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Analysis of the degradation of amorphous silicon mini-modules under a severe sequential UV/DH test

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Abstract. This study presents the results of severe accelerated tests carried out on four encapsulated amorphous silicon (a-Si) mini-modules. All the a-Si mini-modules were exposed to a 85 °C and 85% relative humidity damp heat (DH) prolonged treatment for 5000 h representing five times the duration specified by the IEC 61215 standard for qualification tests. For two of the four mini-modules, the DH test was preceded by a severe UV preconditioning, by applying 30 times the dose of 15 kWh/m^2 at a temperature of 50 °C as prescribed by the IEC 61215 standard, in order to enhance the degradation during the following DH test and to reduce the overall testing time. I–V curves were plotted with a time step of 100 h under standard test conditions (STC) using a class A solar simulator and a source meter in order to monitor the degradation throughout both the tests. A visual inspection with photographic capturing was also performed at each stage to detect the apparent defects. Corrosion observed after 2000 h owing to the ingress of humidity is explained here by two possible infiltration paths in the layers of the mini-modules. Delamination occurred after 5000 h for the PV mini-modules which underwent the extended DH test. After 5000 h of damp heat testing, the degradation of the maximal power ($P_{\max}$) was found to be slightly accelerated for the a-Si mini-modules that were previously exposed to a severe UV preconditioning, with a value reaching 80% of its initial value, whereas, for the others only subjected to the prolonged DH test, the maximal power remained above 80% of its initial value. In all cases, the mini-modules seemed highly reliable with no failure after 5000 h of accelerated testing, and, based on an equivalent time of 20 years for 1000 h of accelerated test, they would exhibit a limited degradation rate of 0.2%/year in outdoor field conditions.

Keywords: Photovoltaic / amorphous silicon / mini-modules / accelerated test / corrosion

1 Introduction

In recent years, the photovoltaic (PV) technology has been considered a key pillar for renewable energy sources with long operating life, low fabrication cost and carbon neutrality during energy provision. Among the three generations of PV systems, the first generation, based on crystalline silicon (c-Si) wafers, still prevalent in the PV market, had a 95.70% share in 2019 [1]. The second generation of solar cells is based on thin-film solar cells such as those made of copper indium gallium selenide (CIGS), cadmium telluride (CdTe), gallium arsenide (GaAs), and amorphous silicon (a-Si), all accounting for 4.3% of the 2019 global market. Within this generation, the a-Si PV cells represented a minor part of the market share with 0.05% in 2019. However, this solar cell technology, remaining widely used for specific small-scale applications, holds some real advantages: better resistance to high-temperature environments, good performance with artificial light conditions (as a consequence of its high absorption coefficient and spectral range) and improved durability in the case of prolonged exposure to sunlight [2,3], the reason why we decided to focus this study on the long-term performance of amorphous PV cells.

Under outdoor conditions, the performance of PV modules gradually decreases over time as they are affected by environmental stress factors such as temperature, humidity, solar intensity and ultraviolet (UV) radiation [4].

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Generally, PV modules have a lifespan of about 25–30 years. Long-term module exposure data is needed so as to evaluate their performance under real weather conditions. In order to simulate real-time aging within a shorter time and to qualify the PV modules, accelerated aging tests are carried out in the laboratories using organized standard qualification test procedures. The IEC 61215 standard [5] for the c-Si and the IEC 61646 standard [6] for the thin-film terrestrial PV modules specify the types of qualification tests and the set of procedures to follow.

At present, accelerated testing of the PV modules is an important approach to understand the impact of climatic conditions under natural aging. Moreover, accelerated aging tests are often utilized to identify the failure and degradation mechanisms in PV modules.

Recently, sequential and combined accelerated tests were performed in view of reducing the indoor test time and also to endorse the lifetime reliability and durability of PV modules. The outdoor field exposure consists of combined multiple stress situations. The outcomes of joined accelerated tests are likely to reveal the coupled effects of humidity, temperature and UV exposure on the reliability of PV modules under lab conditions. Different protocols have been tried in the recent years with these objectives on Si PV modules.

Masuda et al. [7] investigated the degradation mechanisms of polycrystalline silicon (pc-Si) modules by developing new accelerated tests composed of DH (damp heat), TC (thermal cycling), DML (dynamic mechanical load) and HF (humidity-freeze). A drastic degradation of the maximum power point $P_{\max}$ was observed after 3000 h of DH due to corrosion. This was generated by the release of acetic acid resulting from the hydrolysis reaction between the EVA and the water vapor penetrating the modules during the DH test. Following the diverse sequential tests, cracking appeared on the outer backsheet layer and micro-cracks were also identified in the cells based on the fracture of the finger electrodes. Moreover, delamination between the cover glass and the encapsulant was observed.

Ngo et al. [8] investigated the effect of UV exposure on the performance of pc-Si PV modules under accelerated DH tests. Their test of 4000 h of irradiation showed a slight power degradation due to the EVA discoloration on the glass side of the module. The 4000 h DH test revealed a power loss of approximately 80% caused by the release of acetic acid from the EVA, by deacetylation in the presence of moisture. After different kinds of combined UV/DH tests, it was suggested that the main cause of degradation was chemical corrosion of the electrode in the presence of acetic acid generated from the EVA.

Bauermann et al. [9] conducted a variety of accelerated sequential tests with DH (DH/DH at current range 8A, DH/HF – humidity freeze and DH/TC – thermal cycling) so as to analyze the material level to ensure the fast and reliable qualification of good conductive adhesives for solar cells. Firstly, they observed a power degradation owing to a loss in the electrical contact between the solar cells and the interconnections under the accelerated DH test. A power loss was also caused by moisture ingress under the sequential DH-TC test, which indicated an adhesion loss between the solar cell and the polymer layer materials. Following the sequential DH-HF, insignificant performance degradation was reported (less than 1%). Nevertheless, the loss in performance for the conductive adhesives was higher than for the reference module. Finally, under the sequential DH-8A current test, a power loss was noticed due to galvanic corrosion at the metallic wires caused by the conductive adhesive between the EVA encapsulant and the PET backsheet.

Kobayashi et al. [10] examined the effect of light irradiation treatment on the hygrothermal degradation of pc-Si PV modules to understand their performances. During the 2000 h DH test, it was observed that the time required for the $P_{\max}$ to start dropping varied with the water vapor transmission rate (WVTR) of the backsheet. However, in the case of a combined UV/DH test, the $P_{\max}$ of each module began to drop after a shorter DH test time than in the case of a DH test alone. Kobayashi et al. also observed that the electrical degradation was initiated at a similar time for each module, without being influenced by the WVTR. This time difference, between the DH test and the combined UV/DH test, was attributed to a chemical reaction created by the light irradiation: UV light creates chemicals that accelerate the hydrolysis reaction in the EVA and speeds up the decline in performance without any relation to the WVTR of the backsheets.

Owen-Bellini et al. [11] studied the failure mechanisms of pc-Si mini-modules under a combined accelerated test with relative humidity, UV radiation, temperature, voltage bias, mechanical load and rain spray. A combined-accelerated stress test protocol (C-AST) was developed and conducted on modules with three different backsheets based on polyvinylidene fluoride, polyamide (PA) and polyvinyl fluoride. Some degradations were apparent under these multiple tests, although not observable under individual standard tests. Cracks of the PA backsheet appeared, after an equivalence of 4–5 years of outdoor exposure under a Florida climate, as the result of temperature and humidity levels at the upper extremes of the natural environment. Delamination at the edge of the modules also occurred during the combined accelerated tests. The authors also noticed a strong degradation of V_{oc} and $P_{\max}$ due to UV radiation on the passivation surface of the cells.

Faye et al. [2] examined the defects in the consumer-type multi-crystalline modules under DH and TC tests. No performance degradation was observed up to 1000 h of DH test. Nevertheless, a drastic decrease of the short-circuit I_{sc} was observed up to 1300 h on account of hot spots, implying corrosion and delamination. The power loss of the modules was detected for TC tests of 55 and 66 cycles. These outcome results suggested that consumer-type mini-modules were not suitable for hot and humid African climates.

Hagihara et al. [3] explored the chemical mechanisms of PV degradation under accelerated DH test followed by UV test and under outdoor exposure in Japan for about 20 years. The formation of acetic acid (deacetylation reaction) by the hydrolysis of the EVA was accelerated during the DH test, especially after 3000 h. Deacetylation could also be induced by the photodegradation of the EVA under UV illumination. According to this study, the DH test followed by the UV radiation test favored the apparition of acetic acid in two different ways and created supplementary severe degradations.

Li et al. [12] tested a new method, combining both UV and DH accelerated tests in order to investigate the cracking propensity of the backsheet for lifetime prediction and to have a wider material selection of PV modules under combined UV and DH accelerated tests as well. The polyester-based (PET/PET/EVA) samples were exposed to 5% RH and 60% RH at 85 °C for different times with or without UV radiation. Cracks were only seen on the surface of UV-degraded samples but were not present in unaged samples or in those aged without UV radiation.

Kobayashi et al. [13] studied the effect of the gas barrier properties of the backsheet on the degradation of pc-Si PV modules under a combined UV/DH accelerated test. In this study, the $P_{\max}$ of the modules was decreased due to the corrosion at the finger electrode, caused by the formation of acetic acid by hydrolysis of the EVA. It was observed that the gas barrier properties strongly influenced the degradations of the PV modules during the DH test. This was not the case when the modules underwent the sequential UV/DH test: the degradation mechanisms of the modules started at the same time or even earlier than for the DH test. These results show the importance of combined tests to reflect on natural outdoor degradations.

Recently, Mansour et al. [14] examined the effect of the backsheet permeation properties on the encapsulant degradation to understand the reliability of PV modules under a combined accelerated UV/DH test. Thermal oxidation was observed after 500 h of DH test for the PA-based backsheet cells and 1500 h for the PET-based cells of the DH test (air 60 °C/85% RH). This phenomenon is attributable to the higher oxygen transmission rate (OTR) within the PA-based backsheet which induced the photo-oxidation of the EVA.

Shi and Jin [15] tested the durability of new polymeric backsheets on amorphous silicon cells (an FF-based backsheet, a TPT-based and a CPC-based one). The researchers performed several IEC 61215 tests, including an extended 4000 hour DH test and a UV irradiance test. The main cause of the degradation was the corrosion created by the moisture. The cracks in the backsheets allowed water ingress and generated a decrease in the maximum power of the PV cells according to the backsheet technologies. Backsheets play a significant role in the lifetime durability of PV modules.

The maximum power of the PV modules decreases strongly according to the backsheet technologies used. In the IEC 61215 standard, a preconditioning of 15 kWh/m^2 UV dose should be applied before 1000 hours of damp heat for the qualification of photovoltaic modules. It was shown in the state-of-the-art that an increased UV dose for the preconditioning intensified the degradation of the PV modules during the following DH test. Hence, we chose in the present study to consider an augmented UV dose for the preconditioning followed by a prolonged DH test and to compare the obtained results with an extended DH test. A sequential and extended tests were performed in our case on encapsulated amorphous silicon PV cells. The characteristics of the modules were monitored along the accelerated tests with visual inspection to analyze the degradation of the amorphous silicon mini-modules. The paper is structured as follows. First, the samples, the protocol, the equipments for the accelerated tests and the characterizations are described. The obtained results are then shown and analyzed before concluding.

2 Experimental equipment and method

The accelerated tests were performed on four amorphous PV mini-modules of size $150 \times 150 \times 3\,\mathrm{mm}^3$ manufactured by the SOLEMS company (Palaiseau, France). The encapsulated cells are composed of a soda-lime float glass plate with a thickness of 3 mm on which a fluorine doped-SnO_2 layer is first deposited by chemical vapor deposition, which is a relatively high-temperature process to crystallize the SnO_2. The thin silicon PIN junction of 0.26 µm thickness is then deposited on the substrate with an accuracy of ±15% and is next encapsulated with EVA. The cells are finally sealed with a PET-based backsheet by being heated at 140 °C for 30 min at a pressure of 1 bar.

The main electrical specifications of these PV mini-modules are: the maximal power of the cells is 0.93 W, the maximal current 92 mA, the maximal voltage 7.5 V, the short-circuit current 130 mA and the open-circuit voltage 11.2 V at Standard Test Conditions (STC).

All the a-Si mini-modules were exposed to 85 °C and 85% relative humidity damp heat (DH) prolonged treatment for 5000 h representing five times the duration specified by the IEC 61215 standard for qualification tests. For two of the four mini-modules, the DH test was preceded by a severe UV preconditioning with incident radiation on their front face, applying 30 times the dose of 15 kWh/m^2 at a temperature of 50 °C as prescribed by the IEC 61215 standard, in order to enhance the degradation during the following DH test and to reduce the overall testing time.

The UV accelerated aging test was made in a chamber of type INVE 2000 having two 500 W mercury medium pressure UV lamps producing an incident irradiance fixed at 600 W/m^2 in the wavelength range [250–400 nm]. The temperature of the chamber was maintained at $50\,^\circ\mathrm{C} \pm 5\,^\circ\mathrm{C}$ during the UV test. These indoor UV exposure tests were performed using UVA-340 Helios Quartz fluorescent lamps emitting between 250 and 400 nm wavelengths.

The extended DH tests were carried out using a Binder MKF 140 climatic chamber at a constant temperature of $85\,^\circ\mathrm{C} \pm 2\,^\circ\mathrm{C}$ and $85\% \pm 2.5\%$ of relative humidity.

Photographs and I–V curves under STC conditions were captured initially and after progressive 15, 60, 100, 200, 300, 400, 500 and 600 kWh/m^2 UV doses. During the DH test, the photographs and I–V curves were captured each 100 hours, but, for the readability, the graphs were plotted with a 500 h interval for the time. Each I–V curve is the average result of three graphs based on 1000 points of measurement to ensure repeatable and reliable values. Also, two PV mini-modules were tested to check the discrepancies between the samples. A careful visual examination was performed at each step and also, the short-circuit current I_{SC}, the open-circuit voltage V_{oc}, the maximum power $P_{\max}$ and the fill factor FF were extracted from the measured I–V curves.

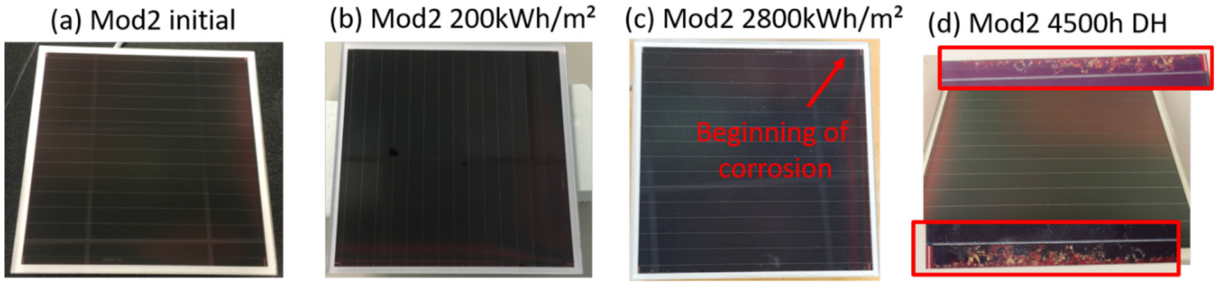

Fig. 1. Evolution of the aspects of a-Si PV mini-modules under gradual UV doses and DH.

The *I*–*V* characteristics of the solar mini-modules were acquired preceding the UV test and for the several aging exposures employing a class A solar simulator (LS1000-6S-002, Solar Light) with a source meter (2651A, Keithley) using 4-wire parallel voltage sensing terminals to exclude the loss in the current-carrying cables. The light source of the solar simulator is a 1000 W xenon lamp with an AM 1.5G filter. The irradiance non-uniformity is evaluated at ±5% (class B) with a maximum intensity of $1000\,\mathrm{W/m^2}$ on a $16 \times 16\ \mathrm{cm^2}$ area. With a temperature-controlled vacuum mount providing an electrical back contact, the temperature is maintained at 25 °C during the measurements to respect the STC conditions for uniform comparisons of solar PV modules. The accuracies of the source meter for the current and the voltage in the range of 1 A and 1 V are 0.08% and 0.02% respectively. To reduce the error generated by the class B uniformity of the solar simulator, the *I*–*V* measurements were taken for each mini-module in the same position. It should be noted that after 3000 h of the DH test, the lamp of the solar simulator had to be replaced due to aging, and the experiment was resumed with a new xenon lamp to complete the full duration of the study. All other experimental conditions and parameters remained constant throughout the experiment, ensuring the consistency and validity of the results.

3 Results and discussions

3.1 Visual inspection and observations

Visual inspection images of the amorphous mini-modules for the different UV doses and DH times are shown in Figure 1. Figure 2 displays the images of the amorphous mini-modules after the extended DH test.

Prior to the tests, we noticed a slight color variation on the surface of the module. The amorphous silicon is deposited on the substrate by PECVD, e.g. *Plasma-Enhanced Chemical Vapor Deposition*, with a uniformity of ±15%. This brown coloration is the result of the variation in the thickness of this 260 nm-thick silicon layer.

After 2800 h of the sequential UV/DH test and as a consequence of moisture penetration inside the encapsulated cell, localized corrosion was observed at weak points corresponding to the positive and negative terminals (weld joints) of the encapsulated cell as can be seen in Figures 1c and 2c. After 4600 h of DH test, delamination of the backsheet was observed for all the samples as depicted in Figures 1d and 2d.

During the DH test, water penetrated the module and generated corrosion around the ribbons. This phenomenon is generally due to the hydrolysis of EVA which creates acetic acid in the module, as reported in the studies of Bauermann et al. [9], Owen-Bellini et al. [11], Masuda et al. [7] and Hagihara et al. [3].

The delamination of the backsheet had already been observed in other studies such as those of Owen-Bellini et al. [11] and Masuda et al. [7]. However, we did not notice any delamination between the cover glass and the encapsulant contrary to the two studies mentioned above. This phenomenon could be explained by the difference in the gas barrier properties between our backsheet and those stated in the two previous researches. As mentioned in the articles of Kobayashi et al. [13], Shi and Jin [15] and Mansour et al. [14], the backsheet properties have an impact on the quantity of water penetration and therefore on the appearing time of related degradations like the delamination between the glass and the EVA.

Indeed, the degradation of any component of a PV module component (delamination, cracks, etc.) may enable moisture and oxygen to penetrate the solar cell, which in turn induces corrosion. As illustrated in the schematic diagram shown in Figure 3, moisture may either penetrate from the edge of the encapsulated cell into the EVA, facilitated by the delamination of the backsheet, or directly from the backsheet aided by cracks.

As back contact of the a-Si solar cell, a coating of aluminum and nickel is placed during the manufacturing process on the silicon. When water vapor reaches the silicon-aluminum interface, the electrical field is modified, and an opposite field is generated. This phenomenon is called a counter diode. It is materialized in Figure 4 by the inversion of the *I*–*V* curves, even more noticeable on the PV cell that underwent the sequential test.

This observation proves that the water penetrated the encapsulated PV cell, though it was not possible to identify the path taken by the water to join this interface.

As shown in Figure 4b, the measurement of the *I*–*V* parameters, especially the V_{oc} value, was not feasible for module 3 by reason of the counter diode effect. The phenomenon appeared at around 1000 h of the DH test and made the V_{oc} measurement impossible after 3000 h of the DH test.

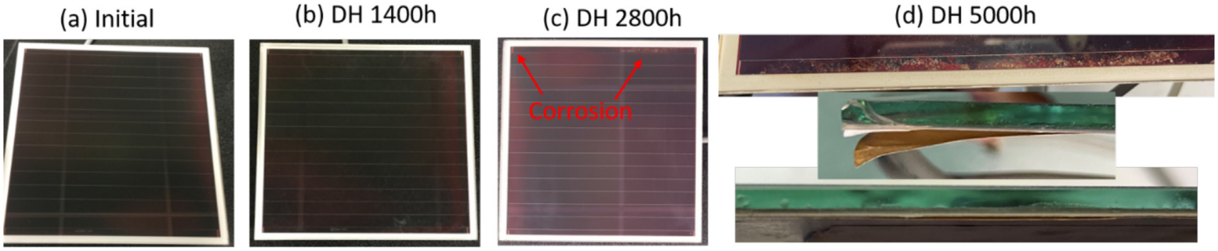

Fig. 2. Evolution of the aspect of a-Si PV mini-modules under DH.

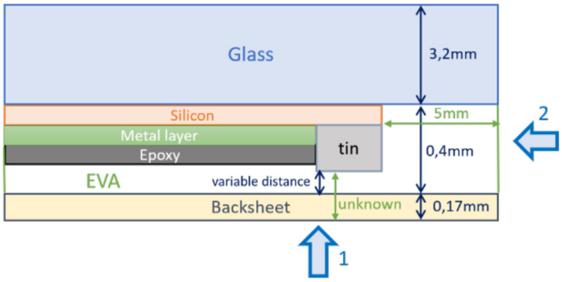

Fig. 3. Schematic of the encapsulated a-Si encapsulated cells with the possible two paths explaining humidity ingress.

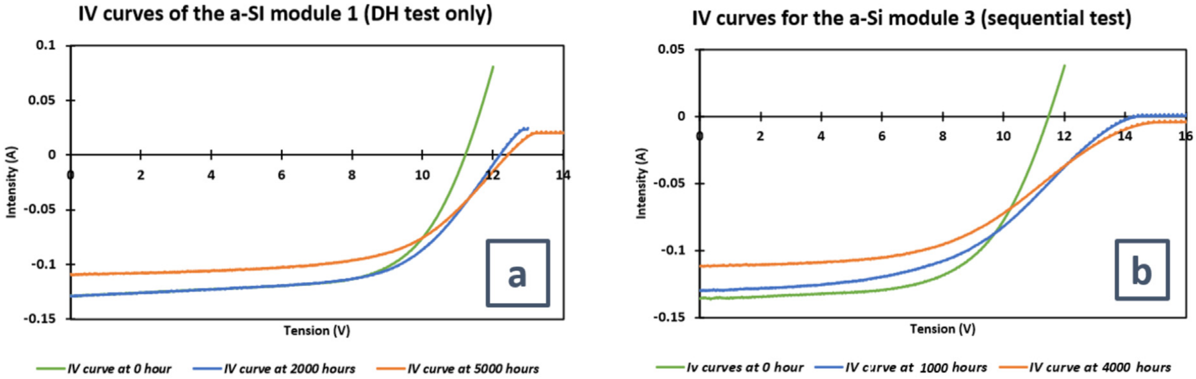

Fig. 4. I–V curves of the four a-Si PV mini-modules during the DH.

3.2 Performance degradations

Figure 5 shows the evolution of I_{sc} during the sequential and the extended DH tests. On these curves, a decrease can be seen down to 81% and 85% for the mini-modules at the end of the test, after 4500 h and 5500 h of damp heat.

As depicted in Figure 5, the short-circuit current decreases significantly with the exposure time of the damp heat testing. Moreover, the drop in the short-circuit current I_{sc} is more pronounced for the modules that had gone through a sequential UV/DH test (Fig. 5b). An increase in the short-circuit current can be observed during both the tests. The interpretation of this variation was attributed to a slight annealing effect at the interfaces.

This slow decrease in the current is due to the presence of corrosion, which also has an impact on the maximal power of the cells. Kobayashi et al. [13] found similar behavior for the I_{sc} degradation during their DH and sequential UV/DH tests. They concluded that the I_{sc} reduction originated from the corrosion of the finger electrodes because of the acetic acid generated from the EVA.

Figure 6 shows the evolution of the P_{max} during the sequential and the extended DH tests. The P_{max} of the modules was determined every 500 h of exposure. At the beginning of the experiment, an improvement in the P_{max} was observed, reaching a peak of 1.032 W after 500 h of the DH test, and 1.024 W after 250 h during the

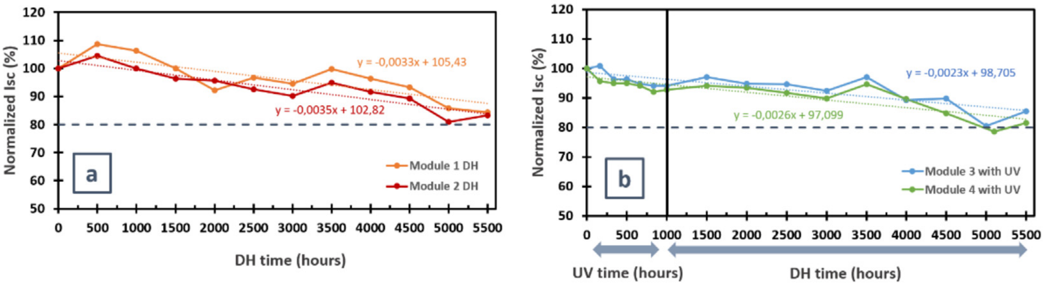

Fig. 5. Degradation of I_{sc} during DH test (a) and the sequential UV/DH test (b).

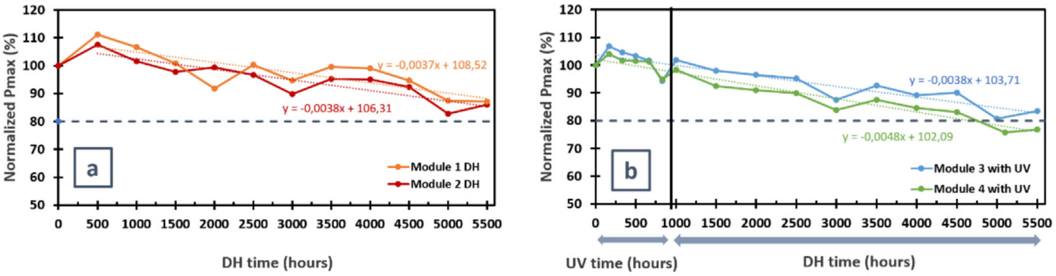

Fig. 6. Degradation of P_{max} during DH test (a) and the sequential UV/DH test (b).

sequential UV/DH test resulting in an improvement of 11.9% and 7.5% respectively. This amelioration of the maximal power at the beginning of the DH test could be explained by the temperature of 85 °C, applied during the tests, which improved the quality of the interfaces (annealing effect). This phenomenon could also be observed to a lesser extent for the sequential test when the UV chamber temperature was 50 °C.

After 1500–2000 h, the P_{max} of the modules exposed to the DH test (Fig. 6a) began to decrease, and it continued to do so for the prolonged exposure times, reaching approximately 85% of its initial value after 5000 h of exposure.

On the other hand, similar behavior was observed for the P_{max} of the modules exposed to the UV/DH sequential test. However, it started to decrease after almost 1000 h of exposure and reached less than 80% of its initial value after 5000 h.

It is worth noting that the replacement of the xenon lamp after 3000 h of DH test caused an upward offset for all the electrical parameters beyond 3000 h of time. This increase is visible in the interval between 3000 and 3500 h in Figures 5 and 6.

According to the IEC 61215 standard, 1000 h of DH testing is comparable to 20 years under real operating conditions in a Florida-type climate. Based on this assumption, the degradation rate of the a-Si modules would be 0.2%/year, which means that P_{max} would remain far above 80% of its initial value after 20 years of use. The present qualification test is satisfactory, and the warranty is strongly verified.

These results show that the amorphous silicon-encapsulated cells without UV exposure have better performances than those with the sequential test as expected, but the preconditioning effect is not as significant here as in the studies of Ngo et al. [8], Kobayashi et al. [13] and Hagihara et al. [3]. A sufficient UV dose to be applied for enhancing the degradation has to be found. A compromise should be determined for the test time required to reach this dose.

4 Conclusion

The DH and UV tests were combined to analyze their effects on amorphous PV mini-modules. The severe DH test substantially degraded the encapsulated cells as expected. The UV preconditioning, before performing the DH test, had no significant impact on the performance degradation of the encapsulated cells. This result is different from the other studies, where the preconditioning generally accelerates the performance degradation of the cells. The difference could be explained by the quality of the materials used, especially the solar glass which blocks the UV rays.

Delamination and corrosion were also observed on the amorphous silicon encapsulated cells after 2800 h of the DH test. These degradations are the consequences of water ingress in the PV modules. The values of the water vapor transmission rate of the backsheet could explain the occurrence speed of these degradations, as suggested in another study. These severe accelerated tests show that the amorphous cells, manufactured by SOLEMS, remain above

80% of the $P_{\max}$ after 5500 h of the DH test. According to the IEC 61215 standard, 5500 h of DH test should correspond to a lifetime of 110 years.

Perspective 1:

One may wonder why our amorphous silicon modules kept high performances during accelerated tests compared to the modules tested in other researches. Different parameters could explain our results such as the WVTR water vapor transmission rate or the OTR oxygen transmission rate (responsible for the backsheet quality), or the UV radiation transmission of the glass. The study of these parameters could be the goal of further research.

Perspective 2:

The results and the reduced impact found for the severe UV preconditioning highlight that the UV dose prior to the DH test needs to be optimized with regard to the test duration and the degradation effects.

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Author contribution statement

Julia VINCENT took on the task of writing this manuscript. The experimental data acquisition and the electrical measurements were performed by Julia VINCENT and Venkata Ramana POSA. The data interpretation and the analysis of the electrical behaviors were carried out by Anne LABOURET and Mustapha EL YAAKOUBI. Ali KHOUZAM and Pierre-Olivier LOGERAIS provided critical feedback and contributed to the shaping of this research work. All authors have reviewed the results and have approved on the final version of the manuscript.

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