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Long-term performance analysis of copper indium gallium selenide thin-film photovoltaic modules

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Abstract. Current accelerated qualification tests of photovoltaic (PV) modules mostly assist in avoiding premature failures but can neither duplicate changes occurring in the field nor predict useful product lifetime. Therefore, outdoor monitoring of field-deployed thin-film PV modules was undertaken at FSEC with the goal of assessing their performance in hot and humid climate under high system-voltage operation. Significant and comparable degradation rate of $-5.13 \pm 1.53\%$ and $-4.5 \pm 1.46\%$ per year was found using PVUSA type regression analysis for the positive and negative strings, respectively of 40W glass-to-glass Cu-In-Ga-Se (CIGS) thin-film PV modules in the hot and humid climate of Florida. Using the current-voltage measurements, it was found that the performance degradation within the PV array was mainly due to a few (8% to 12%) modules that had substantially higher degradation. The remaining modules within the array continued to show reasonable performance ($>96\%$ of the rated power after $\sim$ four years). © 2012 Society of Photo-Optical Instrumentation Engineers (SPIE). [DOI: [10.1117/1.JPE.2.022005](https://doi.org/10.1117/1.JPE.2.022005)]

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1 Introduction

Thin-film photovoltaic (PV) technology, due to its various benefits and niche applications, is expected to capture a significant portion of the PV market. Therefore, it is important to continue efforts to improve the reliability and durability of thin-film modules that can make a significant contribution to address the world energy crisis and at the same time bring extended consumer satisfaction. The idea underlying the outdoor testing and monitoring of PV modules is to ensure that the technology has reached a degree of maturity considerable enough that the lifetime warranty provided by the manufacturer is supported by real-time field-test data. In situations where this goal cannot be met, it becomes essential to determine the fundamental cause behind any specific kind of failure and to investigate it so that the necessary preventive measure can be incorporated during the manufacturing. With continuous efforts of this nature, the robustness and performance assurance of a given product continues to improve.

Infant mortality can be defined as the failures resulting due to latent defects in the products that may escape the quality test during manufacturing. Thus a process to accelerate the latent defect may be needed. The accelerated qualification tests are supposed to serve this purpose. The current accelerated qualification tests of PV modules mostly assist in avoiding infant mortality but cannot duplicate changes occurring in the field nor can predict useful lifetime. A clear correlation between indoor, accelerated testing and outdoor performance is still being sought. The long-term outdoor testing of PV modules aids in determining the degradation rate and the degradation mechanisms of PV modules, thus providing the means to estimate the extent of degradation in PV modules under actual operating conditions.¹ Moreover, it is helpful in detecting long-term degradation, if any, and understanding the correlation of PV performance and the meteorological parameters.

For a PV system with series-connected PV modules reaching maximum open-circuit voltage of up to ± 600 V, some modules are subjected to high-bias voltage as an additional acceleration factor. Hence to guarantee a U.S. Department of Energy (DOE) goal of 30-year useful lifetime, it is necessary to continue the outdoor testing of PV modules for an extended period of time. In order to satisfy this goal, outdoor monitoring of thin-film PV modules from all the leading thin-film PV manufacturers within the U.S. was undertaken as a project from National renewable Energy Laboratory (NREL)/DOE (Fig. 1). This paper presents the performance analysis of commercially available 40 W glass-to-glass copper indium gallium selenide (CIGS) PV modules. Statistical data analysis of continuously monitored PV parameters along with meteorological parameters is carried out on a regular basis with PVUSA type regression analysis.² Current-voltage (I–V) characteristic of module arrays that are obtained periodically complement the continuous data monitoring. One difficulty with the outdoor testing is that due to seasonal changes, several complete cycles are required in order to obtain reasonably accurate degradation rates.

2 Methodology

Several parameters must be taken into consideration in order to characterize the performance of a PV device. These parameters include current and voltage generated by the PV device, solar irradiance, back-of-module temperature, relative humidity, wind speed, ultraviolet (UV) irradiance, and ambient temperature. However, the simulation of such conditions under accelerated testing conditions is prohibitively costly. Hence, it is essential to carry out reliability testing of field-deployed PV modules and to focus on outdoor testing and monitoring of PV modules in the hot and humid and other climates.

A sturdy, hurricane-proof base structure was constructed in 2003 for the installation of thin-film PV modules manufactured in the U.S. The modules were mounted at a latitude tilt of ~ 29 deg facing true South. All modules types were divided in two sets; modules in each set were connected in series so as to build maximum open-circuit voltage of less than ± 600 V with respect to ground for a nominal maximum DC power output of 960 W, standard test conditions (STC). They were connected across fixed-precision load resistors of $175\ \Omega$ and a current measuring shunt. Each array was a standalone system with DC power delivered to a fixed load connected in series. The data acquisition system consisted of two AM 16/32 Multiplexers and a Campbell-Scientific CR10 datalogger to collect all voltage and current data, two pyranometers' readings, and other meteorological data. Initially, the data averaged over every 2 min was recorded. It had significant noise. Hence, later the data was averaged over every 15 min and stored. This improved the quality of the data. I–V measurements were carried out quarterly with a portable Daystar I–V curve-tracer. Continuous recording of PV parameters as well as the meteorological parameters was carried out and analyzed on a daily as well as on a monthly basis. The modules, manufactured in 2003, were monitored regularly from April 2005 to September 2007 at FSEC. While installation of the modules had been completed at the end of 2003, the very active Atlantic hurricane season of 2004 led to a number of disruptions in 2004.

This was one of the worst hurricane seasons in Florida in over 100 years and therefore data could not be recorded during this timeframe. Hurricane protectors were built and tested after these unprecedented five hurricanes (Bonnie, Charley, Frances, Ivan, and Jeanne) hit Florida in 2004. The usage of the hurricane protectors during the subsequent hurricane seasons resulted in minimal loss of data as well as protecting the PV modules from any damage. Additionally, the modules were sent back to NREL in 2005 for I–V characterization. Consequently, continuous monitoring was reinitiated in 2005. The results of this study are presented in this paper.

Fig. 1 Outdoor test bed at FSEC showing thin-film modules from first solar (FS), shell solar (SS), united solar (USSC), energy photovoltaics (EPV), and global solar (GS).

The continuous monitoring of meteorological parameters aids in elucidating the correlation of ambient parameters such as solar irradiance, relative humidity, and ambient temperature with the PV performance.^{3,4} The data is screened for any discrepancies and power ($V \cdot I$) versus Irradiance graphs are plotted as depicted in Fig. 2 on a daily basis and eventually on a monthly basis as shown in Fig. 3. Using a protocol developed by PVs for utility systems applications (PVUSA), PV system performance monitoring by regressions under PVUSA Test Conditions (PTC) is a commonly used method since PV module and array temperature measurements are not needed and the magnitude of power obtained by PTC is much closer to the actual operational power values. PVUSA regression analysis was carried out using a simplified version suited to our requirements using LabVIEW code originally provided by NREL.⁴

As per the PVUSA regression analysis, power is considered to be a function of irradiance, temperature, and wind speed. However, for the analysis presented here, wind speed is assumed to be constant as an approximation. Therefore power is considered a function of irradiance and temperature and is represented mathematically as

$$P = C_1 \cdot E + C_2 \cdot E^2 + C_3 \cdot T \cdot E. \quad (1)$$

Here, P , E , and T represent power, irradiance, and temperature, respectively, while C_1 , C_2 , and C_3 are constants for a given month. A LabVIEW program was developed to estimate the three coefficients using the least square method. These coefficients are then used to calculate the PTC power ($E = 1000 \text{ W/m}^2$ and $T = 20^\circ\text{C}$) for that month. Such continuous data when collected over extensive period of time aids in estimating the PV performance degradation rates,

Fig. 2 Variation of power, solar irradiance for the PV array during a typical sunny day with $SI > 600 \text{ W/m}^2$.

Fig. 3 Variation of power with solar irradiance for a positive module array.

if any. A PTC power trend was plotted from the calculated PTC powers. The trend line will be a straight horizontal line if there is no degradation.

3 Results and Discussion

In Figs. 4 and 5 the PTC regression analysis for the CIGS thin-film PV modules deployed in Florida is shown, respectively for the positive and negative array string. The above-mentioned weather-related interruptions resulted in a shorter data monitoring period. The seven-month interruption in data collection from September 2005 to approximately May 2006 while the modules were awaiting I-V characterization at NREL is indicated by the gap in the figures. The modules were stored in a cool, dark room during this time period and were not exposed to further field degradation.

For analyzing the power data for a PV system under fixed load, it is necessary to use the output power values that are close to the fixed optimum resistance. In order to satisfy this condition, the data was filtered with solar irradiance $>800 \text{ W/m}^2$. Filtering the data for solar irradiance $>800 \text{ W/m}^2$ reduced the scatter in the data points considerably. Using the slopes from the trend line, degradation rates were determined to be $-5.16 \pm 1.53\%$ and $-4.5 \pm 1.46\%$ per year for the positive and negative string, respectively.

The variation in the PTC power values is not an indication of measurement error. CIGS thin-film modules are known for their metastable behavior. Therefore, it was not possible to model the data in order to remove the effect of seasonality from the measured values. The uncertainty within the data includes the seasonality. Surprisingly, the same modules type showed much lower degradation rate in the hot and dry climate of Arizona. The next-generation ST80 modules remarkably showed no degradation in Colorado over several years of field deployment, mainly due to several improvements in manufacturing, including better packaging.⁵ Degradation rates similar to those observed in Florida were also reported recently during a three-year study at Hokuto testing site of the Japanese Mega-Solar project. Twenty-four different technologies were tested in this location. In this study, annual degradation rates of -4.3% and -2.05% were determined for two 30 kW and 3 kW CIS PV systems.⁶ In another study carried out at

Fig. 4 PTC power analysis for the CIGS thin-film positive module array.

Fig. 5 PTC power analysis for the CIGS thin-film negative module array.

Fig. 6 Comparison of peak power values obtained from I–V measurements carried out on LACSS solar simulator and Daystar Curve tracer.

the National Renewable Energy Laboratory (NREL) in a moderate and dry climate, lower degradation rates along with transient behavior in PV parameters were observed during the long-term outdoor testing of CIGS PV modules from 1988 to 2005.⁷ It is postulated that if the studies in all these locations were continued for an extended period of time, the modules would also have shown an increase in the degradation rate. With a limited test period, it is not justifiable to declare success and terminate the test. Therefore it is recommended that such studies be carried out for an extended period of time.

Baseline I–V measurements were carried out for the individual modules at NREL using a Large Area Continuous Solar Simulator (LACSS). During February 2005, I–V measurements were also carried out for the individual modules in field at FSEC. The peak power values were compared with those obtained from PV characteristics obtained from the baseline measurements carried out during 2003 at NREL for each individual module as shown in Fig. 6. It can be seen that most of the modules continued to show consistent performance except a few modules that had shown significant degradation. The blue line plotted in Fig. 6 is not a trend line. It has been drawn at 45 deg so as to compare the measurement before and after at a quick glance. It can also be noted that the measurements at FSEC are higher than those at NREL. Since these values correspond to measurements after adequate light soaking outdoors, this may be considered as an indication that modules are improving in time as a result of light induced transient effect. Figure 7 shows the variation of peak power with respect to rated power in percentage for the positive and negative array during the time frame of outdoor testing of the modules.

It can be noted that after the initial drop in the power values, the modules seem to have performed consistently for the remaining test period. Very low open-circuit voltage was measured during the month of September 2005 for the negative string, which resulted in lower peak voltage and correspondingly lower peak power. Similar phenomena are also observed during August 2005; however, the magnitude is considerably smaller. It is difficult to suggest reasoning for this observed behavior. It was found that three modules in the positive string and two modules in the negative string had shown a power output of less than or equal to 85% of the rated power. These modules were then grouped together within the array towards the high-voltage end of the array. The idea was to be able to take the I–V measurements independently for these modules and the rest of the modules within the array. During February and April 2007, another set of I–V measurements was carried out for the entire array, for modules that had shown lower than 85% performance and for modules that had continued to show performance over 85%. The results obtained from these measurements are tabulated in Table 1.

The results obtained from I–V measurements complement the analysis carried out with PTC power results. The result tabulated in Table 1 point to the fact that as mentioned before, only a few (8% to 12%) of the modules in the positive and negative arrays had shown significant degradation.

Fig. 7 Variation of peak power with respect to rated power (%) for the positive and negative array during the given time frame.

Table 1 Variation of peak power values (% of rated power) from the I–V measurements carried out during February and April 2007.

Title	Array type	Details	Peak power (%) February 2007	Peak power (%) April 2007
SSP_01	Positive	Three modules with performance lower than 85%	79.9	79.2
SSP_02	Positive	Remaining 21 modules that performed better	98.6	99.3
SSP_03	Positive	Entire array	96.3	95.6
SSN_01	Negative	Two modules with performance lower than 85%	85.5	83.8
SSN_02	Negative	Remaining 22 modules that performed better	96.2	96.7
SSN_03	Negative	Entire array	96.6	94.9

It can be seen that the remaining modules in the arrays strings continued to show reasonable performance ($>96\%$ of the name plate power rating after $\sim$ four years) as is evident from the results obtained from I–V measurements. No further degradation was observed in these modules. It may be noted that the specific modules that had shown considerable degradation were from an older generation/different batch while the remaining modules continued to perform satisfactorily. It may also be noted here that the next-generation CIGS modules have shown better and more stable performance on account of several manufacturing improvements.

4 Conclusions

It can be seen that the earlier-generation CIGS modules have showed a significant degradation rate for the time frame they were deployed in the field in the hot and humid climate of Florida. The estimated degradation rates calculated from the PVUSA regression analysis during this time frame were $-5.16 \pm 1.53\%$ and $-4.5 \pm 1.46\%$ per year for the positive and negative string, respectively. It was found that the overall degradation observed within the array strings was due to a few modules in the positive and negative array strings that had shown significant degradation. The remaining modules within the array continued to show consistent performance that was evident from the I–V measurements carried out for the different sets of modules within the array. From these measurements it was determined that the observed performance degradation within the PV array was on account of 8% to 12% modules with considerably high degradation rate while the remaining modules within the array continued to show reasonable performance of $>96\%$ of the rated power after $\sim$ four years of field deployment. The necessity

of carrying out testing of this nature in hot and humid climate cannot be therefore underestimated in terms of its effectiveness in elucidating the performance variation of the PV modules.

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