Light Soaking Measurements of Commercially Available CIGS PV Modules

Lawrence Dunn and Michael Gostein

Atonometrics, Inc., Austin, TX, 78757, USA

***Abstract* — CIGS devices are known to exhibit metastabilities and performance changes with continuous light exposure, or light soaking (see Ref. [1], and references therein). Such metastabilities have an impact on the measurement of CIGS PV module performance, since efficiency and other parameters change on a time scale of hours. For this work we used an indoor continuous solar simulator to expose three commercially available CIGS modules from three different manufacturers to a simulated diurnal light exposure cycle for 16 days. We observed an initial increase in efficiency on the order of ~3% to ~5% at the start of each illumination cycle in all three modules. We also observed a a deviation of approximately -0.17%/°C between the measured value and data sheet value of one module's Pmax/efficiency temperature coefficient, indicating that this module have ~5% lower power output at normal operating temperatures that indicated by the datasheet. In a follow-on experiment, the time required for modules to relax in the dark to their low-efficiency states was investigated by varying the length of time spent in the dark. One module, with an overall power conversion efficiency (PCE) of ~9.3%, required between 2 and 3 hours in the dark to relax to its low efficiency state, while the other two modules, with PCEs of ~10.3%, require between 9 and 16 hours to relax to their low-efficiency states.**

***Index Terms* — photovoltaic cells, thin film devices, solar power generation**

I. INTRODUCTION

It is well known that photovoltaic devices in the Copper Indium Gallium Diselenide (CIGS) family exhibit metastabilities and performance changes with continuous light exposure, or light soaking (see Ref. [1], and references therein). Because observed metastabilities in CIGS devices are associated with changes in efficiency and other module parameters over time scales on the order of hours, these effects are important both for manufacturing process control (determining optimal procedures for in-factory performance evaluation) and for studies of installed field performance (analyzing PV module performance ratios throughout the course of a day or longer periods) [2].

In this work, we particularly wished to focus on the pattern of performance changes in CIGS modules that occurs with daily light exposure. To simulate this pattern, we used an indoor continuous solar simulator to expose three commercially available CIGS modules from different manufacturers to a 16-day light soaking test consisting of cycles of 8-hour light exposures followed by 16 hours in the dark. The modules were exposed to light with an intensity of ~1000 W/m^2 and a close match to the IEC 60904-3 standard reference solar spectrum. While illuminated, the modules were electrically biased at their Maximum Power Point (MPP), with periodic full I-V curves taken.

We followed this experiment with a second cyclical exposure that varied the amount of time the PV modules spent in the dark in an attempt to ascertain the time required for modules to relax from the high-efficiency states resulting from light exposure to their original, low-efficiency states.

II. EXPERIMENTAL DETAILS

Three commercially available CIGS modules from three different manufacturers were kept in the dark at room temperature for 26 days prior to light exposure. In this paper, the three CIGS modules are referred to as "Module 1", "Module 2", and "Module 3". Module 1 and Module 3 were both described as CIS modules in their respective data sheets and Module 2 was described as a CIGS module.

The light soaking tests were performed in an Atonometrics Continuous Solar Simulator chamber with integrated I-V measurement capability. The solar simulator irradiance intensity was monitored with a National Renewable Energy Laboratory (NREL)-calibrated crystalline silicon mini-module. Throughout the light soaking experiments the solar simulator intensity was within 10% of 1000 W/m^2. For the three CIGS modules and the c-Si reference mini-module, module temperatures were measured with a type K thermocouple located on the center of the back of the module. Module temperatures were actively controlled through an air-cooling mechanism integrated into the Atonometrics Continuous Solar Simulator. We stress that the three CIGS modules were tested in the same continuous solar simulator at the same time.

Two experiments were performed. For both experiments, test recipes were created with the continuous solar simulator that actively tracked and adjusted the electrical bias conditions of each CIGS module so that modules were kept at their respective maximum power points as their temperature increased from room temperature to 75 °C. During this process the I-V system was programmed to perform a full I-V measurement (*i.e.*, sweeping the module voltage between *Isc* and *Voc*) on each module approximately once every minute as the modules were heating. The module heating process took approximately 20 to 25 minutes. Once the modules reached

Preprint: L. Dunn, and M. Gostein, "Light Soaking Measurements of Commercially Available CIGS PV Modules," *Proceedings of the 38th IEEE Photovoltaic Specialists Conference (PVSC)*, Austin, TX, June 3-8, 2012.

75 °C, periodic full I-V curves were taken approximately every 10 minutes. Between I-V curves the modules were biased at their respective maximum power points.

I-V curves and extracted parameters (e.g., *Voc*, *Isc*, etc.) were logged to a database on a PC during measurement. The I-V data and extracted parameters were corrected for light intensity variations during the measurement (as measured with the NREL-calibrated mini-module) to the reference intensity value of 1000 W/m^2. Temperature coefficients extracted from the module performance parameters measured while the modules were heating were used to correct the light soaking data for temperature to a reference temperature value of 25 °C.

A. Experiment 1

For the first experiment, the modules were first exposed to light in the continuous solar simulator chamber for a total of 8 hours. Following the 8-hour illumination period, the light source was extinguished and the modules were actively cooled to room temperature. The modules were then held inside the simulator in the dark for 16 hours, after which the cycle was repeated. This cycle was repeated a total of 16 times.

B. Experiment 2

The second experiment was identical to the first experiment, except that modules were kept in the dark for 7 days prior to the experiment, they were exposed to light for 2.5 hours, and the amount of time spent in the dark varied from 1 hour to 9 hours in 1 hour increments.

III. EXPERIMENT 1 RESULTS

A. Temperature Coefficient Changes Over the 16 day Test

We investigated the *Isc*, *Voc*, and *Pmax*/efficiency temperature coefficients of the three CIGS modules over a temperature range of ~35 °C to 75 °C to determine whether the metastabilities associated with light soaking effects resulted in changes in their temperature coefficients. Fully characterizing any such changes would be desirable for a full understanding of module performance changes associated with light soaking effects.

At the beginning of each illumination cycle, I-V curves were made on each module as the module temperatures increased, and temperature coefficients were extracted for Voc, Isc, Pmax/efficiency, and Fill Factor (FF).

Fig. 1 shows an example of a normalized data set used to extract the *Voc*, *Isc*, *Pmax*/efficiency, and *FF* temperature coefficients of Module 3 during a single temperature ramp. Note that in Fig. 1 a line at y = 1.00 has been added to allow for easy distinction between negative and positive temperature coefficients.

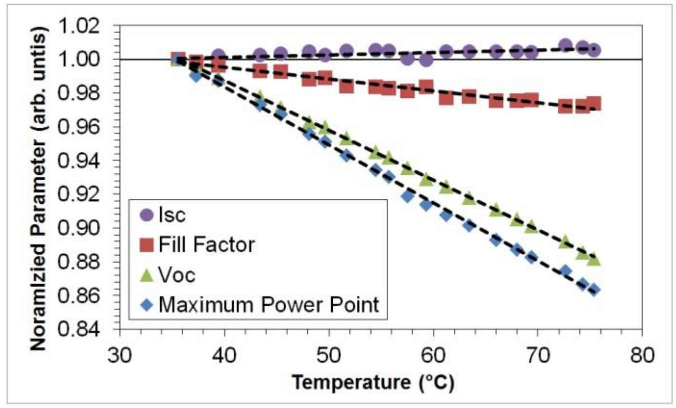

Fig. 1. Normalized extracted parameters for a series of I-V curves along with the linear fits used to extract the corresponding temperature coefficients. A line at y = 1.00 has been added to allow for easy distinction between positive and negative temperature coefficients.

Figs. 2, 3, and 4 show the absolute deviations of the temperature coefficients of *Voc*, *Isc*, and *Pmax*/efficiency, respectively, from the temperature coefficients measured on day 1 of the 16 day test. The data for Modules 1, 2, and 3 are shown in blue, red, and green lines, respectively. We have applied linear fits to the data (which are shown as dashed lines with colors matching the solid lines of their corresponding data sets) to give the reader a sense of how the temperature coefficients changed over time.

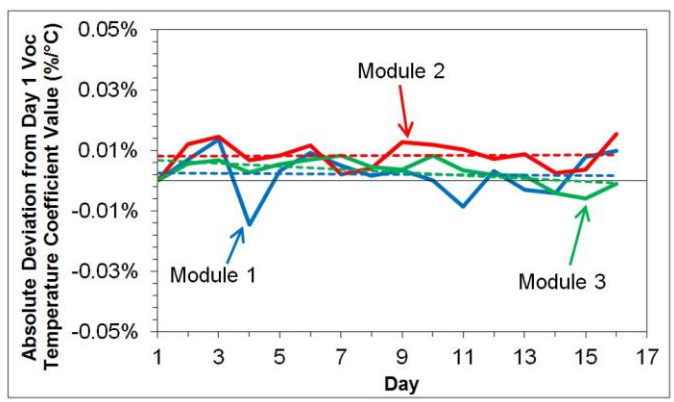

Fig. 2. Absolute deviations, in %/°C, of *Voc* temperature coefficients from the temperature coefficients measured on Day 1 for each module. Note that the data sheet values of the *Voc* temperature coefficients of each module were on the order of -0.3 %/°C to -0.4 %/°C.

Fig. 2 shows that the *Voc* temperature coefficients remained relatively constant throughout the 16-day test. We note that the data sheet values of the *Voc* temperature coefficients themselves were on the order of -0.3 %/°C to -0.4 %/°C.

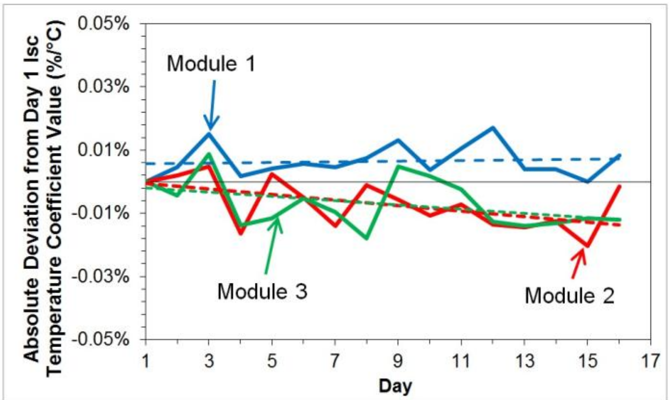

Fig. 3. Absolute deviations, in %/°C, of *Isc* temperature coefficients from the temperature coefficients measured on Day 1 for each module. Note that the data sheet values of the *Isc* temperature coefficients of each module were on the order of 0.01 %/°C.

Fig. 3 shows that the module 1 *Isc* temperature coefficients remained relatively constant throughout the 16-day test, but that the *Isc* temperature coefficients of Modules 2 and 3 become slightly more negative with time. We note that the data sheet values of the *Isc* temperature coefficients of the modules were on the order of 0.01 %/°C

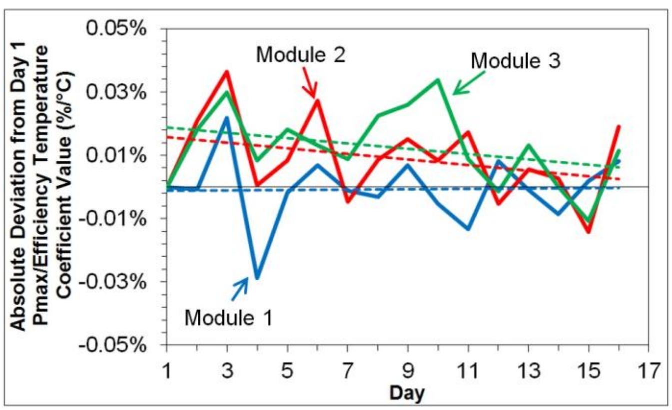

Fig. 4. Absolute deviations, in %/°C, of *Pmax*/efficiency temperature coefficients from the temperature coefficients measured on Day 1 for each module. Note that the data sheet values of the *Pmax*/efficiency temperature coefficients of each module were on the order of -0.3 %/°C to -0.45 %/°C.

Fig. 4 shows that the *Pmax*/efficiency temperature coefficients also remained constant for Module 1, and exhibited an initial increase followed by a slow decline for Modules 2 and 3. We note that the magnitudes of the changes in temperature coefficients indicated by the slopes of the linear fits to the data over the 16-day test were small compared to the magnitudes of the temperature coefficients themselves (on the order of -0.3 %/°C to -0.45 %/°C).

B. Measured Temperature Coefficients Compared to Data Sheet Values

It is interesting to compare the extracted temperature coefficients for each of the three modules over the 16-day test to their corresponding data sheet values. Figs. 5 through 7 show the absolute difference between the data sheet values of the temperature coefficients and the values collected over the 16-day test. The data are plotted using box and whisker plots: The upper and lower limits of the box shown for each module indicate the values of the second and third quartiles of the collected data, respectively (*i.e.*, 50% of measured temperature coefficient values fall within each box). The midpoint of each box indicates the median value of extracted temperature coefficients. The upper and lower limits of the vertical lines drawn through each box indicate the maximum and minimum values measured, respectively.

We emphasize that the values plotted are the *absolute differences* between the data sheet values and the measured values of the various temperature coefficients. To use a hypothetical example, if a module has a listed *Voc* temperature coefficient on its data sheet value of -0.3 %/°C, and the value experimentally measured was -0.35 %/°C, the value that would be plotted in Fig. 5 would be given by the data sheet value subtracted from the measured value, or -0.05 %/°C.

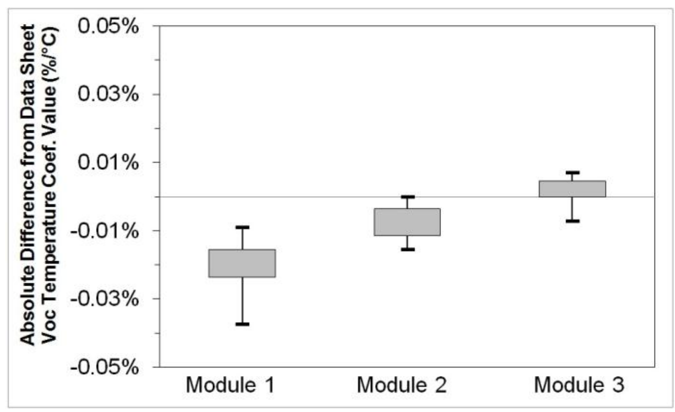

Fig. 5. Whisker-box plot showing the absolute difference between the measured *Voc* temperature coefficients and values from the modules' data sheets. The upper and lower limits of the boxes shown indicate the upper and lower limits of the second and third quartiles of the measured data, respectively (*i.e.*, 50% of the collected data points lie within each box). The center of each box indicates the median value. The upper and lower limits of the vertical lines drawn through each box indicate the maximum and minimum measured values, respectively.

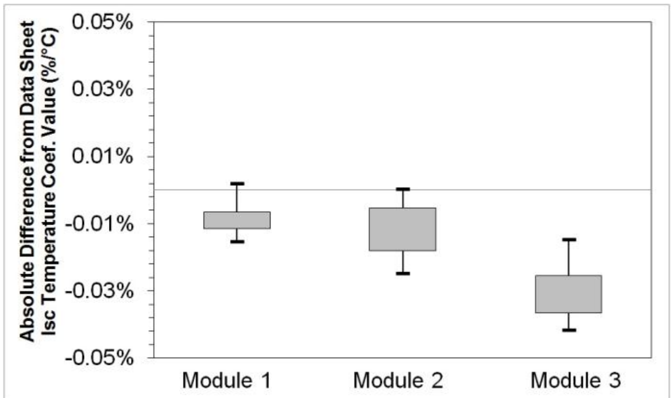

Fig.6. Whisker-box plot showing the absolute difference between the measured *Isc* temperature coefficients and values from the modules' data sheets. The upper and lower limits of the boxes shown indicate the upper and lower limits of the second and third quartiles of the measured data, respectively (*i.e.*, 50% of the collected data points lie within each box). The center of each box indicates the median value. The upper and lower limits of the vertical lines drawn through each box indicate the maximum and minimum measured values, respectively.

Therefore, with respect to Fig. 7, negative values of the absolute difference between the data sheet values and measured values of the *Pmax*/efficiency temperature coefficient would correspond to a module performing more poorly at high temperatures than would be expected from an analysis of the module's data sheet.

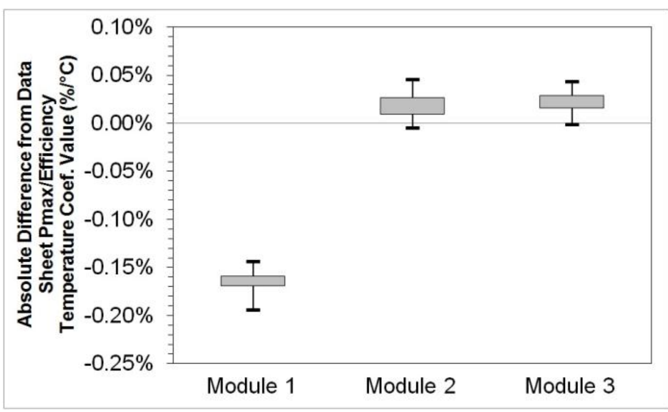

Fig. 7 Whisker-box plot showing the absolute difference between the extracted *Pmax*/Efficiency temperature coefficients and the data sheet values. The upper and lower limits of the boxes shown indicate the upper and lower limits of the second and third quartiles of the data, respectively (*i.e.*, 50% of the collected data points lie within each box). The center of each box indicates the median value. The upper and lower limits of the vertical lines drawn through each box indicate the maximum and minimum measured values, respectively.

The approximate range of the *Pmax*/efficiency temperature coefficients listed on the module data sheets was -0.3 %/°C to -0.45 %/°C. We note that the Module 1 *Pmax*/efficiency measured temperature coefficient shows a significant deviation of between ~35% and ~56% from the listed data sheet value. Notably, the actual power output of Module 1 at normal operating conditions would be ~5% worse than expected from the data sheet, due to the discrepancy of ~0.17 %/°C between the measured and data sheet values of the *Pmax* temperature coefficient.

C. Efficiency Changes with Light Soaking

The main result of Experiment 1 is shown in Fig. 8. From the figure it can easily be observed that each module experiences an increase of a few tenths of a percent in absolute power conversion efficiency, or ~3% to ~5% in relative terms, within approximately the first hour of light soaking. From Fig. 8, it appears that the physical mechanism responsible for this temporary increase in power conversion efficiency lasts only as long as the modules are exposed to light. Following the 16-hour period in the dark, the modules revert back to a lower efficiency state.

We note this behavior is consistent with other light soaking studies of CIGS devices that were exposed to light and dark cycles [3], [4].

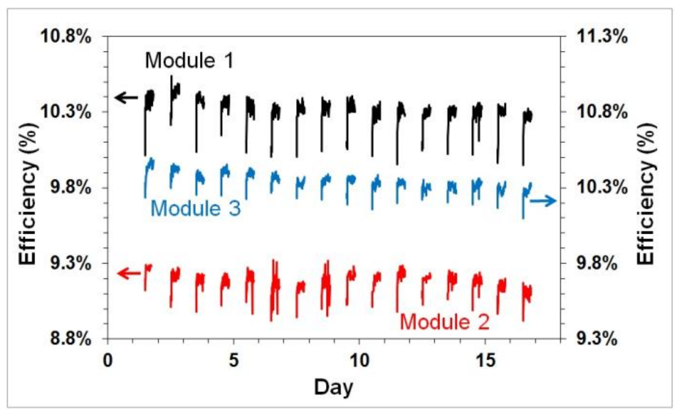

Fig. 8. Efficiency plotted as a function of time. The spaces between data indicate the time the modules were kept in the dark. Note that two y-axes have been used for clarity. Data for modules 1 and 2 correspond to the left y-axis. Data for module 3 corresponds to the right y-axis.

In order to show the effects of light soaking on CIGS module performance on shorter time scales, we show in Fig. 9 a plot of Module 3's relative response to light soaking on day 8 of the experiment described above. Fig. 9 shows the change in *Pmax*/Efficiency, *Isc*, *FF*, and *Voc* with respect to time after light exposure. It can be seen that the module's efficiency increases by ~3.5% on a relative basis within approximately the first hour of light exposure. *Isc*, *Voc*, and *FF* all increase on similar time scales, although by varying amounts. *Isc* increases by ~2%, while *Voc* and *FF* increase by ~1%, all on a relative basis.

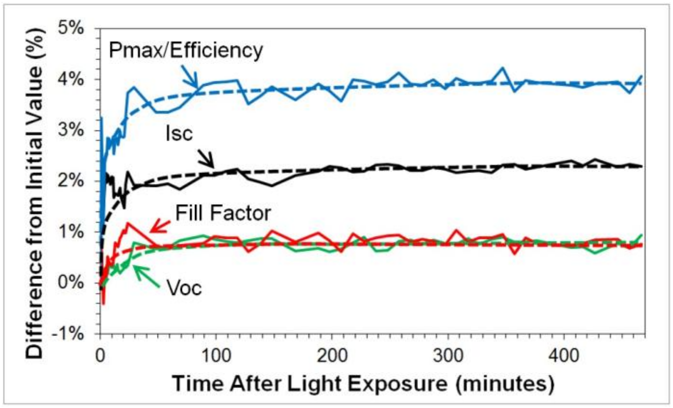

Fig. 9. Relative response of Module 3 to light exposure on the 8th day of Experiment 1. Dashed lines have been added here to the *Pmax*/efficiency, *Isc*, *Voc*, and *FF* data to guide the eye.

IV. EXPERIMENT 2 RESULTS

A. Dark Relaxation Time Scale

From Fig. 8 it is evident that after the 16 hours spent in the dark, all three modules relax back to a low-efficiency state, which is reversed upon light exposure. Fig. 9 indicates that the Module 3 evolves from its low-efficiency state to its high-efficiency state in on the order of 1-2 hours. This time scale was found to be representative for all three modules. In Experiment 2, we attempted to ascertain how long it took the modules to relax to their low-efficiency states in the dark following a period of light soaking. We investigated this by varying the amount of time the modules spent in the dark from 1 hour to 9 hours in 1-hour increments.

Following a 7-day period in the dark, the modules were exposed to a cycle of light exposures and dark for which the light exposure time was 2.5 hours, and the time spent in the dark varied. Aside from light exposure time being 2.5 hours instead of 8 hours, and the amount of time spent in the dark being variable, all of the other details of this experiment were the same as for the previous experiment. The module temperatures were actively controlled to 75 °C during light exposure, and modules were kept at room temperature while in the dark.

The cycle was repeated several times, with the first dark exposure time equal to 1 hour, the second dark exposure time equal to 2 hours, and so on, with the longest dark exposure time being 9 hours. The results are shown in Fig. 10, which clearly shows Module 2 exhibiting a pronounced increase in efficiency with initial light exposure after 3 hours in the dark, but not after 2 hours in the dark. We therefore conclude that Module 2 requires between 2 and 3 hours in the dark to relax to its low efficiency state.

The data from Modules 1 and 3 in Fig. 9 do not show a pronounced increase in efficiency with initial light exposure after 9 hours spent in the dark. However, in Fig. 8, Modules 1 and 3 clearly show a pronounced increase in efficiency with initial light exposure after 16 hours in the dark. We therefore conclude that Modules 1 and 2 require between 9 and 16 hours of time in the dark to relax to their low efficiency states.

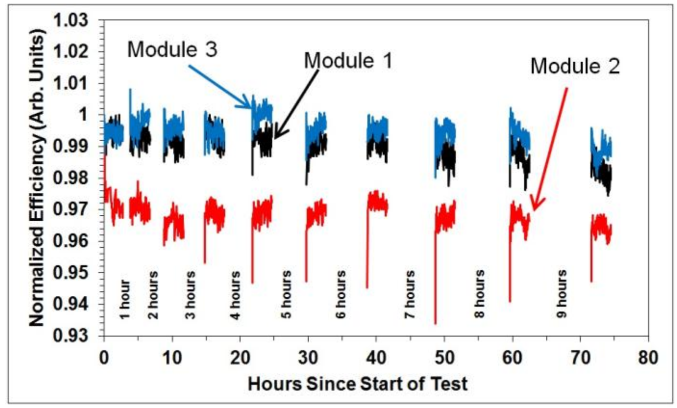

Fig. 10. Efficiency plotted as a function of time. The spaces between data indicate the time the modules were kept in the dark. The amount of time of each period in the dark is indicated by the text on the graph. Note that Module 2 begins exhibiting a pronounced increase in efficiency with initial light exposure after 3 hours in the dark.

V. CONCLUSIONS AND DISCUSSION

The *Voc* temperature coefficients of all three modules remained stable over the 16-day test period of Experiment 1. The *Isc* temperature coefficients exhibited a slight decrease over time for Modules 2 and 3, but remained constant for Module 1. The Pmax/efficiency temperature coefficients exhibited an initial increase followed by a slight decrease for Modules 2 and 3, but remained constant for Module 1. No temperature coefficients showed a significant deviation from the module data sheet values with the exception of the *Pmax*/efficiency temperature coefficient of Module 1, which showed a deviation on absolute terms of approximately -0.17 %/°C. This deviation is significant when compared to a range of *Pmax*/efficiency temperature coefficients of -0.3 %/°C to -0.45 %/°C for the three modules, and would result in Module 1 providing ~5% less power output at normal operating temperatures than would be expected based on the data sheet values.

All three modules were observed to show an increase in power conversion efficiency with initial light exposure of ~3% to ~5% on a relative basis. This initial increase was repeatable when the modules were allowed to relax into a low-efficiency state after 16 hours in the dark.

The dark relaxation time of Module 2 appears to be between 2 and 3 hours, while the dark relaxation times of Modules 1 and 3 appear to be between 9 and 16 hours. We note that Module 2 was also the lowest-efficiency module of the three, with a power conversion efficiency on the order of 9.3%, while the power conversion efficiencies of Modules 1 and 3 were both on the order of 10.3%.

We note that the increase in power conversion efficiency within the first hour of light soaking in the solar simulator chamber may correspond to a slightly longer time scale for CIGS modules in the field, due to the fact that in the simulator chamber we were almost immediately exposing the modules to light with an irradiance intensity of 1000 W/m^2 at the start of each test cycle, while in the field modules are typically exposed to light intensities which increase gradually during the morning hours. Therefore, it could be expected that CIGS modules in the field would show somewhat lower efficiency at the start of each day, with efficiency level rising throughout the first few hours of each morning.

Further work is planned in our group to examine metastabilities in other module performance parameters (e.g., *Voc*, *Isc*, etc.), and for varying test conditions (e.g., varying light exposure times, module temperatures, and electrical bias conditions).

References

[1] M. Gostein and L. Dunn, “Light Soaking Effects on Photovoltaic Modules: Overview and Literature Review,” in *37th IEEE Photovolatic Specialists Conference*, Seattle, WA, 2011.

[2] J. A. del Cueto, S. Rummel, B. Kroposki, C. Osterwald, and A. Anderberg, “Stability of CIS/CIGS Modules at the Outdoor Test Facility over Two Decades,” in *33rd IEEE Photovoltaic Specialists Conference (PVSC)*, 2008.

[3] T. Yanagisawa and T. Kojima, “Behavior of a CuInSe2 solar module under light irradiation in light/dark cycle tests,” *Solar Energy Materials and Solar Cells*, vol. 77, no. 1, pp. 83–87, Apr. 2003.

[4] T. Yanagisawa and T. Kojima, “The stability of the CuInSe2 solar mini-module I-V characteristics under continuous and light/dark irradiation cycle tests,” *Microelectronics Reliability*, vol. 43, no. 3, pp. 503–507, Mar. 2003.

Preprint: L. Dunn, and M. Gostein, “Light Soaking Measurements of Commercially Available CIGS PV Modules,” *Proceedings of the 38th IEEE Photovoltaic Specialists Conference (PVSC)*, Austin, TX, June 3-8, 2012.