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SUCCESSFUL TRANSFER OF SANDIA'S OUTDOOR TEST TECHNOLOGY TO TUV RHEINLAND PTL

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ABSTRACT

Recent years have demonstrated increased demand for high accuracy outdoor photovoltaic (PV) module characterization according to the Sandia Array Performance Model [1]. To help meet this demand, Sandia National Laboratories worked with TUV Rheinland PTL under a competitively bid contract to transfer the capability to fully characterize standard, commercial-scale PV modules according to the Sandia method. Two Round Robin experiments and many months of work and discussion resulted in module performance output calculations which agreed to within +/-2.5% between the two labs.

INTRODUCTION

For as long as photovoltaic cells and modules have been developed and built, the designers and users have wanted to understand their characteristics under standard test conditions as well as how they will perform under any environmental conditions. Sandia National Laboratories has been characterizing module performance outdoors for more than 20 years and during that time has developed a method for modeling the output of modules under any climate conditions [1]. Sandia publishes module parameters translated to Standard Reporting Conditions (SRC) and module modeling coefficients. This data set is currently being used in the Systems Advisor Model (SAM) [2], Maui Solar PV Design Pro [3], and other photovoltaic systems design software.

In the last five years, the demand for module characterization and the calculation of the accompanying modeling coefficients by Sandia National Laboratories' Photovoltaic Systems Evaluation Laboratory (PSEL) has grown significantly. The demand has come from both start-up companies developing thin-film technologies and concentrating PV, as well as from module manufacturers and integrators interested in characterizing established technologies such as crystalline silicon. In response to this demand, the PSEL, in conjunction with Department of Energy's Solar Energy Technologies Program (DOE SETP), decided to transfer the testing and characterization technology to a commercial test lab. This would meet the demand for characterization of existing technologies, allow Sandia to focus on characterization of emerging technologies, and provide a US test house with a new business opportunity. In May 2009, Sandia awarded a contract to TUV Rheinland PTL (TUV-PTL) in Tempe, Arizona following a competitive bid process to transfer Sandia's outdoor PV module testing and characterization process. The contract was successfully completed in August 2010.

This paper provides the requirements, the method followed, and the results of two round robin test campaigns used during the contract process to demonstrate that TUV-PTL is capable of testing, characterizing and modeling PV modules in accordance with Sandia's requirements.

METHOD

Contract Award

Sandia awarded the contract based on these primary requirements:

1. Site and Solar Resource Criteria: Site should reach Air Mass 1.5 at least 300 days per year.
2. Personnel Criteria: Experience in high-accuracy metrology and data analysis techniques.
3. Software Capability: Software capable of analyzing voltage-current (IV) curves on modules and calculating the modeling coefficients.
4. Hardware Capability: Two-axis tracker with +/- 2° precision in elevation and azimuth; curve-sweeping capability for modules up to 400 Wp; thermal assessment; appropriate metrology station.
5. Business Plan: To ensure the test method could be implemented and could be self-sustaining at the end of the contract (value of the DOE investment).
6. Project Management: To ensure the timely and efficient implementation of the contract.

TUV-PTL was chosen from four bidders. TUV-PTL (formerly, Arizona State University Photovoltaic Testing Laboratory) is an ISO 17025 accredited testing laboratory since 1997. The TUV-PTL test site in Tempe, Arizona is ideally suited for the testing per the Sandia method as there are more than 300 clear sky sunny days and the site receives a daily average insolation between 6.3 kWh/m^2 (winter) and 11.6 kWh/m^2 (summer) on a 2-axis tracker.

Round Robin 1: Instrumentation and Test Reproducibility

The first requirement of the contract was to ensure TUV-PTL could accurately test modules according to Sandia's test methods. Sandia and TUV-PTL chose three modules to be tested at each location for comparison, including one triple junction amorphous silicon module (SNL1660), one polycrystalline-Si module (SNL2490), and one monocrystalline-Si module (SNL2491). The modules were tested at Sandia in June and July 2009; they were tested at TUV-PTL in October and November 2009.

Testing at both locations included:

1. Thermal testing: IV sweeps taken over 30-60 minute period while the module heats up during clear, stable sky conditions. Module temperature and irradiance are measured simultaneously. Module temperature coefficients are calculated from these data sets.
2. At least one full day of clear sky testing: IV sweeps taken for a full day while simultaneously measuring module temperature and irradiance. Full Air Mass range expected. Analysis included module performance parameters translated to standard reporting conditions and initial irradiance coefficients calculated.
3. At least half day of cloudy sky conditions: IV sweeps, module temperature and irradiance data measured simultaneously. Low irradiance data are used to refine the calculation of the irradiance coefficients and the diode factor.

Sandia personnel conducted multiple rounds of daylong performance measurements on the three modules using calibrated equipment. Each module was tested over an 8 to 10-day period, collecting more than 5000 IV curves during clear and cloudy sky conditions. The modules were tested on different days. Sandia uses an in-house designed curve tracing system based on Agilent equipment. Each module is mounted on the 2-axis tracker and three thermocouples are attached to the back of the module with tape. Sandia uses a 4-point probe technique for the IV curves, sweeping from short-circuit current to open-circuit voltage every minute from sunrise to sunset. The sweep takes approximately 10 seconds, and the module is held at maximum power between IV curves. Module temperatures and plane-of-array irradiance using a calibrated silicon reference cell and an Eppley PSP are measured simultaneously. Ambient temperature, wind speed and direction, direct normal irradiance, global horizontal irradiance, and global diffuse irradiance are measured every 3 seconds on Sandia's weather station, located approximately 20 yards from the tracker. Figure 1 is a photo of Sandia's weather station, and Figure 2 is a photo of Sandia's primary dual-axis tracker.

Thermal testing is performed under clear, stable sky conditions, typically within two hours of solar noon. The front of the module under test is covered and the module temperature is monitored until it reaches a stable temperature near ambient. The module is then uncovered and IV curves are swept every 10-20 seconds with simultaneous module temperature and irradiance measurements recorded until the module has reached a stable temperature. This typically results in 200-300 IV curves.

Figure 1: Weather station at Sandia's PSEL

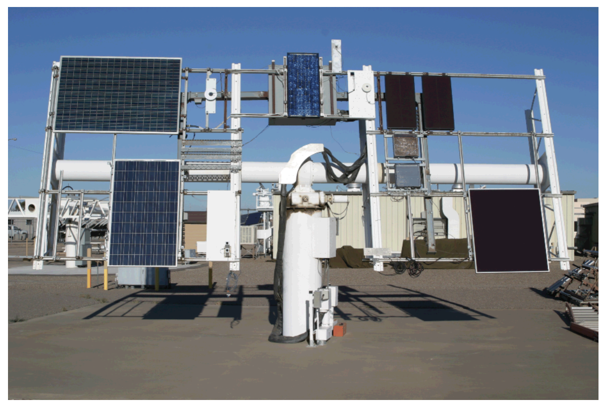

Figure 2: Dual-axis tracker at Sandia's PSEL

Sandia's measurement uncertainty in maximum power is +/- 2.5%, due primarily to the uncertainty in the irradiance measurements.

TUV-PTL personnel conducted two rounds of daylong performance measurements on the Sandia-supplied PV modules in accordance with Sandia procedure and guidance using calibrated equipment. The round 1 measurements included sequential current-voltage (I-V) scans using a DayStar DS-100 curve tracer with multiple modules mounted on a 2-axis tracker, as well as simultaneous measurements of solar irradiance (using reference cell and Eppley PSP) and module temperature in two locations. These daylong tests were performed on multiple days for each module to demonstrate the repeatability of the procedure. A multiplex relay switch, controlled by a DAS, was used to switch connections from one module to the next with Daystar DS-100 tracer. As shown in Figure 3, TUV-PTL used 4-probe connections from the multiplexer to the Daystar and 2-probe connections from the module to the multiplexer. The curves were collected continuously from sunrise to sunset every 6 minutes leading to more than 100 curves per day per module.

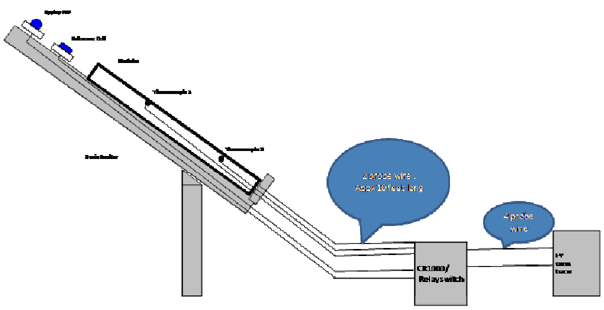

Figure 3: Round Robin 1 Test Setup at TUV-PTL

Table 1 provides the results of the calculated module-scale temperature coefficients for Voc, Vmp, Isc and Imp, as well as the performance parameters at SRC (1000 W/m^2, 25°C, AMa 1.5). The temperature coefficients for the currents are normalized to the current values at SRC. Note that the values at SRC are calculated using the temperature coefficients, and any differences observed in these values will affect the comparisons at SRC. The percent difference is calculated using the SNL value as the baseline.

The variation observed in the thermal characterization and in Imp and FF led to improvements in the test methods used at both locations. At Sandia, the thermal test method was improved by adding insulation to the back of modules during testing to maintain an even temperature distribution and to expand the thermal range. For better measurement accuracy at TUV-PTL, the round 2 test setup was improved and the measurements carried out with 2-minute intervals using a Daystar DS3200 multi-curve tracer with 4-probe connection (as opposed to 2-probe connection in round 1) and three thermocouples (as opposed to two thermocouples in round 1). The temperature coefficients of the modules were obtained by cooling the module down below 20^{o}C and collecting ten I-V curves as the module warmed up uniformly under sunlight. The upper limit of module temperature was increased to more than 70^{o}C using an insulating pad on the backside the test module. The temperature coefficients were determined through linear regression.

One item to note is the percent differences observed in αIsc and αImp. Although these differences appear large, these are differences in very small numbers, and are statistically insignificant. The calculated values for αIsc and αImp from both labs fall within the historical range of calculated values for more than 50 measured crystalline silicon modules [4]. The voltage temperature coefficient plays the primary role in power changes with temperature and uncertainty in βVmp has a greater impact on energy predictions than does αImp by nearly a factor of two [4].

The results of round robin 1 provided good feedback for test method improvements and provided high confidence that the results of testing at both labs would overlap to within measurement error.

Table 1 Results of Round Robin 1

ID #	Area (m^2)	Site	βVoc (V/°C)	βVmp (V/°C)	αIsc (1/°C)	αImp (1/°C)	I_{sc} (A)	V_{oc} (V)	I_{mp} (A)	V_{mp} (V)	FF	P_{mp} (W)
1660	1.29	SNL	-0.0940	-0.0616	0.00120	0.00164	4.59	23.46	3.65	17.05	0.579	62.3
a-Si		TUV	-0.0959	-0.0609	0.00121	0.00290	4.59	23.76	3.46	16.55	0.524	57.2
		%diff	2.0%	-1.2%	1.4%	76%	0.0%	1.3%	-5.2%	-2.9%	-9.5%	-8.2%
2490	0.65	SNL	-0.0782	-0.0809	0.00043	-0.00044	4.96	21.89	4.56	17.22	0.724	78.5
poly-Si		TUV	-0.0829	-0.0885	0.00060	-0.00116	4.90	22.00	4.20	17.00	0.673	71.7
		%diff	6.0%	9.4%	40%	167%	-1.2%	0.5%	-7.9%	-1.3%	-7.0%	-8.7%
2491	1.29	SNL	-0.1634	-0.1701	0.00046	-0.00033	5.21	44.94	4.86	36.27	0.753	176.4
mono-Si		TUV	-0.1687	-0.1698	0.00030	-0.00069	5.18	45.14	4.86	35.76	0.743	173.9
		%diff	3.2%	-0.2%	-33%	107%	-0.6%	0.4%	0.0%	-1.4%	-1.3%	-1.4%
	95% CL						*1.90%*	*1.00%*	*2.00%*	*1.10%*	*1.00%*	*2.30%*

Round Robin 2: Modeling Coefficient Reproducibility

The second requirement of the contract was to ensure TUV-PTL could accurately calculate the parameters and coefficients in the Sandia Photovoltaic Array Performance Model [1]. Sandia and TUV-PTL chose another three modules to be tested at each location for this second comparison. The modules chosen included one film silicon module (SNL2202), one polycrystalline-Si module (SNL0007), and one monocrystalline-Si module (SNL0012). The modules were tested at TUV-PTL in March 2010; they were tested at Sandia in April and May 2010.

Each module was tested as described in round robin 1 with the process changes implemented for TUV-PTL as described. Sandia performed thermal testing and calculated temperature coefficients for both an insulated and non-insulated case for all of the modules. The performance parameters agree more closely when calculated using the temperature coefficients based on the insulated case.

During temperature coefficient measurements, Sandia has historically used the average temperature from three thermocouples distributed diagonally across the back of the module to estimate the average temperature of all the cells in the module. Infrared (IR) thermal imaging of modules during the test indicated the repeatability of temperature coefficient measurements using the historic procedure with an open back surface is too sensitive to variable wind conditions. Insulating the back surface during the test greatly reduces cell-to-cell temperature differences, extends the temperature range, and provides more repeatable results, and these results are also more consistent with expectations based on laboratory testing of individual cells. The historic procedure used at TUV/PTL with modules mounted directly to a solid surface closely mimics an insulated back surface, and represents a good approach.

Table 2 provides the results of the calculated temperature coefficients for Voc, Vmp, Isc and Imp based on the insulated case, as well as the performance parameters at SRC (1000 W/m^2, 25°C, AMa 1.5) calculated using the temperature coefficients from the insulated case.

Although the differences observed in temperature coefficients remained high particularly for the current values, those values again fall within the historical range and the resulting SRC parameters are much closer than in RR1, particularly for Imp, Vmp, FF and Pmp. The differences in the SRC results are within the measurement uncertainties. Note that the insulated case results for the monocrystalline-Si module did not differ from the non-insulated case due to a hot cell in the module which developed between test cases. Interestingly, even with this discrepancy, the resulting parameters at SRC agree to within +/- 2%.

Table 2 Results of Round Robin 2

ID #	Area (m^2)	Site	βVoc (V/°C)	βVmp (V/°C)	αIsc (1/°C)	αImp (1/°C)	I_{sc} (A)	V_{oc} (V)	I_{mp} (A)	V_{mp} (V)	FF	P_{mp} (W)
2202	1.45	SNL	-0.0802	-0.0664	0.00086	0.00084	5.70	23.03	4.81	17.83	0.653	85.7
a-Si		TUV	-0.0756	-0.064	0.00061	0.00059	5.76	22.85	4.89	17.74	0.659	86.8
		%diff	-5.7%	-3.6%	-30%	-29%	1.1%	-0.8%	1.7%	-0.5%	0.9%	1.3%
0007	1.61	SNL	-0.119	-0.1206	0.00037	-0.00033	8.20	36.88	7.53	28.83	0.718	217.0
poly-Si		TUV	-0.1155	-0.1227	0.00051	-0.00023	8.01	36.96	7.40	29.04	0.726	215.3
		%diff	-2.9%	1.7%	39%	-31%	-2.3%	0.2%	-1.7%	0.7%	1.1%	-0.8%
0012	1.28	SNL	-0.226	-0.245	0.00039	0.00018	5.09	59.30	4.55	48.30	0.728	219.7
mono-Si		TUV	-0.187	-0.2059	0.00038	0.00004	5.02	58.63	4.53	47.52	0.732	215.3
		%diff	-17%	-16%	-3.2%	-75%	-1.4%	-1.1%	-0.4%	-1.6%	0.5%	-2.0%
	95% CL						*1.90%*	*1.00%*	*2.00%*	*1.10%*	*1.00%*	*2.30%*

Performance parameters at any irradiance, temperature, wind speed and airmass conditions are calculated based on the coefficients developed according to the Sandia Photovoltaic Array Performance Model. Sandia calculated the parameters for five conditions for each of the modules using the coefficients generated by each lab. In Figure 4, the parameters for Voc, Vmp, Isc, Imp and Pmp are shown as percent changes from the mean value for 1000 W/m^2, 75°C (High Temperature), 1000 W/m^2, 50°C (Typical Condition 1), 800 W/m^2, 50°C (Typical Condition 2), 500 W/m^2, 250°C (Typical Condition 3), and 200 W/m^2, 25°C (Low Irradiance Condition). The differences in the voltages and the currents are within +/-1% and +/-1.5% respectively with the exception of the low irradiance condition. This is likely due to the lack of data for irradiance less than 400 W/m^2 at TUV-PTL.

The ultimate goal of generating modeling coefficients is to predict annual energy output from a PV system using a specified PV module. Sandia used the in-house PVMOD program to calculate annual energy for Albuquerque, NM for each module type based on the coefficients generated by each lab. The assumptions were for a flat-plate, latitude tilt design with a default derate factor of 0.9. The annual energy calculations shown in Table 3 agree to within 2.7%.

Table 3 Comparison of annual energy yield

	Mono-Si		Poly-Si		a-Si	
	SNL	TUV	SNL	TUV	SNL	TUV
SRC Rating (Wp)	220	215	217	215	85.8	86.8
%diff	-2.3%		-0.9%		1.2%	
Annual DC (kWh)	472	467	476	471	187	192
%diff	-1.1%		-1.1%		2.7%	
Annual Yield (kWh/kWp)	2147	2170	2192	2191	2179	2209
%diff	1.1%		-0.05%		1.4%	

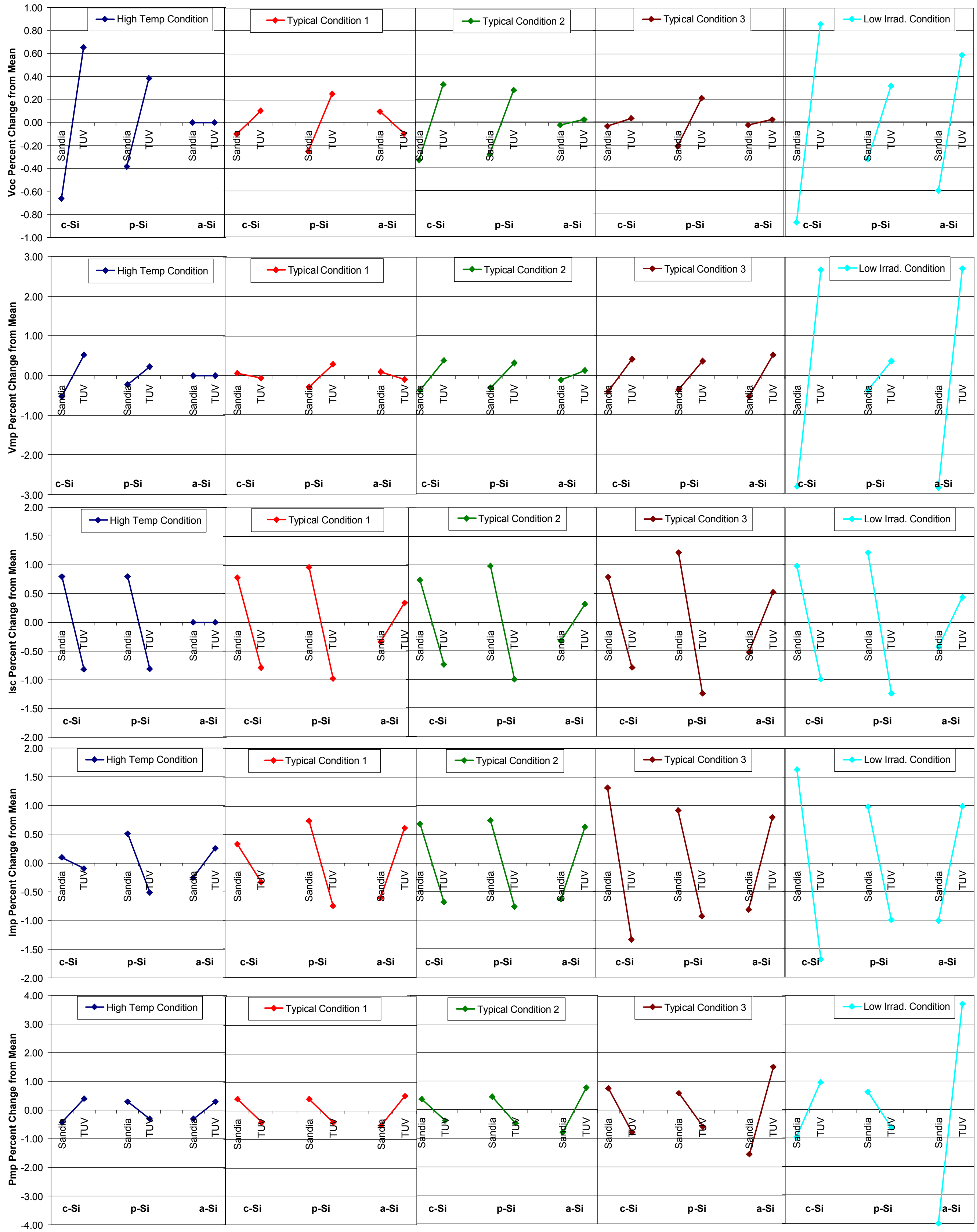

Figure 4: Comparison of Parameters for Five Irradiance/Temperature Conditions

Analysis Capability and Lessons Learned at TUV-PTL

The data analysis software capability developed at Sandia was successfully implemented at TUV-PTL through several steps including: consolidation of daylong I-V curves; elimination of outliers due to inadvertent shading and other issues by charting two ratios (Imp/Isc and Vmp/Voc) and normalizing Isc for 1000 W/m^2 irradiance; and incorporating several other input parameters including temperature coefficients, module area, number of cells in series, and reference cell and PSP constants. The processed I-V data using the conventional outdoor method and daylong Sandia method were determined to be identical. The data obtained on multiple modules using the 4-probe method with multi-curve tracer were determined to be more accurate than the data obtained using 2-probe method with single-curve tracer. Certainly, the experimental setup based on the multi-curve tracer was found to be less complicated and more accurate when a large number of modules are evaluated simultaneously. The data processing skills by TUV-PTL was greatly strengthened with added flexibility for actual airmass function rather than using a default airmass function. The day-to-day repeatability within TUV-PTL and reproducibility between Sandia and TUV-PTL has been established. If needed, additional low irradiance data may be obtained by using an appropriate mesh screen in front of the test module installed on 2-axis tracker or by moving the module away from the direct sun.

SUMMARY

Sandia National Laboratories, under guidance from the DOE SETP, successfully transferred the outdoor module test characterization and analysis technology to TUV Rheinland PTL. Based on the results of the two round robin experiments, Sandia has high confidence in TUV-PTL's capability to perform the module testing and analyze the results according to the Sandia Array Performance method. TUV-PTL is now making this testing and analysis available to their customers and several customers have already tested their modules according to this Sandia method. Sandia continues to characterize and analyze modules of emerging technologies, expand the model, and work with other interested test houses to transfer this technology.

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