DEVELOPMENT AND APPLICATION OF NEW EXTENDED-STRESS TESTING SEQUENCES TO CHARACTERIZE DURABILITY OF BIPV MODULES

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ABSTRACT: As current standards do not necessarily guarantee the long-term performance of building integrated photovoltaic modules, new extended-stress testing sequences for BIPV modules have been developed and put into practice. Three sequences have been proposed based on existing standards and methods: 1) Mechanical Stresses and Environmental Actions; 2) Thermal Fatigue; 3) Combined UV and Thermal Fatigue. The sequences have been tested by application in two innovative BIPV products, the Flexbrick BIPV module and a composite BIPV module developed by Tecnalia, as well as conventional glass-glass PV modules used as reference samples. The characterization of the samples along the degradation tests shows their performance evolution in front of combined stress agents inherent to the building integrated environment, and it validates the use of the developed sequences in the evaluation of the long-term durability of BIPV solutions in real operation conditions.

Keywords: Accelerated Testing, BIPV (Building-Integrated PV), Durability and reliability, Performance testing.

1 INTRODUCTION

As global PV installations reach new record highs every year, many efforts aim at developing and implementing distributed integrated photovoltaic (PV) technologies that bring energy production and consumption closer together. In this line, building integrated PV (BIPV) is an innovative technology solution that turns traditional building components into active energy producing devices. It offers a path towards the decarbonisation and energy resilience of the urban environment, by reducing energy consumption and greenhouse gas emissions of buildings. However, so far the adoption of this technology has been restricted by lack of knowledge and guidance on designing BIPV systems.[1]

One of the key aspects difficulting the application of BIPV at european level is the widely varied regulatory framework that changes from country to country.[2] On the other hand, there is a lack of standards tailored for BIPV products that will guarantee their long-term performance in the building environment.

Current sequences described in IEC 61215, and required for BIPV products by IEC 63092-1, are not intended or able to demonstrate long term performance in all locations. [3,4] Because of that, codes like IEC TS 63209-1 already proposed extended-stress sequences for common PV modules, but nothing equivalent exists for BIPV modules. [5]

For this reason, in this work new extended-stress testing sequences for BIPV modules have been developed and put into practice based on existing standards and methods. These would allow already stablished BIPV modules and technologies to demonstrate their reliability for the long-term durability, safety and efficiency requirements of building integrated applications.

Three sequences have been developed: 1) Mechanical Stresses and Environmental Actions; 2) Thermal Fatigue; 3) Combined UV and Thermal Fatigue. The sequences have been developed so that different sequences of the IEC 61215 and ISO 12543-4 standards are also complied with in order to avoid duplication of effort.

2 METHODOLOGY

2.1 Mechanical Stresses and Environmental Actions sequence

A new extended-stress sequence has been proposed for BIPV products combining mechanical testing with environmental ageing actions, based on IEC 63092:2020, sequences C and E of IEC 61215-1:2021, and sequence 2 of IEC TS 63209-1. Figure 1 shows the testing procedure defined for the Mechanical Stresses and Environmental Actions sequence. 1 sample is subjected to the whole sequence, 3 samples are subjected to every test except for the hail test, and 2 samples only undergo the environmental actions.

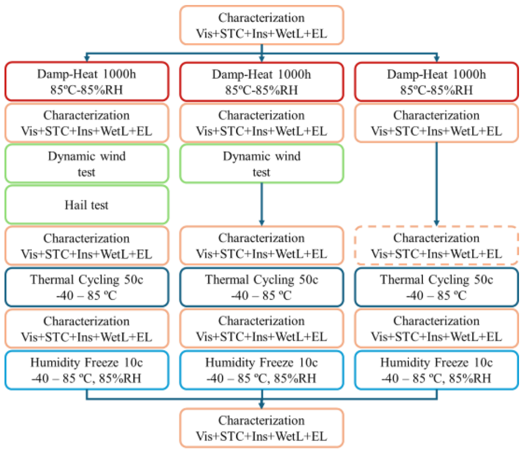

Figure 1: Testing procedure defined in the Mechanical Stresses and Environmental Actions sequence

One of the main novelties is the replacement of the static and dynamic load tests by the new and more realistic wind load test. The dynamic wind test consists of applying different wind level loads using a fan to verify how it affects the test specimen. However, this new test has been included for research purposes, and the sequence could also be performed applying the static and dynamic mechanical load tests of IEC 61215-1:2021 instead. The hail test is performed using steel balls with increasing impact energy.

At intermediate stages of the testing sequence, the BIPV modules are characterized with several techniques including: Visual inspection, to detect any visual defects in the module (IEC 61215-2 MQT 01); Performance at STC, to determine the electrical performance of the module at standard test conditions (STC) i.e. 1000 W/m^2 and 25 ºC, obtaining its IV curve and their parameters (Voc, Vmmp, Isc, Immp, Pmmp, Rs, Rsh) (IEC 61215-2 MQT 06.1); Insulation test, to detect whether or not the module is sufficiently well insulated between live parts and accessible parts (IEC 61215-2 MQT 03); Wet leakage current test, to evaluate the insulation of the module under wet operating conditions (IEC 61215-2 MQT 15); and electroluminescence (EL) imaging, to detect potential cracks or defects in the cells or interconnections. The execution of this sequence takes approximately 2 months.

2.2 Thermal Fatigue sequence

An extended-stress sequence has been proposed for BIPV products based on extended thermal stresses. The Thermal Fatigue sequence is the sequence 1 of IEC TS 63209-1 (three times 200 cycles of thermal cycling) with intermediate characterizations, as shown in Figure 2. The execution of this sequence takes approximately 2.5 months, and performing it also includes the sequence D of IEC 61215-1 (200 cycles of thermal cycling).

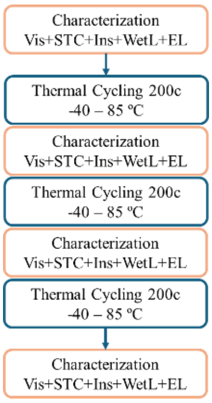

Figure 2: Testing procedure defined in the Thermal Fatigue sequence

2.3 Combined UV and Thermal Fatigue sequence

The new Combined UV and Thermal Fatigue sequence (see Figure 3) is based on IEC TS 63209-1 sequence 3 but replacing the UV test by the ISO 12543-4 UV test, which includes slightly higher quantity of UV accumulated irradiation together with visible radiation. The ISO 12543-4 is the reference standard for laminated glass durability testing. Additional samples are necessary for the humidity and high temperature test also required by the ISO 12543-4, so that this standard can be fulfilled when completing the sequence.

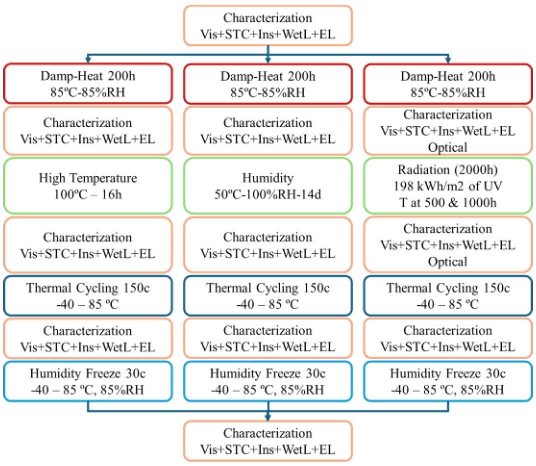

Figure 3: Testing procedure defined in the Combined UV and Thermal Fatigue sequence

In the development of the subsequence containing the extended 198 kWh/m^2 UV exposure, an additional optical characterization of the samples is performed before and after this specific test, according to ISO 12543-4. The execution of the whole sequence takes approximately 4.5 months.

3 EXPERIMENTAL

3.1 Samples for experimental application

The sequences were applied on different innovative BIPV module technologies (see Figure 4), including photovoltaic bricks (Flexbrick BIPV module), lightweight BIPV modules based on composite developed by Tecnalia, and reference laminated glass PV modules.

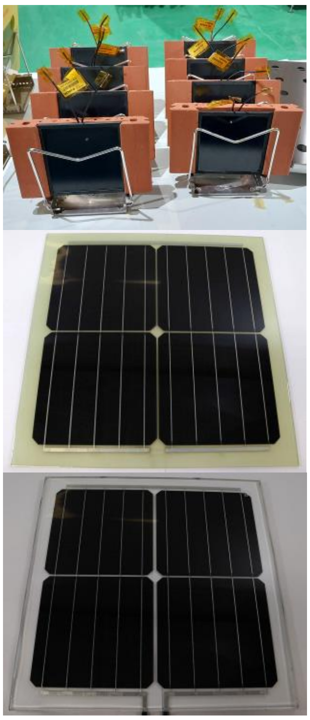

Figure 4: Flexbrick BIPV modules (top), composite BIPV modules (center), and reference glass PV modules (bottom).

The photovoltaic brick product is the evolution of a construction system for external façade panels called Tejido Flexbrick® with some modifications to integrate photovoltaic panels. This can be applied in an interwoven steel wire mesh to control sunlight for energy production and lighting. The composite BIPV modules consist of monocrystalline silicon 5 busbar solar cells encapsulated in composite material providing a 3 mm-thickness to the modules. Finally, reference glass PV modules comprise monocrystalline silicon 5 busbar solar cells laminated with EVA between 4 mm-thick tempered extraclear glass. Table 1 shows the test-sequences performed in each type of module technology.

Table I: Test-sequences performed in each type of BIPV module technology

	Flexbrick BIPV module	Composite BIPV module	Reference glass PV module
Mechanical Stresses & Environmental Actions	X	-	X
Thermal Fatigue	-	X	X
Combined UV & Thermal Fatigue	-	X	X

In the case of the Flexbrick BIPV modules, 8 samples were tested on the Mechanical Stresses and Environmental Actions sequence. Half of them had a rubber framing (G samples) and half had a textile framing system (T samples). From each kind of frame one sample underwent the subsequence with no mechanical test, one module performed the dynamic wind test, and two samples went through the dynamic wind test followed by hail impact testing.

As for the composite BIPV modules, 3 replicas were tested on the Thermal Fatigue sequence. Besides, 3 replicas went through each subsequence of the Combined UV and Thermal Fatigue sequence (9 samples in total).

Finally, the same number of reference glass PV modules as the composite samples went through the Thermal Fatigue sequence and the Combined UV and Thermal Fatigue sequence. Besides, a glass reference PV module sample was tested for the non-mechanical tests in the Mechanical Stresses and Environmental Actions sequence.

3.2 Module characterization

Current-voltage (IV) curves were recorded for the BIPV modules employing an Endeas QuickSun 600 lab solar simulator (class A+). This equipment's integrated high resolution electroluminescence (EL) image acquiring system was used for EL imaging of the samples. For the insulation test and wet leakage test, a Sentry 30 Plus AC//DC/IR Hipot Tester by QuadTech was employed.

3.3 Accelerated degradation test equipment

The environmental degradation tests based on IEC 61215 Damp-Heat, Thermal Cycling and Humidity Freeze assays were carried out in CTS C-70/350S and CS-70/2000/S climatic chambers.

The extended UV degradation test was performed in accordance with EN ISO 12543-4:2021. To this end, the test specimens were placed 1,100 mm away from the 16 ULTRAVITALUX lamps that formed a field of (1 x 1) m. The positioning of the test specimens was as established by standard EN ISO 12543- 4:2021 and their temperature was maintained at (45±5) ºC.

4 RESULTS AND DISCUSSION

4.1 Flexbrick BIPV modules

Figures 5 and 6 show the evolution of the electrical parameters of the Flexbrick BIPV modules in the development of the Mechanical Stresses and Environmental actions sequence. During the tests the measurements of the maximum power (MP) point was unstable, causing large fluctuation, either positively or negatively, of the relative parameters (Pmp, Imp, Vmp). Apparently, this fact was due to the partial oxidation of the cable during the tests, causing variations in the series resistance. This defect seems to be not due to the product itself but rather to an insufficient protection of the cable terminals after the cut, even if they were protected with Kapton tapes as shown in the previous picture. Since the Pmpp is the parameter to be checked to evaluate the result of each test, this fact caused uncertainty. The performance at STC was checked by evaluating the Isc and Voc parameters instead, which are in principle not significantly affected by changes in the series resistance.

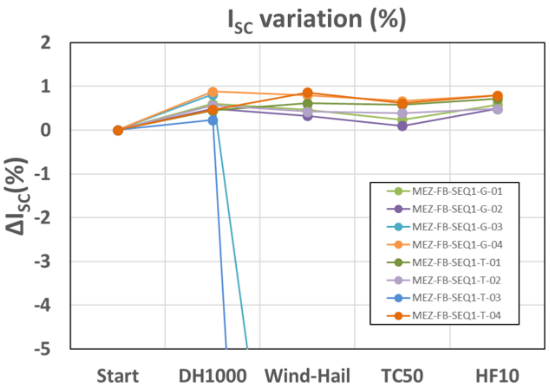

Figure 5: Cumulative percentage variation of Isc after each test of Mechanical Stresses and Environmental actions sequence for Flexbrick BIPV modules.

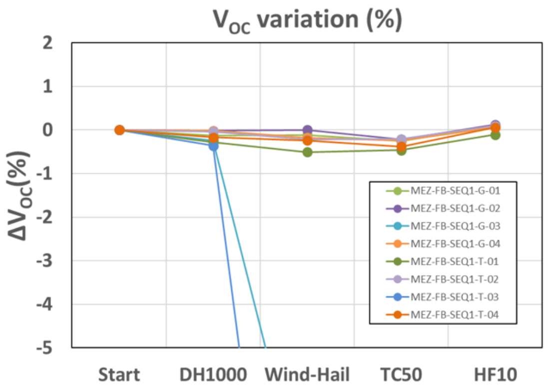

Figure 6: Cumulative percentage variation of Voc after each test of Mechanical Stresses and Environmental actions sequence for Flexbrick BIPV modules.

The evolution of Isc and Voc values indicate that very small variations were observed in the combined test sequence. The slight increments in the Isc parameter may be due to slight variation in the optical characteristics of the front layers or related to other unknown effects. Also, a variability of ±0.5% due to the measuring system should be considered. Only the samples undergoing the

7J impact test suffered fractures causing the loss of Isc and Voc. However, the products withstood the 2J hail impacts and the dynamic wind test with no disturbance. In general, the visual inspection, EL imaging, insulation tests and wet leakage test showed no significant variation in the samples. Therefore, the sequence shows that the Flexbrick BIPV module offers a robust solution for combined mechanical and environmental factors inherent to the building environment.

4.2 Composite BIPV modules

Figures 7 and 8 show the evolution of the electrical parameters of the composite BIPV modules in the development of the Thermal Fatigue sequence and the Combined UV and Thermal Fatigue sequence.

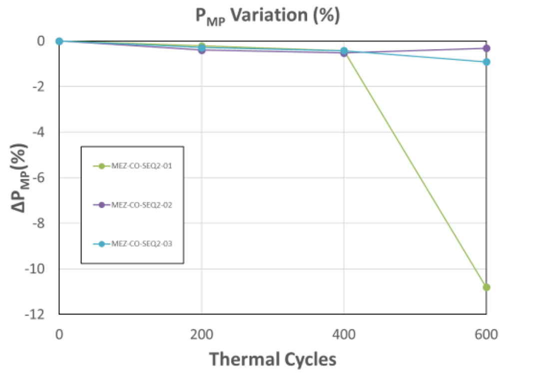

Figure 7: Cumulative percentage variation of Pmp after each test of Thermal Fatigue sequence for composite BIPV modules.

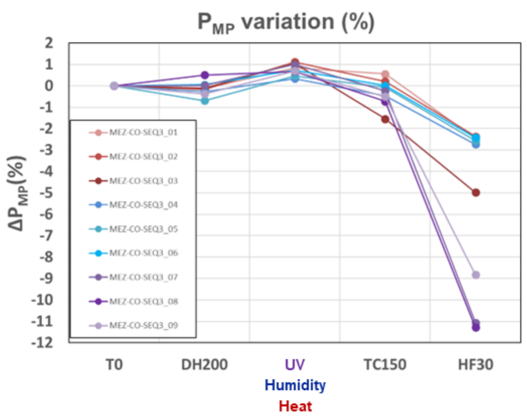

Figure 8: Cumulative percentage variation of Pmp after each test of Combined UV and Thermal Fatigue sequence for composite BIPV modules.

The Thermal Fatigue sequence caused only minor degradation of the electrical parameters of the composite BIPV modules. The outlayer sample showing >10% Pmp loss suffered a fracture of its connectors during characterization and a FF reduction after reparation, so the power loss was not related to the test itself.

Regarding the Combined UV and Thermal Fatigue sequence, the TC150 and HF30 tests resulted in the strongest performance loss. In particular, the samples undergoing the strong UV radiation exposure showed a very sharp performance decrease in the Humidity-Freeze test. This was clearly observed in the visual inspection as the composite of these modules got an orange color after the final test causing a ~10% Isc loss. The effect underlines the importance of combined stressors in the degradation of BIPV modules, which can be evaluated by combined extended-stress test sequences as the ones proposed.

In both sequences, the EL imaging indicated no major variation in the samples. The insulation tests were also passed in all cases. The visual inspection revealed a strong coloration of the composite modules after the final humidity-freeze test, which was more severe in the sample that went through the strong UV radiation test.

The information provided could imply that the tested product would perform well integrated in BIPV systems, regarding the endurance against different environmental factors, except for a combination of high UV exposition together with strong freezing events with high relative humidity. Therefore, an increased UV protection could benefit the design of the BIPV solution.

4.3 Reference glass PV modules

Figures 9, 10 and 11 show the evolution of the electrical parameters of the composite BIPV modules in the development of the Mechanical Ageing and Environmental Actions sequence, the Thermal Fatigue sequence and the Combined UV and Thermal Fatigue sequence, respectively.

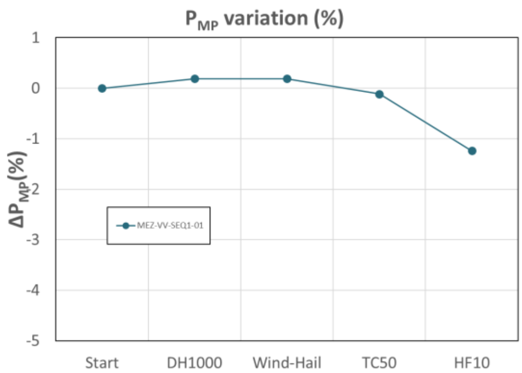

Figure 9: Cumulative percentage variation of Pmp after each test of Mechanical Stresses and Environmental Actions sequence for reference glass PV modules.

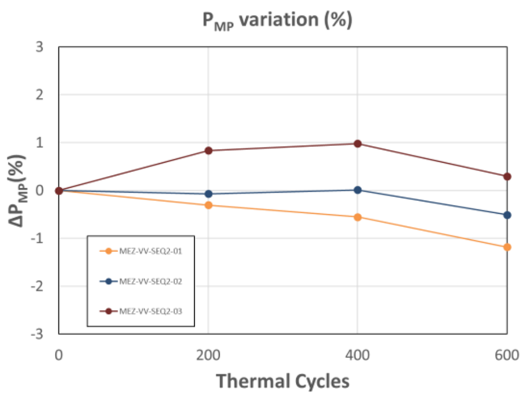

Figure 10: Cumulative percentage variation of Pmp after each test of Thermal Fatigue sequence for reference glass PV modules.

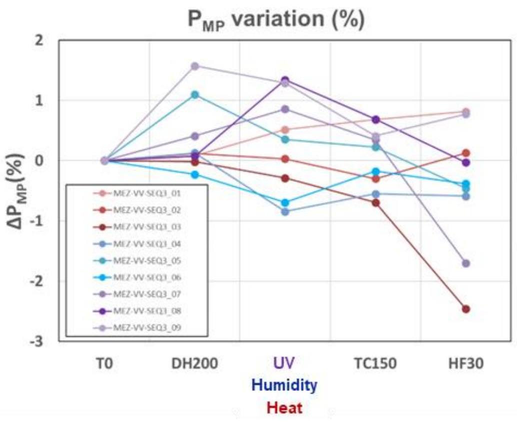

Figure 11: Cumulative percentage variation of Pmp after each test of Combined UV and Thermal Fatigue sequence for reference glass PV modules.

Throughout the Mechanical Stresses and Environmental Actions sequence, the reference glass PV module did not show any major degradation. It must be stated that only the environmental action tests were performed, skipping the mechanical stress tests, as this module was used as a reference for other BIPV module samples following the full sequence.

The Thermal Fatigue sequence caused minor degradation of the electrical parameters of the samples. The first 200 thermal cycles did generate some faults visible by EL imaging directly related to ribbon connection faults (see Figure 12), but these did not get worse in the following 400 cycles.

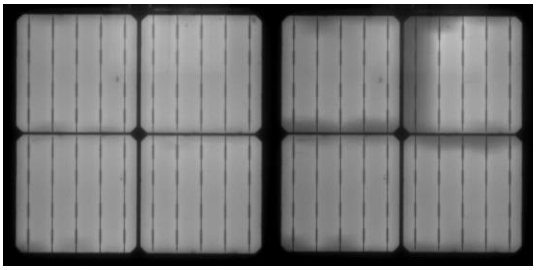

Figure 12: EL imaging of a reference glass PV module at the beginning (left) and after TC200 (right) in Thermal Fatigue sequence.

Regarding the Combined UV and Thermal Fatigue sequence, in general the cumulative variation of the power performance was below 5% in all cases. The degradation of the samples according to the visual and electroluminescence inspection was minimum (although the EL revealed again a slight disconnection of some ribbons due to thermomechanical movements in thermal cycling). Generally, the visual inspection of the samples showed no significant variation throughout the test sequences. The samples passed the insulation tests in all cases too. Therefore, it can be stated that the reference glass PV modules adequately withstood the test combinations comprising the different extended-stress sequences.

5 CONCLUSIONS

In this work 3 new extended stress sequences have been developed for and applied on innovative BIPV module concepts, which enable testing for their long-term reliability.

Although the sequences combine many stress factors and extended tests that could seem harsh for the devices, a significant part of the samples resisted them with no major degradation. The Thermal Fatigue was passed by all tested modules with little degradation. In contrast, the strong UV radiation test in the Combined UV and Thermal Fatigue sequence resulted to be severe for some BIPV solutions. All tested samples withstood the new dynamic wind load test and the Mechanical Stresses and Environmental Actions sequence with no disturbance, except for the fracture of some modules in higher energy levels of hail impact testing, with the added hardness of employing steel balls instead of ice balls, representing a worse case scenario.

During the development of the sequences, combined effects of different tests were observed in sample degradation. This highlights the importance of performing intermediate characterization steps during the sequences, in order to properly identify and understand the faults generated by these combined effects.

The proposed sequences provide information on the reliability and design improvement capabilities of innovative BIPV modules. This information can be key in the standardization of these new products and their acceleration towards commercialization.

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8 LOGO SPACE

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