SAND2018-13371R

Final Project Report

Project Title:	PV Lifetime
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Submission Date:	30 September 2018
Recipient:	Sandia
Address:	P.O. Box 5800 MS1033, Albuquerque, NM 87185
Agreement Number:	SuNLaMP 31427
Awarding Agency:	DOE EERE SETO PV subprogram
Working Partners:	NREL, University of Central Florida
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Executive Summary: Started in 2016, the PV Lifetime Project is measuring PV module and system degradation profiles over time with the aim of distinguishing different module types and technology. Outdoor energy monitoring in different climates is supplemented with regular testing under repeatable test conditions indoors. The focus is on the PV module, as well as other hardware components (junction boxes, bypass diodes, and module-level electronics) attached to it. Hardware is installed at Sandia National Laboratories in New Mexico, at the National Renewable Energy Laboratory in Colorado, and at the University of Central Florida. The systems are continuously monitored for DC current and voltage, as well as periodic I-V curves at the string level.

In the future, once degradation trends have been identified with more certainty, results will be made available to the public online. This data is expected to enable an increase in the accuracy and precision of degradation profiles used in yield assessments that support investments made in new PV plants. Current practice is to assume that degradation is constant over the life of the system. Forthcoming results in the next few years will help to determine whether this assumption is still appropriate.

The FY18 Accomplishments include:

- Installation of systems using modules from Canadian Solar, Hanwha Q-Cells, Panasonic, and LG in New Mexico and Colorado.
- Publication of interim results at the WCPEC-7 conference in Waikoloa, HI. This paper includes results from annual indoor module testing in New Mexico and Colorado.
- Development of the PV Lifetime Module and System Measurement Plan

Background: The degradation of PV module materials that leads to gradual loss in performance is a significant factor in the economics of PV generated energy. Studies measuring the degradation rates of PV modules and systems across a wide range of technology and climate conditions have typically been limited to a small number of modules and typically have significant uncertainty due to small sample sizes, long intervals between measurements, and frequently lack of high quality characterization data from the modules before placing them in the field. Jordan et al., 2016 provides a great compendium these studies. Figure 1 is copied from this compendium and illustrates the wide range in measured degradation rates. What this work does not include is a detailed understand of how degradation proceeds over time. Understanding this is one of the main goals of the PV Lifetime project because it can significantly affect the LCOE (Figure 2).

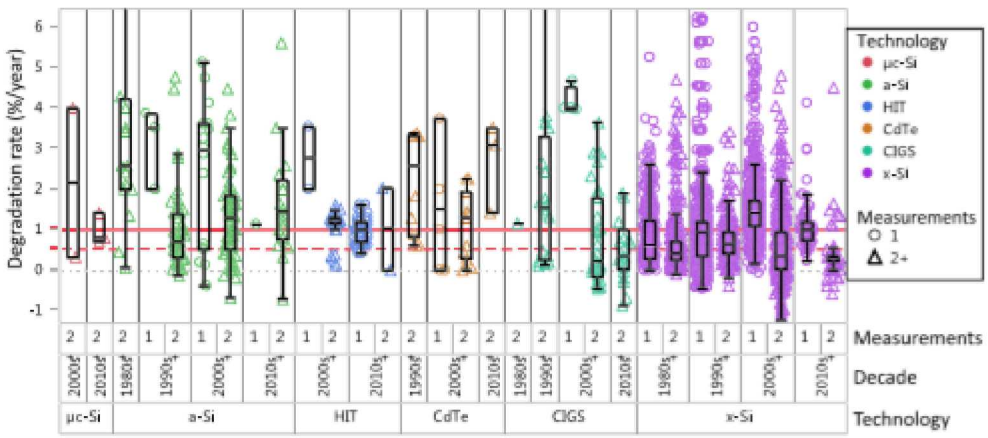

Figure 1. Fig. 4 from Jordan et al., 2016 showing degradation rates partitioned and colored by technology and decade of installation.

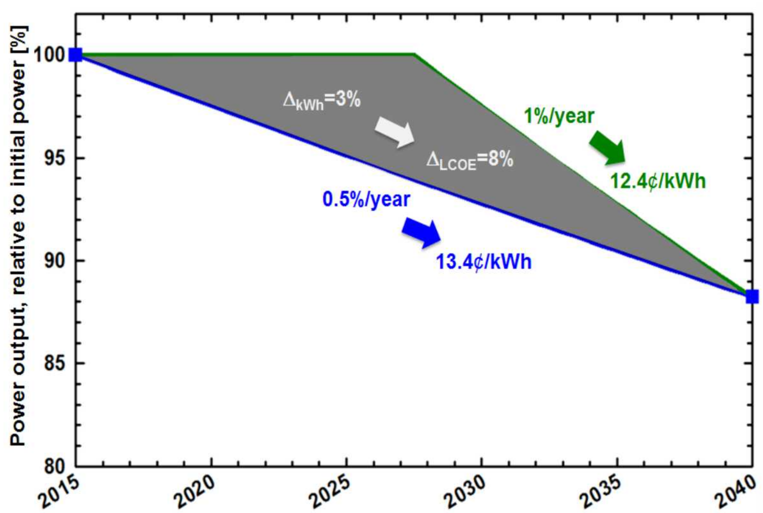

Figure 2. For aged PV modules, intermediate performance values are seldom available. Differences in how PV modules might reach their end-of-life capacity have substantial impact on levelized cost of energy (LCOE). As an illustration, LCOE values for the typical, linear, 0.5%/year degradation rate are shown along with a notional two-step degradation profile: degradation for the first 12.5 years is 0%/year, followed by 1%/year for the remainder of the 25-year period. For this example, a discount rate of 7% was assumed.

Introduction: This project is intended to last at least ten years in order that module degradation trends can be fully measured and documented in that period. The project has the following five tasks.

Task 1: Program Management and Data Distribution

This task covers quarterly reporting to DOE and development of a project website where information and data can be made available to the public.

Task 2: Performance Monitoring

This task covers development of the field monitoring systems for the systems under test as well as indoor and outdoor performance monitoring and characterization throughout the project period.

Task 3: Hardware Procurement

This task includes selection of the module technology to include in the project and procurement of the modules.

Task 4: Installation

This task includes building of racking, installation of modules, inverters, and monitoring systems, and interconnecting these systems to the grid.

Task 5: Process Monitoring and Improvement

This task covers work to improve program efficiency, lower costs for system installations, and develop procedures for ensuring that high data quality is maintained throughout the project.

Project Results and Discussion:

Task 1: Program Management and Data Distribution

The primary outcome of this task has been the development and maintenance of two PV Lifetime websites (One at Sandia and the other at NREL).

- https://pvpmc.sandia.gov/pv-research/pv-lifetime-project/
    - Full list of project publications and presentations including download links.
    - Table of modules under test
    - Table of systems at each site
- https://www.nrel.gov/pv/lifetime.html :
    - Brief summary of initial results measured at NREL systems.
    - Links to other related resources (e.g., RdTools) and related publications.

Task 2: Performance Monitoring

We are measuring system performance using two different methods: (1) monitoring dc string performance before the inverter (MPPT monitoring) and (2) String level IV curve monitoring using an automatic IV tracer developed in conjunction with Pordis LLC.

We are also developing new methods for analyzing string-level IV curves. One challenge is that arrays sometimes experience partial shading (usually early or late in the day) due to nearby structures. Figure 3 shows an example of using fill factor and its inverse relationship to irradiance as a filter to detect partial shading.

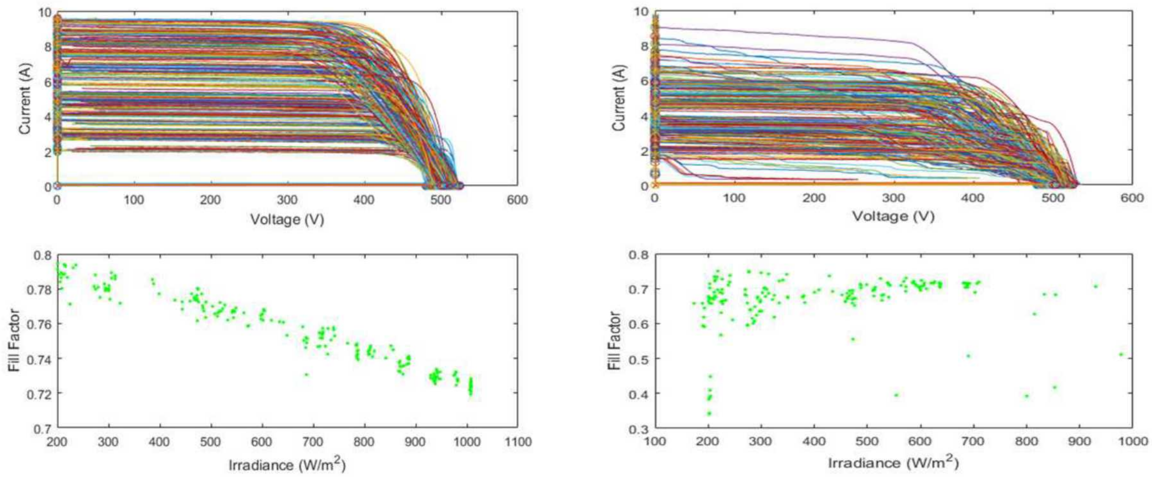

Figure 3. Example measured string-level IV curves. Curves on left were accepted using a fill factor filter. Curves on the right were excluded using the same filter.

More extensive analysis of this field monitoring data is planned for FY19.

In addition to field monitoring we also characterize all of the modules at the beginning of the project (before and after initial light soaking) and some of the modules each year thereafter to track degradation.

We are just beginning to get indoor results after the second year of indoor testing and we are seeing a wide range in degradation rates. Figure 4 below shows initial results from some of the modules from Jinko and Trina in Colorado and New Mexico. Degradation rates vary significantly between sites and between years. In Colorado, they are even seeing performance recover a bit in year 2. Stein et al., 2018 summarizes these early results from the indoor testing.

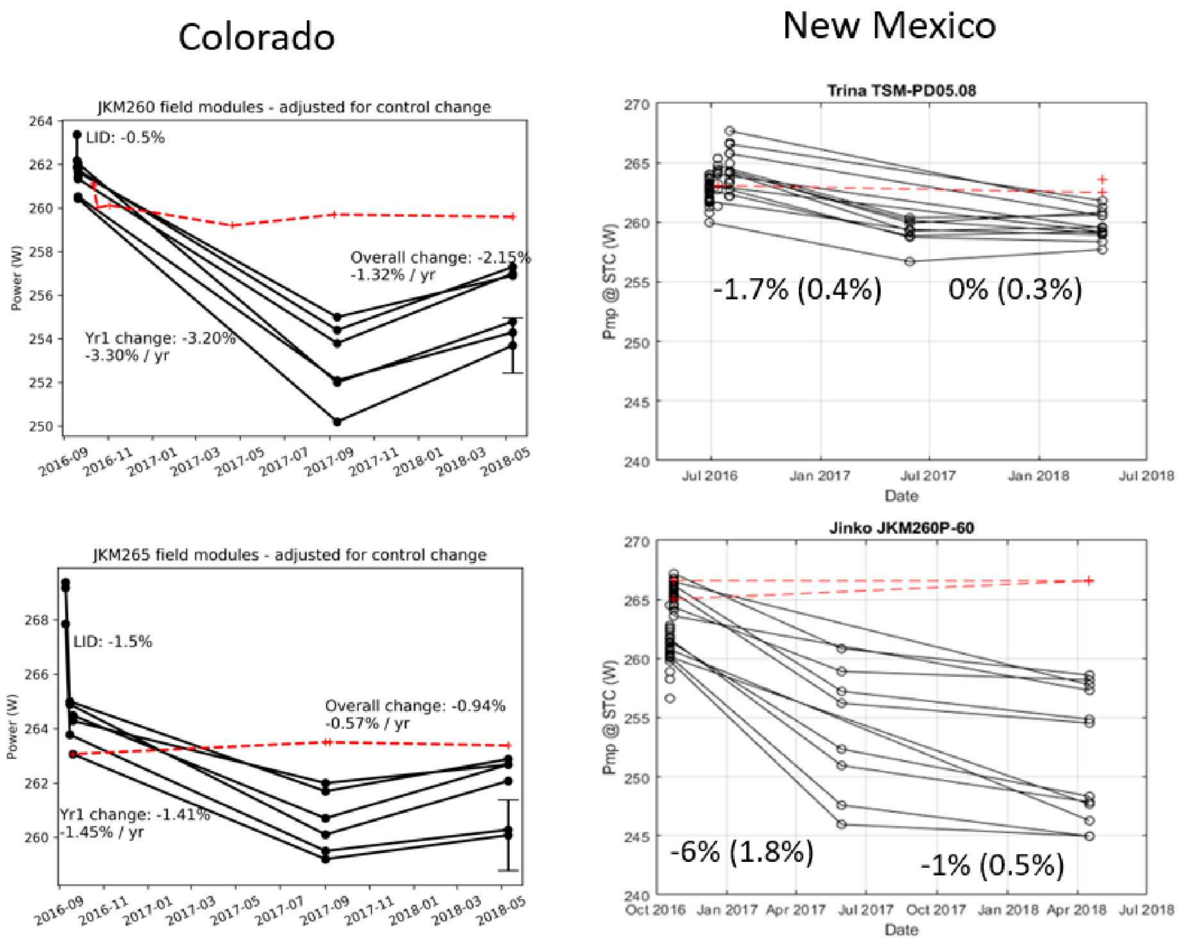

Figure 4. Some early results of indoor measurements of degradation on fielded modules in Colorado and New Mexico.

By the end of FY18, the PV Lifetime project has characterized and installed in the field 787 PV modules. These come from seven different manufacturers and include a range of cell and module technologies. Table 1 lists the number of each module type installed at each site.

Table 1. Modules Under Test in the PV Lifetime Project

Site	Manufacturer	Model	Technology	# of	Installation Date
NM	Trina Solar	TSM-PD05.08 260W	poly-Si	56	Jun-16
NM	Jinko Solar	JKM260P-60 260 W	poly-Si	56	Jun-16
NM	SolarWorld	SW 245W Mono	mono-Si	21	2013
NM	Canadian Solar	CS6K-270P 270W	poly-Si	48	Oct-17
NM	Canadian Solar	CS6K-275M 275W	mono-Si	48	Oct-17
NN	Hanwha Q-Cells	Q.Plus BFR-G4.1 280W	poly-Si PERC	48	Oct-17
NM	Hanwha Q-Cells	Q.Peak BLK G4.1 290W	mono-Si PERC	48	Oct-17
NM	Panasonic	N325SA16 325W	HIT Mono	48	Jun-18
NM	LG	LG320N1K-A5 320W LG	N-type Si	48	Jun-18
CO	Trina Solar	TSM-PD05.08 260W	poly-Si	56	Sep-16
CO	Jinko Solar	JKM260P-60 260W &	poly-Si	56	Sep-16
CO	Hanwha Q-Cells	Q.Plus BFR-G4.1 280W	poly-Si PERC	28	Oct-17
CO	Hanwha Q-Cells	Q.Peak BLK G4.1 290W	mono-Si PERC	28	Oct-17
CO	Canadian Solar	CS6K-300MS 300W	mono Si PERC	28	Jun-18
CO	Panasonic	N325SA16 325W	HIT Mono	30	Jun-18
CO	LG	LG320N1K-A5 320W	N-type Si	28	Jun-18
FL	Trina Solar	TSM-PD05.08 260W	poly-Si	56	Sep-17
FL	Jinko Solar	JKM260P-60 260 W	poly-Si	56	Sep-17
			Total	**787**	

Task 4: Installation

During the past two and a half years we have installed nine systems in New Mexico, seven systems in Colorado and two systems in Florida. Four of the systems in New Mexico were cost shared by Sandia's High-Performance Computing department in exchange for the energy credits from the systems.

Task 5: Process Monitoring and Improvement

We have made good progress ensuring that data quality can be maintained over the entire project period, which is estimated to last at least ten years. One concern has been how to ensure that the indoor flash testers used to perform annual recharacterizations of sampled modules do not drift over time. And if they do drift, how to quantify that drift so it can be accounted for in long term degradation analyses. We have adopted an extensive program to monitor the long-term performance of our indoor flash testers. This plan is documented in the PV Lifetime Project Measurement Plan.

The basis for monitoring flash tester stability is a collection of PV modules of different technologies and vintages that is stored indoors and flashed every day that the flash tester is used. These data help to detect any changes that occur in the flash tester over time. Initial results are now available for 2018 and we have learned some important lessons already. Figure 5 shows short circuit current (Isc) measured on each of the 18 modules that are currently in the library at Sandia. Isc is a good indicator of any shift in spectrum or intensity, especially when a variety of different module and cell types are included. We have mono and multi c-SI, Cd-Te, and CIGS modules included in the library. The red horizontal lines represent a +/- 0.5% deviation. In all but a few cases, the Isc appears to be very stable. The exceptions will be monitored further and reported on in subsequent reports.

Figure 6. shows a similar control chart for maximum power point (Pmp). This chart shows some significant deviations beyond the +/- 0.5% lines. It turns out that these deviations are most likely caused by increases and fluctuations in the resistance of the module connectors. It appears that the connectors on certain modules have loosened over time and no longer make a good connection. This theory is supported by examination of the slope of the IV curve near Voc (Rvoc), which is seen to rise for the affected modules (Figure 7). We plan in early FY19 to replace all the connectors on these performance library modules with muti-contact, self-cleaning, gold plated connectors to correct this problem. We will monitor the Rvoc of fielded modules over time to determine if similar degradation occurs for these modules.

We plan to propagate this method for monitoring the stability of the flash testers to the other sites in FY19. Those sites have similar methods in place, but efforts will be made to ensure that we have similar controls and procedures at each site going forward.

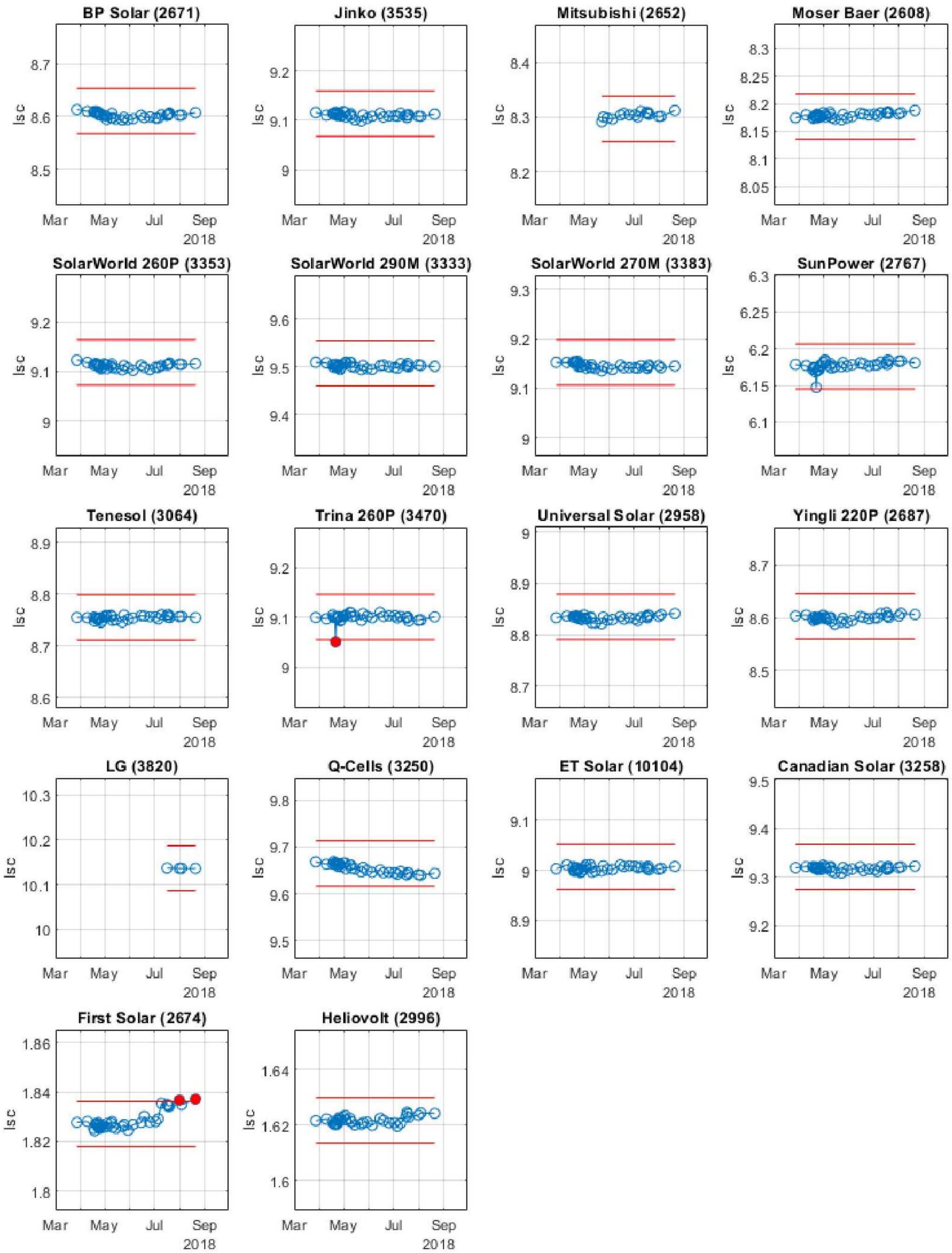

Figure 5. Isc control chart for Spire Performance Monitoring Library modules.

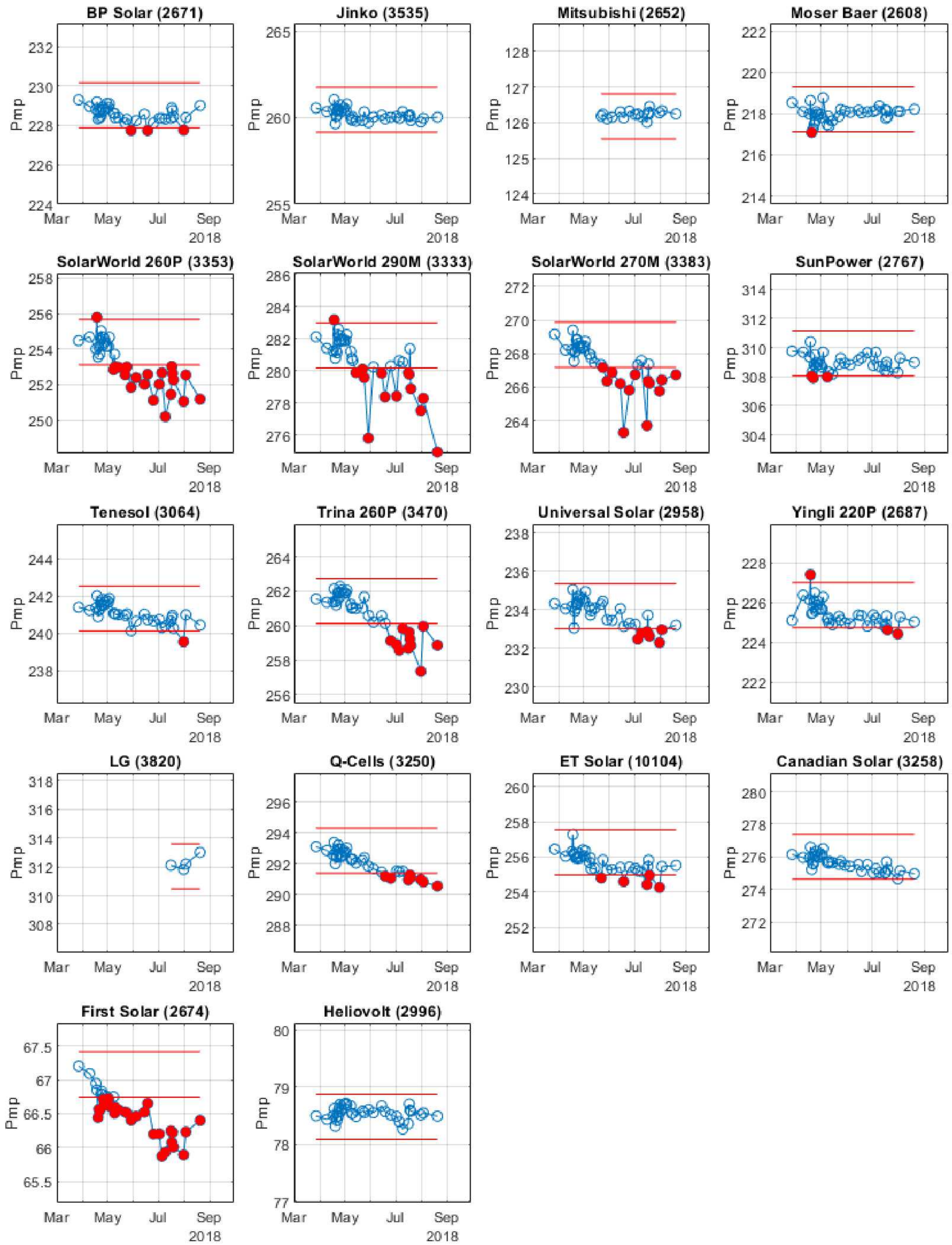

Figure 6. Pmp control chart for Spire Performance Monitoring Library modules.

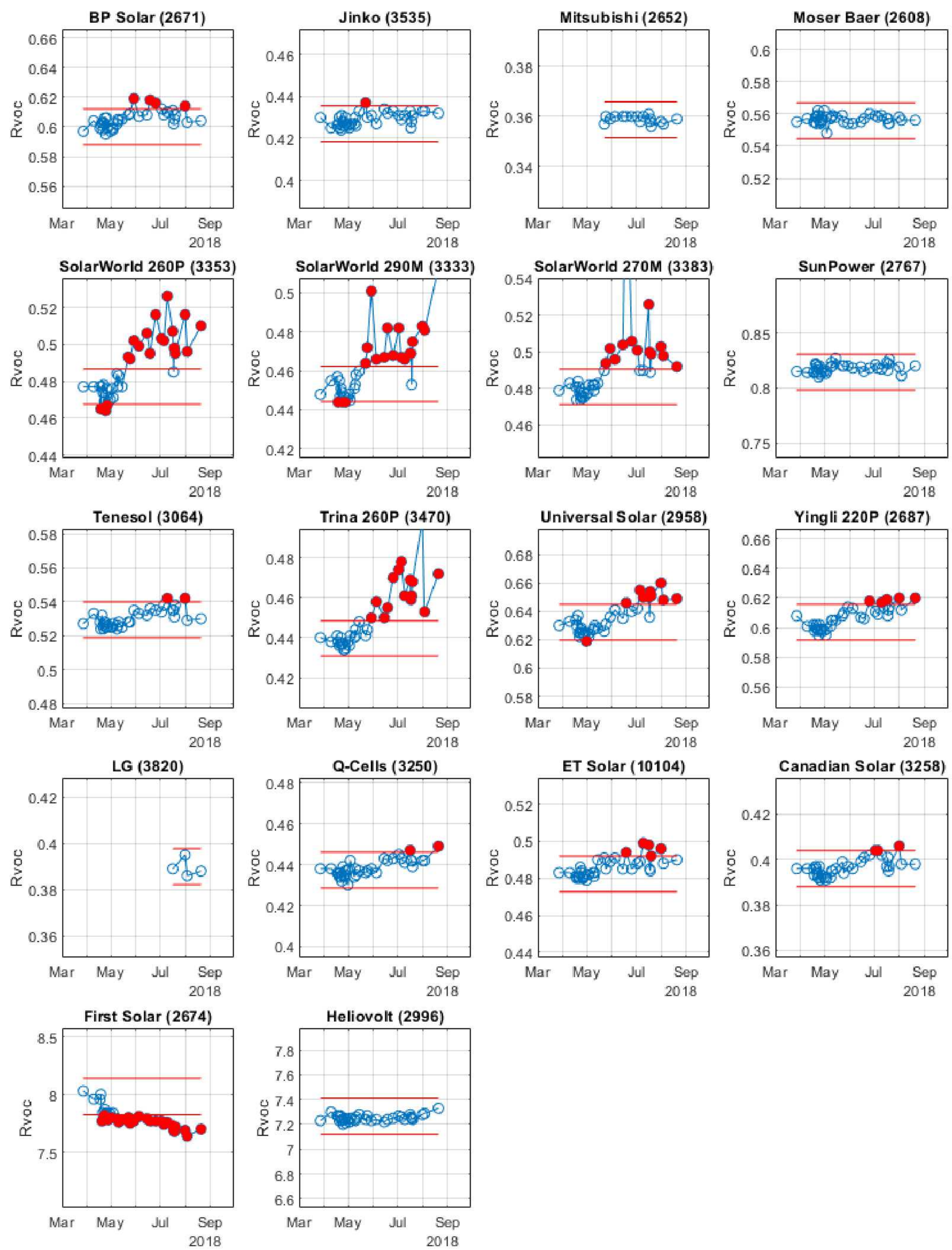

Figure 7. Rvoc control chart for Spire Performance Monitoring Library modules.

Conclusions: This project has initially characterized almost 800 PV modules and installed them in systems located in New Mexico, Colorado, and Florida. Each year selected modules from these systems are measured indoors so that any performance degradation can be tracked over time. Outdoor monitoring of string-level dc power and IV curves are also collected. This data set is just beginning to yield results and is anticipated to even more valuable as time progresses. Careful attention to measurement stability and repeatability is taken so that confidence in these measurements will be high over the relatively long project period of at least ten years.

Budget and Schedule: Initially, this project was 100% funded by DOE. However, after the project started, Sandia was able to obtain cost share from Sandia's High-Performance Computing group, which wanted to install PV in order to meet clean energy goals. They provided $300k of funding to install approximately 60Kw of PV which was included in the PV Lifetime project. At the end of FY18, the project had ~$309k of carryover due to this unplanned cost share. These funds will be used in FY19 to add more systems in New Mexico.

The table below provides a summary of the project spend plan and actual expenses by quarter.

II. Project Spend Plan				A. Federal Share Initial Plan	B. Federal Share Updated Actuals & Plan
Year	Quarter	From	To		
2016	Q1	5/1/2016	7/31/2016	$250,000	$102,729
2016	Q2	8/1/2016	10/31/2016	$250,000	$270,182
2016	Q3	11/1/2016	1/31/2017	$250,000	$166,865
2017	Q4	2/1/2017	4/30/2017	$250,000	$159,670
2017	Q1	5/1/2017	7/31/2017	$195,335	$187,976
2017	Q2	8/1/2017	9/30/2017	$195,335	$162,343
2017	Q3	11/1/2017	12/31/2017	$195,335	$233,903
2018	Q4	1/1/2018	3/31/2018	$195,335	$246,285
2018	Q1	4/1/2018	6/30/2018	$125,731	$274,394
2018	Q2	7/1/2018	9/30/2018	$125,731	$171,122
Totals				**$2,284,265**	**$1,975,468**

Path Forward: This project will continue as part of a new program called the PV Proving Grounds, which has been approved by DOE as a Core Capability at Sandia National Laboratories and NREL for FY19-21. Additional systems will be added and existing systems will continue to be monitored both indoors and outdoors.

Publications Resulting from This Work:

- Stein and Jordan (2018) Glass-Glass Photovoltaic Modules – Overview of Issues, Fall DuraMAT Workshop, Stanford, CA

- Stein et al. (2018) PV Lifetime Project: Measuring PV Module Performance Degradation: 2018 Indoor Flash Testing Results, WCPEC-7, Waikoloa, HI.

- Stein et al. (2018) PV Lifetime Project –Challenges of Measuring PV Module Degradation, 2018 PV Module Reliability Workshop, Denver, CO
- Stein, J.S. (2017) Challenges of PV Degradation Analysis: PVLIB and Performance Data Analysis, Fall DuraMAT Workshop, Albuquerque, NM
- Hansen and Jordan, (2017) Sample size guidelines for PV lifetime project , SAND2017-483R.

References:

Jordan, D. C., S. R. Kurtz, K. VanSant and J. Newmiller (2016). "Compendium of photovoltaic degradation rates " Progress in Photovoltaics **24**: 978-989.