PERFORMANCE TEST OF AMORPHOUS SILICON MODULES IN DIFFERENT CLIMATES: HIGHER MINIMUM OPERATING TEMPERATURES LEAD TO HIGHER PERFORMANCE LEVELS

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ABSTRACT

To assess the performance of thin-film amorphous silicon (a-Si) devices operating in different climatic conditions, three identical sets of commercially available a-Si PV modules from five different manufacturers were simultaneously deployed outdoors in three sites with distinct climates (Arizona-USA, Colorado-USA and Florianopolis-Brazil) in a round robin exposure experiment. The four-year experiment aims to determine the light-induced degradation and stabilization characteristics of a-Si regarding specific history of exposure, and to monitor and compare degradation rates in different climates. We present results from the first year of measurements, showing that modules deployed at the site with the highest minimum operating temperature experienced the highest stabilized output level.

1. INTRODUCTION

In amorphous silicon (a-Si) thin-film PV devices, the reversible light-induced degradation (Staebler-Wronski effect - SWE [1]) results in decreased performance after prolonged exposure to sunlight. The SWE leads to module performance reaching a stabilized state after the first year outdoors; most of this degradation can be reversed by thermal annealing at 150°C for 2 hours in the dark. It has been suggested that the stabilization of the Staebler-Wronski degradation does not occur because an equilibrium between light-induced degradation and thermal or light-induced annealing is reached, but rather that it occurs because the degradation phenomenon itself is self-limiting, and that once enough degradation has been introduced (at a given minimum temperature), the degradation process fades away [2]. From this model, we derive the hypothesis that a-Si PV module long-term power output depends not only on the operating conditions, but also on the temperature history of light exposure, and that a-Si devices operating at a year-round high temperature site, with higher minimum operating temperatures, will stabilize at higher performance levels than identical modules deployed at sites where minimum operating temperatures are lower, even if at both sites modules experience the same maximum operating temperatures. This aspect, associated with the negligible temperature coefficient of power of stabilized a-Si [3], gives this material a competitive adge for applications in warm climates [4].

2. EXPERIMENTAL DESIGN

To assess the performance of a-Si devices under different conditions, three identical sets of multi-junction a-Si modules from five different manufacturers were simultaneously deployed outdoors in three sites with distinct climates as shown below:

- **Site A**: Golden, Colorado - USA (National Renewable Energy Laboratory - NREL)
  Climate: dry continental, with cold winters and warm summers;
- **Site B**: Mesa, Arizona - USA (Arizona State University Photovoltaic Testing Laboratory - PTL)
  Climate: dry desert, with cool winters and hot summers;
- **Site C**: Florianopolis, Santa Catarina - Brazil (Laboratorio de Energia Solar - LABSOLAR)
  Climate: moist maritime, with warm winters and hot summers.

The four-year experiment aims to determine the light-induced degradation and stabilization characteristics of multi-junction a-Si PV modules with regards to geographic location- and climate-specific dependent effects, specific history of exposure effects, and to monitor and compare degradation rates in different climates. An experimental procedure was designed, in which each PV module set would be deployed outdoors at one site for 12 months, be shipped back to NREL for measurements under a SPIRE 240A simulator at Standard Testing Conditions (STC = 1000 W/m^2; AM 1.5 spectrum, operating cell temperature 25°C); be sent to the next (second) site in the second year; and to the remaining site (third) in the third year, before being sent back to the original site were it was first deployed outdoors for a final deployment period. Every permutation of sites includes STC measurements at NREL. Initially, all modules from the three identical sets of double- and triple-junction, commercially available a-Si PV modules were measured for a baseline I-V trace at NREL at STC before shipment to each site for deployment outdoors.

In early 2001, within a one-week time window, each of the three sites started deploying one of the identical sets of modules outdoors, at fixed latitude tilt as per each site (40°, 33°, and 27° for sites A, B, and C respectively), facing toward the equator, and I-V characteristics under real operating conditions were measured on a monthly basis and normalized to STC.

In this paper, we report on results from the first year of measurements in this round robin exposure experiment, showing that modules deployed at the site with the highest minimum operating temperature experienced the highest stabilized output.

3. RESULTS AND DISCUSSION

Table I presents information on each of the five module manufacturers' STC-rated power and cell design. Figures 1 – 4 show respectively the losses in conversion efficiency (Eff), open circuit voltage (Voc), short-circuit current (Isc) and fill factor (FF) for each of the five multi-junction PV module types deployed at each test site. The losses shown correspond to measurements carried out at the NREL SPIRE 240A simulator for all modules before exposure to sunlight, and after 12 months outdoor deployment, with modules exposed to 1500 - 2300 kWh/m^2. The efficiency losses seen in Figure 1 show that for the double- and triple-junction a-Si PV modules produced by Manufacturers #1 to #4, the output performance was highest after 12 months of outdoor exposure at the site with the highest winter temperatures (Site C – Florianopolis / Brazil). The strongest degradation was observed at the site with the lowest winter temperatures (Site A – Colorado / USA), and an intermediate degree of efficiency loss was observed for modules exposed at the (Arizona) site with winter temperatures in between those experienced at the other two sites.

Table I: Rated power at STC and solar cell design for each of the five PV module manufacturers used in this experiment.

Manufacturer	Power (Wp)	Solar cell design
#1	40	double-junction, same bandgap
#2	40	double-junction, same bandgap
#3	32	triple-junction, dual bandgap
#4	32	double-junction, same bandgap
#5	5	double-junction, dual bandgap

Figure 1 also shows that there is a considerable difference among different manufacturers's device quality, with efficiency losses ranging from ~20% to ~35% for different modules exposed at the Colorado site. The smaller degradation effect observed at the warmer Brazilian location is consistent with previous experiments carried out under similar climate conditions in Australia for double-junction devices [5].

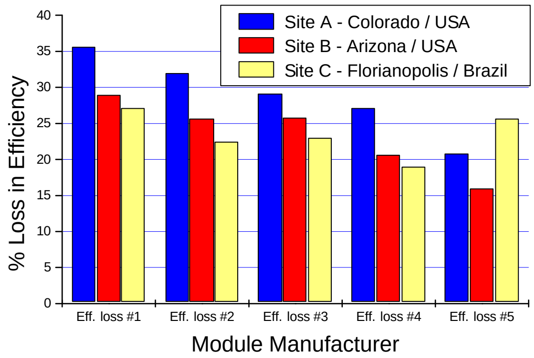

Figure 1: Losses in conversion efficiency for the three sets of five different multi-junction a-Si PV modules after 12 months of outdoor exposure at the three different test sites. Measurements carried out at NREL under a SPIRE 240A solar simulator at STC.

The apparently unexpected behavior of modules produced by Manufacturer #5 (which consists of double-junction dual bandgap devices) exposed at the warmest site might have been caused by temperature activated moisture ingression. This might have resulted in an increase in series resistance, with degradation of the Isc and FF as we will show below. Losses in Voc, shown in Figure 2, were also more prominent at the coolest site (Colorado), with triple-junction devices (Manufacturer #3) showing the strongest Voc degradation. It is noteworthy that for Manufacturer #2 Voc losses in Colorado were nearly twice as large as in Brazil, and that for Manufacturer #1 and #5 Voc degradation varied little among sites.

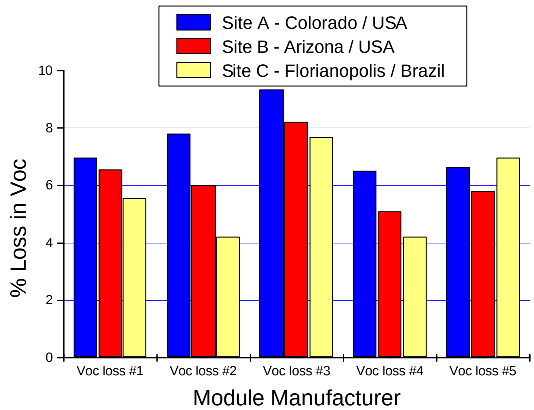

Figure 2: Losses in open circuit voltage (Voc) for the three sets of five different multi-junction a-Si PV modules after 12 months of outdoor exposure at the three different test sites. Measurements carried out at NREL under a SPIRE 240A solar simulator at STC.

Performance degradation of a-Si modules is known to result mostly from a reduction of the FF, caused by an increase of the series resistance due to corrosion in the intercell zone, and a decrease of the lifetime of minority carriers in the intrinsic layer due to the SWE, which directly affect the Isc. An increase in the defect density, which causes the quasi Fermi levels to narrow, reducing Voc, has been found to account for 15% to 24% of the total power losses, with less than 3% of arising from Isc losses [6].

Figure 3 shows our results for Isc losses over the 12 month deployment period, which were more evenly distributed, around 6%, among Manufacturers #1 to #4, and more prominent for Manufacturer #5 at all sites.

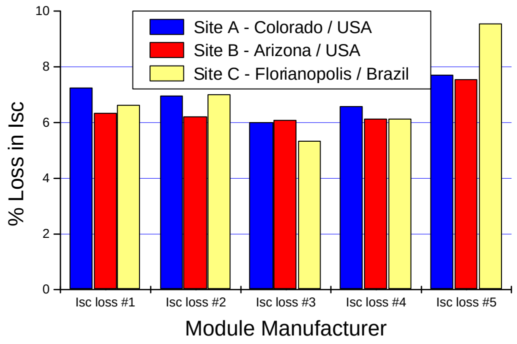

Figure 3: Losses in short circuit current (Isc) for the three sets of five different multi-junction a-Si PV modules after 12 months of outdoor exposure at the three different test sites. Measurements carried out at NREL under a SPIRE 240A solar simulator at STC.

Fill factor losses for different manufacturers' modules exposed at the same site ranged from 8% to 26% at the coolest site (Colorado), and from 10% to 17% at the warm site (Florianopolis), with modules from manufacturers #1 to #4 showing intermediate levels of degradation at site B (Arizona), and an apparently unexpected behavior arising from manufacturer #5 deployed at the warmest site.

Figure 5 shows the evolution of the power output with outdoor exposure of the five different multi-junction a-Si modules deployed at the warmest site (Florianopolis) for 12 months. The graph shows the ratio of the real operating output at maximum power point measured outdoors (and normalized to STC), and the nominal power at STC (nameplate rating). These measurements were carried out outdoors at LABSOLAR (with G $\geq$ 850 W/m^2) with a portable MINI-KLA I-V curve measurement device (Ingenieurbüro Mencke & Tegtmeyer, www.ib-mut.de), and show the typical evolution of the SWE. For manufacturers #1 to #4, original output ranged from 125% to 145% of STC-rated output, stabilizing at 100% to 108% of rated power after 12 months outdoors. Devices produced by manufacturer #4 presented the smallest degradation level of all modules tested, confirming previous reports in the literature [7] that lower degradation rates can be achieved at the expense of a lower initial efficiency.

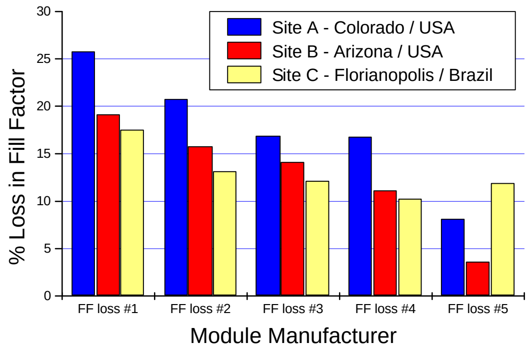

Figure 4: Losses in fill factor (FF) for the three sets of five different multi-junction a-Si PV modules after 12 months of outdoor exposure at the three different test sites. Measurements carried out at NREL under a SPIRE 240A solar simulator at STC.

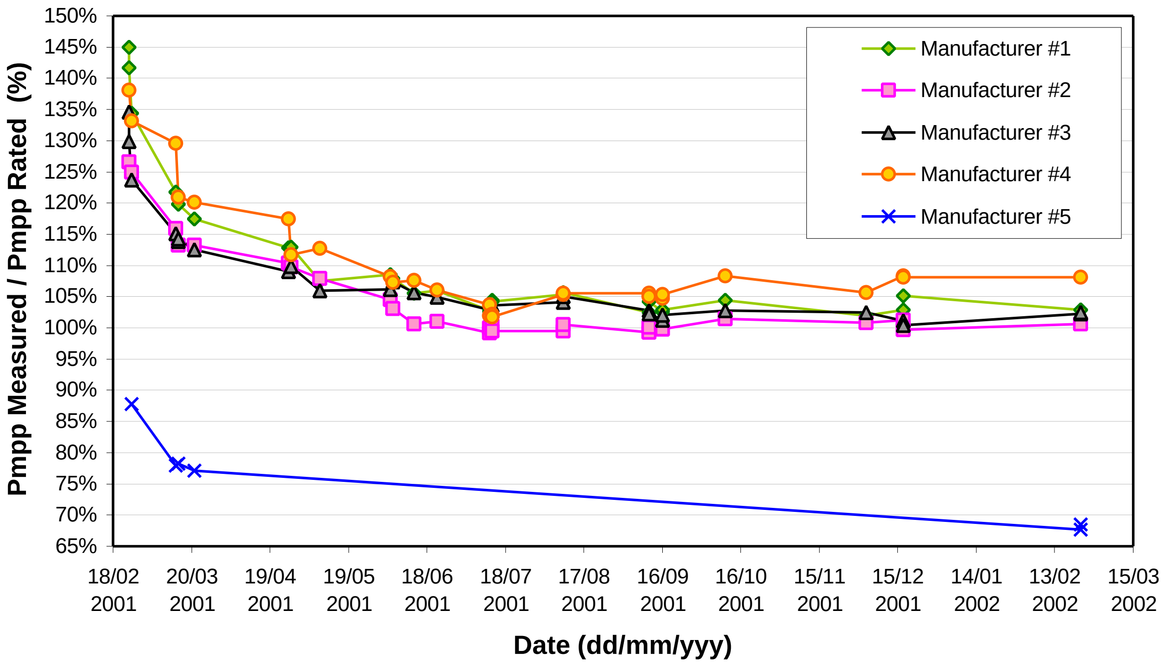

Figure 5: Evolution of the normalized output power (ratio of the real operating output at maximum power point measured outdoors, normalized to STC, and the nominal – nameplate rating - power at STC), for the five different multi-junction, commercially available a-Si PV module types used in this experiment. Measurements carried out at LABSOLAR under outdoor conditions, with irradiation levels above 850 W/m^2.

For manufacturer #5, efficiency losses were the smallest at the cooler sites (Colorado and Arizona), as shown in Figure 1, but Figure 5 shows that original output was poor; below 90% of rated power in the undegraded state, and below 70% of rated power after 12 months outdoors.

In the light of the results presented in Figures 1-4, current efforts to predict kWh/kWp performance for a-Si thin-film modules [8-10] will have to take into account deployment site conditions, as well as manufacturer nameplate rating, which figure 5 has shown to vary among manufacturers.

4. CONCLUSIONS

The hypothesis this experiment is engaged in confirming is that a-Si thin-film module performance stabilization levels may be determined by lifetime exposure history, when the predominant degradation mechanism entails the Staebler-Wronski effect. PV modules exposed at all three sites experienced similar maximum operating temperatures in summer, but minimum operating temperatures in winter were highest for the Brazilian site. This condition establishes the hypothesis underlying the experiment presented: multi-junction a-Si performs better in warm climates, where devices always "see" light at moderate to high temperatures. After the first year of outdoor esposure reported here, module sets have now been swapped among sites and are being deployed outdoors for a further period, to determine whether or not they have a lifetime memory of the stabilized state.

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