Thin-Film Reliability Trends Toward Improved Stability

Preprint

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Presented at the 37th IEEE Photovoltaic Specialists Conference (PVSC 37)
Seattle, Washington
June 19-24, 2011

Conference Paper
NREL/CP-5200-50726
July 2011

Contract No. DE-AC36-08GO28308

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THIN-FILM RELIABILITY TRENDS TOWARD IMPROVED STABILITY

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ABSTRACT

Long-term, stable performance of photovoltaic (PV) modules will be increasingly important to their successful penetration of the power grid. This paper summarizes more than 150 thin-film and more than 1700 silicon PV degradation rates (R_d) quoted in publications for locations worldwide. Partitioning the literature results by technology and date of installation statistical analysis shows an improvement in degradation rate especially for thin-film technologies in the last decade. A CIGS array deployed at NREL for more than 5 years that appears to be stable supports the literature trends. Indoor and outdoor data indicate undetectable change in performance (0.2±0.2 %/yr). One module shows signs of slight degradation from what appears to be an initial manufacturing defect, however it has not affected the overall system performance.

INTRODUCTION

Long-term performance of PV systems is vital to their continuing success in the market place. The gradual energy output loss over long periods of time is a major concern to all renewable energy stakeholders. A wide variety of degradation rates has been reported in the literature with respect to technologies, age, manufacturers, and geographic locations, and has been recently summarized. [1] For crystalline technologies, there are several reports in the literature with very small degradation rates over many years, even decades; however, equivalent reports on thin-film technologies are not as plentiful. [2, 3, 4, 5, 6, 7] Musikowski et al. only recently reported on a CIS array in Germany that displayed apparent stability over 6 years. [8] This paper consists of two distinct parts. In the first part, we discuss trends that can be learned by examining literature values, especially with respect to thin-film technologies. The second part examines in detail a grid-connected CIGS system deployed at NREL for more than 5 years.

DEGRADATION RATE LITERATURE

Figure 1 shows the result of an extensive literature search resulting in more than 150 thin-film and more than 1700 silicon PV degradation rates (R_d) quoted in over 100 publications and locations worldwide. [1] A decrease in performance is defined as a positive degradation rate. Conversely, a negative rate indicates an improvement. The median degradation rate for all technologies is 0.5 %/year.

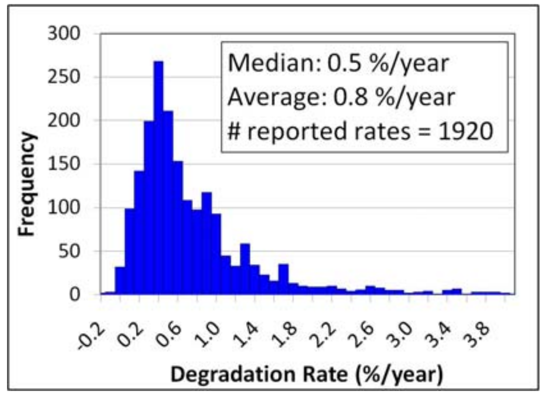


Figure 1. Histogram of reported degradation rates with median reported rate of 0.5 %/year.

The results of a Monte Carlo simulation we conducted are illustrated in Fig. 2, showing the effect degradation rates have on the probability that a module will retain the warrantied power. The data are partitioned by date of installation into before (pre) and after (post) 2000. Assuming linear degradation rates and that no catastrophic failures occur, we can pick a degradation rate at random from the literature distribution and calculate what the projected power output will be after 25 years for a 200W module. Repeating this procedure thousands of times, a smooth distribution was obtained that can be compared to a typical manufacturer warranty of 80% standard test conditions (STC). [9] The warranty default probability is the integrated probability to the right of the green dashed line.

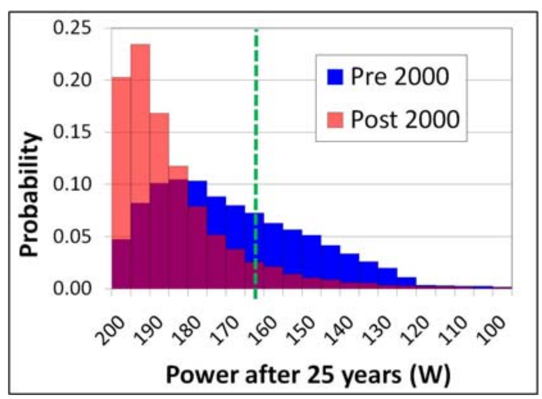


Figure 2. Results of a Monte Carlo simulation for a 200-W module and its power output after 25 years. The green dashed line indicates a typical warranty.

Two important effects for the PV industry are demonstrated by this Monte Carlo simulation: 1. It shows the tremendous impact degradation rates have on the long-term performance and economics of PV systems; 2. The warranty default risk decreased from 26% to 6% for modules deployed before 2000 and after 2000, demonstrating that PV stability appears to have improved for the more recent products.

When these reported literature results are partitioned by technology in addition to date of installation, further conclusions can be drawn. Figure 3 shows the results of such an analysis of the reported literature results (a) and of a set of more than 40 modules at NREL (b) the authors reported on previously.[10] The crossbars are indicative of the average for each category and the diamonds indicate the 95% confidence interval (CI). The number of data points per category is given at the top of the figure. Some of the CIs, especially for silicon technologies, are very narrow, while "tails" of data points appear above and below. This effect is due to many data points stacked on top of each other and are therefore only visible as a singular point in the variability chart. Crystalline Si technologies appear to have remained steady at rates of approximately 0.5%/year for installations before and after

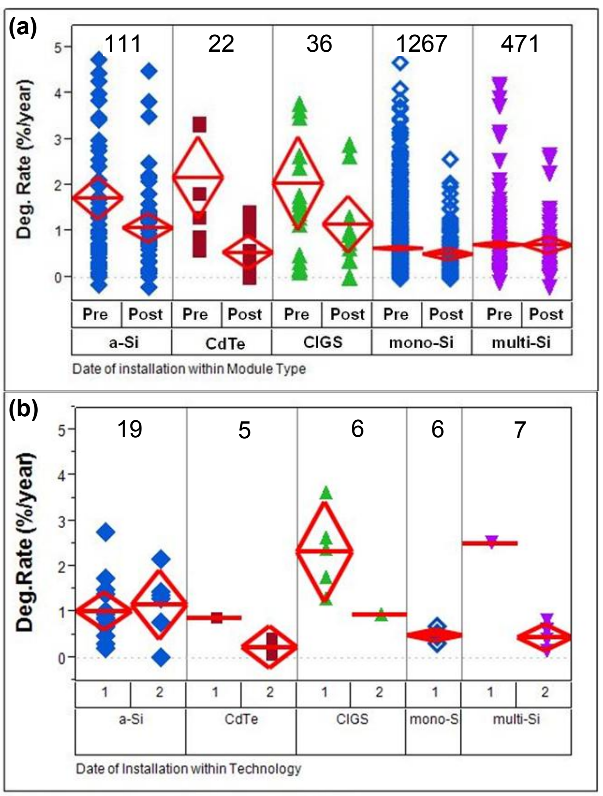


Figure 3. Analysis of degradation rates (a) reported in the literature and (b) from NREL's Performance and Energy Rating Testbed (PERT) partitioned by technology and date of installation (pre and post means before and after year 2000, respectively.)

the year 2000. However, thin-film technologies, particularly CdTe and CIGS, showed a significant move towards stability for post 2000 installations. These literature findings are similar to our own study in Fig. 3(b), despite the small sample size in some categories.

NREL CIGS SYSTEM

Figure 4. Shell Solar E80-C modules deployed at NREL. Photo credit: Harin Ullal, NREL PIX 14725

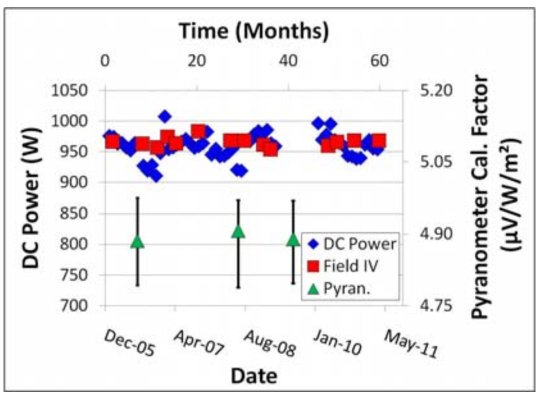
Figure 4 shows a photo of the array located at the Outdoor Test Facility (OTF) at NREL. The system consists of 14 Shell Solar PowerMax Eclipse® 80-C modules, installed in portrait orientation with two parallel strings for a nominal power output of 1120W DC STC. The array was mounted at a latitude tilt of 40º facing due south and was utility grid-tied through a SMA Sunnyboy inverter with its own maximum-power-point-tracking algorithm. The Eclipse 80-C module houses two 1'x4' circuits in a glass-glass package design with an edge seal from Truseal. [11, 12]

System Information		**Module STC Rating**	
Manufacturer	Shell Solar	Power (W)	80
Module Type	Eclipse 80-C	I_{mp} (A)	2.41
Technology	CIGS	V_{mp} (V)	33.2
System Size	1.12 kW	I_{sc} (A)	2.68
Configuration	2 parallel strings	Voc (V)	46.6
No. of modules	14	Array tilt	40º
Date of installation	Jan 2006	Array azimuth	180º (S)
Inverter		**Geographic Information**	
Manu-facturer	SMA	Altitude (m)	1792
Types	Sunny Boy	Site Latitude	39.7404
Model	1800U	Site Longitude	-105.1774

Table 1: Summary of system and module information of the NREL CIGS array.

A summary of the system and the modules is given in Table 1. The array has been fielded and continuously monitored since January 2006, except for a period in 2009 due to PV yard upgrades. The pyranometer, a Kipp & Zonen CM11, was used to collect in-plane irradiance and was calibrated every 1-2 years using NREL's Broadband Outdoor Radiometer Calibration (BORCAL) procedure.[13]

To assess the reliability of the system comprehensively, we used several performance metrics including PVUSA methodology [14 , 15], performance ratio [16], and quarterly obtained field I-V curves. Data at irradiance levels below 800 W/m^2 were eliminated from the analysis because extrapolation from low-irradiance levels to PTC increases the model uncertainty. A portable Daystar I-V tracer was used on cloudless days around solar noon and corrected for temperature and irradiance in accordance with IEC 60891 Method 3. [17] Figure 5 shows the results of the PVUSA methodology overlaid with the corrected field I-V curves. It appears that no statistically significant decline has occurred.



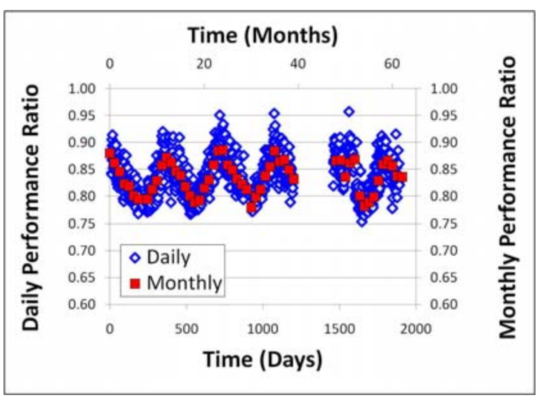


Figure 5. (a) PVUSA methodology and field I-V curves for the Shell CIGS array. Pyranometer calibration values are given on the second vertical axis. (b) Performance ratio in daily and monthly increments.

Table 2 summarizes the results for the different methodologies including some time series modeling such as classical decomposition and ARIMA that have been shown to reduce uncertainty by removing seasonality. [18] The uncertainties given here refer to Type A uncertainties according to the ISO guide to the Expression of Uncertainty. [19] The overall median degradation rate with the pooled standard deviation is indicated by the last shaded line. While there are slightly different results for the individual methodologies, they agree fairly well with the overall median degradation rate.

R_d	Uncertainty	Method	Interval
-0.13	0.18	PVUSA Linear Fit	Monthly
-0.32	0.07	PVUSA Cl.Decomp [18]	Monthly
-0.16	0.07	PVUSA ARIMA [18]	Monthly
-0.14	0.30	Performance Ratio Linear Fit	Monthly
-0.23	0.11	PR Cl.Decomp	Monthly
-0.09	0.20	PR ARIMA	Monthly
-0.25	0.08	Performance Ratio Linear Fit	Daily
0.03	0.13	Field IV	Quarterly
-0.15	**0.18**	**Overall median ± pooled Standard deviation**	

Table 2: Summary of degradation rates (R_d) for the Shell Solar system at NREL.

In 2009, the outdoor array field underwent some major upgrades providing the opportunity to measure all modules indoors by various techniques and compare them to baseline data taken before the system was deployed. Figure 6 shows the results for maximum power (Pmax), fill factor (FF), open-circuit voltage (Voc) and short-circuit current (Isc) measured in 2005 and 2009. Three techniques available at NREL—the large area continuous solar simulator (LACSS), the Spire 240A pulsed simulator, and standard outdoor measurement system (SOMS)—were utilized and are color coded in Fig. 6. [20] Each of the 14 modules with a different serial number was denoted by a different symbol.

Marion et al. found a degradation rate for a CdTe array at NREL of 0.6%/year. [21] Individual modules were tested by Spire and SOMS at the end of a 5.5-year test period and compared to baseline measurements taken before system deployment. While the average degradation rate for all modules agreed with the rate determined from continuous data, individual module performance ranged from ca. -15% to +23%. This appears not to be the case for this particular array, as shown in Fig. 6 (a). Only the module with serial number 61 shows a significant decline in Pmax that is visible in all three different test methodologies. All other modules show no significant degradation similar to the overall system performance. The decline is also consistently visible in FF for all three test methodologies while only the Spire measurement indicated a decline in Isc. Figure 7 shows an IR image and optical image of module 61. The arrow in the optical image indicates a line that appears to be a manufacturing defect and runs perpendicularly to the manufacturing scribe lines. The hot spot developed at the end of this line near the contact line. Except for module 61, whose degradation appears to be linked to the manufacturing process, all other modules show no decline in electrical parameters.

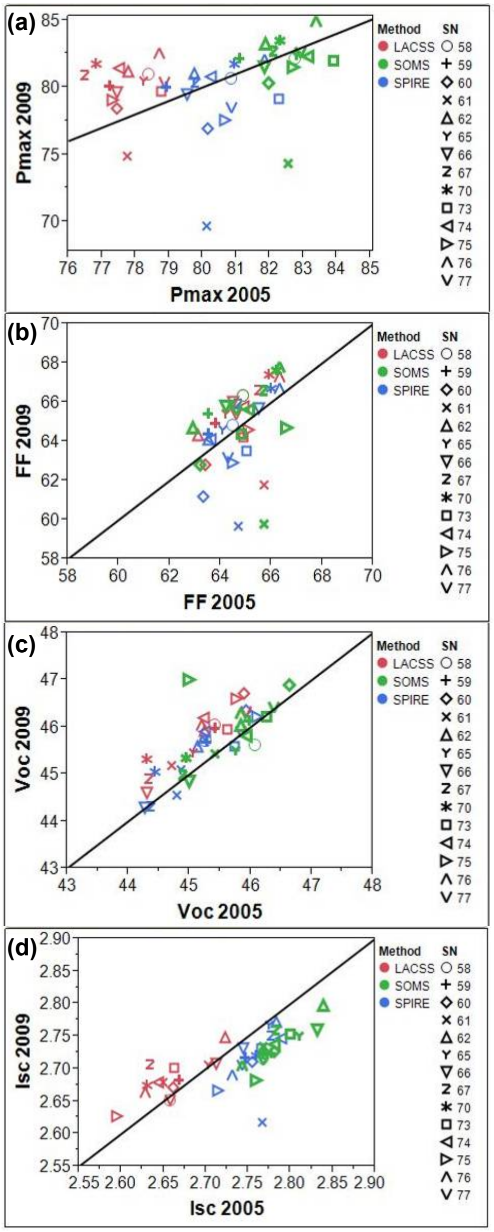


Figure 6. Pmax, FF, Voc, and Isc measured by LACSS (red), SOMS (green) and Spire (blue). Each module with a different serial number is denoted by a different symbol. The straight line indicates no change.

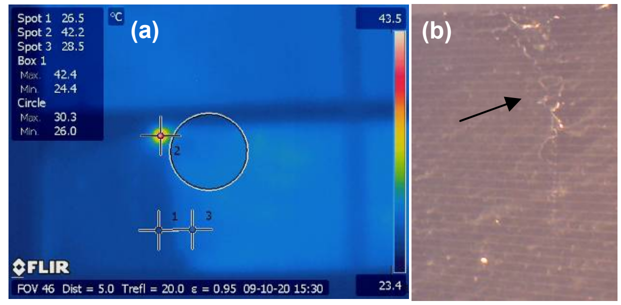


Figure 7. IR image of module 61 (a) and optical image (b)

Figure 8 shows the change in series resistance and shunt resistance from dark and light IV measurements obtained from the derivatives dV/dJ and dJ/dV, respectively, and their extrapolation to zero. [22]

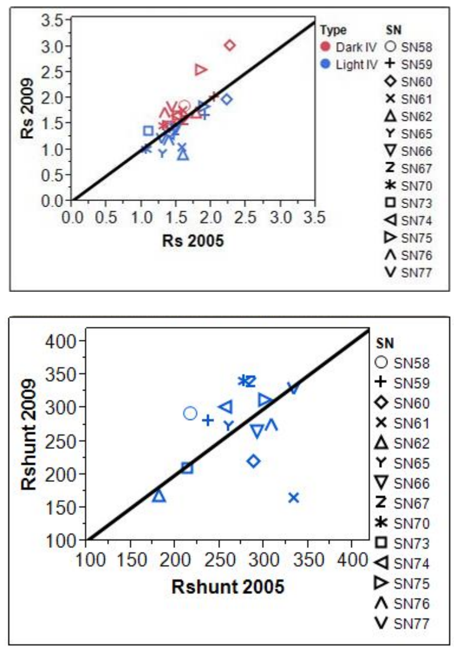


Figure 8. Change in series and shunt resistance obtained from the derivatives dV/dJ and dJ/dV, respectively.

The measurement uncertainty is 5%, however the overall uncertainty is much larger due to the choice of fitting interval. [23] Two modules show an increased series resistance separated from the other module measurements. These two modules, 60 and 75, also show slightly decreased fill factor in Fig. 6 (b). In addition, module 61 shows an almost 50% decrease in shunt resistance. This observation is consistent with previously reported shunts developing at the P3 interconnect lines. [24]

CONCLUSION

Reported degradation rates in the literature appear to show a significant improvement for thin-film technologies during the past decade mirroring findings of our own study encompassing more than 40 modules. A Shell Solar CIGS 1.12 kW system fielded at NREL provides a clear example of stable operation. No significant performance decline has been found for the array after 5 years of outdoor exposure using several different performance metrics. Indoor measurements taken before and after field exposure confirm the stability of the system with the exception of one module that showed ~5% decline, possibly caused by a defect introduced during the manufacturing process.

ACKNOWLEDGEMENT

We would like to thank Ryan Smith, Bill Sekulic, Kent Terwillinger, Dale Tarrant, Bob Wieting, Harin Ullal, John Pern and Ingrid Repins for the help with the array and useful discussions and Joe del Cueto for review of the manuscript. This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.

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