Systems Long Term Exposure Program: Analysis of the First Year of Data

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Abstract — **While indoor accelerated testing of products is important for development, it is equally important to conduct field-testing to determine performance and degradation under real world conditions. To address this need, Sandia has developed an outdoor small systems evaluation laboratory. The Systems Long Term Exposure (SLTE) project spans three geographic locations: one in a hot/dry climate, one in a hot/humid climate and one in a cold climate. Identical systems representing three commercial technologies are installed at each location. In this paper we present the results and analysis from the first year of monitoring of these systems.**

Index Terms — **photovoltaic modules, photovoltaic systems, performance, outdoor testing, field testing**

I. Introduction

Over the last decade, the PV industry has expanded rapidly. The number and size of new installations has grown quickly, along with the appearance of new manufacturers and new cell and module technologies. Measuring and predicting system-level performance and reliability have become important to the PV community as a whole. The typical service environment of a PV system is as extreme as that experienced by high volume products in other industries such as automotive. PV systems are exposed to extremes of temperature, humidity and sunlight. While indoor accelerated testing of products is important for development and determining potential failure modes, it is equally important to conduct field-testing of PV systems to determine performance and degradation under real world conditions.

In the late 1990's, Sandia recognized the need for this type of characterization and established the Module Long Term Exposure (MLTE) program. This program ran for approximately five years with the goal of monitoring individual modules to define module degradation rates. Baseline tests were followed by module deployment at SWRES (run by New Mexico State University) and SERES (run by Florida Solar Energy Center). IV curves were measured in the field on a monthly basis and the modules were periodically retested at Sandia until the conclusion of the program. A significant finding of this program was the establishment of a degradation rate of <1%/year in maximum power for c-Si [1].

However, as the market has grown, there is a continued need for this type of study. C-Si products have continued to mature and at the same time newer technologies such as CdTe and CIGS have become commercially relevant. Performance models have become more sophisticated requiring more accurate estimates of degradation rates. As emphasis shifts from developing an understanding of performance of the module to understanding performance of the system, there is a need to study performance and degradation at the string and system level.

To address this need, Sandia developed an outdoor small systems evaluation laboratory, first described in 2006 [2]. This complements similar work described by other labs [3]-[6]. Initially developed using single strings of ~1kW and at a single location in Albuquerque, the effort has recently been expanded to facilitate larger systems and other locations with greater climatic variation. The original locations for the MLTE project, NMSU and FSEC, were again selected for this study to represent hot/dry and hot/humid climates. An additional site was established at the University of Vermont (UVM) to represent a mostly cold climate. Each site has ~ 25 kW of capacity.

The systems under investigation in this study are < 1 kW in size. Unlike the MLTE study, each system under evaluation is maximum power point tracked by a grid-tied residential inverter. Systems are instrumented for continuous monitoring and localized irradiance sensors provide reference conditions for comparison to measured energy production.

In this paper we present the results and analysis of data collected from April 2012 through March 2013, the first full year of monitoring of the first set of systems to be deployed at the satellite locations, NMSU, FSEC and UVM.

II. Current Work

The Systems Long Term Exposure (SLTE) project at Sandia spans four geographic locations: two in a Hot/Dry climate (SNL, NMSU), one in a Hot/Humid climate (FSEC) and one in a Cold climate (UVM). Identical systems representing three different technologies are installed at each of the three satellite locations (Table I). Additional systems are installed at Sandia, but are not addressed in the current analysis.

TABLE I
SYSTEM LOCATIONS AND CLIMATES

Location	Climate
Florida Solar Energy Center (FSEC)	Hot/Humid
New Mexico State University (NMSU)	Hot/Dry
University of Vermont (UVM)	Mostly Cold

Baseline performance characterization of representative modules from each system was performed outdoors on Sandia's two-axis tracker. These modules were then deployed as part of the system and will be periodically retested throughout the life of the project. Coefficients for use in the Sandia Array Performance Model (SAPM) [7] or the System Advisor Model (SAM) [8] were generated for use in future system analysis.

A. System Descriptions

The three technologies under investigation include a high efficiency mono-crystalline silicon product, a thin film product and a multi-crystalline silicon product (Table II). The systems at each location are mounted at local latitude tilt. Each system under evaluation is MPPT tracked by a grid-tied residential inverter. Systems are instrumented for continuous monitoring. Onsite weather stations and localized irradiance sensors provide reference conditions for comparison to measured energy production.

TABLE II
SMALL SYSTEMS UNDER TEST

Technology	Size, W	System Voltage	Inverter
mono-Si	690	146	SMA Sunny Boy 700
Thin Film	580	177	
mc-Si	880	146	

The systems utilize commercially available modules. These systems were initially designed to mimic the original MLTE program and so are relatively small, sized in the few modules per system range. Consequently, system power and voltages are also relatively low and small residential inverters are used for each. The systems at each site are co-located on the same racking structures. Representative systems at two of the locations are shown in Fig. 1.

a). b).

Fig. 1. Three small systems installed at a). Florida Solar Energy Center and b). University of Vermont.

B. Instrumentation

Each system is instrumented to measure DC voltage and current and AC power. Module temperature is monitored using type-T thermocouples adhered to the backside of selected modules. Local EETS RC01 (Energy Environmental Technical Services, LTD, Pontypridd, UK) silicon reference cells mounted in the plane of array provide reference irradiance. Other parameters such as power factor are also measured, however these are not considered in this study.

Each satellite location utilizes a single Campbell Scientific CR1000 (Campbell Scientific, Logan, UT, USA) to monitor the three systems on-site. To minimize measurement differences, identical monitoring systems are employed across the three locations. Since the systems are co-located, a single pair of reference cells provides reference irradiance for each site. Data is sampled and recorded at a rate of 1 minute.

TABLE III
SYSTEM INSTRUMENTATION

Parameter	Units	Sensor/Transducer
AC Power	W	OSI Power Transducer
DC Current	A	Empro current shunt
DC Voltage	V	Caddock voltage divider
Irradiance	W/m^2	EETS Ref Cell
Module Temp	°C	Type-T Thermocouple
Ambient Temp	°C	Campbell Sci. Temp Probe

III. RESULTS AND DISCUSSION

Full system commissioning was completed in late December of 2011 and the data collection period was considered to begin on January 1, 2012. Collection of the first year of data was completed on December 31, 2012. Problems with this first data set necessitated removing the first three months of data from this comparison. Thus, the analysis presented here spans the period from April 2012 to March 2013.

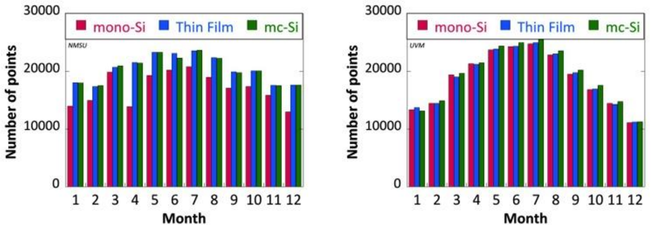
A. Data Filtering and Analysis

Monthly data records were assembled into a single annual data file for filtering, processing and analysis. For each site, annual data files were globally filtered by irradiance to remove overnight or incomplete data records. Next, filters were applied to individual data records for each system. Filtering conditions are listed below in Table IV.

TABLE IV
FILTERING CONDITIONS

Filter	Condition
Irradiance	$< 25\ W/m^2$
AC Power	< 5 W
DC Current	$< 0; > 1.25\ I_{sc}$
AC/DC Ratio	> 1.0

A consequence of filtering was an imbalance in the number of data points for each system. This only affected the mono-Si system located in New Mexico. This system displayed noise in the power measurement and as a result, on average about 10% more data was removed. This primarily affected summed quantities such as energy generation. Because of the method used to calculate normalized quantities such as performance ratio, these quantities were unaffected.



a). b).

Fig. 2. Data filtering to remove noise resulted in an imbalance in the number of data points, a). NMSU and b). UVM. This negatively impacted comparisons of summed data such as total energy generation. Normalized quantities such as performance ratio were unaffected.

After the filtered data sets were assembled, PV system yield (Y_f) and reference yield (Y_r) were calculated for each 1-minute data point. These were then used to calculate Performance Ratio [9, 10] for each 1-minute time period (referred to here as the instantaneous Performance Ratio) as well as other time intervals of interest. Note that, as defined, the Performance Ratio across longer time intervals does not equal the average of the instantaneous Performance Ratios; Y_f and Y_r must be summed separately. Since all Performance Ratio calculations were made using a summation of Y_f and Y_r values calculated for each 1-minute data point, comparisons could be made between data sets regardless of the number of data points available for a particular time interval.

$$Y_f = \frac{Measured\ AC\ Power}{60(Nameplate\ Power)}\ (kWh/kW) \tag{1}$$

$$Y_r = \frac{Measured\ Irradiance}{60(Reference\ Irradiance)}\ (hours) \tag{2}$$

$$P_r = \frac{\sum Y_f}{\sum Y_r}\ (dimensionless) \tag{3}$$

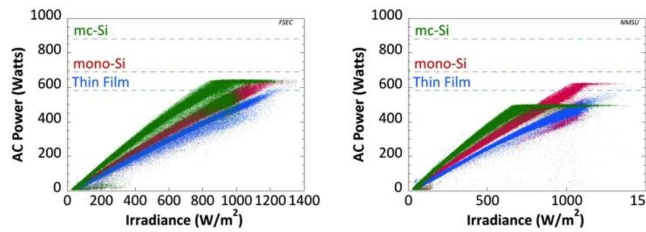
B. Annual Energy Observations

Annual energy production and Performance Ratio for each system and location are given in Table V. Comparing Performance Ratio, the mono-Si and Thin Film systems performed nearly identically, with the Thin Film system having a slight edge in the Hot/Humid and Mostly Cold climates. In contrast, the mc-Si system performed slightly behind the other two in the Hot/Humid climate and significantly behind in the other locations.

However, AC Power for each one-minute data point plotted against Irradiance (Fig. 3) revealed significant clipping on all three of the mc-Si systems and minor clipping of the mono-Si systems. Further, the inverters used for the mc-Si systems at NMSU and UVM were configured to a lower maximum power than at FSEC, leading to even greater clipping in these locations. The onset of this clipping was at Irradiance as low as 650 W/m^2, contributing to the generally lower performance of the mc-Si systems. The mono-Si system only displayed clipping at high irradiance, above 1000 W/m^2.

TABLE V
AC ENERGY AND PERFORMANCE RATIO FOR EACH SYSTEM

	mono-Si		Thin Film		mc-Si	
Site	kWh	Pr	kWh	Pr	kWh	Pr
FSEC	1072	0.80	924	0.82	1298	0.76
NMSU	1060	0.80	1100	0.80	1385	0.67
UVM	842	0.73	732	0.75	898	0.61



a). b).

Fig. 3. Comparison of AC Power as a function of Irradiance for two sites. The inverters used for the mc-Si systems in both locations are undersized, leading to significant clipping. Clipping is also observed for the mono-Si system at high irradiance values.

The effects of filtering can clearly be seen in the total energy generation of the mono-Si system located at NMSU. This system produced slightly less energy than the same system located at FSEC, whereas the Thin Film system located at NMSU produced nearly 20% more energy than its counterpart at FSEC. Since both of these systems performed nearly identically based on performance ratio, it can be concluded that the reduction in energy for the mono-Si system is due to the removal of data, not due to a reduction in performance. It's also worth noting that had performance ratio been calculated by summing energy across an arbitrary time interval without regard for the missing data, then this parameter would have also indicated underperformance. By calculating performance ratio using a summation of the individual instantaneous yield values for each system, this negative bias was avoided.

C. Performance Ratio Comparisons

Plots of instantaneous Performance Ratio against Irradiance revealed the same trend as seen in the comparison of AC Power against Irradiance (Fig. 6). The effects of inverter clipping can be seen in both the mc-Si systems and the mono-Si systems, as indicated by the smooth, curved reduction in P_r at higher irradiance. The trends below the clipping range reveal a few differences in system performance. In Florida, the maximum observed P_r for all three systems was nearly the same. In New Mexico, the mono-Si system had a peak P_r that was noticeably higher than the other systems, while in

Vermont the mc-Si system had a noticeably lower peak P_r than the other two. Interestingly, in both Florida and New Mexico, the peak P_r occurred at low irradiance while at high irradiance it decreased. In contrast, in Vermont P_r rose to a predominantly steady value as irradiance increased. Presumably this behavior is due to thermal effects, but further analysis is required to confirm this.

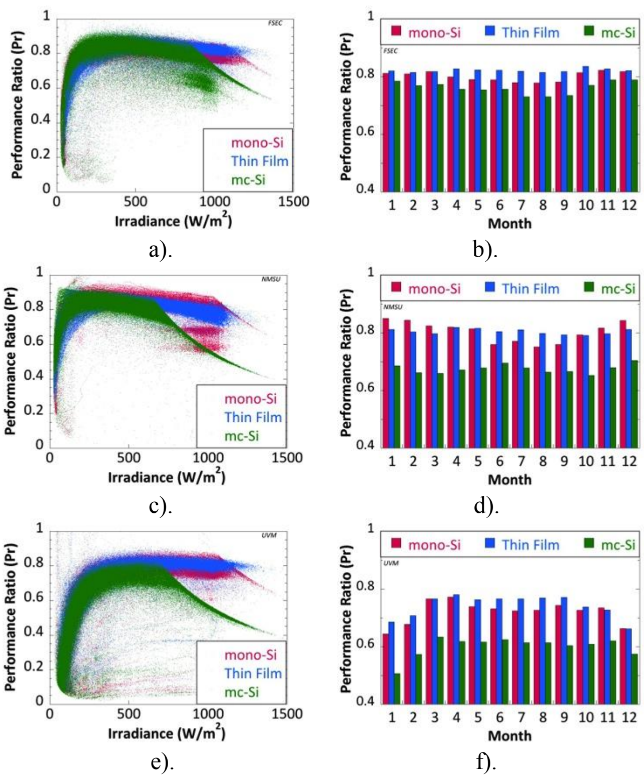


Fig. 6. Performance Ratio comparisons at FSEC, a) - b), NMSU, c) – d) and UVM, e) - f). Plots in on the left summarize instantaneous performance ratio as a function of irradiance and plots on the right show performance ratio calculated for each month.

A monthly comparison of P_r at the three sites revealed mild seasonal variability in Florida and New Mexico and pronounced seasonality in Vermont. Across all technologies, P_r was at it's lowest during the winter months in Vermont. All three mono-Si systems displayed a dip in performance from March to September. Peak performance for the mono-Si systems in the hotter locations was during the winter months and near the equinoxes in the cold climate. The thin film systems had flat performance throughout the year in the hotter climates and during the summer months in the cold climate. The mc-Si system in Florida had a dip in P_r during the summer, however the system in New Mexico experienced a slight increase, peaking in June. This likely was a side effect of the longer days and the system operating at peak power as a result of inverter clipping.

To investigate the effects of time of day, P_r was calculated for 1-hour time blocks for one month during each season. This calculation was only made for the systems located in Florida. The seasonal effects noted above can be seen in each plot. The relatively flat response of the thin film system is even more evident here, as is the deep trough in P_r during the middle of the day for the mc-Si system as a consequence of inverter clipping.

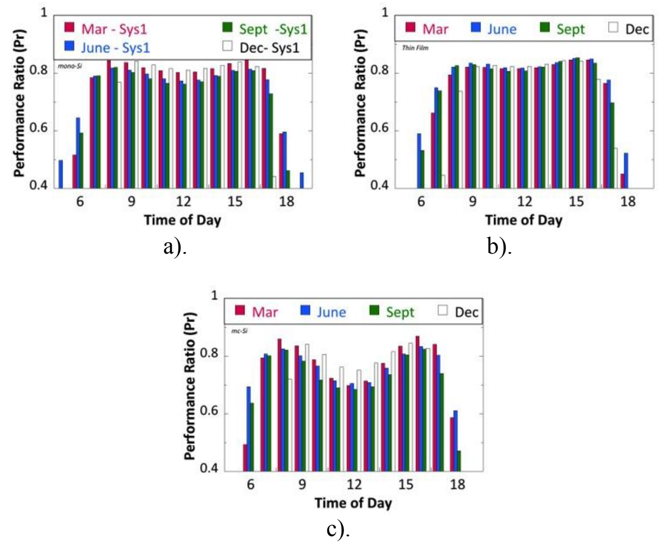


Fig. 7. Hourly Performance Ratio calculated for each technology for one month from each season. Mono-Si, a), Thin Film, b). and mc-Si, c). (Florida only).

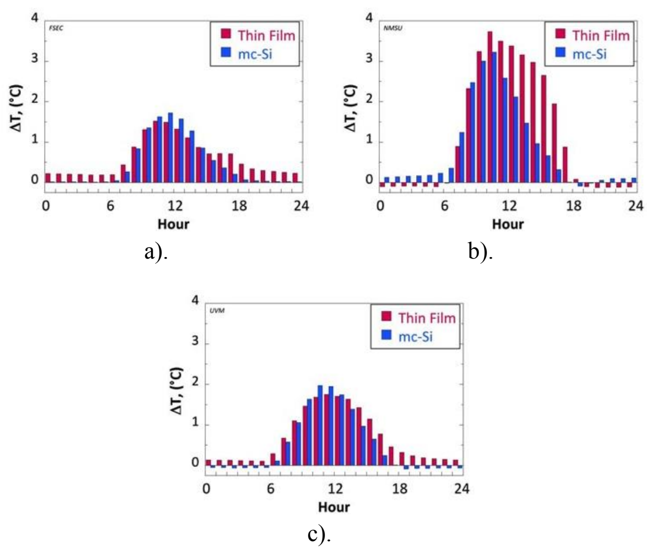


Fig. 8. Average Hourly Temperature Differences calculated for each technology for the full year. The mono-Si system at each location consistently operated at a lower temperature than the other two systems. The calculated ΔT is the difference between each of the other technologies and the mono-Si system at their respective locations. FSEC a), NMSU b) and UVM c).

D. Temperature Differences

The mono-Si system at each location consistently operated at a lower temperature than the other two systems. Average hourly temperature difference between each of the other technologies and the mono-Si system was therefore calculated for each location (Fig. 8). On average, systems in Florida and Vermont ran 2° hotter at peak, while systems in New Mexico ran ~3.5°C hotter. For the thin film systems, there was generally a bias toward the afternoons. These modules are of a double-glass construction and presumably don't cool off as quickly as the polymer-backed Si modules. However, despite operating at a higher temperature, performance of the thin film systems did not appear to be adversely affected relative to the higher efficiency mono-Si. Unfortunately, due to inverter clipping, any comparison between the two Si products will be difficult. Temperature effects are still under investigation

IV. Conclusions

The Systems Long Term Exposure program run by Sandia will operate for a period of 3-5 years. Continuous monitoring of these systems will provide climatic and degradation comparisons between several technologies. Analysis of the first year of operation is underway and has revealed several challenges in long-term monitoring of fielded systems and data filtering. Annual Performance Ratio calculations can be misleading when comparing technologies and climates. Annual P_r between Thin Film and c-Si are nearly the same, however Thin Film generally shows less variation with climate and season. Early exploration of temperature differences reveals that high efficiency mono-Si systems can run 2-4°C cooler than other technologies.

V. Future Work

The small systems described in this paper represent a foundation for the expansion of our knowledge about long-term system performance and appropriate approaches to system monitoring and analysis. We are currently in the final construction and baseline characterization phase of the expansion of this effort to larger systems. This next generation of systems will be installed at all four locations and will follow the original model of employing identical system designs at each. These systems will also operate at voltages that are representative of the industry as a whole.

Acknowledgements

The authors would like to thank the personnel at FSEC, NMSU and UVM for their oversight and maintenance of the systems at their respective locations. We would also like to thank Corey Asbill of NMSU for assembling the monthly data files from each site.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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