OUTDOOR PERFORMANCE OF ORGANIC PHOTOVOLTAICS AT TWO DIFFERENT LOCATIONS: A COMPARISON OF DEGRADATION AND THE EFFECT OF CONDENSATION

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ABSTRACT

Tests on OPV mini modules, fabricated through a R2R process, in air and without hazardous solvents have been conducted in order to compare their outdoor performance, in Belo Horizonte, Brazil, and Bangor, North Wales, and assess the impact of the latitude and climate on the installation on the power generation and modules' lifetime. The test showed different profiles of degradation for each region and formulation, with a surprisingly faster degradation in Bangor. One of the possible sources of the increased degradation is the greater levels of condensation observed in Bangor. To verify the impact of condensation on the module stability, indoor tests have been conducted to relate the dew point depression to module degradation times. The results show that condensation is a significant stress factor in OPVs and should be considered more prominently in reliability studies.

KEYWORDS Organic photovoltaics, Module, Stability, Outdoor testing, Lifetime

1. INTRODUCTION

Organic photovoltaics (OPV) have developed rapidly in recent years, especially in terms of power conversion efficiency. With the development of new donor materials, fullerene and non-fullerene-based acceptors and the optimization of device design and morphology [1–5], efficiencies above 17% have already been achieved for both single junction [6] and tandem devices [7]. Costs are attractive and studies [8,9] show that mass-produced OPV can be a highly competitive alternative energy source, especially for building integrated photovoltaics (BIPV) and other applications that can benefit from its transparency and light weight , due to its cheaper large-scale production methods and the use of less materials. For its complete commercialization, though, it is still necessary to enhance the stability. Most of the progress reached in the field is related to record performance values and no relevant data on stability is usually presented to support the new materials [2,3,7,10,11]. In fact, only a few of the recent studies about OPV have stability studies [2,12] and with the recent increase of installations with this technology [13–16], it is crucial to determine the lifetime for customer warranties and expectations.

The introduction of the consensus tests that followed the International Summit on Organic solar cell Stability (ISOS) conference [17] in 2011 was an important milestone in the roadmap of OPV technology, since the standards for traditional PV technologies do not fit the specificities of OPV [18]. From that moment on, it became possible to reliably compare results from different institutions and assess the progress in stability studies. However, despite advances, the difficulty in predicting the lifetime of OPV modules remains. Indoor tests can stress samples with the factors that are known to affect the stability of organic modules - light, temperature and humidity - and accelerate degradation processes [19–22], but they fail to simulate the actual dynamics, where these factors act simultaneously and with variations that are somewhat unpredictable. Moreover, outdoor conditions are local and season dependent. Therefore, finding a correlation between indoor accelerated testing and the OPV lifetime is not easy. There are a number of important studies that have been carried out [23–26], but often they were conducted at a single geographic location or with low efficiency devices, based on the polymer poly(3-hexylthiophene-2,5-diyl)

(P3HT) and the fullerene phenyl-C61-butyric acid methyl ester (PCBM). In this work, two different OPV materials have been tested outdoors at operational conditions in two different locations (Belo Horizonte in Brazil and Bangor, Wales) in order to compare the stability at both locations.

2. EXPERIMENTAL

2.1 Sample preparation

The OPV devices used in this study were manufactured by CSEM Brasil following the inverted structure, as depicted in Figure 1. The modules were processed in a single station roll-to-roll (R2R) machine (Smart Coater SC09 from Coatema Coating Machinery GmbH, modified by CSEM Brasil) on a flexible substrate sputtered with indium tin oxide/metal/indium tin oxide (IMI), supplied by Oike, using non-chlorinated solvents. All layers were processed in air. A standard amine based polymer was used as electron transport layer (ETL) and polyethylenedioxythiophene:polystyrenesulfonate (PEDOT:PSS) as hole transport layer (HTL). Two blue commercial active layer formulations by Merck were tested, referred as first and second-generation (Gen-I and Gen-II respectively). Both inks are fullerene-derivatives based and differ in donor due to a small change in the Gen-II co-polymer for improved light stability. The six coated strips were serially connected by a silver top electrode 80% rich in Ag deposited via a flatbed semi-automatic screen printer, resulting in modules with 6 cells and total active area of 21.6cm^2.

(a) (b) (c)

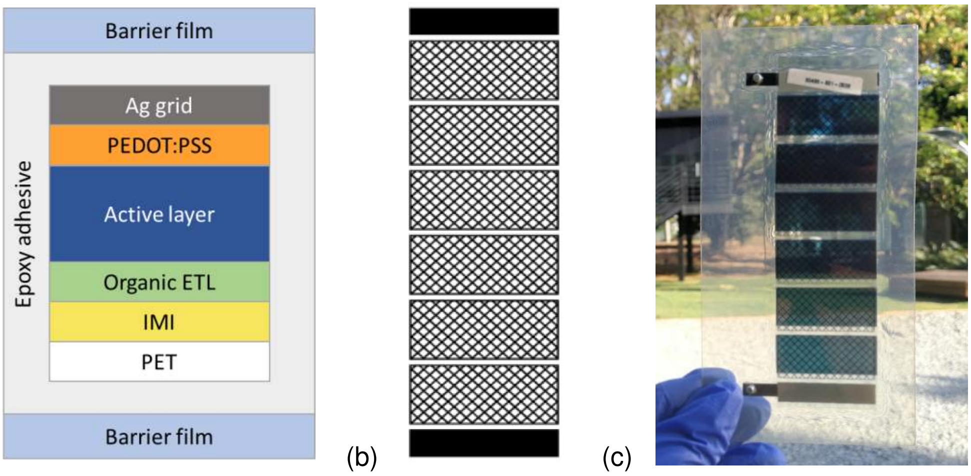

Figure 1 - Schematics of (a) individual layers and (b) the six cells connected as a module. (c) Encapsulated sample.

The samples were further encapsulated with a multilayer of PET-based barrier film with a water vapor transmission rate (WVTR) in the order of 10^{-3} gcm^{-2}day^{-1} from Mitsubishi, using a Delo epoxy-based UV-curable adhesive with barrier properties (6 gcm^{-2}day^{-1}), in a R2R lamination machine, built in house, which uses a nip pressure to reach a thin and homogeneous layer of glue of approximately 40 µm. The performance of the modules was first evaluated at CSEM Brasil under an AAA solar simulator, Wacom WXS-156S-10, AM 1.5G, with illumination of 1,000 W m^{-2}. Electrical parameters of the selected devices after encapsulation were: short-circuit current density, J_{SC} = (8.87 ± 0.09) mA cm^{-2}, open-circuit voltage, V_{OC} = (5.02 ± 0.03) V, fill factor, FF = (54 ± 3) % and power conversion efficiency, PCE = (4.0 ± 0.2) %, for Gen-I modules, and J_{SC} = (9.4 ±0.2) mAcm^{-2}, V_{OC} = (5.11 ± 0.02) V, FF = (57.0 ± 0.4) % and PCE = (4.56 ± 0.07) % for Gen-II. These results are averaged from 6 devices of each generation. In order to avoid any problems during the shipment, such as light degradation or mechanical stress, the samples were sent to Bangor in nitrogen bags, protected from humidity and light exposure, and sandwiched between rigid plates.

2.2 Outdoor test

The samples were subjected to the outdoor test in two different sites, Belo Horizonte (BH), Brazil (19.9° S, 43.9° W) and Bangor, Wales (53.2° N, 4.1° W), following the protocol of ISOS-O-2 [17] and using local existing testing installations and measurement systems. In both locations, the tilt angles were chosen as the optimum fixed tilt angle considering yearly generation [27].

3 modules were tested in Belo Horizonte, exposed to outdoor conditions on a rooftop on a rack facing North at an angle of 20° and connected to a measurement system that uses relay plates and a multiplexer. Current-Voltages (I-V) curves of each sample were taken automatically every hour and, when not under measurement, the modules were connected to resistive loads in order to operate close to the maximum power point (MPP). Weather data was collected with a weather station and the irradiance values were taken with a pyranometer (Solys 2 from Kip & Zonnen), tilted at the same angle. In this system, irradiance measurements were taken before and after each I-V curve in order to exclude data collected when there was important irradiance change, such as when clouds passed.

In Bangor, 2 modules were tested, orientated southwards at an inclination angle of 35º, also biased at MPP, with IV measurements every 10 minutes. Weather parameters were collected using a Davis weather station Vantage Pro and irradiance data was collected using calibrated silicon solar cells and a pyranometer, tilted at the same angle. Pictures of the setups are shown in Figure 2.

(a) (b)

Figure 2- Outdoor monitoring setup used to perform the tests in (a) Belo Horizonte, Brazil, at an angle of 20°, facing North, and (b) Bangor, Wales, with an inclination of 35°, facing South. The already existing installations and measuring systems were used.

2.3 Data analysis

The data was analyzed, based on the rules: (i) only using data points collected between 7:00 and 18:00; (ii) a range of 5% for each selected irradiance, i.e., (300 ± 15) W m^{-2}; (iii) exclusion of data points differing up to 30% from adjacent measurements, to eliminate measurement errors due to equipment failure or the effect of clouds/moving shades; (iv) in the case of Belo Horizonte, exclusion of data points where the irradiance measurements before and after each I-V curve differed more than 5%.

3. RESULTS AND DISCUSSION

3.1 Gen-I modules

Figure 3 (a-d) shows how the performance of the modules fabricated with the first-generation ink changed over time. The test was initialized in January 2018, which corresponds to winter in Bangor and summer in Belo Horizonte. Despite the lower irradiance levels in the winter season, modules in Bangor exhibited a higher degradation than those in Belo Horizonte (BH). For the test conducted in Bangor, the curve is clearly divided in two linear segments, the first one, up to 50 days, showing a steeper slope. Considering the data in Figure 4 , this seems to be connected with J_{SC}. The other electrical parameters, V_{OC} and FF, exhibited less relative variation with a minor increase in V_{OC} which is offset by a moderate reduction in FF. By contrast, modules deployed in Belo Horizonte show an exponential decrease in the first days, what is commonly called in the literature as *burn-in* [20], and a steady performance afterwards. The parameter that shows the greatest relative change was J_{SC}, which is usually attributed to the photoinduced dimerization of the fullerene acceptor [28,29]; FF and V_{OC} remained approximately constant. By analyzing the plots under different irradiance levels, it could be seen that the general shape of the degradation curves pattern is the same, although BH modules show higher PCE values under 150 W m^{-2}, which could be attributed to measurements on cloudy days and spectral mismatch. This difference was not as pronounced in Bangor. In either case, there was no visual sign of delamination or corrosion of the contacts.

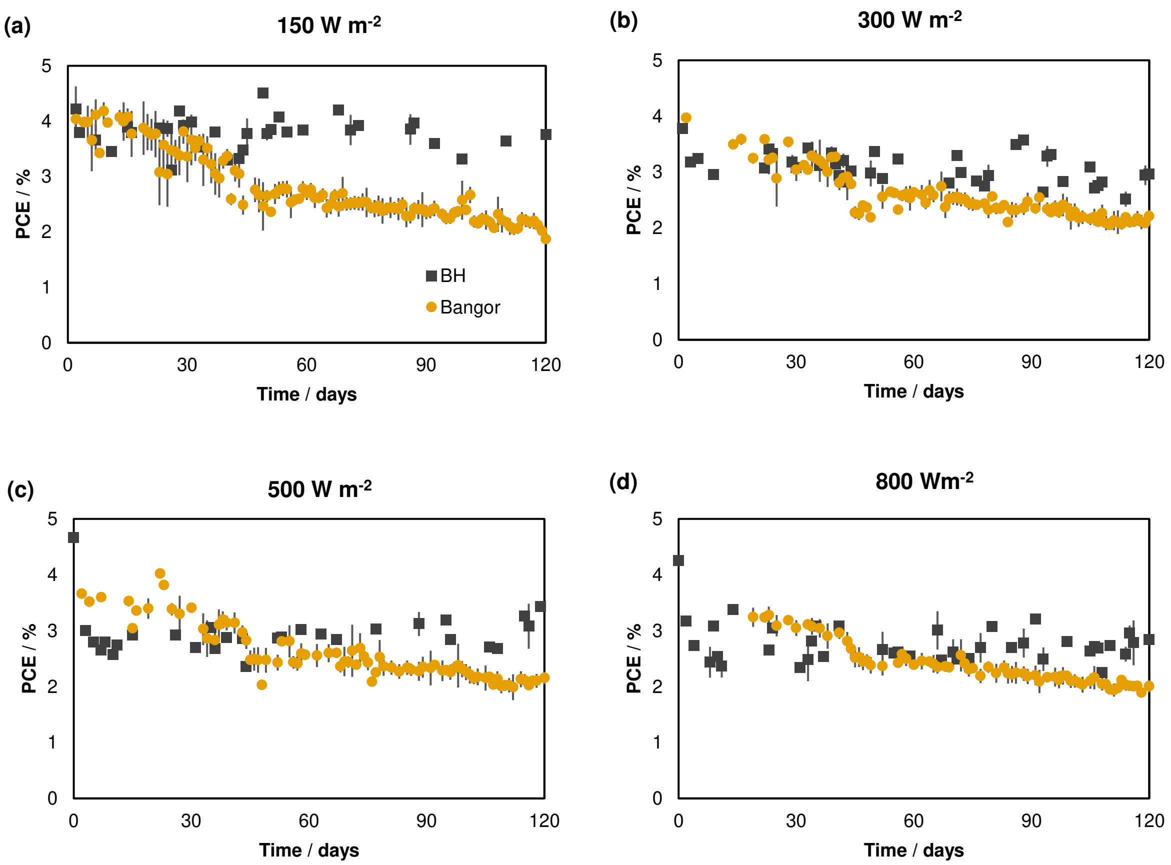

Figure 3 - Performance over time for Gen-I modules tested in Belo Horizonte and Bangor, measured at the irradiance of (a) 150 W m^{-2}, (b) 300 W m^{-2}, (c) 500 W m^{-2} and (d) 800 W m^{-2}. The test was started in January 2018. Error bars represent the standard deviation.

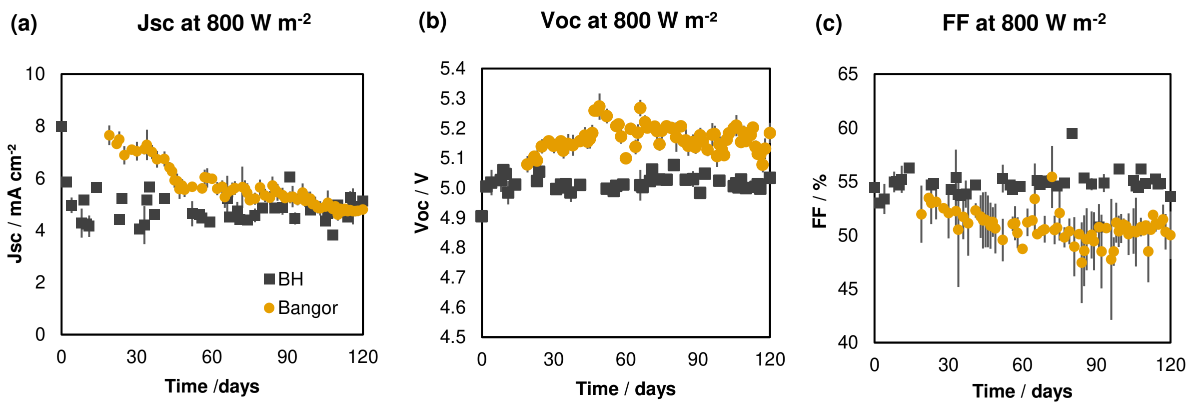

Figure 4 - Evolution of the electrical parameters of Gen-I modules at 800 W m^{-2}: (a) J_{SC}, (b) V_{OC} and (c) FF. Error bars represent the standard deviation.

In Bangor, the measured drop of J_{SC} is lower than in BH in the first days of testing, which is consistent with the lower level of irradiance in January in that region. The energy dose delivered in the period was 1025 MJ m^{-2} in Bangor, against 1837 MJ m^{-2} in Belo Horizonte. The lifetime of the modules was estimated based on a linear regression as the time to reach 80% of the efficiency after the burn-in (T80). In Belo Horizonte, Gen-I modules were expected to last 180 days, with a burn-in of 30%, while in Bangor, T80 was reached after 50 days.

The additional weather data collected during this period is shown in Figure 5. The change in slope observed for the modules in Bangor coincides with the period of increasing temperature. In Belo Horizonte, there was no significant change up to 90 days, when the temperature drops slightly. Overall, the temperature in Belo Horizonte was higher in Bangor, but the averaged relative humidity was similar (although the amplitude was significantly higher). These environmental conditions seemed at odds with the faster degradation observed in Bangor, which is discussed in more detail later.

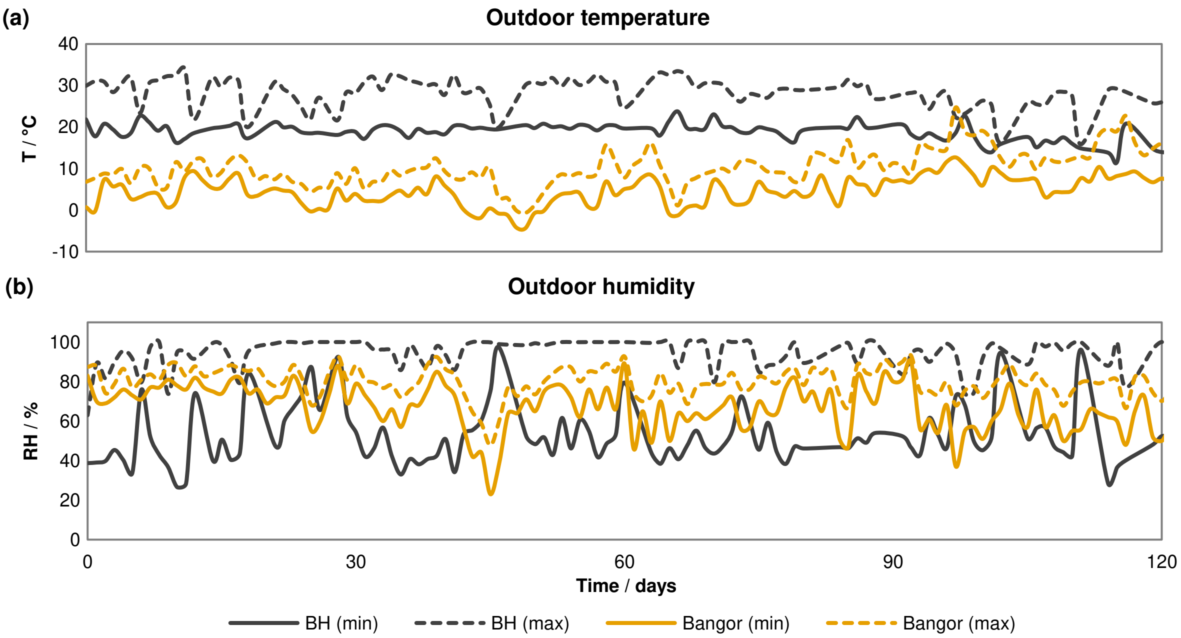

Figure 5 - Weather conditions during the first campaign, with maximum and minimum daily values of (a) temperature and (b) humidity.

3.2 Gen-II modules

A second generation of modules was tested using the same experimental procedure and number of modules as the previous test. Gen-II is a modified ink that aimed at better light stability, which was confirmed in indoor tests. Monitoring started in early Autumn in Belo Horizonte and Spring in Bangor and the PCE results are shown in Figure 6. As with the first campaign, Gen-II modules also exhibited a faster degradation in Bangor, but, in this case, the curve had a different shape: a high burn-in was noted, resulting in a ~ 25% loss in PCE, followed by a linear degradation thereafter. Comparing the different light levels, the degradation curve was very similar, although at 150W/m² the first data point depicts a higher PCE. This would result in a higher burn-in, but there is no evidence that modules would present a different pattern of degradation at different light levels; thus it is possible that the first measurement is not accurate, and could be a result of shading on the pyranometer at that moment of the IV tracing. In Belo Horizonte, the burn-in could not be easily seen, since the first data days were cloudy. However, considering that samples had very similar initial parameters, it is likely that these modules did not experience a high initial degradation and were, thus, more stable in Belo Horizonte. By considering the electrical parameters, shown in Figure 7, it can be seen that J_{SC} values decreased at a similar rate at both sites, whilst the V_{OC} and FF dropped at a greater rate in Bangor. A drop in Voc is usually seen when there is water penetration on the samples, which also causes an increase in series resistance and reduction of FF. Water is absorbed by the hydrophilic PEDOT:PSS HTL and increases the resistivity and modifies the HTL/phot-active layer interface, which can ultimately lead to delamination of the layers[19,30]. Data on series and shunt resistance are included in the Supplementary Information.

During the second campaign, the differences in the weather conditions were not as large as in the first case, as shown in Figure 8. However, the temperature and maximum levels of relative humidity daily values, as well as the energy dose, were higher in Belo Horizonte: 1800 MJ m^{-2} against 1505 MJ m^{-2} in Bangor. As with Gen-I modules, it is clear that the elevated ambient parameters in BH do not seem to increase the degradation rate of the OPV modules. The estimated lifetime for the modules in Belo Horizonte, was 279 days, against 90 days for modules in Bangor, considered after the burn-in of approximately 25%.

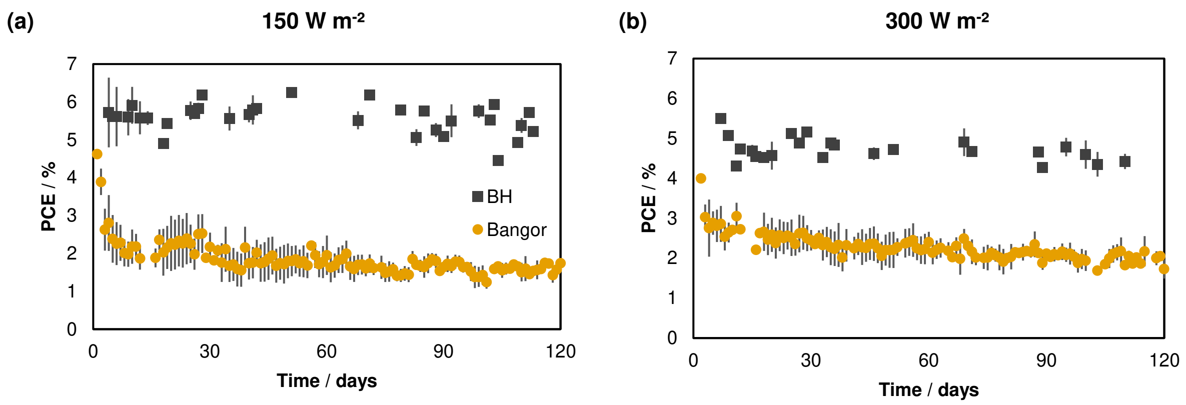

Figure 6 - Performance over time for Gen-II modules tested in Belo Horizonte and Bangor, measured at the irradiance of (a) 150 W m^{-2}, (b) 300 W m^{-2}, (c) 500 W m^{-2} and (d) 800 W m^{-2}. The test was started in May 2018. Error bars represent the standard deviation.

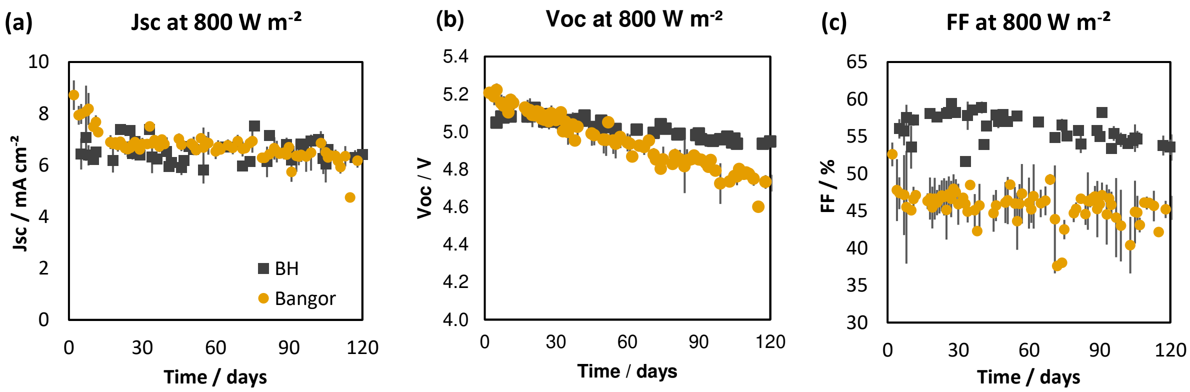

Figure 7 - Evolution of the electrical parameters of Gen-II modules at 800 W m^{-2} (a) J_{SC}, (b) V_{OC} and (c) FF. Error bars represent the standard deviation.

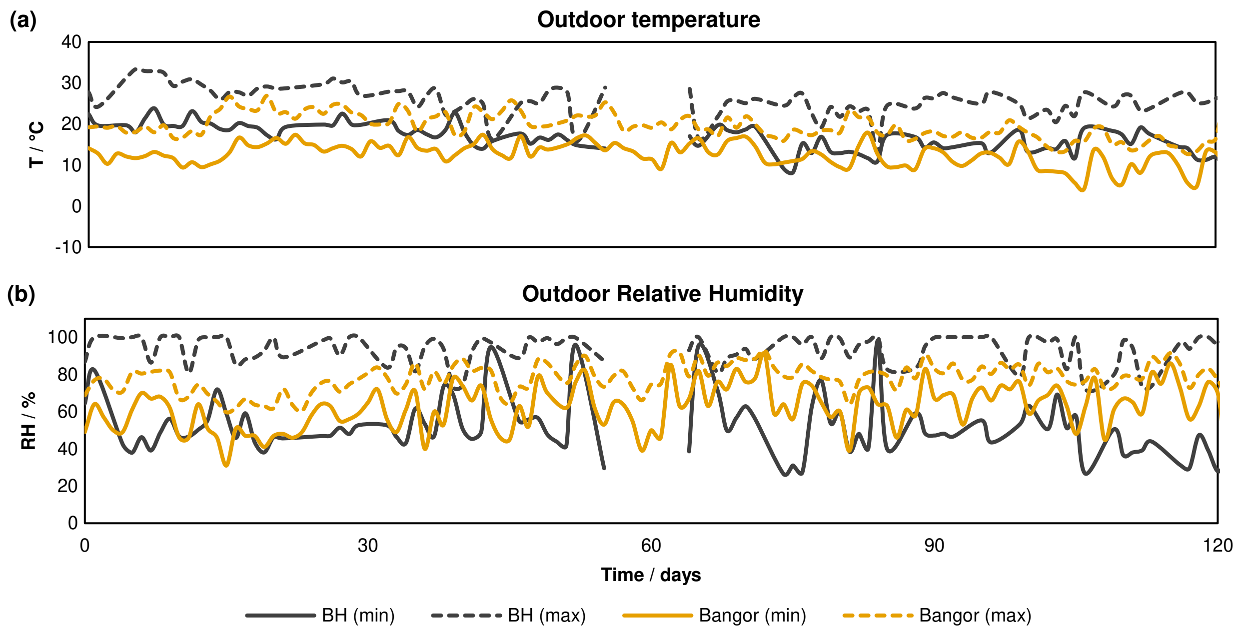

Figure 8 - Weather conditions during the second campaign, with maximum and minimum daily values of (a) temperature and (b) humidity.

Given that both sites used the same modules from the same production run, the reasons for the variation in stability are limited. Differences in light spectra between the locations could possibly explain the different burn-in values observed. Potentially transportation could also induce some mechanical issues. Furthermore, the measurement system in Bangor is located around 400m east of the Menai straits, so salinity is likely to be higher (although prevailing winds come from the west). This could be a contributing factor to the greater degradation observed in Bangor, but the increased levels of condensation on modules in Bangor could also be an issue. Condensation could induce a number of failure mechanisms, such as weakening of barrier layers and the adhesive, absorption of water into the modules as well as higher levels of localized relative humidity.

Although more rainy days were observed in Belo Horizonte, the daily amplitude of relative humidity was similar to Bangor, but the minimum levels of relative humidity were often much lower than Bangor as a result of the higher temperatures in BH. In Bangor, the maximum and minimum values of relative humidity were very close and constantly high. Combined with low temperature, especially during the first campaign, this could indicate higher condensation, which could have had a significant impact on the module degradation.

3.3 Condensation effect

To evaluate the impact of condensation on the results, the dew point temperature was approximated using the Magnus-Tetens equation:

$$T_d = \frac{b\ x\ \alpha(T,RH)}{a - \alpha(T,RH)}$$

and

$$\alpha(T,RH) = ln\frac{RH}{100} + a\ x\frac{T}{b+T}$$

where T_d is the dew point temperature; T is the temperature; RH is the relative humidity of the air; a and b are coefficients. For Sonntag90 constant set, a = 17.62 and b = 243.12 °C [31,32]. One way to evaluate the level of condensation at both sites is to consider the average dew point depression (DPD), i.e., the difference between the ambient temperature and the dew point temperature, which was calculated for each day of testing at both locations. Figure 9 presents this data in a histogram. The graphs show that, in both periods, the average dew point depression in 50% of the days analyzed was lower than 3.5 °C in Bangor, against 5.5 °C in Belo Horizonte. When raised to 80%, the numbers change to 5.5 °C and 7.9 °C, respectively. As there are more hours when the ambient (and hence module) temperature is closer to the dew point in Bangor, it can be deduced that condensation levels in Bangor were higher than in Belo Horizonte, which could have increased the water penetration through the encapsulation.

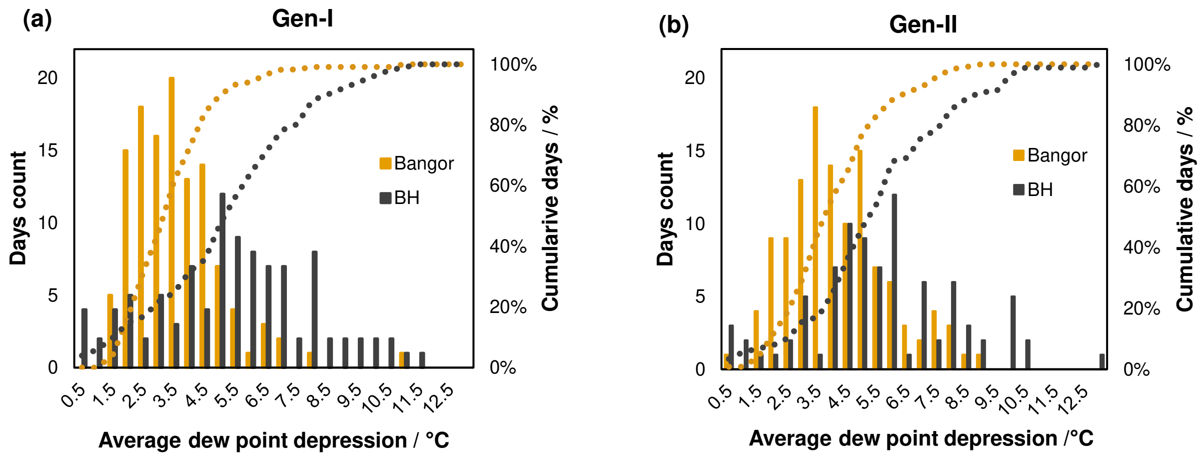

Figure 9 - Histogram of the average daily dew point depression for the periods of (a) Gen-I and (b) Gen-II monitoring.

Condensation is rarely studied in the context of PV degradation, possibility because this is unlikely to be a major issue in crystalline silicon modules given the use of glass as encapsulant material. However, flexible OPVs are encapsulated with polymeric films that are prone to water penetration, which can degrade contacts, transport and active layers [20,22]. Therefore, special attention is required in this case.

An experiment ran in Bangor with a different low band-gap polymer and fullerene acceptor formulation shows the effect of condensation on the degradation of OPV modules. The test was performed with six identical modules inside a climate chamber with a controlled environment, following the ISOS-D-3 standard, where the temperature and relative humidity (RH) of the chamber were set to 65°C and 85% respectively, as shown in Figure 11 (a). Two modules were tested at these standard conditions, whilst four other modules were placed on Peltier cooling devices, which lowered the modules' temperature to 60 °C and 57 °C, as depicted in Figure 10 (two modules at each temperature condition). By lowering the temperature, water drops were allowed to form on the surface of the modules simulating the outdoor condensation. As the dew point at 65 °C is 61.4 °C, the temperature conditions tested corresponded to a dew point depression of 3.6°C for the control sample and -1.4 and -4.4 ºC for the cooled samples, respectively. In practice, a negative dew point is unlikely to occur in operation, but it is a common effect at night, particularly in cold regions with high relative humidity, such as continental and northern Europe. At night, the panel releases heat into the atmosphere by radiation and if its temperature falls below the dew point, water condensates on the surface [33].

In order to only evaluate the effect of the dew point depression, the samples were kept horizontally, excluding the influence of inclination of the samples, which was different in each test site. The I-V measurements were done in situ and samples were monitored at constant conditions. Thus, the level of condensation on the modules was kept constant throughout the test, without evaporation and the samples were not subjected to temperature or humidity cycling.

Figure 11 shows the impact of cooling the modules during the ISOS-D-3 tests. Since the performance measurements were done in situ and not at the standard temperature, data was normalized to the first value. It is clear that the modules that were cooled the most, exhibited the greatest degradation. More condensation was formed on the module surface, providing confirmation that modules, when operated in Bangor, should exhibit faster degradation, induced by the reduction of FF and V_{OC}, with greater periods at lower DPD ranges.

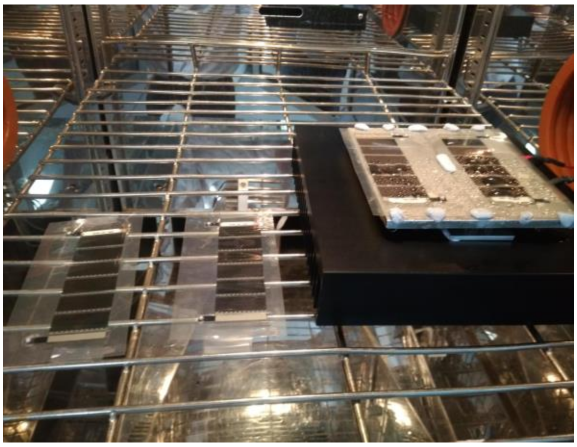

Figure 10 - Samples under the indoor test. The climate chamber was set at 65 °C and 85 % RH and two samples were placed over a peltier and cooled by -5 and -8°C (test under -5°C being depicted). The formation of water drops on top of the samples is evidence of induced condensation.

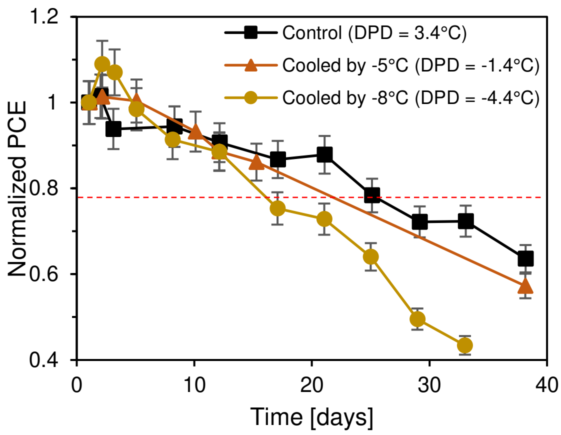

Figure 11 – PCE of OPV modules tested under ISOS-D-3 conditions (65°C, 85% RH) with different levels of cooling applied to induce greater condensation on modules, which leads to different dew point depression (DPD) values. The red line identifies the points when T80 was reached. Error bars represent the standard deviation.

4. CONCLUSION

The study showed that OPV modules fabricated with the same materials and processes can suffer different degradation when applied to different locations and seasons. In this case, modules fabricated at CSEM Brasil in the same coating run underwent a faster degradation when tested in Bangor, North Wales, compared to Belo Horizonte, Brazil. Different factors could have contributed to this, such as different light spectra and higher salinity in Bangor, but the main contribution was likely due to higher condensation in Bangor, based on the lower dew point depression showed by weather data and corroborated by an indoor test. The influence of condensation is poorly addressed in the literature about the stability of organic modules and raises the importance of carrying out more outdoor tests in different climates and under real conditions to assess the most important stressors for each case. Based on this, OPV materials and stacks could be optimized not only for specific applications, but also for different locations, seeking the best performance with the longer lifetime. From this test, it was clear that in environments such as Bangor, encapsulation is critical, and this problem could be addressed by the use of high-performance barrier films or even the use of self-cleaning and hydrophobic coatings; whereas in environments with high irradiance levels throughout the year, such as Belo Horizonte, a search for more photostable materials is of paramount importance.

SUPPLEMENTARY MATERIAL

See supplementary material for the data of series and shunt resistance of the outdoor test.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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