Seasonal dependence of diurnal efficiency degradation and recovery in perovskite mini-modules during outdoor testing

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***Abstract*—The diurnal efficiency degradation and subsequent recovery of several identical perovskite mini-modules has been investigated during outdoor testing over different seasons. Seasonal dependence of recovery and diurnal efficiency degradation in perovskite devices has been demonstrated. The higher irradiation and ambient temperatures during summer months were found to enhance the diurnal efficiency degradation-to-recovery ratio over the first days of testing, leading to significant accelerated performance degradation in the perovskite modules tested in those conditions. For the rest of the test period after the modules had degraded significantly, smaller diurnal efficiency degradation and recovery values were obtained in summer compared to modules tested outdoors in winter months.**

Keywords—perovskites, mini-modules, performance measurements, recovery, outdoor testing

I. Introduction

In less than a decade, perovskite technology has emerged with immense promise as potentially the cheapest alternative to the present commercially available photovoltaic technologies. However, despite an expeditious rise in their efficiency, perovskite-based solar cells are still far from commercialization because of inadequate stability. Reversible/temporal changes in perovskite performances have been observed creating doubts about the amount of real degradation of perovskites under light. Several papers report that during recovery in the dark, the loss in perovskite device performance under previous light exposure can be fully or partially reversed. Perovskite recovery was found to depend on cell aging with higher recovery to be obtained in perovskite cells at early stages of degradation[1]. Since limited experience of long-term recovery of perovskites is available so far, this study aims to give insight into the seasonal dependence of diurnal efficiency degradation and recovery in identical perovskite modules exposed outdoors for several months.

II. Experimental approach

Four (4) identical perovskite modules have been mounted outdoors in a fixed plane array at different seasons and current-voltage (I-V) measurements have been collected at regular intervals over several months of testing. The first batch of modules (Batch 1) consisted of 2 identical modules and was located outdoors from the middle of January until the beginning of May. The second batch of modules (Batch 2) consisted of another two modules and was located outdoors from the end of August until December. The active layer of the perovskite modules under test is a two-cation perovskite ($Cs_{0.18}Fa_{0.82}PbI_{2.82}Br_{0.18}$). An identical testing procedure was applied to the two batches of modules for the collection of their electrical parameters. Open-circuit loading was applied between the I-V scans. A dummy module was located alongside each batch of modules outdoors for the measurement of temperature at the backside of the modules. Forward and reverse voltage sweeps have been applied during each I-V curve. Alongside the I-V traces from the devices, environmental sensors have been used to collect solar irradiance in the plane of array, ambient and device temperature, wind velocity and humidity/precipitation levels. The electrical measurements have been acquired by a single current-voltage source-meter multiplexed to take sequential measurements from the devices under test. LabVIEW software was designed to record the I-V-traces every 5 minutes at high Global Normal Irradiance (GNI) conditions (GNI>400 W/m^2). Both forward (<0V to > open-circuit voltage (Voc)) and reverse (> Voc to < 0V) voltage sweeps have been applied to the devices. Forward-first voltage sweeps have been used at all instances. The voltage sweep rate was chosen to be 1V/sec.

III. Results and Discussion

A. *PCE Degradation*

The Batch 2 modules exposed outdoors during the summer period presented a rapid drop in performance. For a better understanding of the performance degradation of the modules over the first days of outdoor exposure, the power conversion efficiency loss was calculated for each module over that period. The graph in Fig.1. demonstrates that modules located outdoors during the summer period presented significant reduction in their efficiency from the first week of outdoor exposure. During the first week of outdoor exposure for Batch 1 modules the mean module temperature was around 28°C and the total weekly solar irradiation applied on the modules was 20.22 kWh/m^2. On the other hand, during the first week of exposure for Batch 2 modules the mean module temperature was found to be 49.6°C and the total weekly solar irradiation applied on the modules 41.25 kWh/m^2. This module temperature was collected only during the collection of current-voltage characteristics of the modules at irradiance values higher than 400W/m^2. The results suggest that higher levels of irradiance and temperature present during summer months are likely to be the major causes of accelerated performance degradation in the perovskite mini-modules.

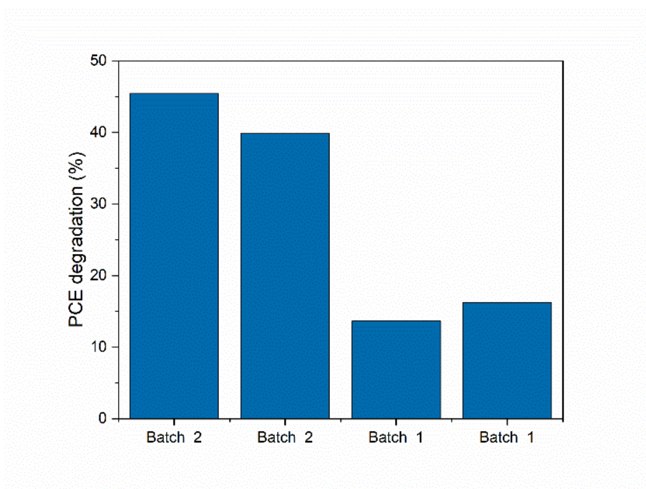

Fig. 1. Efficiency degradation of modules in batches 1 and 2 after one week of outdoor testing. Batch 1 was located outdoors during winter months while Batch 2 modules located outdoors during summer months.

To identify the root cause of efficiency degradation of the modules, the electrical parameters of the modules have been studied over the testing period. The decrease in power conversion efficiency of the modules is linked to reduced current output. The current losses presented in the Batch 2 modules were significantly higher than those obtained in Batch 1 modules. In particular, the maximum current drop the first week of testing in Batch 1 modules was found to be around 13% while in Batch 2 modules the current losses the first week of testing were up to 48%. Small voltage losses were detected in both batches of modules. Voltage losses were much lower than current losses in all modules under test.

B. *Diurnal efficiency degradation*

The efficiency of the perovskite modules changes over the day. The diurnal efficiency degradation of all modules under test was calculated for each day in the field to investigate any possible trend between the two batches of modules tested at different seasons. The diurnal efficiency degradation was calculated based on the efficiency values at the beginning and the end of each day. The values have been normalized to the initial efficiency value to have comparable results. The results are depicted in Fig. 2, where distinct trends for the two different batches can be seen: modules exposed during the summer period (Batch 2) present lower diurnal efficiency degradation than modules exposed during winter months (Batch 1) after the 15th day of exposure. Over the first week of exposure more instances of higher diurnal efficiency degradation are obtained in Batch 2 which is exposed to higher irradiance and temperature levels. This drives the accelerated performance degradation of the module seen in Fig.1. After this period and for another 1 week of testing (until the 15th day of outdoor testing) similar diurnal efficiency degradation is exhibited by the two batches. Then for the rest of the testing period the diurnal efficiency degradation for modules in Batch 1 is higher.

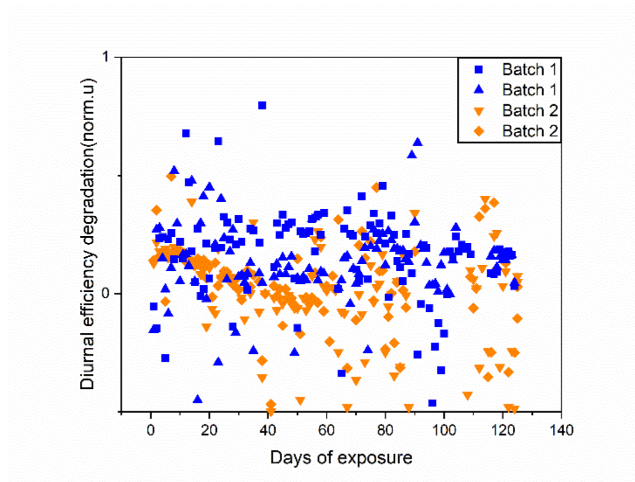

Fig. 2. Diurnal efficiency degradation of the two batches of modules for the first 120 days of outdoor exposure.

One common trend of the diurnal efficiency degradation of both batches is the larger variation of daily degradation after some days of exposure. The larger dispersion of the diurnal degradation which results in either positive or negative values of the degradation is attributed to the fact that the modules in those degradation stages have lost up to 50% of their initial power conversion efficiency and larger fluctuations of their diurnal efficiency is more likely to be present. Larger dispersion of the diurnal efficiency is presented in Batch 1 after the 70th day of exposure while in Batch 2 after the 40th day of exposure due to the quicker performance degradation present in this batch. More analysis of the data is underway to investigate in more detail the impact of environmental conditions on the diurnal efficiency degradation.

C. Performance recovery

Performance recovery was analyzed for the two different batches of modules for the whole period of exposure (see Fig.3). The recovery was calculated by considering the final efficiency values of the previous day and the initial efficiency values of the next day. The results have been normalized for comparative purposes. A clear classification of the two batches of modules can be obtained based on their recovery values after the 15th day of exposure. Over the first week of testing more instances of higher recovery are obtained in Batch 2. Over the second week of operation almost similar recovery is obtained in both batches while after the 15th day of outdoor operation recovery in Batch 2 is always lower. The recovery results agree with diurnal degradation data. A larger dispersion of the efficiency recovery is obtained after some period in agreement with the diurnal efficiency degradation data. Diurnal efficiency degradation and efficiency recovery are driven mainly by the diurnal current degradation and current recovery. Investigation of the ratio between diurnal efficiency degradation and recovery was implemented over the whole period of testing. A higher diurnal efficiency degradation /recovery ratio was found in Batch 2 modules the first two weeks of outdoor exposure thus explaining the higher performance degradation in those modules. After this period no clear classification of the two batches can be obtained based on their diurnal degradation/recovery ratio.

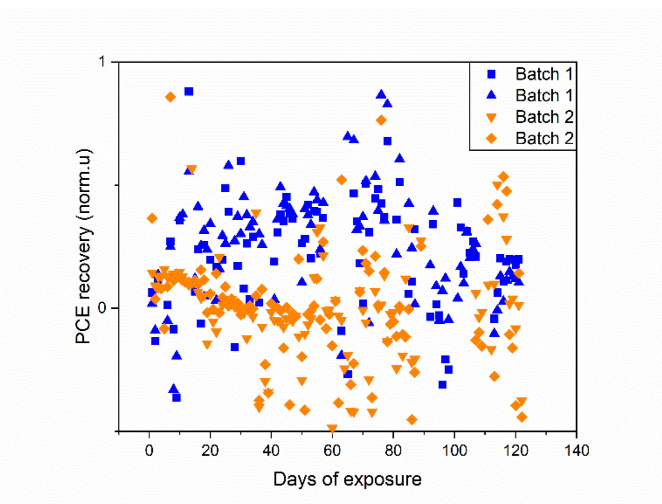

Fig. 3. Efficiency recovery of the two batches of modules the fist 120 days of outdoor exposure.

The total irradiation received by the devices over time and the average ambient temperature present during the outdoor exposure of the two batches have been plotted in Fig. 4. Fig. 4 demonstrates the higher total irradiation applied to Batch 2 and also the higher temperature levels present over the first 80 days of outdoor testing. By comparing the degradation levels of the modules after the application of the same amount of irradiance it can be observed that the performance degradation of Batch 2 exposed at higher temperatures is higher. This fact supports the conclusion that the temperature more strongly determines the daily efficiency degradation and recovery processes in perovskite mini modules outdoors.

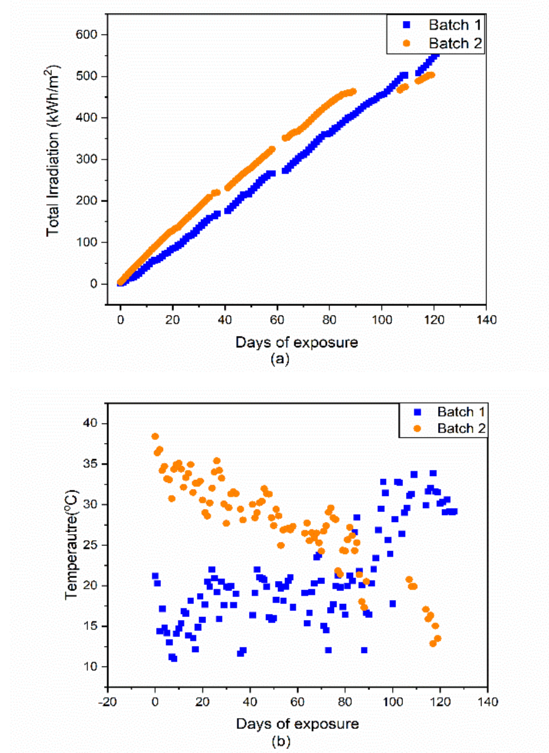

Fig. 4. (a) Total irradiance applied on the two batches of modules and (b) mean temperature levels present during the field testing of the batches.

IV. Conclusions

The higher irradiation and ambient temperature present during summer months were found to cause higher diurnal efficiency degradation-to-recovery ratios over the first weeks of testing, causing accelerated efficiency degradation in modules. After the first weeks of outdoor exposure when the modules lost significant performance, low diurnal efficiency changes and recovery are obtained for the rest of the period. Temperature and irradiance levels just after the outdoor exposure of modules in the field is critical for the perovskite modules operation. More data analysis is underway to give further insight towards the degradation and recovery processes at different ambient environmental conditions.

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