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Nondestructive monitoring of damage caused by accelerated ageing in photovoltaic modules

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Abstract

Accelerated ageing tests of photovoltaic laminates are requested by the IEC 61215 standards for quality control, which require the assessment of the electrical power losses after a prescribed amount of temperature and/or humidity cycles inside a climatic chamber (thermal cycling and humidity freeze tests). Since electric damage is measured only at the end of such tests, its kinetics induced by thermo-elastic stresses and the related degradation phenomena are not well understood. The aim of this study is to investigate the progress of damage, reporting the results of an unprecedented experimental campaign on a photovoltaic mini-module composed of nine multi-crystalline silicon solar cells, one of them containing a cracked cell, subject to thermal cycling. Every 40 cycles, and up to 460 (corresponding to 1840 hours of testing), the progress of electric damage is assessed by monitoring the evolution of the overall electric resistance of the module. Moreover, electroluminescence images are taken with the same time interval, to assess also local damage phenomena responsible for electric power-losses. Cracks are found to significantly accelerate the progress of damage as compared to intact solar cells, inducing progressive gridline failure and the spread of electrically inactive zones.

Keywords

Photovoltaics, Nondestructive monitoring, Accelerated ageing tests, Thermo-mechanical stresses, Electroluminescence

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Abstract

Accelerated ageing tests of photovoltaic laminates are requested by the IEC 61215 standards for quality control, which require the assessment of the electrical power losses after a prescribed amount of temperature and/or humidity cycles inside a climatic chamber (thermal cycling and humidity freeze tests). Since electric damage is measured only at the end of such tests, its kinetics induced by thermo-elastic stresses and the related degradation phenomena are not well understood. The aim of this study is to investigate the progress of damage, reporting the results of an unprecedented experimental campaign on a photovoltaic mini-module composed of nine multi-crystalline silicon solar cells, one of them containing a cracked cell, subject to thermal cycling. Every 40 cycles, and up to 460 (corresponding to 1840 hours of testing), the progress of electric damage is assessed by monitoring the evolution of the overall electric resistance of the module. Moreover, electroluminescence images are taken with the same time interval, to assess also local damage phenomena responsible for electric power-losses. Cracks are found to significantly accelerate the progress of damage as compared to intact solar cells, inducing progressive gridline failure and the spread of electrically inactive zones.

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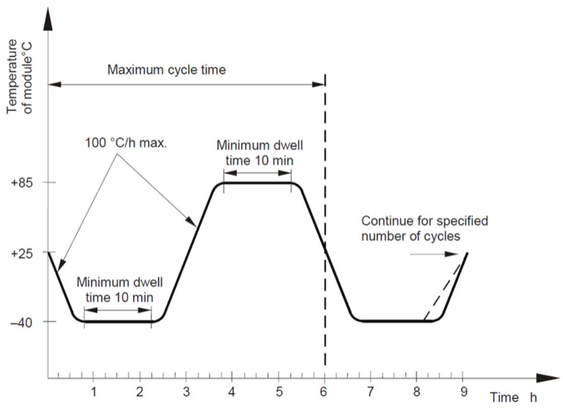
Introduction

Due to outdoor exposure, photovoltaic (PV) modules are subjected to degradation phenomena during their warranty period (20-25 years). Producer warranties claim power losses lower than 10% of the initial nominal power during the first 10-12 years, and up to 20% after 20-25 years of operation, also with different power loss rates [1]. Many external stressor, like solar radiation, wind, high temperature excursions, moisture, hail impacts, vibrations, fatigue, etc. contribute to PV damage [1–7]. PV degradation manifests itself as a gradual deterioration of materials and components, affecting the optimal working conditions [8,9]. As a result of that, electrical performances might decrease over time. In addition to this, safety issues are also related to material and component degradation. Conventionally, relevant degradation occurs when the PV power output drops below 80% of its initial value [2], while the excess of degradation over a threshold could be critical for PV operation [10].

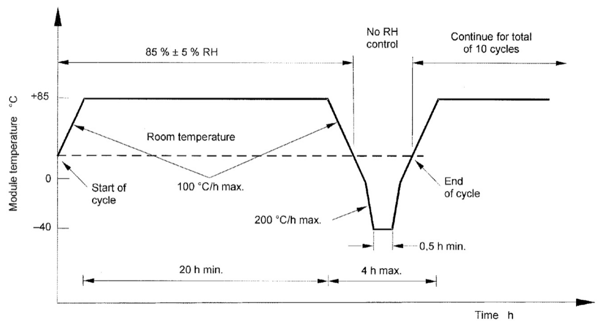
Different outdoor conditions generate multiple degradation phenomena [4,4,11–18], and statistical data on PV module failures in the field indicate that delamination counts for the majority of defect cases, but also corrosion, glass breakage, discoloration and ribbon cracks do matter [19].

Manufacturers certificate their products according to IEC standards [20]. Specifically, certification tests are prescribed in the IEC 61730 (Photovoltaic (PV) module safety qualification – Requirements for testing) [21], IEC 61215 (Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval) [20], and IEC 61215-1-3 (Thin-film amorphous silicon based photovoltaic modules) [22].

IEC standards prescribe three main types of accelerating ageing tests: (i) thermal cycling, (ii) humidity freeze, and (iii) damp heat. The thermal cycling test requires control of temperature at the ambient relative humidity, see Fig.1(a), and it is applied for up to 200 cycles. It is a stress test for cell inteconnectors due to different thermo-elastic parameters of the laminate components. The Task 13 on performance and reliability of PV systems of the Photovoltaic Power Systems Programme of the International Energy Agency reported 4% of failures for thin film PV modules after 50 thermal cycles, and 8% after 200 cycles [19] (p.7). The humidity freeze test is similar to thermal cycling in terms of minimum and maximum temperatures imposed during the test, but a much longer time period at 85° is considered, followed by a rapid cooling down to $-40°$ to induce a thermal shock, see Fig.1(b). Although only 10 cycles are requested, this stress was responsible for 6% of detected failures. Finally, the damp heat test prescribes testing of PV modules at a constant temperature of 85° and a relative humidity of 85% for 1000 h inside the climatic chamber. Such a test was responsible for 22% of reported failures.



(a) Thermal cycling test



(b) Humidity freeze test

Figure 1. Accelerated ageing tests prescribed by IEC stadards [20].

Correlation between data from standard accelerated tests [3,23] and outdoor exposure [1,24–29] is still controversial and under debate. Adding humidity to the test seems to increase failure rates, but many questions related to the effect of the velocity of the temperature ramps have not yet been addressed.

Generally, accelerated tests cause thermal stresses in the PV modules and also thermal fatigue which may cause interconnections (failure of the busbars connecting solar cells) and gridline (thin electric conductors deposited onto the solar cell, perpendicular to busbars) failures[30]. Experimental results in[31] on rapid thermal cycling tests on three different types of mini-modules reported an increase of the impedance due to interconnection failures. Recently, a study on failure induced by the acid corrosion of the gridline in[28] showed a behavior similar to what observed from damp heat accelerated ageing tests. Monitoring the AC impedance and the I-V curves of solar cells led to the discovery that the impedance and the series resistance were both increasing over time, as an effect of hygrothermal stresses.

From this brief literature survey, it appears that all the three major standard qualification tests present some deficiencies. The thermal cycling test does not include moisture, and 200 cycles could be not enough as compared to the number of cycles experienced in the field by PV modules. The humidity freeze test includes moisture and, although it is repeated only for 10 cycles, is too much severe due to the very short time of rest at $-40°$C that does not allow stress relaxation into the viscoelastic encapsulating polymer. The damp heat test, on the other hand, does not consider temperature variations, which are indeed an important source of stresses in the composite laminate.

Therefore, this work reports an original experimental characterization of the evolution of damage in a PV mini-module composed of 9 multi-crystalline solar cells subjected to thermal cycling tests with temperature profiles inspired by the IEC 61215 standard and modified by adding also relative humidity control with set point of 85% when the module is at the maximum temperature. Since the research aim is to explore the combined effect of moisture and temperature, cycles up to 460 have been considered, which is much beyond what is prescribed by thermal cycling tests.

We also conduct a detailed report of time evolution of dark areas of silicon solar cells by taking electroluminescence (EL) images every 40 thermal cycles, up to 460 cycles (which corresponds to 1840 hours of testing that, considering also the time requested for EL inspection, leads to approximately three months of continuous experimental activities). To take the EL images, the PV module is temporarily removed from the climatic chamber every time the photo is shot, since the glass window of the climate chamber is not transparent to the EL radiation and therefore EL pictures cannot be taken inside the chamber. This is a time-consuming operation which is in fact not requested by IEC standards during thermal cycling, but it is essential for research purposes to assess the local evolution of damage over time. Such results are therefore particularly novel and of high research relevance, since they cannot be easily obtained in R&D laboratories devoted to massive testing of PV modules according to IEC standards. In addition to EL images, the variation of the overall electrical resistance is finally assessed as a quantitative indicator of the module electrical degradation. Results highlight the criticality of initial cracks in silicon solar cells, which did not influence the power output before ageing, but are found to severely promote and accelerate the process of gridline failure.

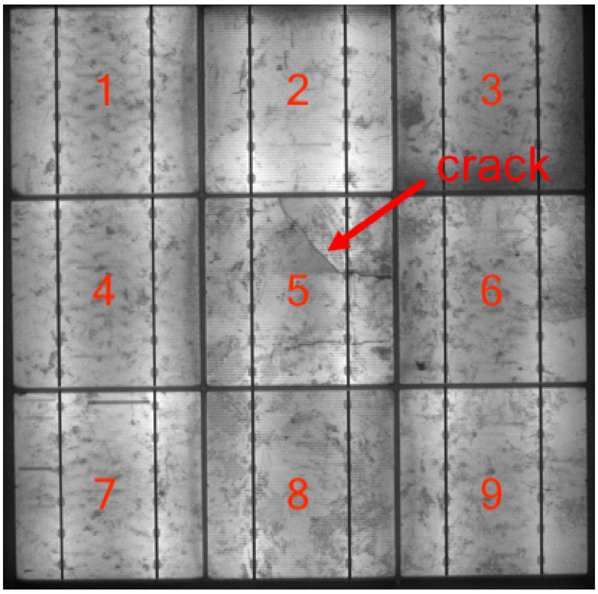
Experimental characterization

Accelerated ageing is performed in reference to a 9-cell square PV mini-module (50 $\times$ 50 cm), subjected to thermal cycling[20]. The module was manufactured in the Institute for Solar Energy Research Hamelin (Germany), and laminated without junction box or frames. The module consists of two-busbars 3$\times$3 multi-crystalline silicon solar cells (15.6 cm wide), protected by a 4 mm thick white glass and encapsulated with commercial poly(ethylene-co-vinyl-acetate) (EVA). The backsheet is 0.17 mm thick, and it is composed of three tedlar-based layers. The solar cells are electrically connected in series. The cell in the middle of the module presents one main crack. EL and flash tests have been performed on the module before accelerated ageing. The initial crack clearly visible in the solar cell no. 5 (the central one in Fig.2(a)) does not lead to electric power losses, since there are no dark zone in the image that would imply electrical insulation.

Initial flash test data (see Tab. 1) report a short circuit current (the peak current a solar panel can produce with its output shorted) I_{SC}=8.26 A, an open circuit voltage (the output voltage under no load) V_{OC}=5.49 V, a current at the maximum power point I_{MPP}=7.72 A, a voltage at the maximum power point V_{MPP}=4.44 V, a power at the maximum power point P_{MPP}=33.97 W, efficiency η=13.59, and a fill factor (the ratio between the maximum power from the PV module and the product of V_{OC} and I_{SC}) $FF = 74.91$. The power and electrical measurements have been made according to IEC 60904 standard with a class AAA flash system at the Institute for Solar Energy Research Hamelin that can handle solar module sizes up to 200 cm $\times$ 140 cm and with electrical characteristics in the range 20 mA to 20 A and 0.5 V to 120 V. To perform the accelerated ageing test, the PV module is placed inside the climatic chamber (Challenge 250, Angelantoni) with controlled temperature and moisture, see Fig. 2(b). The actual temperature and moisture inside the chamber are also acquired with the WinKratos Software with a sampling frequency of 1/60 s^{-1}.

Applied cycles are designed to reproduce the maximum and minimum temperatures prescribed by the IEC 61215 standard, Sec. 10.11, adding also a high relative humidity control into the picture when the module is at the highest temperature. The duration of each cycle is 4 h, dwell times are 1 h at $85°$ and 1 h at $-40°$. These durations have been selected as shortest as possible to contain the total cycle duration, albeit keeping the dwell times long enough to allow the Young modulus of the EVA thermo-visco-elastic encapsulant reaching the asymptotic value for an infinite time corresponding to the plateau temperatures of $85°$ and $-40°$, respectively, see[32]. A total of 460 cycles have been considered, for a total of 1840 h testing. The recorded temperature and the relative humidity for a generic cycle are shown in Fig. 3 with black lines, while the set point values are superimposed to the same figures in red.

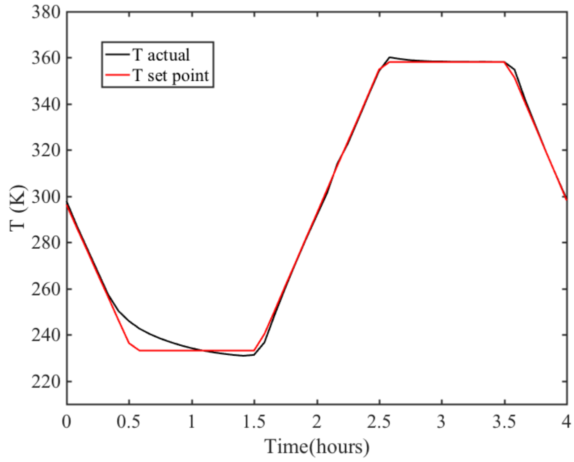
EL images, taken according to the methodology detailed in[33], are acquired every 40 cycles to monitor the evaluation of cracking and electrical damage. The cut-offs applied to analyze the EL images were 600 nm and 2300 nm. Electrical damage is also quantified by calculating the change in the overall electrical resistance of the PV module, R_D, defined



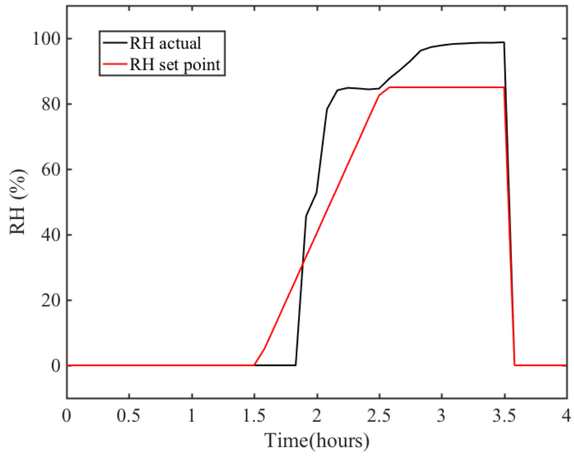
(a) EL image of the PV mini-module after production.

(b) PV mini-module inside the climatic chamber

Figure 2. EL image of mini-module as received (a), and photo of the PV module inside the climatic chamber (b).



(a) Temperature



(b) Humidity

Figure 3. Recorded temperature (a) and relative humidity data (b) inside the climatic chamber (in black) and the corresponding set point values (in red).

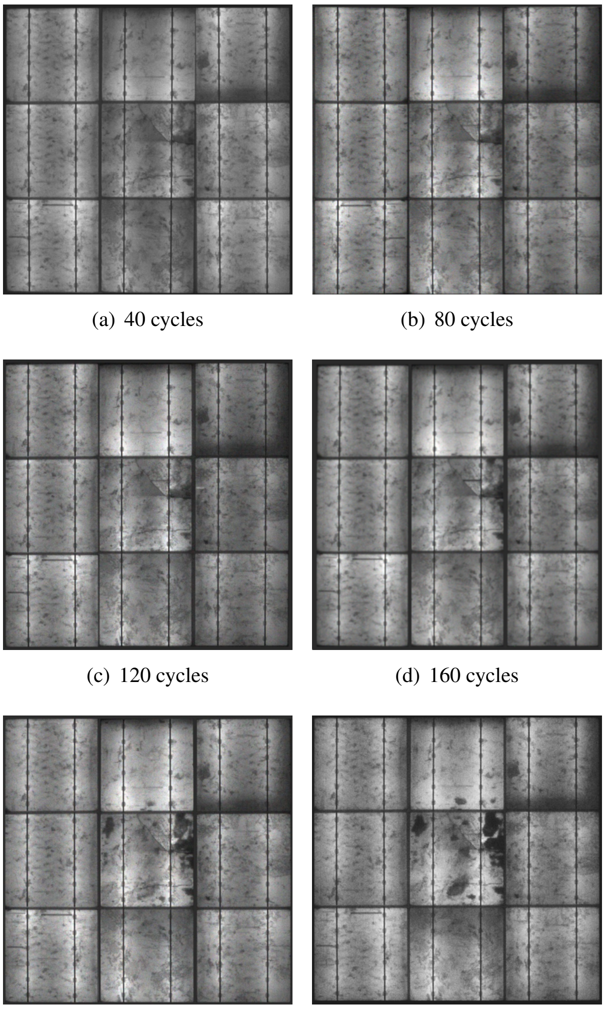
as:

$$\Delta R_{\mathrm{D}} = \frac{V - V_{\mathrm{i}}}{I}, \qquad (1)$$

where V_{i} is the voltage corresponding to the imposed current I before thermal cyclic test, and V is the voltage measured after a given number of thermal cycles. Eventually, the flash test has also been made at the end of the whole thermal cyclic campaign.

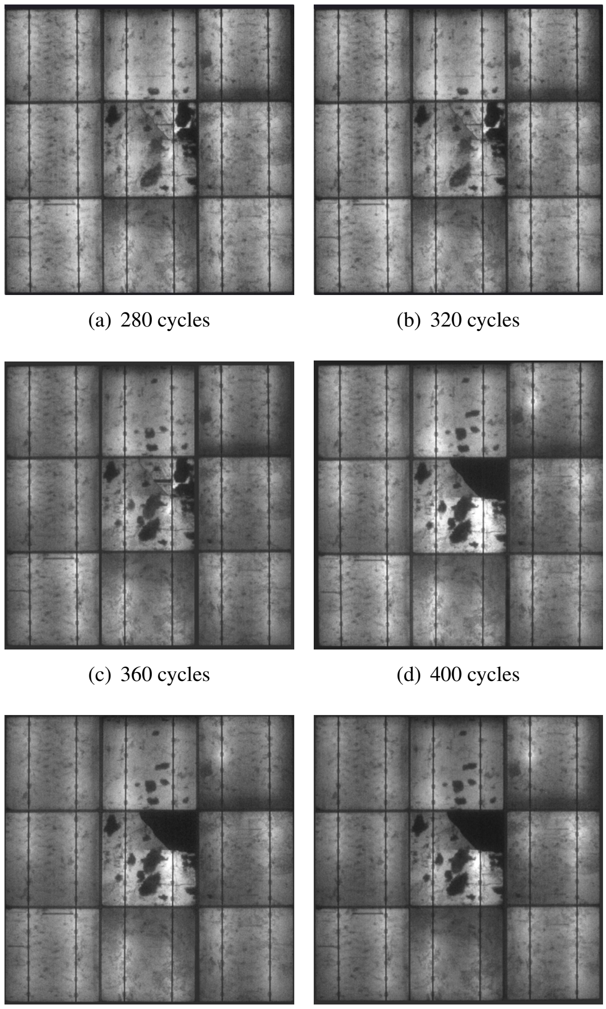
Results and discussion

Modified thermal cycling tests to account for a high relative humidity environment led to a progressive shift of the EL signal towards dimmer tones, due to thermo-mechanical stresses (see Figs. 4 and 5). Focusing the attention on the central cell of the module, which contains an initial crack, we note that after 80 cycles, the size of the dimmer area near the crack increases (Fig. 4(b)). This phenomenon can be attributed to thermo-mechanical stresses which accelerate the gridline failure. This degradation is particularly promoted by the presence of cracks, as it can be noted by comparing the EL image of the central cell with the other ones. After 160 cycles (Fig. 4(d)), failure of a finger takes place in the central cell, see the horizontal dark line starting from the busbar. After 200 cycles (Fig. 4(e)) dark spots appear also far from the crack and spread over the testing time. After 200 cycles, the heavily damaged portion of the gridline starts conducting again at cycle no. 280 (Fig. 5(a)), suggesting its progressive failure and disconnection. Eventually, the complete electrical disconnection of the area comprised between the crack and the busbar takes place in correspondence of 400 cycles (Fig.



(a) 40 cycles (b) 80 cycles (c) 120 cycles (d) 160 cycles (e) 200 cycles (f) 240 cycles

Figure 4. Electroluminescence images during accelerating ageing after: (a) 40 cycles; (b) 80 cycles; (c) 120 cycles; (d) 160 cycles; (e) 200 cycles; (f) 240 cycles.



(a) 280 cycles (b) 320 cycles (c) 360 cycles (d) 400 cycles (e) 420 cycles (f) 460 cycles

Figure 5. Electroluminescence images during accelerating ageing after: (a) 280 cycles; (b) 320 cycles; (c) 360 cycles; (d) 400 cycles; (e) 420 cycles; (f) 460 cycles.

5(d)). This severe form of damage and its kinetics are not observed in the other solar cells that had no initial cracks.

The shift of the EL signal towards dimmer tones is quantified in the histograms of the EL signal (Fig. 6). Such histograms for the whole mini-module are almost symmetric and a shift towards lower EL intensities is noticed with the progress of the test (Fig. 6). Focusing on some representative solar cells, the evolution of the EL histograms for the central cracked cell is shown in Fig. 7(a) and it is quite different from that of solar cells without cracks (see Fig. 7(b) for the solar cell no. 4). The presence of cracking accelerates the shift of the EL intensities towards dimmer tones, i.e., towards low EL intensities.

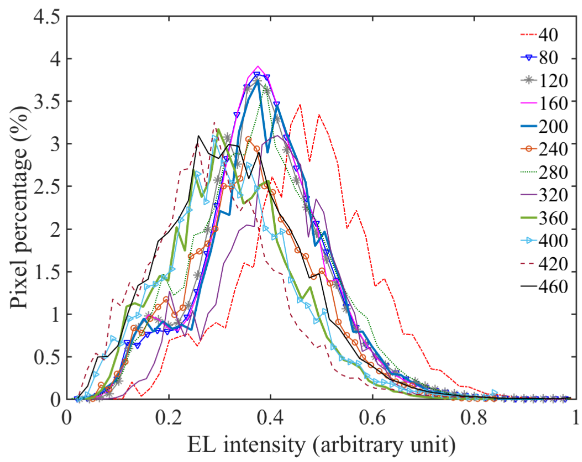
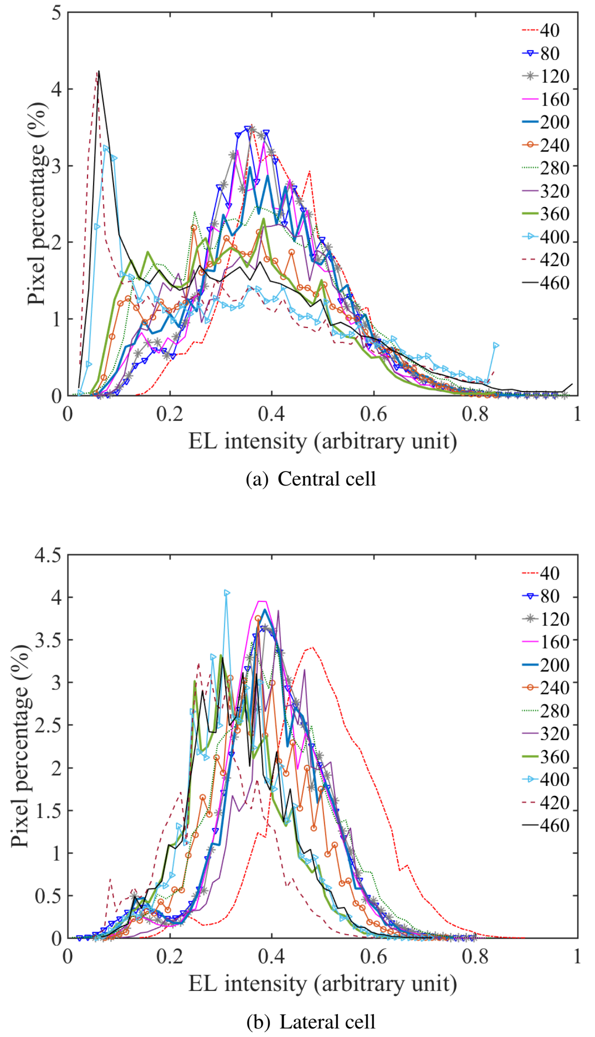


Figure 6. Histograms of the EL intensities after 40, 80, 120, 160, 200, 240, 280, 320, 360, 400, 420 and 460 cycles for the whole mini-module.

Table 1 reports flash test data before and after accelerated tests, where I_{SC} is the short circuit current, V_{OC} is the open circuit voltage, I_{MPP} is the maximum power current, V_{MPP} is the maximum power voltage, P_{MPP} is the maximum power, η is the efficiency, and FF is the fill factor. Flash tests remark an overall efficiency reduction of 21% and a comparable reduction (20.09%) in the maximum power. We also detected a significant increase in the PV module electric resistance R_D over cycles, especially after 300 cycles (Fig. 8), which corresponds to 1200 h of testing. Thermal cycling tests are



(a) Central cell

(b) Lateral cell

Figure 7. Histograms of the EL intensities after 40, 80, 120, 160, 200, 240, 280, 320, 360, 400, 420 and 460 cycles for the central cell (cell no. 5) (a), and for a lateral one (cell no.4) (b).

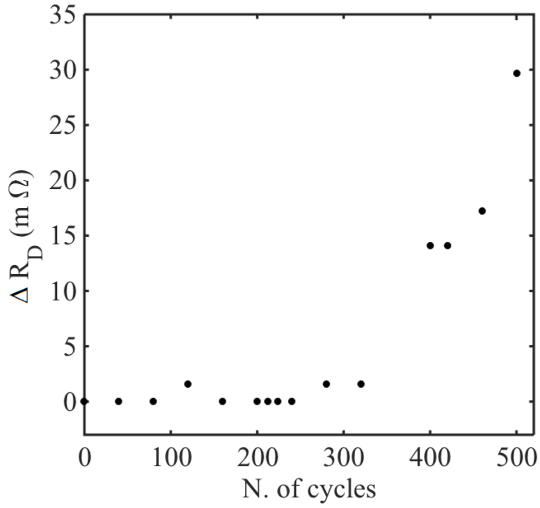


Figure 8. Evolution of the degradation of the electric resistance over time.

Table 1. Flash test data of the mini-module.

	I_{SC} A	V_{OC} V	I_{MPP} A	V_{MPP} V	P_{MPP} W	η %	FF %
Before ageing	8.26	5.49	7.72	4.40	33.97	13.59	74.91
After 460 cycles	6.69	5.50	6.13	4.38	26.84	10.73	72.98

usually limited up to 200 cycles, and therefore these results strongly suggest increasing the number of thermal cycles up to 400 cycles to gain a more comprehensive understanding of degradation phenomena.

For comparison purposes, another mini-module with similar characteristics has been tested according to the damp-heat standard test sequence. Even in the presence of cracks as in the other mini-module, the EL image after 1000 hours of damp-heat exposure is bright (see Fig.9), with a modest overall reduction of 0.84% in efficiency and of 0.92% in maximum power output P_{MPP}. The slight reduction of the power output seen in the test is consistent by results in[34–37]. Indeed, high darkening reported in[34] appeared only after 2800 hours of testing. In that case, moisture induced corrosion of the doped oxide that provides the electrical contact to the emitter of the Silicon cell. Therefore, this comparison reasonably confirms that humidity alone is not able to induce the fast degradation process observed near cracks when also thermal cycling is considered.

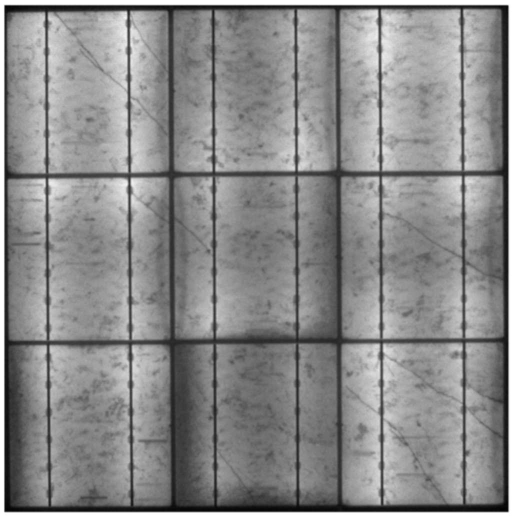


Figure 9. EL image of a mini-module after 1000 h of damp-heat.

Conclusions

Modified thermal cycling tests on PV modules are found to cause electrically inactive zones and dark areas in EL images due to thermo-mechanical stresses which damage and break the gridline deposited onto solar cells. EL images provide a quantitative description of time evolution of the local electric damage, macroscopically quantified also by the increase in the overall electric resistance of the PV module. Moreover, the EL intensity histograms allow the comparison between cracked and intact solar cells, and should be included in IEC testing protocols, especially for PV modules containing cracked solar cells that do not induce power losses before ageing. The present experimental results have showed how cracks promote gridline failure and their potential relevance for the long-term performance of PV modules exposed to the enviroment. Extension of thermal cycling tests above 200 cycles, up to 400 cycles, is recommended as a possible revision of IEC standards, to gain a more comprehensive understanding of degradation phenomena related to cracked solar cells.

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