Electrical and Electroluminescence Evaluation of 17 Year Old Monocrystalline Silicon Building Integrated Photovoltaic Modules

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Abstract — **Longterm reliable operation of photovoltaic modules is necessary to ensure the technology is key to reducing the cost of solar energy. However, degradation mechanisms in the field are not always consistent or predictable. We present a dataset of 72 building integrated photovoltaic (BIPV) monocrystalline silicon modules that were operated on the rooftop of a building at the National Institute of Standards and Technology (NIST) for 17 years. Electrical performance shows a majority of modules exhibit severe degradation beyond the typical ~1 % loss per year. Xenon lamp flash solar simulator I-V curve measurements were compared to historical performance data to verify that the degradation seen in I-V measurements also existed during operation. While the open circuit voltage remained unchanged for most modules, a decrease in short circuit current and increase in series resistance led to deterioration of the operation current and maximum power. Hyperspectral electroluminescence (EL) imaging of three modules shows further evidence of significant series resistance increase for degraded modules. A module with a standard degradation rate has a clear EL image while a very degraded module has a very faint EL emittance at the same voltage due to series resistance losses. Further work will include calibrating the EL imaging system to quantify poor performing and current limiting regions within the module and determine the I-V curves of individual cells using the reciprocity relationship between EL and External Quantum Efficiency.**

I. INTRODUCTION

As the installation of photovoltaic (PV) modules increases exponentially [1], **understanding their longterm degradation mechanisms is critical for projecting the performance, power generation, and economic impacts.** While manufacturing-related defects are inevitable, understanding how other, in-field defects form, grow and progress is crucial to understand the lifetime of the module. This is particularly relevant for silicon PV as it is the most pervasive solar technology. While the typical rate of degradation (~1 % per year) is generally agreed upon [2], [3], some sets of modules will show a higher degree of variation despite typical operation and can be of particular interest for better understanding PV degradation mechanisms [4].

Frequently, just a small portion of the module, even just a couple of cells, will degrade and lead to a significant reduction in performance of the entire module. Therefore, techniques to analyze and determine the location of these defects are important. Current vs voltage (I-V) curve measurements, which describe the electrical performance of PV modules and cells, are one technique. However, I-V measurements only show how the electrical performance of a whole module has been impacted by the degradation mechanisms and can only suggest what defects (e.g., increased series resistance) have occurred. Electroluminescence (EL) imaging is a commonly used technique to gain insight into where defects are located in the module [5]. When current is sourced through a silicon module, the module emits a luminescence signal. Locations where the module does not emit signal indicates a defect region where current cannot flow well. When used together these techniques show where defects have developed and to what extent they impact the module performance.

We share a particular group of 72 modules with an atypically high degradation rate and, as a collection, have an electrical performance profile that is non-Gaussian. These 72 building integrated photovoltaic modules (BIPV) were operated and monitored as part of a 234 module array on the roof of a building in horizontal alignment at the National Institute of Standards and Technology in Gaithersburg, MD in the United States from 2001 through 2018 [6]. Along with performance data of the array, weather and irradiance data was also collected throughout the array's deployment. Unfortunately, the modules were incorrectly removed during a reroofing project. This means that many were lost and the original location of each module within the array is unknown. The spread of electrical performance was measured with a flash solar simulator as well as in-field measurements during operation to show that significant degradation was also seen in the field. We also share qualitative images from measuring module electroluminescence as a further means to show the degradation of the modules.

The BIPV modules are made up of 72 series connected monocrystalline cells. The modules are covered with tempered glass, have a multi-layered polymer backsheet, and an ethylene-vinyl acetate (EVA) encapsulant for environmental protection and electrical isolation. The modules have 4 branches, each with a bypass diode.

II. I-V MEASUREMENTS

I-V measurements under a solar simulator are an indicator for overall module electrical performance. Included in our data is a comparison between I-V measurements after removal and models of the on-site electrical performance data of the strings in the array fitted to standard reference conditions to show that the removal process had little impact on the module performance.

A. Flash Solar Simulator I-V Measurements

The I-V curves for all 72 modules were measured under a Xenon lamp flashed tower solar simulator with power adjusted to reach AM1.5G with the temperature held to 25 °C ± 1 °C. The system's spatial nonuniformity is less than 1.5% and temporal nonuniformity is less than 2-%. IV curve measurements were conducted from short circuit (SC) current to open circuit (OC) voltage and from OC to SC to verify that hysteresis effects were negligible.

As seen in Fig. **1**., with a few representative modules from the batch included, there is a very wide range of performance across this subset from typical degradation seen in module BIPV-101-052, to more than normal in BIPV-101-011, to an amount that renders the module impractical to deploy like with BIPV-101-012.

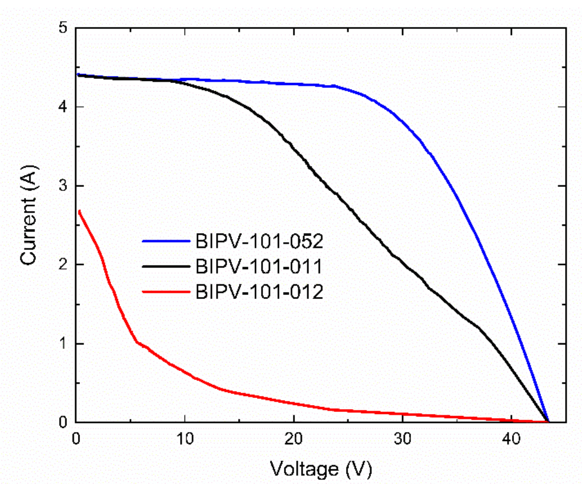


Fig. **1**. I-V Curves of three modules in the dataset, showing large variability in performance.

The spread of the modules' performance, shown in Fig. **2**, is particularly interesting. The vast majority of the modules experienced very little degradation to the open circuit voltage (V_{oc}). There are a few modules that show the bypass diodes were used for one branch (indicated by the cluster of modules around 32 V). Otherwise, there are only a few modules that exhibit severe degradation from the rated 43.4 V at open circuit. The short circuit current (I_{sc}) is where we begin to see a more noticeable decrease in performance. No module had an I_{sc} equal to the manufacturer's rated value of 4.8 A and the largest measured value of any module was 4.5 A. And there are 20 modules with a short circuit current of less than 4.0 A. The degraded I_{sc} and rounding of the knee of the I-V curve (i.e., the Fill Factor) yields a wide range of maximum power (P_{max}) values for the 72 modules. Assuming a 1 % loss every year for 17 years, one typical module would be expected to produce about 126 W at P_{max}. But the largest P_{max} of any of the 72 modules was 116 W and only 17 of the 72 modules have a P_{max} above 100 W. Meanwhile, another 30 modules have a P_{max} between 50 W and 90 W and 25 produce 45 W or less showing very severe degradation. These I-V curves would suggest that, assuming the 17 best performing modules experienced typical degradation without any catastrophic failures, that the modules saw closer to 2.5 % losses every year.

These results are very surprising given the consistent maintenance performed. Due to the removal of the array being unplanned and in an unexpected fashion, there are natural concerns that some of the measured degradation in output may be due to the removal of the modules and not from natural degradation experienced while deployed. We address these concerns below.

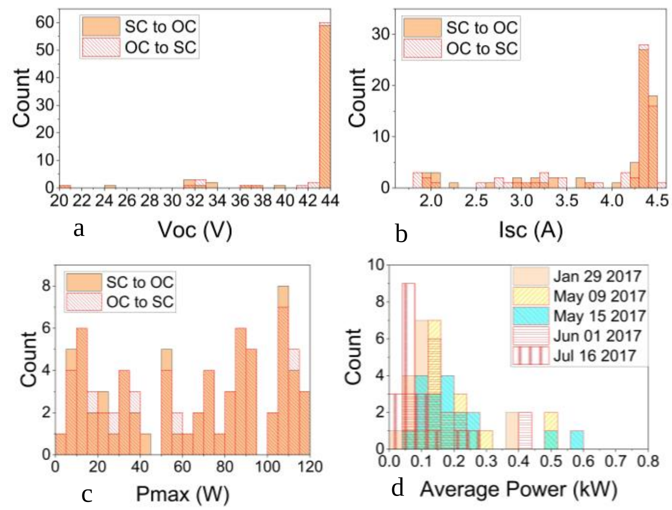
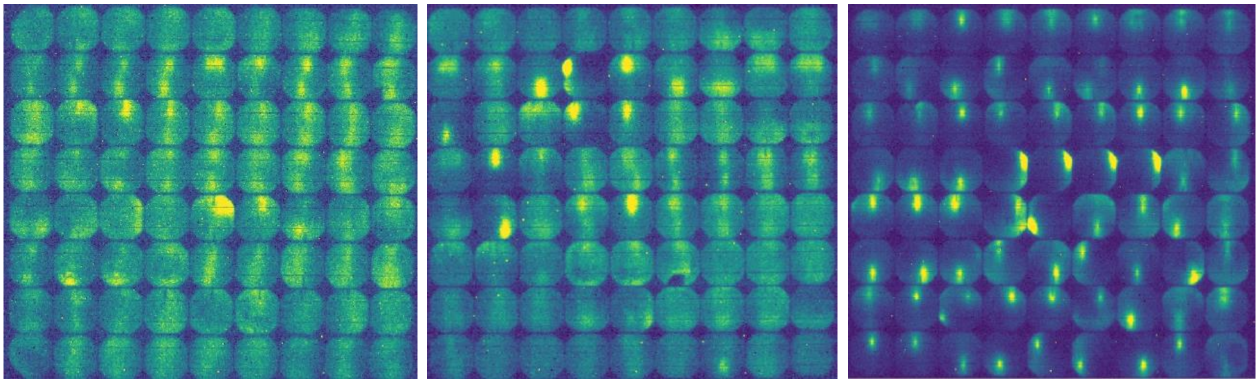


Fig. **2**. Histogram summary of the 72 modules tested from Isc to Voc and from Voc to Isc. Open circuit voltage of the modules (a) did not degrade significantly. Short circuit current (b) shows some degradation and compounded with rounding of the IV curve, the maximum power shows (c) significant reduction in output with a notable spread. The module performance is constrasted with average power output from the 18 strings on 5 high irradiance days in (d).

B. Historical Performance Data

Before considering the granular data of each string, we did an immediate evaluation of the entire array's performance and found that the total degradation over the course of the 17 years was about 7 % per year. To further verify that the removal of the array did not cause damage to the modules, we also evaluated the performance of the strings from the historical electrical and weather data before the array was taken down. This data was taken from the most recent data in 2017 on 5 sunny days when the irradiance was close to 1000 W/m^2. Since we are unsure of where each module was located within the array, we compared the spread of the data from the 18 strings to the spread among the 72 modules. Fig. **2**(d) shows the average power from 11 am to 3 pm of the 18 strings. We see that the string performance is even more degraded than the I-V curve data in Fig. **2**(c). Since each module has degraded at a



a b c

Fig. **3.** EL Images at 1140 nm of modules with 2.0 A applied with the same color scale. Yellow indicates a high luminescence, blue indicates low. BIPV-101-052 (a) operating at 44.4 V, BIPV-101-011 (b) at 51.2 V, and BIPV-101-012 (c) at 80.0 V.

different rate, there is an I-V curve mismatch between the modules in each string. So, the output of each string will be even worse with a decrease in overall maximum power. Our data backs this up as we mostly saw degradation rates of more than 10 % per year for each string. This data gives us confidence that the module I-V data was not due to destruction upon removal, but from natural degradation mechanisms during deployment.

III. EL Imaging and Future Work

The defect mechanisms of these modules and reason for the variation is unknown at this time. So along with I-V measurements taken during operation in the field and under a flash solar simulator, we have also begun to utilize EL imaging to better understand failing regions of the modules in individual cells.

We used an in-house hyperspectral imaging system, with custom-designed optics, to capture electroluminescence images of an entire module. The module is placed into a rig at a distance of 4 meters from special optics that directs the luminsence signal into the hyperspectral imaging camera. A power supply was connected to the same modules as shown in Fig. **1** with the voltage adjusted until 2.0 A was run through the module. Under these conditions, EL images were acquired at 1140 nm (the peak emittance wavelength of silicon) with the HS imager. As seen in Fig. **3**, module BIPV-101-052, with the least degraded I-V curve, showed a very uniform luminescence across all cells suggesting the fewest defects. This module also required the lowest voltage (44.4 V) for 2.0 A to run through the module. BIPV-101-011 had more noticeable defect regions and dead areas and required 51.2 V to be applied for the same current. Finally, BIPV-101-012 had noticeable dark regions and defects on nearly every cell. It also required 80.0 V to be applied for a current of 2.0 A to flow through it. We can infer a much larger series resistance for module 012 than 011 or 052 given the higher required voltage to operate at 2.0 A. These results match the I-V curve measurements and further support the wide ranging degradation seen in these modules. These images are our first steps towards determining where the defects are within the module and working to quantify the electrical performance of each individual cell in the module in a nondestructive fashion.

IV. Conclusion

The 72 modules we were able to save from the building array at NIST exhibit severe degradation effects that are beyond typical degradation rates. We have further demonstrated with EL imaging that degradation of individual cells is significant in the modules with poor I-V curves. Plans include completing the EL imaging on all remaining modules and using the EL results to estimate series resistance losses or other degradation effects within each module. We plan to continue this work by modelling the I-V curves of all cells in each module using the reciprocity relationship between EL and EQE. Ultimately, module coring will be performed to verify the materials degradation that led to the performance degradation in these modules.

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