Si), and the cells' main electrical and physical parameters are,

- 72 • Short circuit current density J_{sc} is equal to 38.8 mA/cm².
- 73 • Open-circuit voltage V_{oc} is equal to 0.61 V.
- 74 • Peak power at maximum power point is 3.685 W.
- 75 • The solar cells are made of three busbars.
- 76 • Conversion efficiency of 17.4%.

77 A full-scale PV module (Figure. 2(c)) is then assembled using 60 series-connected solar cells,
78 providing a total of 221.1 W output power at standard test conditions (solar irradiance 1000
79 W/m², when the PV module and cells are at standard ambient temperature of temperature 25°C
80 with sea level air mass (AM) of 1.5 (1 sun)).

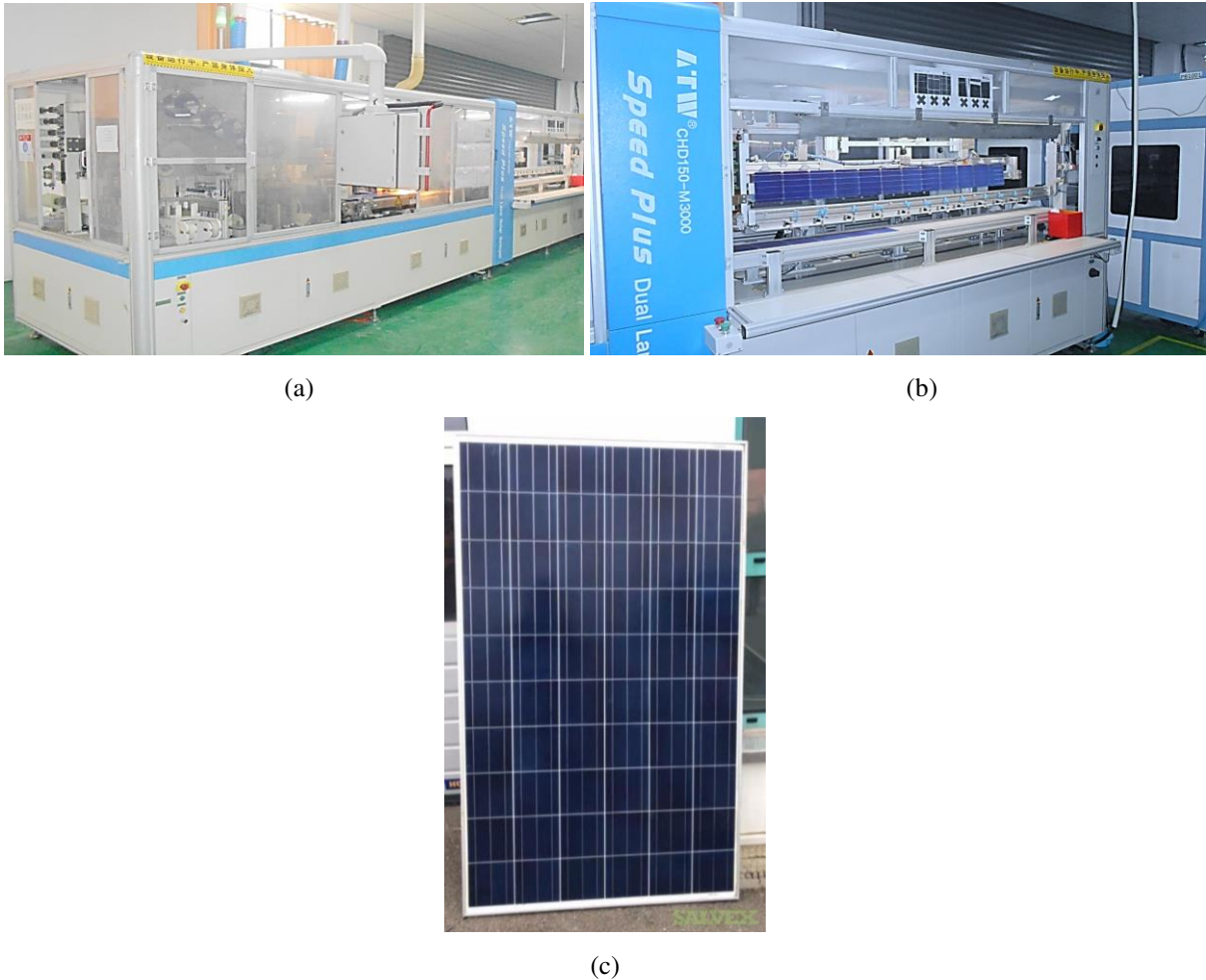


Figure 2. (a) Solar cell manufacturing line, (b) Solar cells ready to be assembled into full-scale PV module, (c) Full-scale PV module after production is completed.

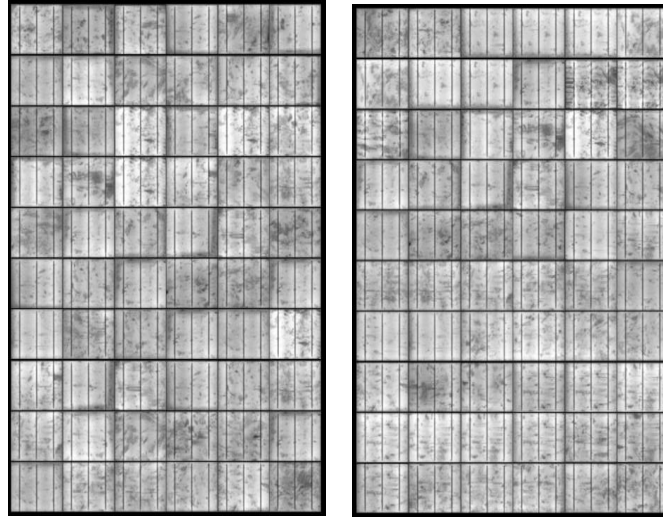
81 2.2 Electroluminescence Imaging

82 Initially, EL imaging setup (Figure. 3(a)) has been used, the EL camera is provided by
 83 BrightSpot Automation. The EL comprises a digital single-lens reflex camera with a resolution
 84 of $6k \times 4k$ pixels, and the filter is removed and calibrated to allow sensitivity to
 85 electroluminescence picture (peak wavelength 1150nm) [18, 19]. The camera lens is 18-55
 86 mm, and a programmable 15 A, 60 V power supply is available to connect with the PV
 87 modules.

88 The EL imaging provides a detailed picture of how healthy the solar cells have been assembled
 89 into full-scale PV modules that, in practice, are ready for the output power testing phase. For
 90 example, Figure. 3(b) presents the EL image of two examined PV modules. There are no
 91 cracking or breakdown regions observable in either PV sample. The dots and points (dark areas
 92 in some solar cells) represent healthy solar cells; these usually develop due to the low radiative
 93 recombination of carriers when completing the EL test.



(a)



(b)

Figure 3. (a) EL imaging setup, (b) Example of EL images for two examined PV modules.

94 **2.3 Output Power Loss Estimation**

95 A PV simulator (SPI-Sun Simulator 4600SLP) was used to measure the PV modules' output
 96 power and control the relevant parameters (sun simulation and temperature). The output power
 97 loss is determined using (1), where P_{ref} is the output measured power of the reference PV
 98 module (221.1 W, theoretical maximum output power), and the P_{sample} is the output measured
 99 power for the tested PV module.

100
$$\text{Output Power Loss (\%)} = \frac{P_{ref} - P_{sample}}{P_{ref}} \times 100 \quad (1)$$

101 An irradiance and temperature cycle must be performed following the IEC61215 standard for
 102 testing PV modules after their production is complete. This step is required to guarantee PV
 103 modules are reliable and their current-voltage (I-V) and power-voltage (P-V) curves are
 104 accurately detailed in the manufacturer datasheet. During this experiment, it is expected to
 105 observe a minimal reduction in the output power. If the output power is reduced by 2% or more,
 106 the PV module fails the test and is recycled.

107 The testing procedure has the below Sun and temperature cycle, the temperature is measured
 108 in Celsius and 1 Sun is equivalent to 1000 W/m²,

- 109 1) Sun cycle 1: 0.1, 0.5, 1.
 110 2) Sun cycle 2: 0.1, 0.5, 1.
 111 3) Temperature cycle 1: 30, 5, 50
 112 4) Temperature cycle 2: 30, 5, 50

113 This procedure has been performed on a pack of 186 PV modules. The output of the Sun and
 114 temperature cycles against output power losses are presented in Figure. 4. According to the
 115 Sun cycles (Figure. 4(a)), the output power loss slightly decreases as the sun level increase.
 116 The maximum output power loss is 0.27% for a 0.5 Sun level. In contrast, there are nearly
 117 identical output power losses during the temperature cycles (Figure. 4(b)). The maximum
 118 output power loss is 0.23% at 50°C.

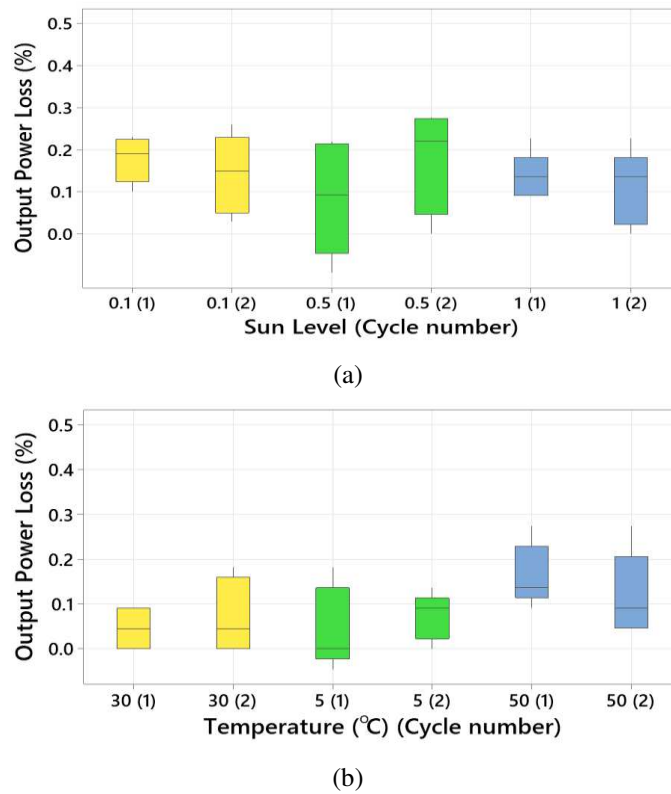


Figure 4. Performance of the PV modules before packaging/shipment. (a) Output power loss at varying Sun levels, (b) Output power loss at varying temperatures.

119 These results confirm minimum power losses in the PV modules, and therefore, at STC
 120 conditions the new reported maximum output power is 219.34 ± 0.66 W. In addition, in Figure.
 121 5, illustrates the averaged I-V and P-V curves for all PV samples.

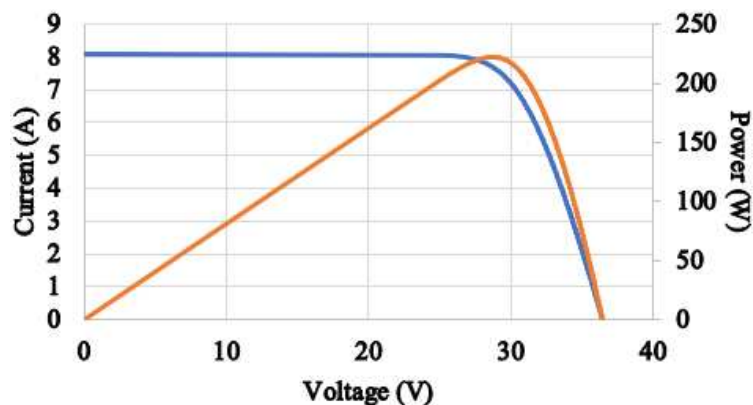


Figure 5. I-V and P-V curves of the manufactured PV modules are taken after performing the Sun and temperature cycles under STC conditions.

122 Before discussing the shipping/packaging process, there are several outcomes from these
123 conduct tests to be highlighted:

- 124 1) After completing solar cells manufacturing and PV-scale assembling, no cracks or
125 breakdowns were observed for all PV module samples.
- 126 2) The output power is slightly adjusted (from 220 into 219.34 ± 0.66 W) after
127 completing the Sun and temperature cycles testing procedure.
- 128 3) There was no overheating or what is known by hotspots detected for all the
129 considered PV modules.

130 3. Experimental Procedure: After Shipment/Packaging Process is Completed

132 3.1 Shipment/Packaging Procedure

133 The PV modules were packed and transported to the installation site in six pallets, and every
134 pallet contained 31 PV modules (Figure. 6(a)). Therefore, 186 PV modules with a maximum
135 PV site capacity of 40.92 kW. This process was managed with careful consideration using a
136 courier delivery (Figure. 6(b)). The site is located 10 miles away from the actual PV
137 manufacturer (Changsha District, China). The complete PV setup after being installed is shown
138 in Figure 6(c).



(a)

(b)



(c)

Figure 6. (a) Pallet of PV modules, this pallet contains 31 PV modules, (b) Forklift handling two pallets simultaneously; this picture was taken during the transport phase of the PV modules from the PV manufacturer to the installation site, (c) PV site after the models were installed.

139 **3.2 Field Electroluminescence imaging – Cracking modes**

140 After receiving the PV modules at the installation site, another EL test was performed following
141 the IEC/TS60904-13 [3]. Four PV modules have been affected by different cracking modes
142 (2.2% of the total PV modules) appeared after transportation. After being installed, the
143 complete PV setup is shown in Figure 6(c).

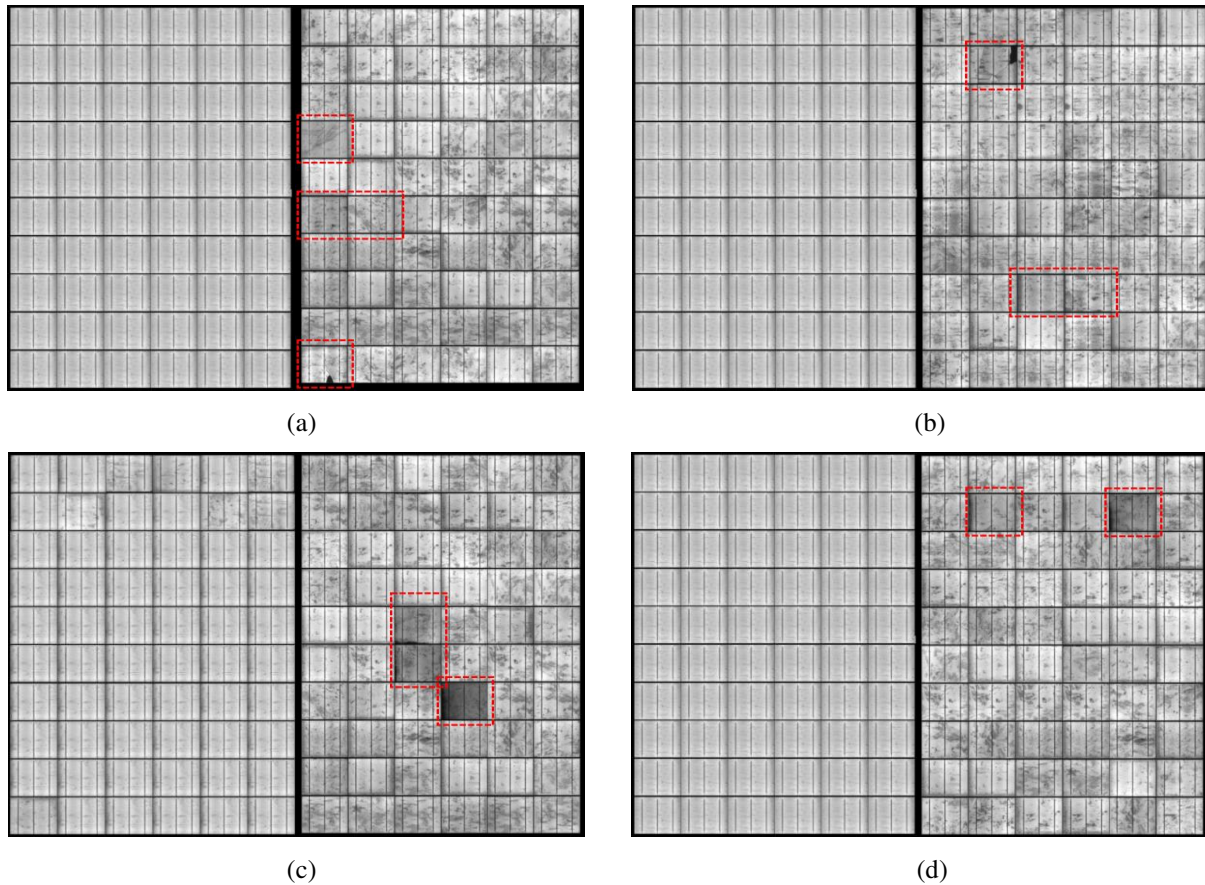


Figure 7. EL images before and after shipment for the cracked PV modules. (a) PV module #1, (b) PV module #2, (c) PV module #3, (d) PV module #4.

144 Three solar cells in the middle of the first PV module have micro-cracks (Figure. 7(a)). In
145 addition, the EL image shows a breakdown area on the bottom edge cell. The same observation
146 is seen in PV module #2 (Figure. 7(b)). It is not usual to observe micro-cracks in modules, as
147 packing/unpacking PV modules can usually result in minor defects. However, the breakdown
148 regions representing a complete in-active area often happen after PID. The modules are new to
149 the site and have not been exposed to environmental conditions. Therefore, it is unlikely that
150 these defects in the cells are due to PID or prior testing. Thus, the valid reasons that these
151 breakdown regions are transpired in the modules during the transportation phase.

152 PV modules #3 and #4 have partially shaded solar cells but with no observed micro-cracks or
153 breakdown regions. From previous research [20-22], it is understood that these cells can be
154 inactive after PID affects the PV modules. In addition, these cells are also most likely to
155 develop hotspots. This will be discussed further in the next section.

156 To investigate the additional power losses caused by the cracks, the PV modules were tested
 157 using the SPI-Sun solar simulator under STC conditions; the results are shown in Figure. 8.
 158 The modules are dismantled from the PV array and tested with a sun simulator. A professional
 159 engineer has carefully handled this testing stage. There is no alternative procedure to test the
 160 modules under STC conditions other than following this strategy. These tests might have
 161 created a new cracked, but, evidenced from the EL images in Figure 7, the cracks already
 162 existed, and the power losses are also predictable.

163 The output power losses range from 0.53% to 1.43%. The output power loss is significantly
 164 more than the output power loss boundary taken before shipment/packaging (highest at 0.27%
 165 in Figure. 4). This suggests that a permanent reduction in the output power of these PV modules
 166 is warranted, and the PV modules reliability has been obstructed.

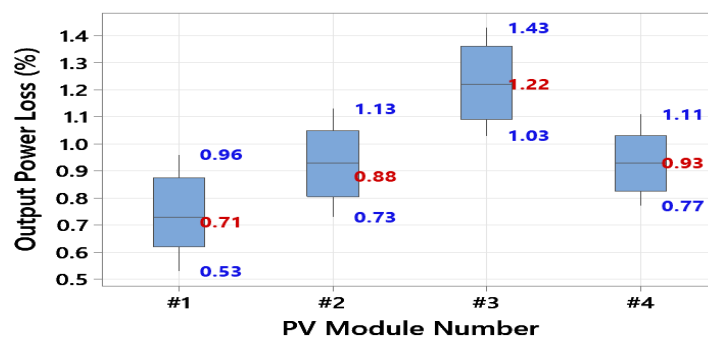


Figure 8. The output power loss of the PV modules (#1 - #4) under STC conditions.

167 3.3 PV Hotspots development

168 For PV hotspots to develop, the good practice is to inspect the PV modules after a couple of
 169 months of field operation. For example, Figure. 9 shows the thermal image of the PV module
 170 #1 taken at 693 W/m² and a PV cell temperature of 21.7°C. It is clear that there is no alleviation
 171 of the cell's temperature (no hotspots).

172 following these results, the PV modules were thermally examined after 6-months of field
 173 operations (Figure. 10) taken under solar irradiance of 772 W/m² and cell temperature of
 174 23.3°C. The thermal images were captured using FLIR E75 (thermal sensitivity ±0.1°C) and
 175 calibrated using FLIR software.

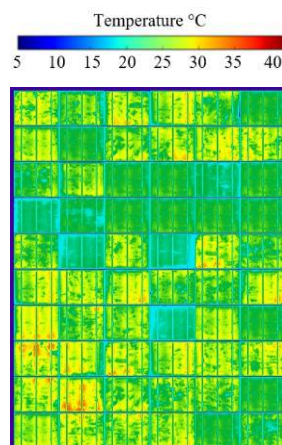


Figure 9. Thermal image of PV module #1 before field operation (no presence of hotspots).

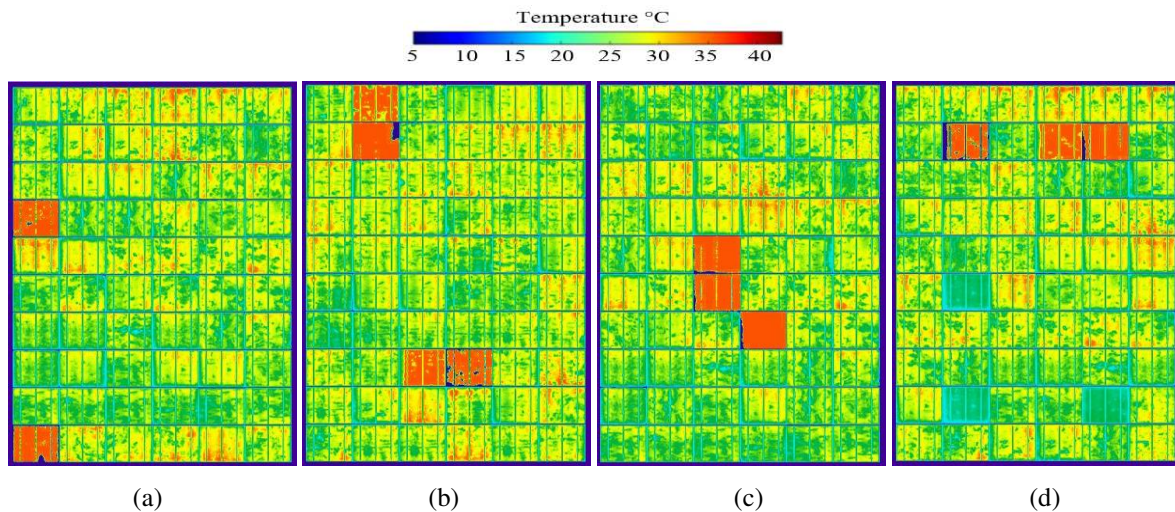


Figure 10. Thermal images of the cracked PV modules after 6-months of field operation, taken under solar irradiance 772 W/m^2 and cell temperature 23.3°C . (a) PV module #1, (b) PV module #2, (c) PV module #3, (d) PV module #4.

176 As expected, the cracked PV modules are now exhibiting severe hotspots. The hotspots
 177 temperature varies from 35°C to nearly 40°C , compared with non-hotspot cells at
 178 approximately 23.5°C . Furthermore, the location of the hotspots is identical to the cracked cells
 179 in the original EL images shown in Figure. 7. The cracks in the PV modules can act as an
 180 inactive region (permanent shade). Consequently, the hotspots developed in a relatively short
 181 period. As developed by [15, 23], these methods proposed suitable techniques to recover PV
 182 hotspots by replacing the bypass diodes with power electronics devices, yet the hotspots
 183 themselves are challenging to mitigate completely.

184 A Solmetric PVA-1000S PV analyzer has been used to record the output I-V curves (Figure.
 185 11) under solar irradiance of 772 W/m^2 and cell temperature of 23.3°C . During the test, an
 186 overcasting condition in the sky explains the step change in the I-V curves. The accuracy for
 187 the PV analyzer is $\pm 5\%$. It is observed that the PV modules have a power loss ranging from
 188 $0.77\pm 5\%$ to $1.44\pm 5\%$ compared with an adjacent PV reference module (a healthy PV module
 189 with no cracks or hotspots). The maximum decrease in the short circuit current is equal to 0.2
 190 A, and no significant difference in the open-circuit voltage (approximately 0.07 V).

191 In Figure 11, it can be observed that the power losses of the PV modules are not exactly
 192 consistent with the development of the hotspot in the modules. For example, even though PV
 193 module #2 has four hotspots, its power loss is less than PV module #3, which has three hotspots.
 194 There are two reasons behind this behaviour, (i) the hotspots in PV module #3 have a higher
 195 temperature increase compared with the PV module #2, (ii) the development of the hotspot is
 196 not necessarily a sign of the impact of the actual crack on the modules; hence, EL imaging can
 197 illustrate the differences between the crack sizes and breakdown in the cells, while the thermal
 198 image can only show the increase of the surface temperature.

199 As the PV modules are still in the first year of operation, it could be concluded that the PV
 200 modules' degradation rate is the same as the power losses, averaged at $1.03\pm 5\%$. Usually, this
 201 is not a considerable degradation rate of PV modules in their first year. Yet, it is expected that
 202 due to the cracking, the PV modules will result in a further increase in the hotspots temperature
 203 and a significant degradation rate in the near future. Therefore, an excellent exercise to replace
 204 those with newer PV modules.

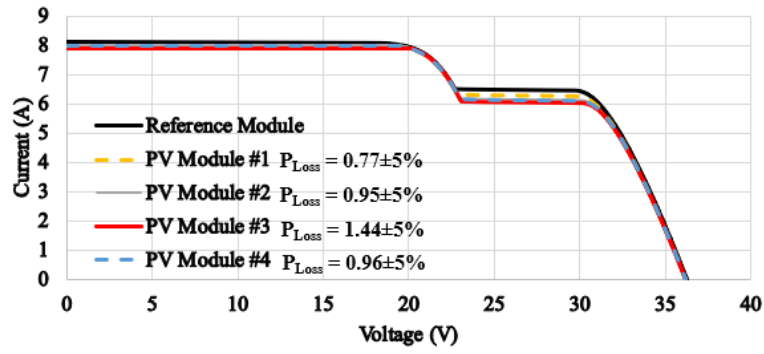


Figure 11. Output I-V curve taken for the hotspotted PV modules under solar irradiance 772 W/m^2 and cell temperature 23.3°C .

205 **4. PID Testing**

206 If the cracked PV modules were left under field operation, PID likely affects them due to cracks
 207 and hotspots. Therefore, the cracked PV modules were dismantled and a PID test performed.
 208 For comparative investigation, the PID test on the healthy PV module were also completed.
 209 Following the IEC/TS60904-13 PID-testing standard, the examined PV modules were
 210 subjected to a temperature of 60°C with 80% humidity and under 1000 V load for 96 hours.
 211 The EL images before and after the PID test was completed are shown in Figure 12.

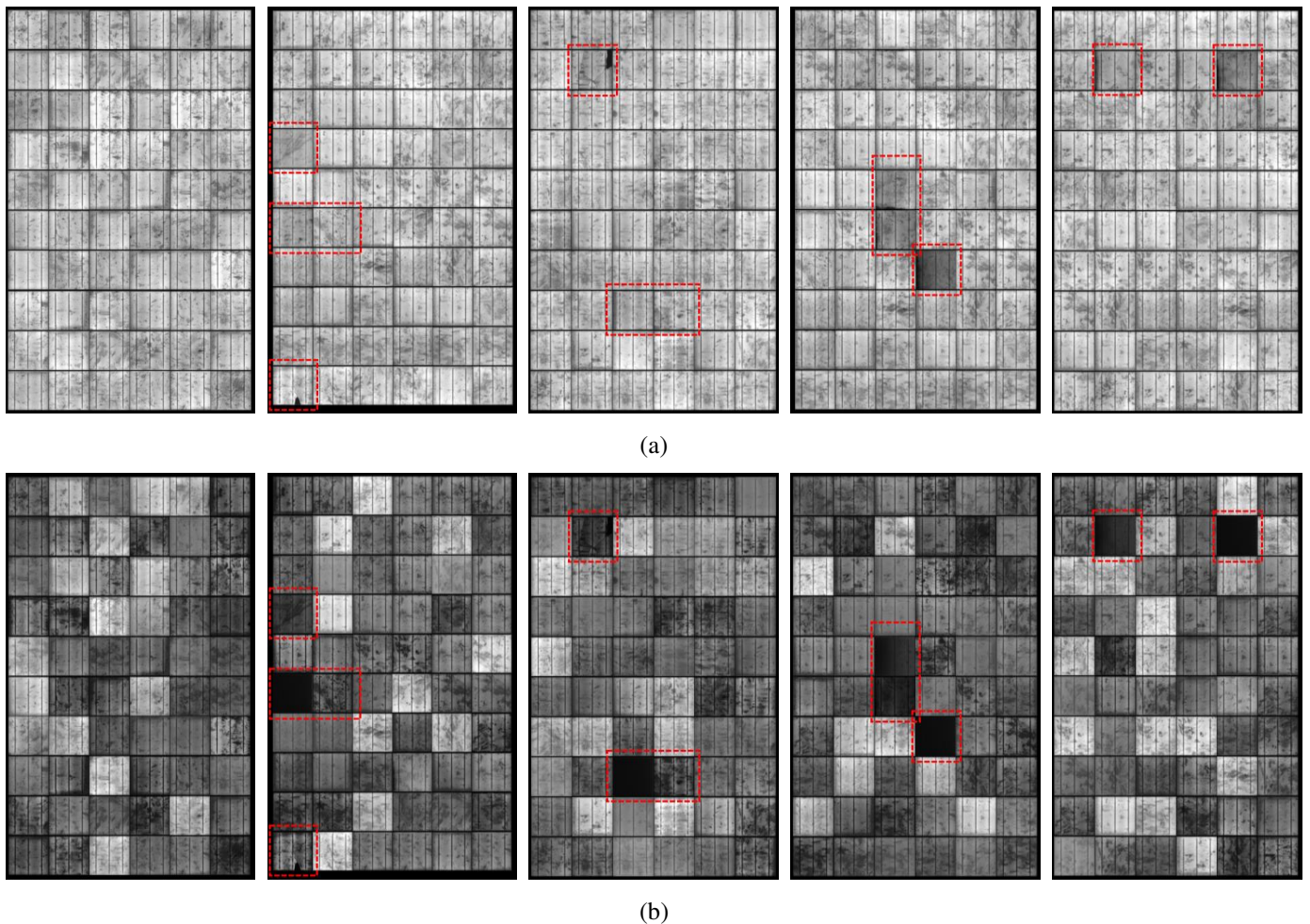


Figure 12. EL images of the examined PV modules samples. (a) Before the PID test, (b) After the PID test is completed. In this figure, from left to right, the first EL image is for the reference module (crack-free and with no power losses), followed by PV#1, PV#2, PV#3, and PV#4 which are already affected by cracks, even before the PID test started.

212 In practice, the PID forms in PV strings in two different settings, but both are attributed to the
 213 inverter or power electronic device having no grounding. First, it creates either +1000 V or -
 214 1000 V biasing for the affected PV string. The PID will then cause the PV modules to leak the
 215 current from the semiconducting material to the actual framing or glass [26]. Consequently, it
 216 will degrade the modules and cause a considerable drop in the output power production [27].

217 Prior work on PID has considered testing the PV modules under a controlled environment by
 218 applying the existing PID testing procedure: humidity 85%, PV surface temperature at 65°C
 219 and bias of the PV module with either +1000 V or -1000 V, for at least 96 hours [27-29]. This
 220 test can, of course, lead to an understanding as to how PID can affect the PV modules. For
 221 example, in [30], it was shown that PID could reduce the module's output power by more than
 222 30%. However, there is currently little information on whether the same percentage of power
 223 losses would result from PID under outdoor field conditions. In addition, it is unidentified if
 224 repairing the grounding issue of the affected PID strings would result in an increase in the
 225 output power and improve the quality of the affected modules. Finally, from [27, 31], through
 226 electroluminescence (EL) imaging, PID can cause shunting, cracks, and breakdown areas at a
 227 solar cell level [32].

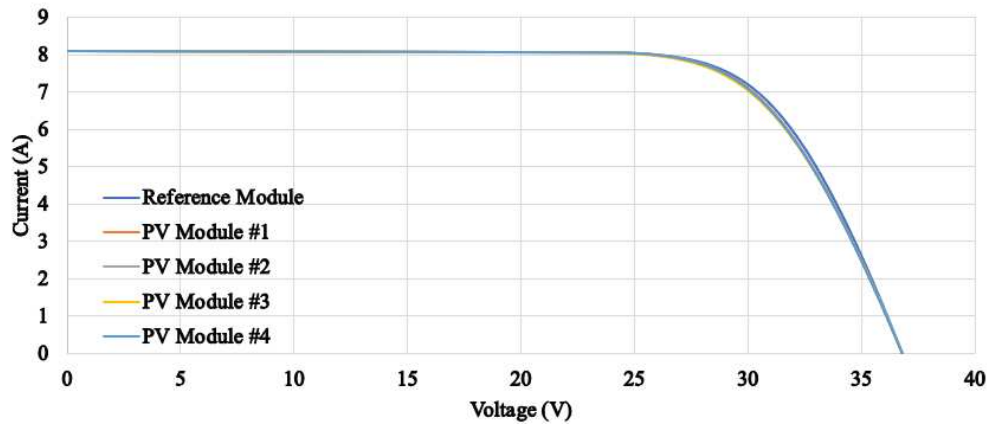
228 In this paper, the output EL images after the PID test show that full breakdown solar cells
 229 (expressed by blacked cells) have only been exhibited for the PV modules where cracks have
 230 already formed. This outcome supports previous conclusions, as cracked solar cells are likely
 231 to impact PV modules with a significant degradation rate.

232 Previous research [24, 25], has suggested that the PID test can result in a nearly 20-30% drop
 233 in the output power, even for healthy PV modules. For the examined PV modules, the
 234 comparison between the output power loss at STC conditions before and after the PID test is
 235 shown in Figure 13, using an I-V curve illustration. All the electrical parameters results are
 236 also summarised in Table 1.

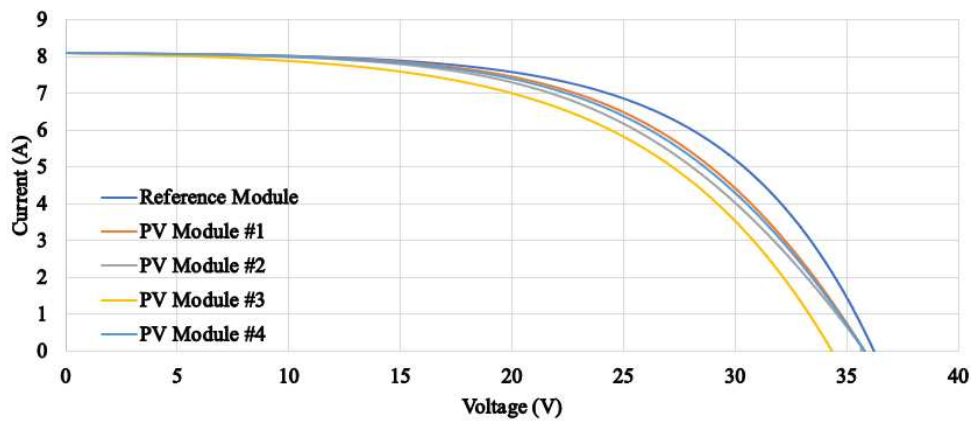
237 Before the PID test, the maximum output power loss was observed for the third PV module at
 238 1.36%, compared with the reference PV module. However, after the PID test, there was a
 239 significant drop in the output power of the cracked modules compared with the
 240 healthy/reference module. For example, the third PV module has an output power loss of 33%,
 241 while the drop in the output power of the reference module was 21.8%.

Table 1 Summary of the electrical parameters of the tested PV modules

PV Module	<i>Voc</i> (V)	<i>Voc</i> (V)	<i>Isc</i> (A)	<i>Isc</i> (A)	<i>Pmax</i> (W)	<i>Pmax</i> (W)
	Before PID	After PID	Before PID	After PID	Before PID	After PID
Reference Module, crack free	36.6	36.2	8.1	8.1	219.2	171.4
PV #1	36.6	35.8	8.1	8.1	217.7	161.9
PV #2	36.6	35.6	8.1	8.0	217.4	154.9
PV #3	36.5	34.4	8.1	8.0	216.2	146.8
PV #4	36.6	35.8	8.1	8.1	217.6	159.5



(a)



(b)

Figure 13. Comparing the output power loss before and after the PID test. (a) I-V before PID test, (b) I-V after PID test.

242 According to the other electrical parameters, there were no significant changes before the PID
 243 test was performed in the short circuit current and V_{oc} . After the PID experiment was
 244 completed, there was an insignificant drop in the short circuit current; however, the V_{oc} has
 245 dropped in the range of 1.1% to 4.9%. This demonstrates the significance of having cracks in
 246 PV modules. Therefore, over time, the cracks will lead to a drastic drop in output power
 247 production, and they are also plausible, compared with healthy PV modules, and they
 248 accelerate the degradation if the modules were affected by PID.

249 5. Conclusions

250 This paper reports the reliability of 186 PV modules from the production to the installation
 251 stage. Initially, no cracks or hotspots for the PV modules were found after being assembled.
 252 However, a minor reduction in the output power, $\pm 0.3\%$ was observed. The PV modules were
 253 delivered using standard practice, and no further precautions were considered. The EL images
 254 of all PV modules were taken at the installation site, 2.2% evolved cracks were discovered.
 255 Depending on the crack size, the estimated output power losses under STC conditions varied
 256 from 0.53% to 1.43%.

257 To allow hotspots to develop, the cracked PV modules had thermal images taken after being
258 under operation for 6-months. As a result, it was observed that PV hotspots developed in all
259 cracked PV modules and their temperature varied from 35 to 45°C. The cracked PV modules
260 were dismantled from the PV installation, and a PID test was performed. From these tests it
261 was discovered that the difference in the output power loss reached 10.9% after the PID test
262 was completed, compared with 1.29% before the PID test.

263 These results suggest that improving the current standards for packaging and delivering PV
264 modules must be documented. In addition, these investigations explain that the reliability of
265 PV modules can be severely impaired if the PV modules are affected by any form of cracking
266 modes, including micro-cracks or breakdown regions.

267 **CRedit Authorship Contribution Statement**

268 **Mahmoud Dhimish:** Formal Analysis, Methodology, Visualization, Conceptualization,
269 Writing – original draft. **Ameer Ahmad:** Software, Validation, Visualization, Writing – review
270 and editing. **Andy M. Tyrrell:** Validation, Funding Acquisition, Resources, Writing – review
271 and editing.

272 **Declaration of Competing Interest**

273 The authors declare that they have no known competing financial interests or personal
274 relationships that could have appeared to influence the work reported in this paper.

275 **References**

- 276 [1] Carolus, J., Tsanakas, J. A., van der Heide, A., Voroshazi, E., De Ceuninck, W., & Daenen, M. (2019).
277 Physics of potential-induced degradation in bifacial p-PERC solar cells. *Solar Energy Materials and*
278 *Solar Cells*, 200, 109950. <https://doi.org/10.1016/j.solmat.2019.109950>
- 279 [2] Zhang, J. W., Cao, D. K., Diahm, S., Zhang, X., Yin, X. Q., & Wang, Q. (2019). Research on potential
280 induced degradation (PID) of polymeric backsheets in PV modules after salt-mist exposure. *Solar*
281 *Energy*, 188, 475-482. <https://doi.org/10.1016/j.solener.2019.06.019>
- 282 [3] Review on Infrared and Electroluminescence Imaging for PV Field Applications. Retrieved from:
283 [https://iea-pvps.org/wp-](https://iea-pvps.org/wp-content/uploads/2020/01/Review_on_IR_and_EL_Imaging_for_PV_Field_Applications_by_Task_13.pdf)
284 [content/uploads/2020/01/Review on IR and EL Imaging for PV Field Applications by Task 13.p](https://iea-pvps.org/wp-content/uploads/2020/01/Review_on_IR_and_EL_Imaging_for_PV_Field_Applications_by_Task_13.pdf)
285 [df](https://iea-pvps.org/wp-content/uploads/2020/01/Review_on_IR_and_EL_Imaging_for_PV_Field_Applications_by_Task_13.pdf)
- 286 [4] Dhimish, M. (2020). Micro cracks distribution and power degradation of polycrystalline solar cells
287 wafer: Observations constructed from the analysis of 4000 samples. *Renewable Energy*, 145, 466-477.
288 <https://doi.org/10.1016/j.renene.2019.06.057>

- 289 [5] Qian, X., Li, J., Cao, J., Wu, Y., & Wang, W. (2020). Micro-cracks detection of solar cells surface via
 290 combining short-term and long-term deep features. *Neural Networks*, *127*, 132-140.
 291 <https://doi.org/10.1016/j.neunet.2020.04.012>
- 292 [6] Wang, H., Zhao, P., Yang, H., Chang, J., Song, D., & Sang, S. (2018). Performance variation of dark
 293 current density-voltage characteristics for PID-affected monocrystalline silicon solar modules from the
 294 field. *Microelectronics Reliability*, *81*, 320-327. <https://doi.org/10.1016/j.microrel.2017.11.003>
- 295 [7] Sporleder, K., Turek, M., Schüler, N., Naumann, V., Hevisov, D., Pöblau, C., ... & Hagendorf, C. (2021).
 296 Quick test for reversible and irreversible PID of bifacial PERC solar cells. *Solar Energy Materials and*
 297 *Solar Cells*, *219*, 110755. <https://doi.org/10.1016/j.solmat.2020.110755>
- 298 [8] Akram, M. W., Li, G., Jin, Y., Zhu, C., Javaid, A., Akram, M. Z., & Khan, M. U. (2020). Study of
 299 manufacturing and hotspot formation in cut cell and full cell PV modules. *Solar Energy*, *203*, 247-259.
 300 <https://doi.org/10.1016/j.solener.2020.04.052>
- 301 [9] Carolus, J., Breugelmans, R., Tsanakas, J. A., van der Heide, A., Voroshazi, E., De Ceuninck, W., &
 302 Daenen, M. (2020). Why and how to adapt PID testing for bifacial PV modules?. *Progress in*
 303 *Photovoltaics: Research and Applications*, *28*(10), 1045-1053. <https://doi.org/10.1002/pip.3311>
- 304 [10] Dhimish, M., Hu, Y., Schofield, N., & G Vieira, R. (2020). Mitigating Potential-Induced Degradation
 305 (PID) Using SiO₂ ARC Layer. *Energies*, *13*(19), 5139. <https://doi.org/10.3390/en13195139>
- 306 [11] Sertel, T., Ozen, Y., Baran, V., & Ozcelik, S. (2019). Effect of single-layer Ta₂O₅ and double-layer
 307 SiO₂/Ta₂O₅ anti-reflective coatings on GaInP/GaAs/Ge triple-junction solar cell performance. *Journal*
 308 *of Alloys and Compounds*, *806*, 439-450. <https://doi.org/10.1016/j.jallcom.2019.07.257>
- 309 [12] Wang, J., Ge, J., Hou, H., Wang, M., Liu, G., Qiao, G., & Wang, Y. (2017). Design and sol-gel
 310 preparation of SiO₂/TiO₂ and SiO₂/SnO₂/SiO₂-SnO₂ multilayer antireflective coatings. *Applied*
 311 *Surface Science*, *422*, 970-974. <https://doi.org/10.1016/j.apsusc.2017.06.133>
- 312 [13] Papargyri, L., Theristis, M., Kubicek, B., Krametz, T., Mayr, C., Papanastasiou, P., & Georghiou, G. E.
 313 (2020). Modelling and experimental investigations of microcracks in crystalline silicon photovoltaics: A
 314 review. *Renewable Energy*, *145*, 2387-2408. <https://doi.org/10.1016/j.renene.2019.07.138>
- 315 [14] Dhimish, M., d'Alessandro, V., & Daliento, S. (2021). Investigating the Impact of Cracks on Solar Cells
 316 Performance: Analysis based on Nonuniform and Uniform Crack Distributions. *IEEE Transactions on*
 317 *Industrial Informatics*. <http://doi.org/10.1109/TII.2021.3088721>
- 318 [15] Olalla, C., Hasan, M., Deline, C., & Maksimović, D. (2018). Mitigation of hot-spots in photovoltaic
 319 systems using distributed power electronics. *Energies*, *11*(4), 726. <https://doi.org/10.3390/en11040726>
- 320 [16] Dhimish, M., & Badran, G. (2020). Current limiter circuit to avoid photovoltaic mismatch conditions
 321 including hot-spots and shading. *Renewable Energy*, *145*, 2201-2216.
 322 <https://doi.org/10.1016/j.renene.2019.07.156>
- 323 [17] Tang, S., Xing, Y., Chen, L., Song, X., & Yao, F. (2021). Review and a novel strategy for mitigating hot
 324 spot of PV panels. *Solar Energy*, *214*, 51-61. <https://doi.org/10.1016/j.solener.2020.11.047>
- 325 [18] Rajput, A. S., Ho, J. W., Zhang, Y., Nalluri, S., & Aberle, A. G. (2018). Quantitative estimation of
 326 electrical performance parameters of individual solar cells in silicon photovoltaic modules using
 327 electroluminescence imaging. *Solar Energy*, *173*, 201-208.
 328 <https://doi.org/10.1016/j.solener.2018.07.046>
- 329 [19] Akram, M. W., Li, G., Jin, Y., Chen, X., Zhu, C., Zhao, X., ... & Ahmad, A. (2019). CNN based automatic
 330 detection of photovoltaic cell defects in electroluminescence images. *Energy*, *189*, 116319.
 331 <https://doi.org/10.1016/j.energy.2019.116319>

- 332 [20] Islam, M. A., Hasanuzzaman, M., & Abd Rahim, N. (2018). A comparative investigation on in-situ and
 333 laboratory standard test of the potential induced degradation of crystalline silicon photovoltaic
 334 modules. *Renewable Energy*, 127, 102-113. <https://doi.org/10.1016/j.renene.2018.04.051>
- 335 [21] Zhang, J. W., Cao, D. K., Cui, Y. C., Wang, F., Putson, C., & Song, C. (2019). Influence of potential
 336 induced degradation phenomena on electrical insulating backsheet in photovoltaic modules. *Journal of*
 337 *Cleaner Production*, 208, 333-339. <https://doi.org/10.1016/j.jclepro.2018.10.057>
- 338 [22] Oh, W., Bae, S., Chan, S. I., Lee, H. S., Kim, D., & Park, N. (2017). Field degradation prediction of
 339 potential induced degradation of the crystalline silicon photovoltaic modules based on accelerated test
 340 and climatic data. *Microelectronics Reliability*, 76, 596-600.
 341 <https://doi.org/10.1016/j.microrel.2017.07.079>
- 342 [23] Dhimish, M., Holmes, V., Mehrdadi, B., Dales, M., & Mather, P. (2018). PV output power enhancement
 343 using two mitigation techniques for hot spots and partially shaded solar cells. *Electric Power Systems*
 344 *Research*, 158, 15-25. <https://doi.org/10.1016/j.eprsr.2018.01.002>
- 345 [24] Mirtchev, A., Mouselinos, T., Syrigos, S., & Tatakis, E. (2021). Behavioral Analysis of Potential Induced
 346 Degradation on Photovoltaic Cells, Regeneration and Artificial Creation. *Energies*, 14(13), 3899.
 347 <https://doi.org/10.3390/en14133899>
- 348 [25] Luo, W., Khoo, Y. S., Hacke, P., Naumann, V., Lausch, D., Harvey, S. P., ... & Ramakrishna, S. (2017).
 349 Potential-induced degradation in photovoltaic modules: a critical review. *Energy & environmental*
 350 *science*, 10(1), 43-68. <http://doi.org/10.1039/C6EE02271E>
- 351 [26] Sulas-Kern, D.B. et al. Electrochemical degradation modes in bifacial silicon photovoltaic modules.
 352 *Prog. Photovolt.* 1-11 (2021). <https://doi.org/10.1002/pip.3530>
- 353 [27] Dhimish, M. & Lazaridis, P. I. An empirical investigation on the correlation between solar cell cracks
 354 and hotspots. *Scientific Reports*. 11, 23961 (2021). <https://doi.org/10.1038/s41598-021-03498-z>
- 355 [28] Dhimish, M. & Kettle, J. Impact of Solar Cell Cracks Caused During Potential-Induced Degradation
 356 (PID) Tests. *IEEE Trans. Electron Devices*. 69, 604-612 (2021).
 357 <http://doi.org/10.1109/TED.2021.3135365>
- 358 [29] Carolus, J. et al. Physics of potential-induced degradation in bifacial p-PERC solar cells. *Sol. Energy*
 359 *Mater. Sol. Cells* 200, 109950 (2019). <http://doi.org/10.1016/j.solmat.2019.109950>
- 360 [30] Dhimish, M. & Tyrrell, A.M. Power loss and hotspot analysis for photovoltaic modules affected by
 361 potential induced degradation. *NPJ Mater. Degrad.* 6, 1-8 (2022). [http://doi.org/10.1038/s41529-022-](http://doi.org/10.1038/s41529-022-00221-9)
 362 [00221-9](http://doi.org/10.1038/s41529-022-00221-9)
- 363 [31] Bedrich, K.G. et al. Quantitative electroluminescence imaging analysis for performance estimation of
 364 PID-influenced PV modules. *IEEE J. Photovolt.* 8, 1281-1288 (2018). DOI:
 365 <http://doi.org/10.1109/JPHOTOV.2018.2846665>
- 366 [32] Dhimish, M., & Badran, G. Recovery of Photovoltaic Potential-Induced Degradation Utilizing
 367 Automatic Indirect Voltage Source. *IEEE Transactions on Instrumentation and Measurement*. 71,
 368 (2021). DOI: <http://doi.org/10.1109/TIM.2021.3134328>