

PHOTOVOLTAIC MODULE POWER RATING PER IEC 61853-1 STANDARD:

A Study Under Natural Sunlight

Prepared by

Govindasamy TamizhMani

Karen Paghasian

Joseph Kuitche

Meena Gupta Vemula

Ganesh Sivasubramanian

Arizona State University
Photovoltaic Reliability Laboratory (PRL)

Solar America Board for Codes and Standards

www.solarabcs.org





Solar America Board for Codes and Standards Report

PHOTOVOLTAIC MODULE POWER RATING PER IEC 61853-1 STANDARD

A Study Under Natural Sunlight:

Prepared by

(Mani) Govindasamy TamizhMani
Karen Paghasian
Joseph Kuitche
Meena Gupta Vemula
Ganesh Sivasubramanian

Arizona State University
Photovoltaic Reliability Laboratory (PRL)
March 2011

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Download a copy of the report:
www.solarabcs.org/ratingper61853

EXECUTIVE SUMMARY

Photovoltaic (PV) modules are typically rated at standard test conditions (STC) of 25°C cell temperature, 1000 W/m² irradiance, and air mass (AM) 1.5 global (G) spectrum. However, the PV modules in the field operate over a range of temperatures, irradiance, and spectra. Recognizing this issue, the International Electrotechnical Commission (IEC) Technical Committee 82 Working Group 2 (TC82/WG2) has been developing an appropriate power and energy rating standard (IEC 61853) for more than 15 years. The first part of this four-part standard requires the generation of a 23-element maximum power (P_{\max}) matrix at four different temperatures and seven different irradiance levels. The P_{\max} matrix can be generated using an indoor solar simulator method or outdoor natural sunlight method. The outdoor test method introduces little/no spectral mismatch error and is much less expensive than the indoor test method because it avoids the use of very expensive solar simulators. However, obtaining an accurate and repeatable P_{\max} matrix using the outdoor method over time (several months or years) would be extremely challenging. The objectives of this study related to the power rating of PV modules using natural sunlight were to:

- identify measurement repeatability issues with a non-standardized test setup,
- standardize the measurement setup,
- verify the device linearity per IEC 60904-10,
- generate the power (P_{\max}) matrix per IEC 61853-1, and
- validate four different current-voltage translation/interpolation techniques of IEC 60891 and the National Renewable Energy Laboratory Method (NREL Method).

This study report deals with two rounds of outdoor measurements and results to realize the above five objectives. We carried out the round one (2009) measurements to identify the repeatability issues of the non-standardized test setup. We carried out the round two (2010) measurements to standardize the test setup, check the PV device linearity, generate the P_{\max} matrix, and validate four different current-voltage (I-V) translation/interpolation techniques of IEC 60891 and NREL Method.

Based on the round one 2009 study, we concluded that the repeatability issues can be minimized to an acceptable level by an appropriate selection of outdoor measurement conditions and test equipment. Outdoor measurement conditions should be clear sunny days (> 90% direct normal irradiance) at lower air mass values (< 2.5). Test equipment should include:

- a manual or automatic two-axis tracker for tracking the sun;
- a fast (< 1 second) I-V curve tracer to minimize issues related to changing irradiance, spectrum, and module temperature;
- a matched technology (or matched spectral response) reference cell to practically eliminate spectral mismatch error;
- a transmittance calibrated neutral-density mesh screen with good spatial uniformity to change the irradiance level (to improve the light uniformity on the module, a 1.5-inch minimum distance shall be maintained between test module surface and mesh screen, and to accurately measure the irradiance without screen thread shadowing, the small area reference cell used in the test setup shall be kept outside the screen); and
- a pre-cooled test module to naturally change the module temperature while exposed to sunlight (to obtain data at the temperature of 75°C, a thermal insulating foam can be used to cover the backside of test module).

The 2010 measurements with the standardized test setup (2-inch module-to-screen gap and matched reference cells kept outside the screen) were used to verify the device linearity and to demonstrate that the 23-element P_{max} matrix of IEC 61853-1 standard can be generated using 8 to 23 measured reference I-V curves and four translation/interpolation procedures of IEC 60891 and NREL Method. This study used 23 reference curves for the first two procedures (called translation procedures 1 and 2), and 8 to 10 reference curves for the other two procedures (called interpolation procedures 3 and 4). Procedures 1 and 2 required the use of five mesh screens, and procedures 3 and 4 required only three or four mesh screens to generate the entire 23-element P_{max} matrix of IEC 61853-1. This report presents the power rating results for four commercial module technologies—crystalline silicon (c-Si); amorphous silicon (a-Si); cadmium telluride (CdTe); and copper indium gallium diselenide (CIGS). We also present a detailed investigation on the validation of the four translation/interpolation procedures for all four technologies.

Here are the major conclusions corresponding to the five objectives:

- *Outdoor measurement repeatability issues:* The repeatable power rating measurements at various irradiance levels under natural sunlight within an acceptable deviation limit of 2% could not be achieved when uncalibrated mesh screens were placed directly (0-inch distance) on the test module and reference cell.
- *Standardization of measurement setup:* A standardized measurement setup was established with reference cells kept outside the calibrated mesh screens, which were placed at a 2-inch distance above the test modules.
- *Verification of device linearity per IEC 60904-10:* The linearity requirements of open-circuit voltage, short-circuit current, and maximum power versus temperature are met by all four test technologies. Similarly, the linearity requirement of open-circuit voltage versus the logarithm of irradiance is also met (with two minor exceptions presumably due to some experimental errors) by all four test technologies. For the short-circuit current versus irradiance, the devices met the linearity requirement (2% deviation limit) for irradiance levels above 200 W/m² but they surprisingly showed a higher deviation for the irradiance levels below 200 W/m². This higher deviation was objectively attributed to some minor experimental errors related to the calibration of low transmittance mesh screens under natural sunlight.
- *Generation of P_{max} matrix per IEC 61853-1:* The required 23-element P_{max} matrix of IEC 61853-1 was successfully generated for all four module technologies using the four translation/interpolation procedures of IEC 60891 and NREL Method. Unless the data processing personnel pay extreme attention or commercial test laboratories automate the data processing, the translation procedures (1 and 2) are more prone to human error than the interpolation procedures (3 and 4). However, procedures 1 and 2 would work extremely well if multiple narrow irradiance ranges are used with individual sets of correction values for each narrow irradiance range or multiple sets of correction values are used for a single wide irradiance range.
- *Validation of procedures of IEC 60891 and NREL Method:* An extensive validation analysis of the four translation/interpolation procedures, at both narrow and wide irradiance ranges indicates that all four procedures are remarkably accurate within an average error of 3% and a root mean square error (RMSE) of 4.5%.

AUTHOR BIOGRAPHIES

Dr. (Mani) Govindasamy TamizhMani is the president of TUV Rheinland PTL (Photovoltaic Testing Laboratory) and a professor in the Department of Electronics Systems at Arizona State University. Dr. Mani has been involved in research and development activities related to photovoltaics (PV) and fuel cells for more than 26 years, and PV module testing and certification activities for more than 12 years. He has been involved in the development of PV standards since 1996. He has served as a member of various standards committees, including Canadian Standards Council, Institute of Electrical and Electronics Engineers (IEEE), International Electrotechnical Commission (IEC), and American Society for Testing and Materials (ASTM). He has taught graduate level courses related to PV, fuel cells, electrolysis, and batteries, has published more than 50 journal and conference papers, and has made more than 65 presentations in various conferences, seminars, and workshops. He has served as a reviewer of numerous federal grant applications and conference and journal publications, including *IEEE Photovoltaic Specialists Conference*, *Progress in Photovoltaics*, and *Journal of the Electrochemical Society*.

Ms. Karen Paghasian, Mr. Joseph Kuitche, Ms. Meena Gupta Vemula, and Mr. Ganesh Sivasubramanian are graduate students at Arizona State University.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the scientific and editorial comments of all the reviewers, especially Dr. John Wohlgemuth, Dr. Bill Marion, Dr. Sarah Kurtz, Dr. Gary Nakarado, Mr. Howard Barikmo, and Mr. Dave Click. Thanks to TUV Rheinland PTL for the permission to carry out some of the experiments in their facility.

SOLAR AMERICA BOARD FOR CODES AND STANDARDS

The Solar America Board for Codes and Standards (Solar ABCs) is a collaborative effort among experts to formally gather and prioritize input from the broad spectrum of solar photovoltaic stakeholders including policy makers, manufacturers, installers, and consumers resulting in coordinated recommendations to codes and standards making bodies for existing and new solar technologies. The U.S. Department of Energy funds Solar ABCs as part of its commitment to facilitate widespread adoption of safe, reliable, and cost-effective solar technologies.

For more information, visit Solar ABC's website:

www.solarbcs.org

TABLE OF CONTENTS

Disclaimer	ii
Executive Summary	iii
Author Biographies	v
Acknowledgements	v
Solar America Board for Codes and Standards.....	v
INTRODUCTION	1
BACKGROUND.....	1
OUTDOOR POWER RATING MEASUREMENTS	2
Round One Measurements (2009).....	3
Measurements With Non-Standardized Test Setup.....	3
<i>Light Transmittance</i>	3
<i>P_{max} Matrix Generation</i>	9
Round Two Measurements (2010)	15
Measurements With Standardized Test Setup	15
<i>Light Transmittance of Calibrated Mesh Screens</i>	15
<i>Linearity of Test Modules With Temperature and Irradiance</i>	16
<i>P_{max} Matrix Generation With Mesh Screen Placed 2 Inches Above Module Surface</i>	22
<i>Validation of Current-Voltage Translation/Interpolation Procedures</i>	25
CONCLUSIONS	28
REFERENCES	29
APPENDIX.....	30
ACRONYMS	40

INTRODUCTION

This study report addresses five objectives related to the power rating of photovoltaic (PV) modules using natural sunlight. These objectives are to:

- identify measurement repeatability issues with a non-standardized test setup,
- standardize the measurement setup,
- verify the device linearity per IEC 60904-10,
- generate the power (P_{max}) matrix per IEC 61853-1, and
- validate four different current-voltage (I-V) translation/interpolation techniques of IEC 60891 and the National Renewable Energy Laboratory Method (NREL Method).

BACKGROUND

Manufacturers typically rate PV modules at standard test conditions (STC). The STC rating involves only one temperature (25°C), one irradiance (1000 W/m²), and one sunlight spectrum (AM [air mass] 1.5G [global]). However, the actual energy production of field installed PV modules is a result of a range of operating temperatures, irradiances, and sunlight spectra. Therefore, there is an urgent need to characterize PV modules at different temperatures and irradiances to provide more comprehensive rating information.

One of the most relevant PV standards being developed by the International Electrotechnical Commission (IEC) Technical Committee 82 Working Group 2 (IEC/TC82/WG2) is the IEC 61853 standard titled *Photovoltaic Module Performance Testing and Energy Rating* (IEC, 2011). This standard consists of four parts:

- *IEC 61853-1: Irradiance and temperature performance measurements and power rating*, which describes requirements for evaluating PV module performance in terms of power (watts) rating over a range of irradiances and temperatures;
- *IEC 61853-2: Spectral response, incidence angle, and module operating temperature measurements*, which describes test procedures for measuring the effect of varying angle of incidence and sunlight spectra as well as the estimation of module temperature from irradiance, ambient temperature, and wind speed;
- *IEC 61853-3: Energy rating of PV modules*, which describes the calculations for PV module energy (watt-hours) ratings; and
- *IEC 61853-4: Standard days*, which describes the standard time periods and weather conditions that can be used for the energy rating calculations.

IEC published the first part of the standard in January 2011. This standard specifies the performance measurements of PV modules at 23 different sets of temperature and irradiance conditions, as shown in *Table 1*, using either a solar simulator (indoor) or natural sunlight (outdoor). There are several possible indoor and outdoor techniques, and this standard allows many of them. Validation of these techniques for repeatability over time within the same laboratory and for reproducibility among multiple laboratories is extremely important for the successful implementation of this standard. The power rating measurements at various temperatures and irradiance levels are more challenging under prevailing outdoor conditions than under controlled indoor conditions.

This study report deals with two rounds of outdoor measurements and results. In round one (2009), we carried out measurements to identify various test setup issues and select a test setup. In round two (2010), we carried out measurements to standardize the test

setup, generate the 23-element P_{\max} matrix of IEC 61853-1, and validate four different I-V translation/interpolation techniques of IEC 60891 (IEC, 2009) and NREL Method (Marion, Rummel, and Anderberg, 2004). We studied four different commercial PV technologies—crystalline silicon (c-Si), amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium diselenide (CIGS). We limited this study to the repeatability (within laboratory) issues excluding the reproducibility (among the laboratories) issues. We carried out all the measurements at AM levels less than 2.5, and with matched reference cell technologies to minimize the spectral mismatch error (Lad, 2010). A detailed version of this report is presented elsewhere (Paghasian, 2010).

TABLE 1
 I_{sc} , P_{\max} , V_{oc} , and V_{\max} at 23 Sets of Irradiance and Temperature Conditions

Irradiance (W/m ²)	Module Temperature (°C)			
	15	25	50	75
1100	NA	1	2	3
1000	4	5	6	7
800	8	9	10	11
600	12	13	14	15
400	16	17	18	NA
200	19	20	21	NA
100	22	23	NA	NA

OUTDOOR POWER RATING MEASUREMENTS

We carried out the outdoor power rating measurements in Tempe and Mesa, Arizona (a desert climatic condition) using IEC 61853-1 standard's Technique-3 of Clause 9.1.4: Pre-condition the test specimen to a point below the target temperature and then let the module warm up naturally. We chose clear sunny days, and used a module placed on a manual two-axis tracker (see Figure A1 in Appendix for the test setup details) when the AM was less than 2.5.

As shown in Table 2, we studied four commercial flat-plate module technologies—c-Si, a-Si, CdTe, and CIGS. To measure incident irradiance on the test modules with minimized spectral mismatch errors, we used appropriate reference cells as shown in Table 2 (Lad, R., 2010). To obtain data at various irradiance levels, we used different mesh screens with varying light transmittance (see Figure A2 in the Appendix for the screen details). To obtain data at various temperatures, we pre-cooled the test module in an air-conditioned wooden cabinet or an environmental chamber, and then took a series of I-V measurements under sunlight while the module warmed up naturally. To obtain data at temperatures higher than 45°C, we covered the test module's backsheet with a thermal insulator.

We took two rounds of measurements. The round one (2009) measurements helped us to identify the repeatability issues of non-standardized test setups and select a test setup. We carried out the round two (2010) measurements to finalize the standardized test setup, check the PV device linearity, generate the P_{\max} matrix, and validate four different I-V translation/interpolation techniques of IEC 60891 and NREL Method (IEC, 2009) (Marion, B. et al., 2004).

TABLE 2
 Test Module Technologies and Corresponding Reference
 Cell Technologies Used in This Investigation
(we used two reference cells for redundancy and cross checking purposes)

Test Module Technology	Reference Cell Technology	
	Primary Reference Cell	Secondary Reference Cell
Monocrystalline Silicon (mono-Si)	Mono-Si	Mono-Si
Amorphous Silicon (a-Si)	Mono-Si (filtered)	Mono-Si
Cadmium Telluride (CdTe)	GaAs	Mono-Si
Copper Indium Gallium Diselenide (CIGS)	Mono-Si	Mono-Si

Round One Measurements (2009)

Measurements With Non-Standardized Test Setup

In the non-standardized test setup, the reference cells were placed under the uncalibrated mesh screen and the mesh screen was placed directly on the module with no air gap between the module surface and the mesh screen. This setup has two major advantages—the mesh screen does not need to be calibrated for light transmittance, and the flexible mesh screen can be simply placed (rolled around) on the module with no need for rigid framing or a support structure. However, this setup introduced measurement accuracy and repeatability issues involving light transmittance and P_{max} matrix generation.

Light Transmittance

The uncalibrated mesh screens can be used to reduce irradiance levels on the test module. However, this method requires that the calibrated reference cells be placed under the screens. Because the area of a typical reference cell is very small (less than one inch by one inch), the reference cell output is very sensitive to the spatial uniformity of the mesh screen. We used five mesh screens (see Figure A2 in Appendix for details) to reduce the irradiance level on the test modules. These screens are designated as S-100 (smallest opening screen providing approximately 10% transmittance), S-200, S-400, S-600, and S-800 (largest opening screen providing approximately 80% transmittance). The reference cell output was recorded using a data logger to measure the irradiance values at predetermined locations below the screen. The percent transmittance of light for each of the five screens was determined on a clear day using a two-axis tracker and two calibrated reference cells used as irradiance sensors—one outside the screen and the other under the screen.

Measurement accuracy of the light under a screen could be affected either by the mesh opening dimension with respect to reference cell dimension or by the number of openings per unit area (spatial non-uniformity) from one position to the other of the screen. The IEC 61853-1 standard specifies that the maximum filter mesh opening dimension shall be less than 1% of the maximum linear dimension of the reference device. This specification is met by the small opening screens (used in this study) but not by the large opening screens such as S-800. We determined the spatial non-uniformity of each screen by moving the screen over a 1-inch by 1-inch calibrated reference cell with 0-inch screen distance from the reference cell.

The second calibrated reference cell used outside the screen accounts for the incident irradiance variability, if any, outside the screen. We moved each screen in a row from one end to the other along the length of the screen. We did this experiment—using a test platform normal to the sun—very quickly on a perfectly clear sunny day while the irradiance was constant. The irradiance data were continuously recorded during the entire time of the experiment. As shown in Figure 1, the entire screen (100-inch by 50-inch) was divided into four rows along the width and 25 columns along the length for spatial uniformity mapping. We present the results for the S-800 screen in Figure 2. The variability chart and contour map shown in Figure 2 indicate that there is a large variation in irradiance values across the screen.

The spatial non-uniformity influence on the irradiance measurement can be reduced if the 1-inch by 1-inch reference cell is replaced with a 4-inch by 4-inch reference cell. The results obtained with the 4-inch by 4-inch cell are shown in Figure 3. The lower standard deviation with 4-inch by 4-inch reference cell—4.7 W/m² for S-800 screen compared with 7.5 W/m² for S-800 screen for the 1-inch by 1-inch reference cell—further indicates an improvement in measurement accuracy with the 4-inch by 4-inch reference cell. We attribute the 4% difference in irradiance between Figures 2 and 3 to the fluctuation in the incident irradiance outside the screen at the time of testing. Figure 4 shows the distribution and deviation of data points for the S-800 screen, at and from the average (shown by a horizontal line) for small (1-inch by 1-inch) and large (4-inch by 4-inch) area reference cells. This indicates that the spatial uniformity of the light under the screen is heavily influenced by the size of the test device or the size of the solar cell in a module. Increasing the distance between the screen and the test/reference device, which we discuss below, can further reduce the irradiance measurement error due to spatial non-uniformity.

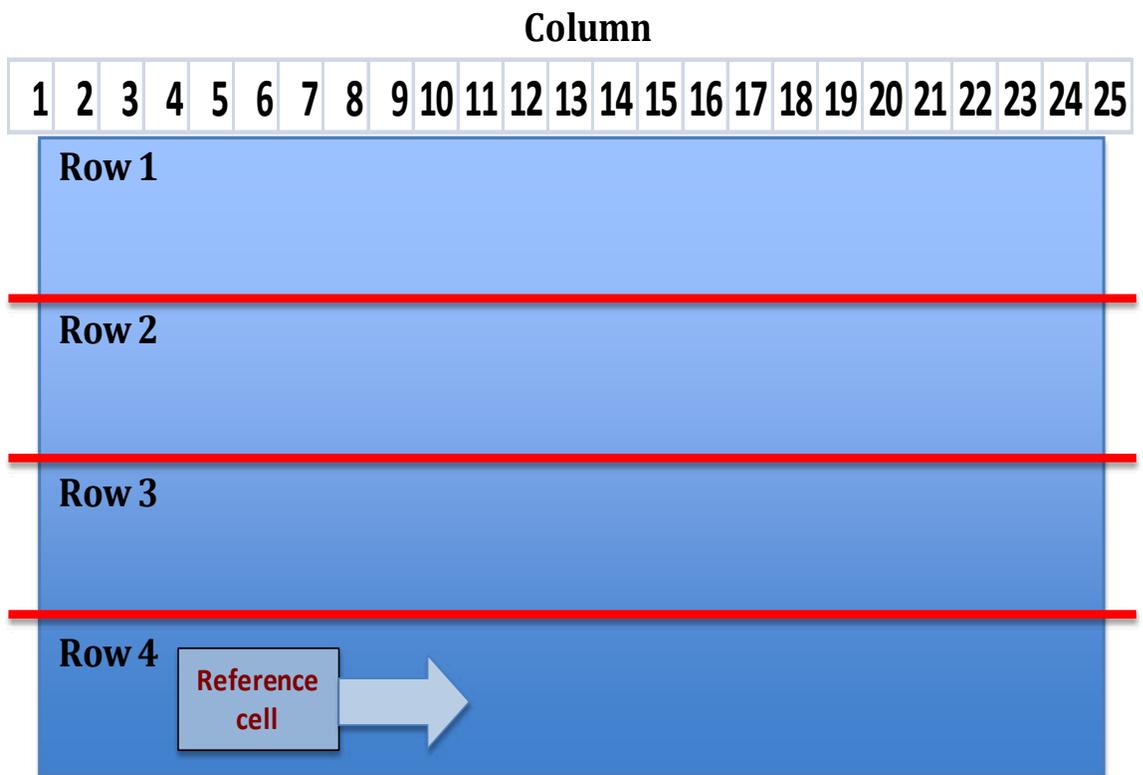
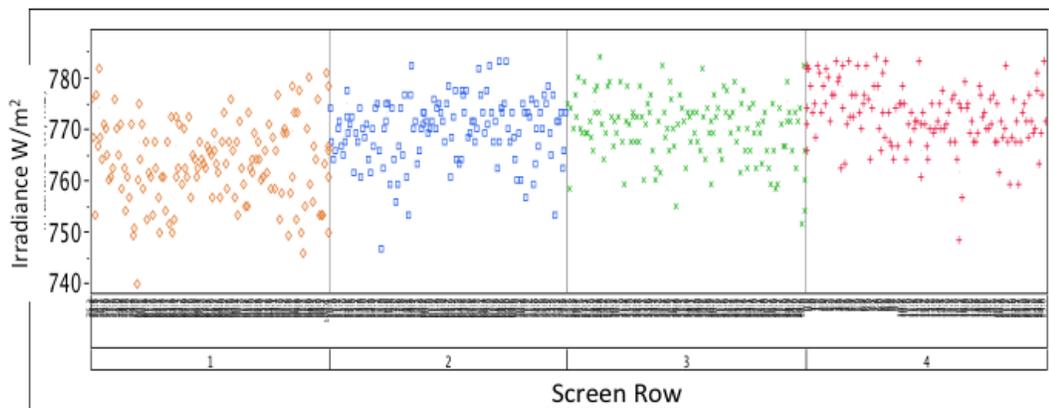


Figure 1. Division of a mesh screen for spatial uniformity determination.

a) Variability chart



b) Contour map

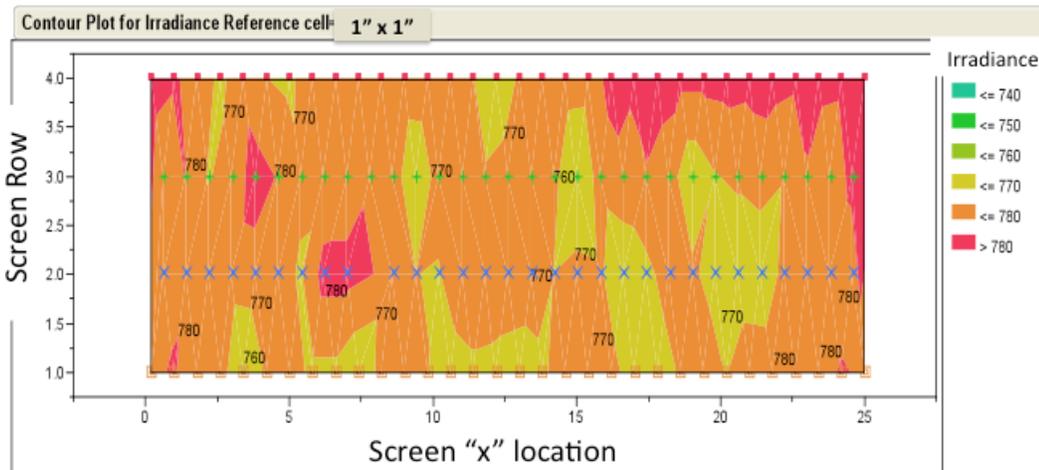
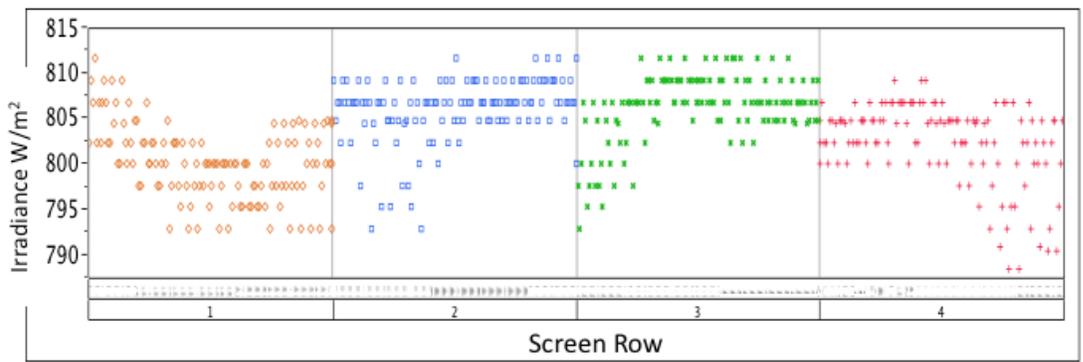


Figure 2. a) Variability chart. b) Contour map showing uniformity mapping of S-800 screen using 1-inch by 1-inch polycrystalline reference cell (0-inch distance between the cell and screen).

a) Variability chart



b) Contour map

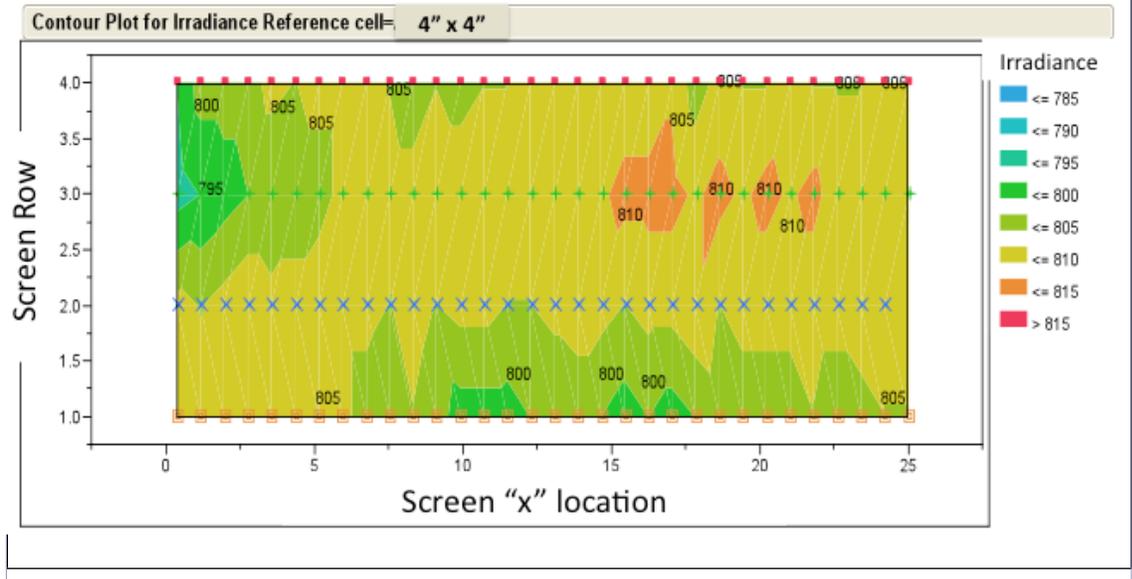


Figure 3. a) Variability chart. b) Contour map on uniformity improvement of S-800 screen for 4-inch by 4-inch reference cell (0-inch distance between the cell and screen).

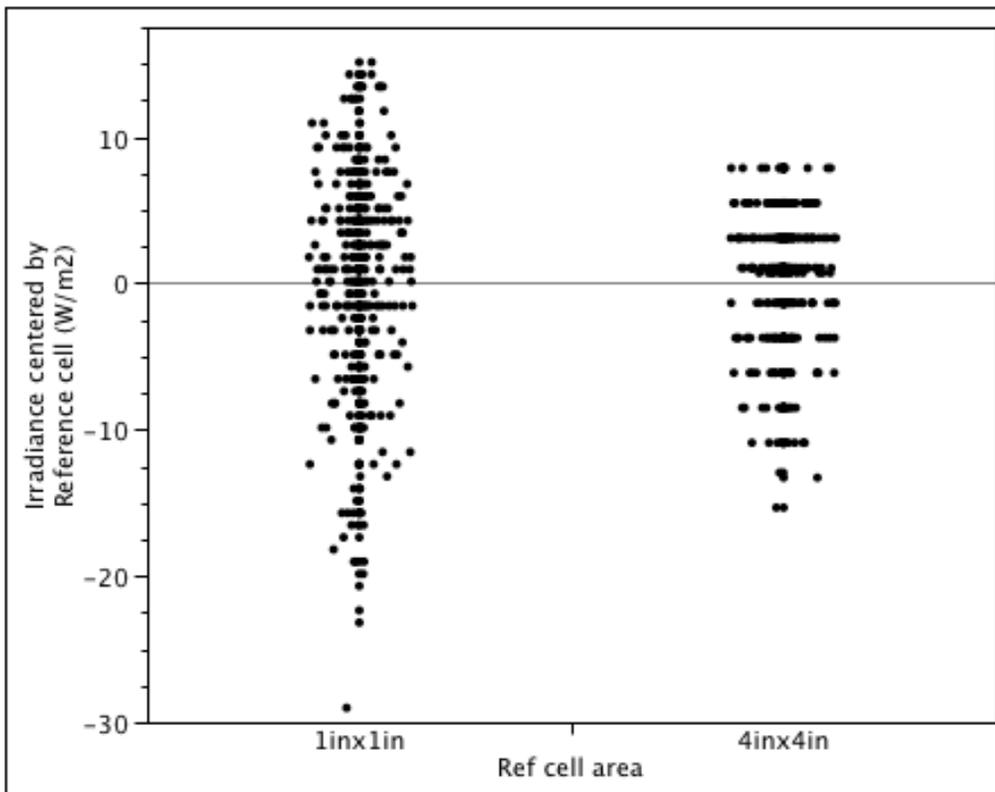


Figure 4. Deviation of data points from the average for small (1-inch by 1-inch) and large (4-inch by 4-inch) area irradiance sensors (S-800 screen, 0-inch screen gap from irradiance sensor).

As shown above, the spatial uniformity of the screens has an influence on the irradiance measurements (and hence module performance measurements). One way to reduce this spatial non-uniformity issue to a negligible level is to increase the distance/gap between the module (and reference cell) surface and the screen. We used the S-800 screen to determine the optimum gap distance between the test device (in this case a 1-inch by 1-inch reference cell) and the screen. We arbitrarily chose the distances of 0, 1.5, 3, and 6.5 inches, and then compared the collected irradiance data with the 0-inch irradiance data. We collected data at six different locations under each of the screens, totaling about 40 data points at each location (including the 0-inch location), for a grand total of about 240 data points for the six locations. We monitored the slight variation, if any, in intensity of sunlight outside the screen using a reference cell, and we accounted/normalized the variation to calculate the average and standard deviation of light intensity under the screen. Table 3 shows the average and standard deviation for these six locations at each of four distances. The 0-inch data showed a standard deviation of 7.1 W/m², and the 1.5 to 6.5 inch data shows a standard deviation of only 4.5 to 5.7 W/m², indicating a great improvement in spatial uniformity if the distance is increased from 0-inch to or above 1.5-inch (the reduction in standard deviation between three-inch and 6.5-inch data is significant but we did not repeat the experiment to determine if this reduction is real). Figure 5 is a visual representation of the distribution of these 240 data points for each of the distances. The green line across the data points indicates the average. Therefore, this study recommends maintaining a minimum distance of 1.5 inches between the module and screen. Table 4 shows the transmittance data obtained on all the screens with a distance of 6.5 inches.

TABLE 3

Influence of Gap Between the Screen and Irradiance Sensor on the Average and Standard Deviation

Distance (inch)	Number of Data Points	Mean (W/m ²)	STD Dew (W/m ²)
0	240	845.6	7.07
1.5	240	841.6	5.72
3	240	838.7	5.51
6.5	240	844.6	4.57

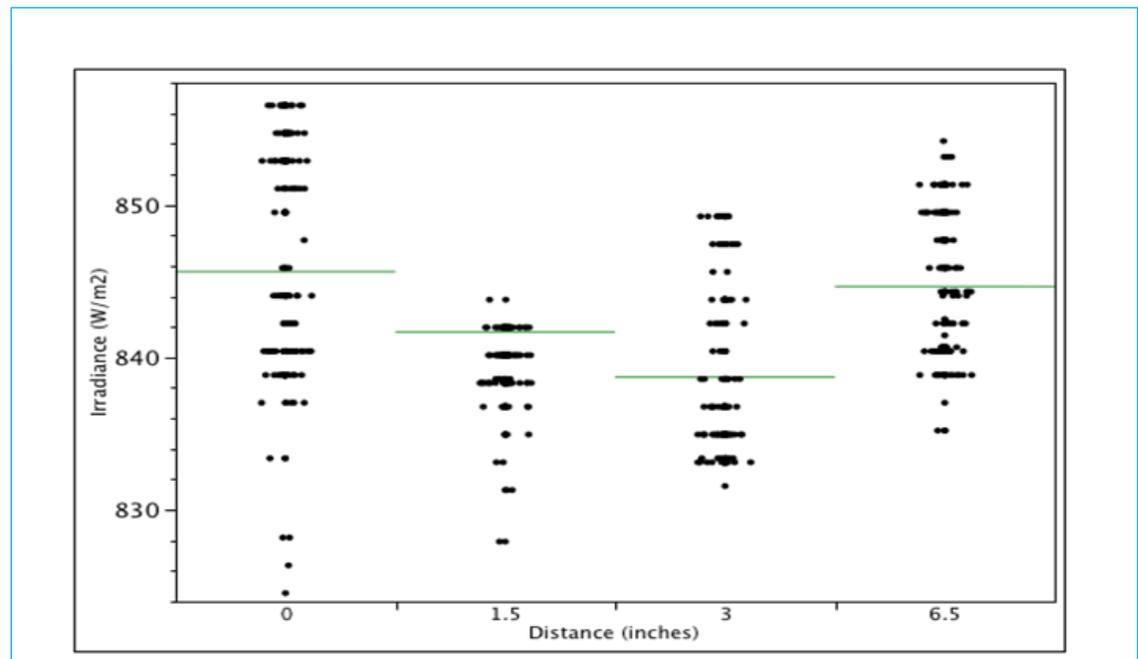


Figure 5. Influence of distance between screen (S-800) and irradiance sensor using a 1-inch by 1-inch reference cell (due to higher sensitivity of small area cell to screen spatial uniformity, we chose the 1-inch by 1-inch cells for this experiment).

TABLE 4

Percent Transmittance Calibration of Mesh Screens Using 1-inch by 1-inch Reference Cells (screen distance from reference cell = 6.5 inches)

Screen code	Average irradiance under the screen (W/m ²)	Average irradiance outside the screen (W/m ²)	% Transmission	Standard deviation
S-100	156.16	1074.25	14.54	1.44 %
S-200	178.27	1063.55	16.76	2.65 %
S-400	468.15	1067.46	43.86	0.80 %
S-600	618.01	1075.50	57.46	0.50 %
S-800	871.58	1086.10	80.25	0.56 %

P_{max} Matrix Generation

Based on the results presented above, we expect the worst-case repeatability issue to occur when the screen is placed directly on the test module surface (0-inch air gap) and on the 1-inch by 1-inch reference cell surface (0-inch air gap). Table 5 shows the influence of this worst-case setup on the repeatability of performance (P_{max}) data for three runs. We obtained three runs of data that spanned more than 75 days between May 16, 2009, and July 30, 2009. The P_{max} data obtained in 2010 with the best-case setup (reference cell kept outside the screen and the test module kept at a minimum distance of 1.5 inches from the screen) are presented in the next section (Round Two Measurements). As shown in Table 2, all the measurements were carried out at air mass levels less than 2.5 and matched reference cell technologies to minimize the spectral mismatch error (Lad, 2010).

Note that the IEC 61853-1 standard specifies P_{max} data requirements only at 23 different test conditions (not 28 test conditions) in the seven by four matrix as shown in Table 1. In this report, the P_{max} data are reported (Table 5) only for 18 different test conditions, because the 2009 test setup was not designed to obtain the test data at either 15°C or 75°C. The goal in round one tests was to identify the measurement repeatability issues related to the test setup only, without the influence of errors related to the current-voltage translation or interpolation procedures. In order to minimize the errors related to translations/interpolations, we used the irradiance-specific temperature coefficients shown in the Appendix (Table A1), and the temperature and irradiance conditions during the tests were maintained very close (within $\pm 2^\circ\text{C}$ and 50 W/m^2) to the reporting conditions of 20, 25, and 45°C and 100, 200, 400, 600, 800, 1000, and 1100 W/m^2 .

The extent of measurement repeatability issue, among the three runs shown in Table 5, was determined using standard deviations presented in Figure 6 (A,B,C,D). For all the four technologies tested, the standard deviation was found to be less than one watt for all but two data points (2 out of 72 data points). Unfortunately, only three runs were available for this standard deviation calculation. The measurement repeatability of the three runs was also determined from the maximum P_{max} deviation over the average—(highest P_{max} - lowest P_{max}) / Average P_{max} —and Figure 7 (A,B,C,D) shows the repeatability data (% P_{max} deviation from average). The % P_{max} deviation obtained using the worst-case setup (0-inch air gap and reference cell kept under the screen) is higher (as high as 6%) than the acceptable limit of 1-2%. Due to time limitations, the entire repeatability study with the best-case setup (2-inch air gap and reference cell kept outside the screen) could not be performed for the second time. However, based on the results presented in Table 3 and Figure 5 above, the repeatability of measurements using the best case setup (2-inch air gap and reference cell kept outside the screen) are expected to be much better. The results obtained using the best-case setup are presented in the next section, Round Two Measurements.

TABLE 5

P_{max} Measurement Repeatability for Four PV Module Technologies at Different Temperatures and Irradiance Levels

(data obtained at 0-inch air gap between uncalibrated screen and test module and reference cell)

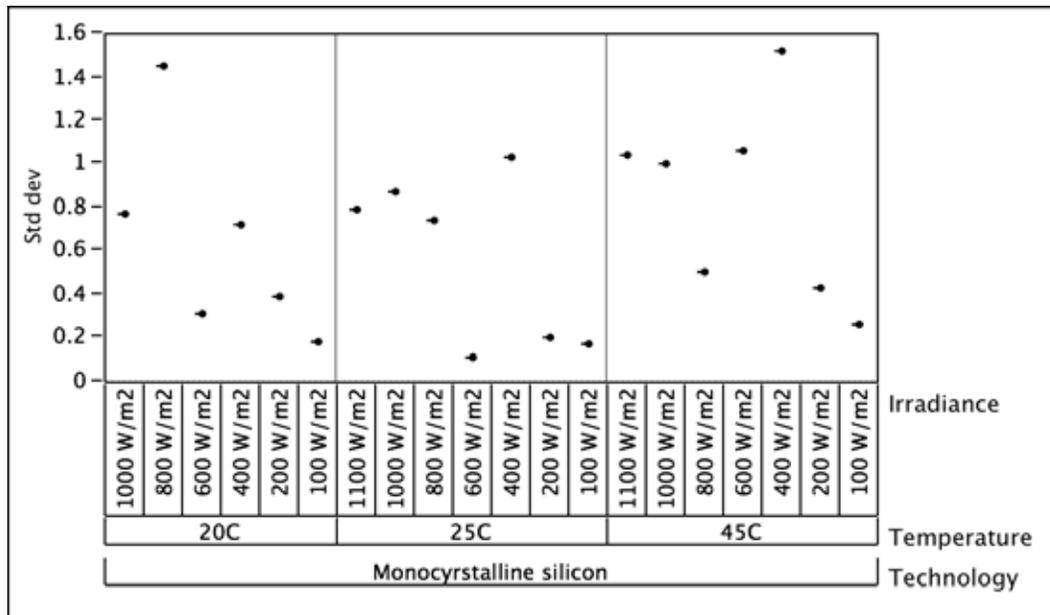
Mono-Si									
(Zero inch air gap between uncalibrated screen and module / reference cell)									
	20°C			25°C			45°C		
W/m ²	Run1	Run2	Run3	Run1	Run2	Run3	Run1	Run2	Run3
1100	NA	NA	NA	179.02	178.52	177.46	160.26	158.61	158.35
1000	167.21	166.78	165.71	162.89	161.66	161.20	145.59	143.77	143.97
800	129.48	131.90	132.08	127.16	128.50	128.37	114.78	115.52	115.73
600	100.74	100.39	101.01	98.29	98.11	98.09	87.52	85.89	87.87
400	64.10	64.67	65.53	62.25	62.52	64.15	55.76	58.13	58.58
200	30.79	31.05	31.55	30.24	29.96	30.34	26.47	27.29	27.06
100	13.86	14.13	14.20	13.61	13.67	13.94	12.43	12.94	12.80

CIGS									
(Zero inch air gap between uncalibrated screen and module / reference cell)									
	20°C			25°C			45°C		
W/m ²	Run1	Run2	Run3	Run1	Run2	Run3	Run1	Run2	Run3
1100	NA	NA	NA	29.94	30.20	30.26	31.49	31.78	31.52
1000	27.36	26.78	26.95	28.40	27.19	27.49	29.99	28.68	28.60
800	21.84	21.02	21.46	22.36	21.94	22.33	24.15	23.43	23.66
600	17.26	16.78	17.16	17.78	17.34	17.72	18.62	18.21	18.26
400	12.42	11.81	12.07	12.47	12.22	12.18	12.44	12.04	11.93
200	6.15	6.44	6.53	5.98	6.56	6.42	5.73	5.94	5.88
100	3.18	3.25	3.15	3.18	3.20	3.13	3.14	3.03	3.04

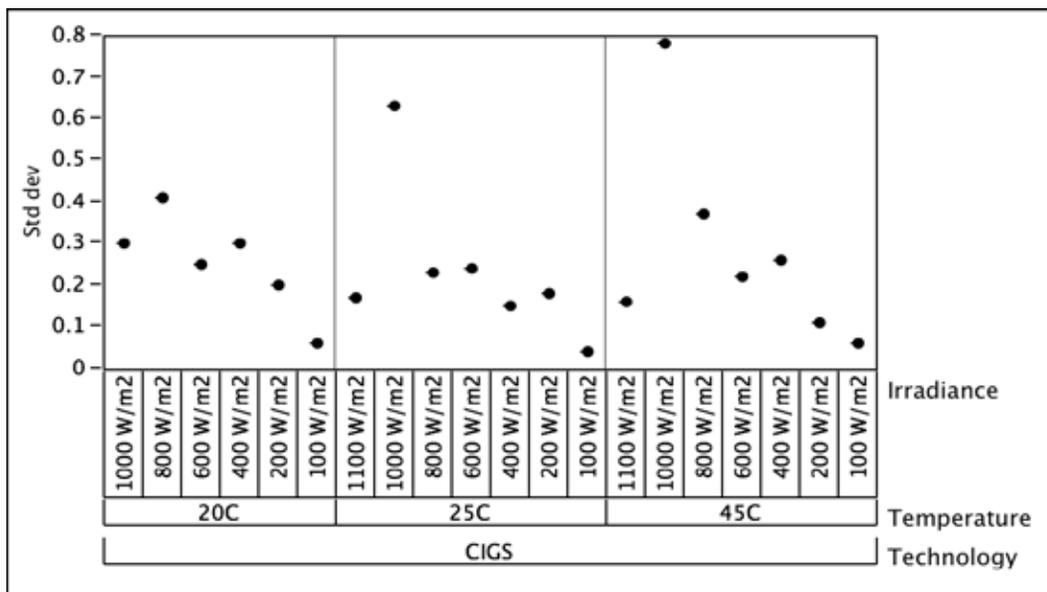
a-Si									
(Zero inch air gap between uncalibrated screen and module / reference cell)									
	20°C			25°C			45°C		
W/m ²	Run1	Run2	Run3	Run1	Run2	Run3	Run1	Run2	Run3
1100	NA	NA	NA	39.13	40.65	40.96	37.40	38.79	38.76
1000	36.08	37.28	37.56	35.59	36.96	37.25	33.96	35.21	35.22
800	28.11	28.89	29.58	27.76	28.67	29.00	26.33	27.14	26.70
600	21.57	21.66	21.59	21.34	21.34	21.18	20.46	20.06	19.53
400	13.86	14.03	13.64	13.60	13.64	13.32	12.34	12.18	12.51
200	5.71	5.59	5.65	5.55	5.56	5.49	5.20	5.20	5.01
100	2.56	2.60	2.49	2.46	2.54	2.46	2.20	2.30	2.30

CdTe									
(Zero inch air gap between uncalibrated screen and module / reference cell)									
	20°C			25°C			45°C		
W/m ²	Run1	Run2	Run3	Run1	Run2	Run3	Run1	Run2	Run3
1100	NA	NA	NA	74.47	75.29	74.83	71.48	72.15	71.90
1000	68.47	69.20	68.66	67.72	68.46	68.06	64.95	65.52	65.33
800	55.39	54.69	54.90	54.96	54.26	54.45	52.58	51.89	51.81
600	21.57	21.66	21.59	21.34	21.34	21.18	20.46	20.06	19.53
400	13.86	14.03	13.64	13.60	13.64	13.32	12.34	12.18	12.51
200	5.71	5.59	5.65	5.55	5.56	5.49	5.20	5.20	5.01
100	2.56	2.60	2.49	2.46	2.54	2.46	2.20	2.30	2.30

A: Mono-Si

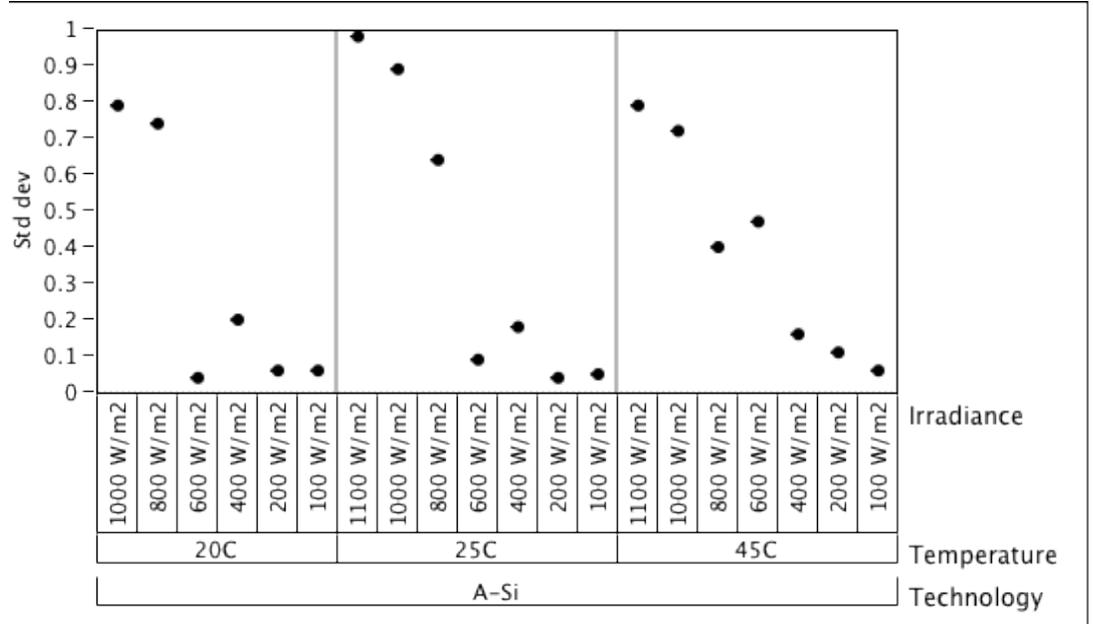


B: CIGS

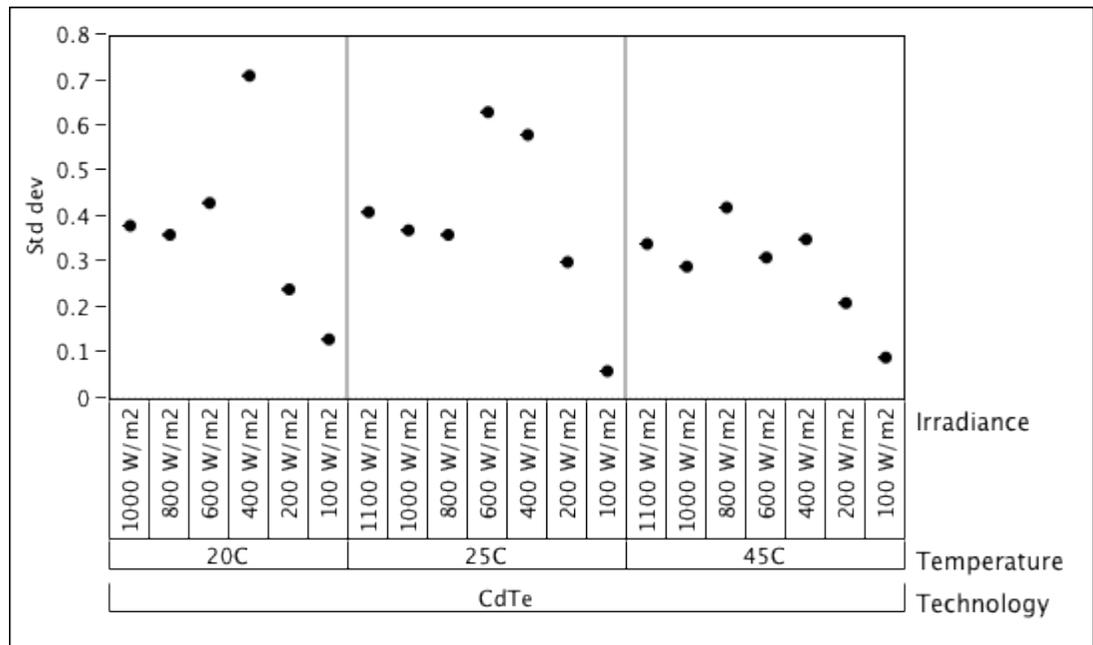


Figures 6A and 6B. Measurement repeatability of P_{max} over three runs (standard deviation in watts).

C: Amorphous-Si

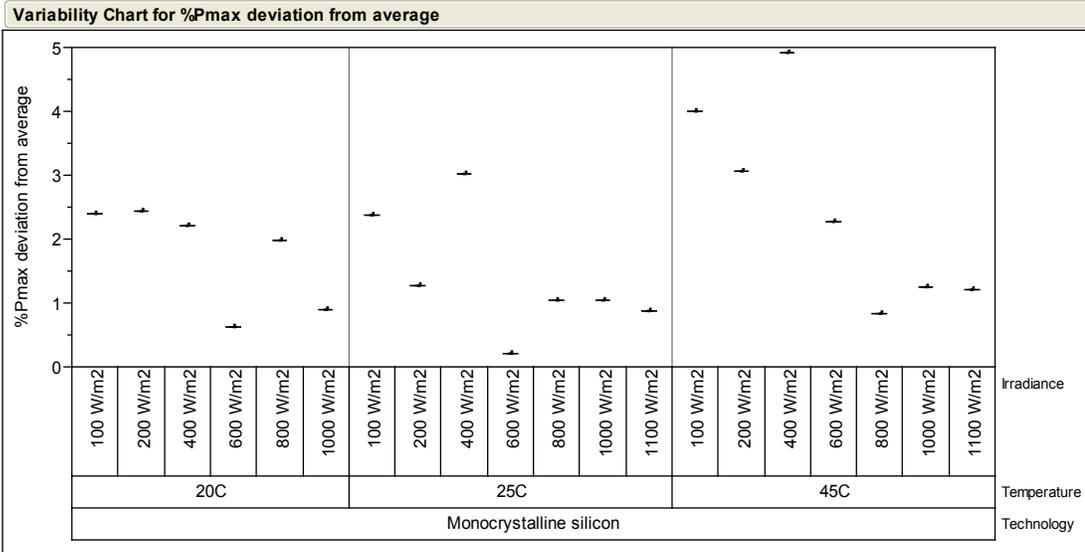


D: CdTe

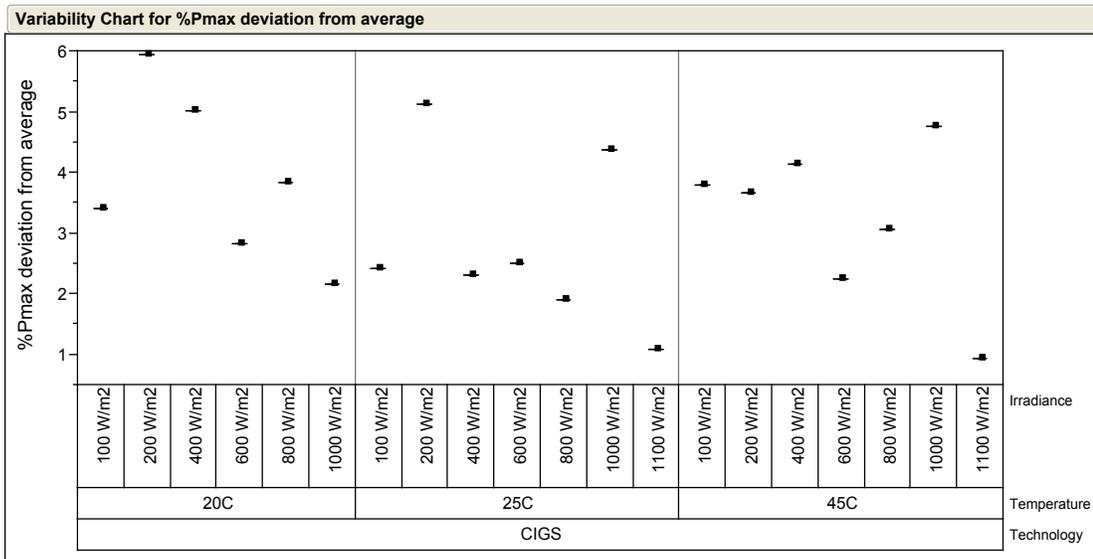


Figures 6C and 6D. Measurement repeatability of P_{max} over three runs (standard deviation in watts).

A: Mono-Si

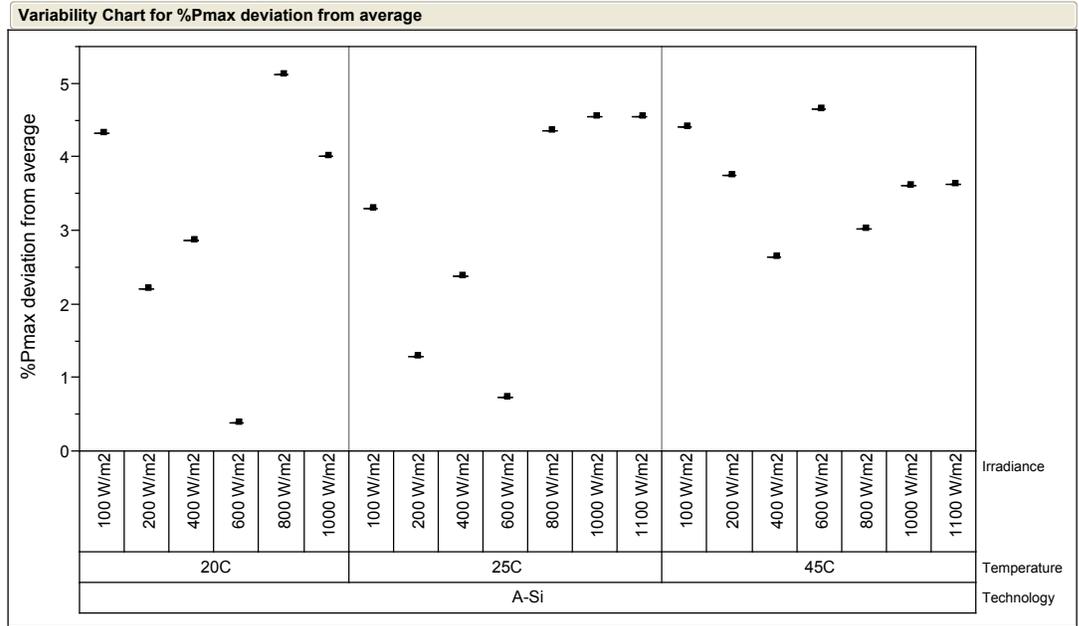


B: CIGS

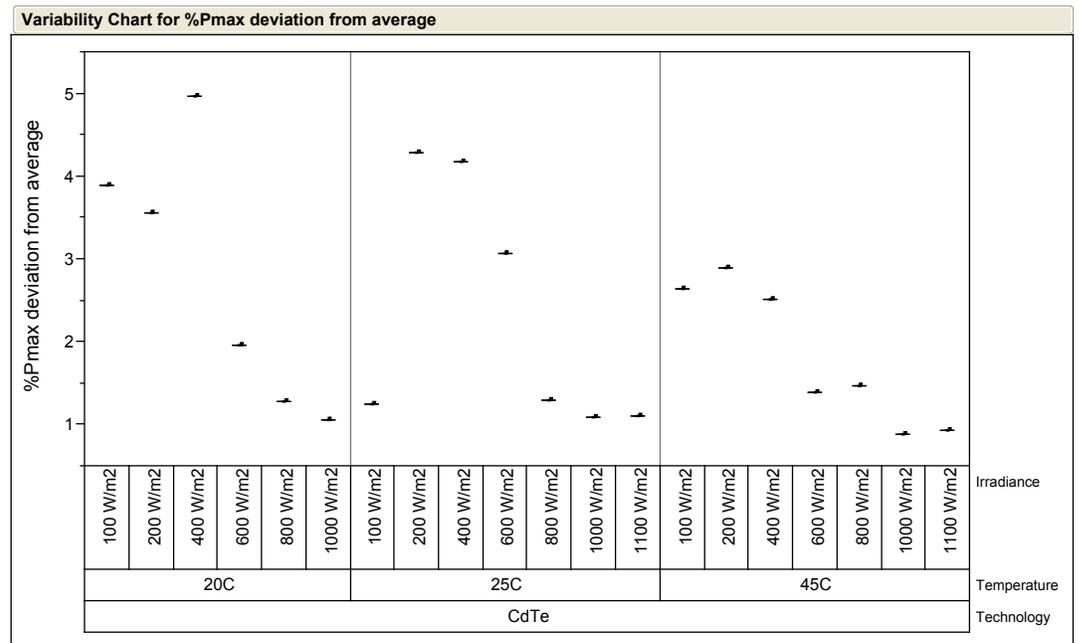


Figures 7A and 7B. Measurement repeatability of P_{max} over three runs (maximum P_{max} deviation from average).

C: Amorphous-Si



D: CdTe



Figures 7C and 7D. Measurement repeatability of P_{max} over three runs (maximum P_{max} deviation from average).

Round Two Measurements (2010)

Measurements With Standardized Test Setup

In the standardized test setup, the reference cells were placed outside the calibrated mesh screen and there was a 2-inch air gap between the module surface and the mesh screen. This setup has two major advantages—the measurements are more accurate and the measurements are repeatable. However, this setup requires calibration and rigid framing of mesh screens.

Light Transmittance of Calibrated Mesh Screens

Because most commercial reference cells are small area cells (typically less than 1 square inch), the light transmittance data (or the irradiance data) is very sensitive (as demonstrated in the round one measurements) to the spatial non-uniformity of the uncalibrated screens. Therefore, we suggest using only transmittance-calibrated screens. The transmittance calibration of the screens can be achieved using PV modules composed of large area cells.

In round two measurements, we used the short-circuit current values of the modules composed of large cells, per IEC 61853-1, to calibrate the screens for light transmittance. We used five crystalline silicon commercial modules from two different manufacturers for this screen calibration study. We assumed that each cell of the module generates an equal current. To gain confidence in this assumption, we used the average transmission of five modules instead of just one module.

Table 6 shows the transmittance values we obtained using five large area modules with a 2-inch air gap. By comparing the average transmission values and the standard deviation values between Table 3 and Table 6, it is clear that the light transmission is overestimated and the standard deviations are higher when a small reference cell-based irradiance sensor is used under the screens. As shown in column 4 [(Max-Min)/Max] of Table 6, the transmittance measurements become very sensitive for the irradiance levels below 200 W/m². To gain a higher level of confidence in the transmission calibration of the screens, it may be necessary to measure the I_{sc} value of each and every cell of a large size module (preferably, a module composed of current matched cells), but it requires an intrusive technique to cut the backskin and access the individual cells.

TABLE 6

Percent Transmittance Calibration of Mesh Screens Using Large Commercial Modules
(screen distance from module = 2 inches)

Screen code	Transmittance (%)					Average transmission (%)	(Max-Min)/Max (%)	Std. dev.
	Module 1	Module 2	Module 3	Module 4	Module 5			
S-100	9.63	9.62	9.73	9.75	9.77	9.70	1.5%	0.72%
S-200	15.94	15.92	15.86	16.04	15.98	15.95	1.1%	0.44%
S-400	41.97	41.92	42.16	42.11	41.99	42.03	0.6%	0.24%
S-600	55.73	55.90	56.40	56.27	56.07	56.07	1.2%	0.48%
S-800	76.49	76.40	76.58	76.70	76.52	76.54	0.4%	0.14%

Linearity of Test Modules With Temperature and Irradiance

The test modules can be classified as linear or non-linear devices. A PV device is declared to be linear if the linearity requirements of IEC 60904-10 (clause 7.3) are met. If the device is not linear, then the measurements at or close to (within 100 W/m²) all the 23 sets of conditions in Table 1 shall be carried out. The translation procedures of IEC 60891 or NREL Method may be used to translate from the actual measured condition to the reporting conditions of Table 1. If the “Simplified Procedure” of IEC 61853-1 (clause 8.2) is used, then the device must meet the additional linearity requirements of IEC 61853-1. If the linearity requirements of both IEC 60904-10 and IEC 61853-1 standards are met, then I-V measurements made at about 13 test conditions of Table 7 are sufficient to fill the 23 data points of Table 1 just by using the performance parameter measured at a single temperature with multiple irradiance levels and the temperature coefficient of the respective performance parameter.

TABLE 7
Required Test Conditions for Simplified Procedure of IEC 61853-1

Approximate irradiance (W/m ²)	Approximate module temperature (°C)				
	15	25	50	75	Equilibrium module temperature under prevailing outdoor condition (for example, 58°C)
1100	NA	NA	NA	NA	1
1000	6	7	8	9	2
800	NA	NA	NA	NA	NA
600	NA	NA	NA	NA	NA
400	NA	NA	NA	NA	3
200	10	11	12	13	4
100	NA	NA	NA	NA	5

For the ease of reference, the linearity requirements of IEC 60904-10 (clause 7.3) and IEC 61853-1 (clause 8.2) are reproduced below:

IEC 60904-10 requirements for device linearity:

“When a given device is claimed to be linear, the applicable range of temperatures, irradiance, voltage, or other necessary conditions shall also be stated. The requirements for the acceptable limits of non-linearity (variation) are:

a) For the curve of short-circuit current versus irradiance, the maximum deviation from linearity should be less than 2 %; b) For the curve of open-circuit voltage versus the logarithm of irradiance, the maximum deviation from linearity should be less than 5 %; c) For the curve of open-circuit voltage, short-circuit current and maximum power versus temperature, the maximum deviation from linearity should be less than 5 %. If the temperature coefficient of short circuit current is less than 0.1 %/K, the device can be considered linear with respect to this parameter.”

Additional device linearity requirements of IEC 61853-1 for “Simplified Procedure”:

“For some modules that are known to be linear (per IEC 60904-10), the maximum power dependence on irradiance and the maximum power dependence on temperature are independent. In this case it is sufficient to measure:

a) the parameters (I_{sc} , V_{oc} , P_{max} and V_{max}) dependence on irradiance at fixed temperature over the range of 100 W/m² to 1 100 W/m²; b) The parameters (I_{sc} , V_{oc} , P_{max} and V_{max}) dependence on temperature at two fixed irradiances, one of which is between 800 W/m² and 1 000 W/m² and the second of which is between 100 W/m² to 300 W/m².

Compare the relative temperature coefficients for maximum power and open circuit voltage determined from the two irradiance sets. If the two values for the relative temperature coefficient of open circuit voltage agree within 10 % and the two values for the relative temperature coefficient of maximum power agree within 15 %, the average of the two temperature coefficients measured in b above can be utilized to fill out the tables. If not the table should be completed by measuring at each set of conditions.”

For the ease of experimental setup planning, a suggested measurement sequence is shown by numbers: 1 through 23 in Table 1 and 1 through 13 in Table 7. Based on these 13 data points and the average temperature coefficient obtained at two irradiance levels as per clause 8.2b of IEC 61853-1 (for example, at approximately 1000 W/m² and 200 W/m² as shown in Table 7), all the 23 data points required at 23 exact sets of irradiance and temperature conditions of Table 1 can be filled using the simplified procedure.

As indicated in Table 8, none of the four test modules is qualified for the use of simplified procedure because they all fail to meet the stringent IEC 61853-1 linearity requirements. As a result, we have only used the four translation procedures of IEC 60891 and NREL Method in this work. All the test modules were also verified for the linearity requirements as per IEC 60904-10 using wide ranges of temperature (15 to 75°C) and irradiance (100 to 1100 W/m²). Figures 8A and 8B show the results. As presented in the summary of Table 9 for mono-Si and of Table 2A through 4A in the Appendix for the other three technologies, all the modules meet all the linearity requirements of P_{max} , V_{oc} , and I_{sc} with respect to temperature (except a-Si at 50°C, which is apparently due to slight experimental error because this device meets the requirement above and below 50°C). These tables also indicate that all these devices meet the linearity requirements of V_{oc} with respect to irradiance, except at 1100 W/m² for CIGS and at 600 W/m² for a-Si. (We suspect that the data at 600 W/m² for a-Si is a slight experimental or processing error, because the linearity requirements of this device are met at above and below 600 W/m². The data at 1100 W/m² for CIGS could be a real device issue due to series resistance or a slight experimental/processing error.)

For the short-circuit current versus irradiance, the devices practically met the linearity requirement (2 % deviation limit) for irradiance levels above 200 W/m² but they, surprisingly, showed a higher deviation (more than 5 %) for the irradiance levels below 200 W/m². As evidenced from the screen transmittance calibration data presented in Table 6 [column 4: (Max-Min)/Max], this higher deviation could be attributed to some minor experimental errors related to the calibration of low transmittance mesh screens under natural sunlight. Moreover, for the thin-film technologies with already low I_{sc} values even at one sun irradiance, the 100 W/m² irradiance level becomes very sensitive for the I_{sc} determination as the current level approaches the sensitivity limit of the I-V curve tracer.

It is important to note that the IEC 61853-1 standard restricts the irradiance limit for the translation to 100 W/m² as per the following requirement: *“Measurements need not be taken at exactly the irradiances and temperatures specified. Translation of I-V curves from*

the actual irradiance and/or temperature values to the values prescribed by the tables can be performed in accordance with IEC 60891. Such interpolation should be over no more than 100 W/m².” Considering this 100 W/m² irradiance limit imposed by the IEC 61853-1 standard and that all the test devices have been demonstrated to be linear with respect to temperature, it may be stated that all the test devices of this work meet the linearity requirements for a wide range of temperature (15 to 75°C) and a narrow irradiance limit (< 100 W/m²).

TABLE 8

Linearity Checking of Test Modules as per “Simplified Procedure” of IEC 61853-1
(the red highlighted data do not meet the linearity deviation limit)

	Mono-Si	CIGS	a-Si	CdTe
Difference between relative temperature coefficient at 1000 and 200 W/m ² for P_{max} (allowed limit: < 15 %)	-13.2 %	-4.0 %	50.7 %	72.1 %
Difference between relative temperature coefficient at 1000 and 200 W/m ² for V_{oc} (allowed limit: < 10 %)	-31.3 %	16.7 %	-11.8 %	-38.4 %

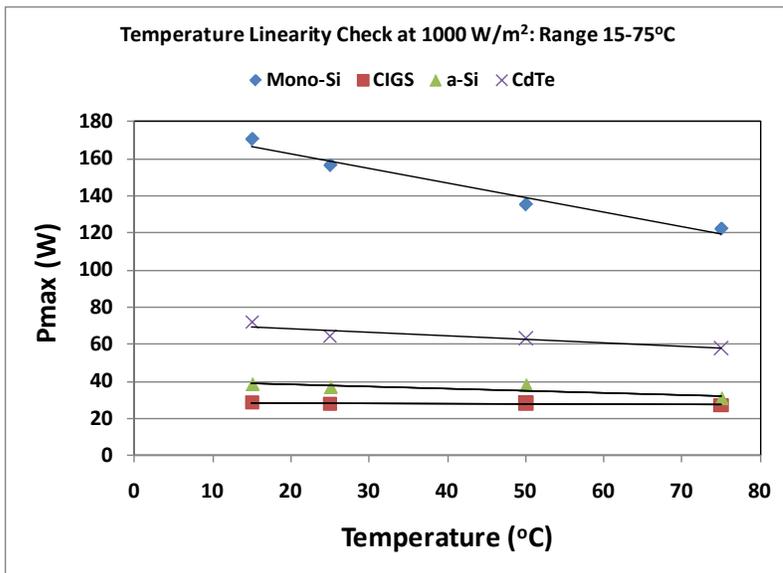
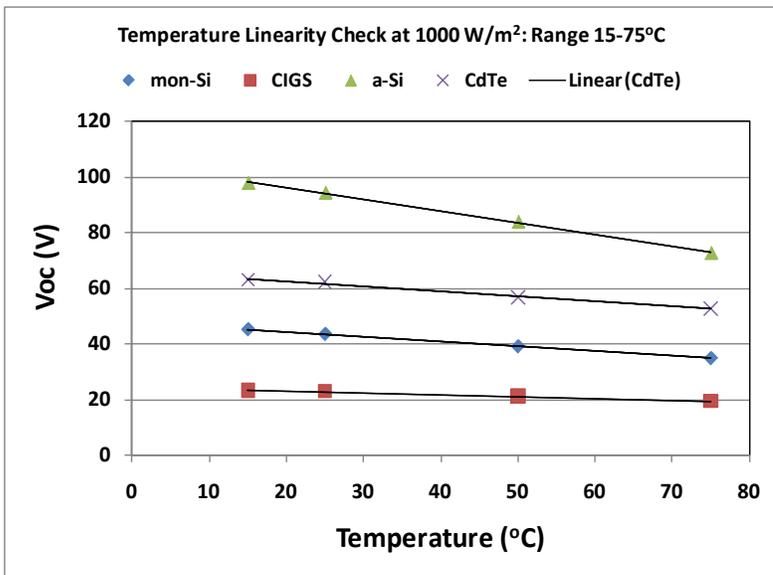
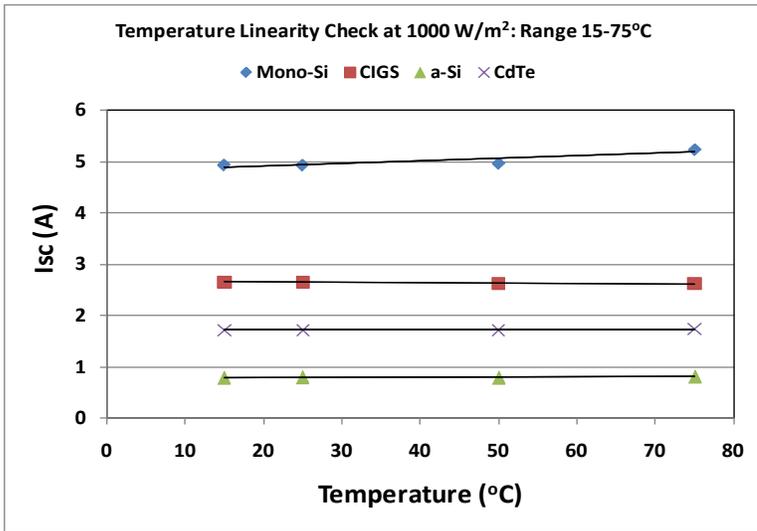


Figure 8A. Linearity checking of test modules for temperature as per IEC 60904-10.

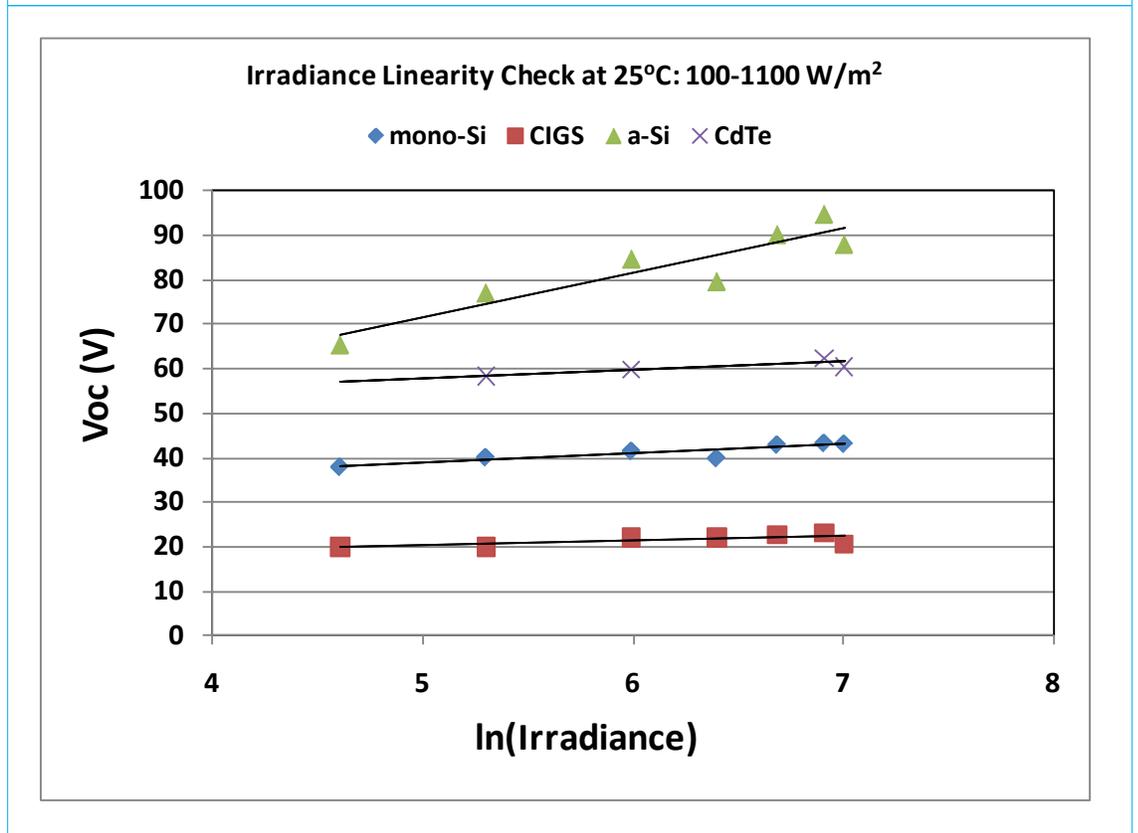
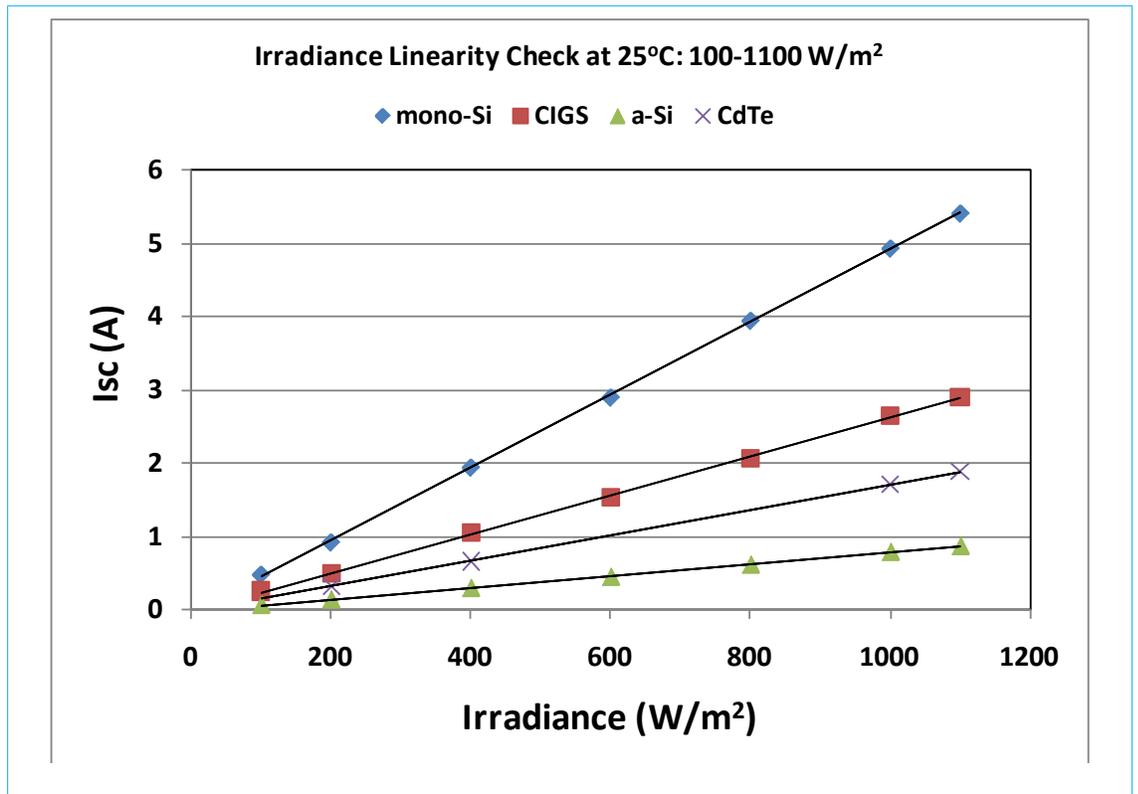


Figure 8B. Linearity checking of test modules for irradiance as per IEC 60904-10.

TABLE 9.

Linearity Checking of Test Modules as per IEC 60904-10
 (the red highlighted data do not meet the linearity deviation limit)

Mono-Si	Linearity Deviation for Temperature (°C)						
	15	25	50	75			
Linearity deviation of I_{sc} for temperature at 15-75°C temperature range and a single irradiance of 1000 W/m ² (allowed limit: < 5%)	-0.9%	0.1%	1.9%	-1.1%			
Linearity deviation of V_{oc} for temperature at 15-75°C temperature range and a single irradiance of 1000 W/m ² (allowed limit: < 5%)	0.0%	-0.1%	0.2%	-0.1%			
Linearity deviation of P_{max} for temperature at 15-75°C temperature range and a single irradiance of 1000 W/m ² (allowed limit: < 5%)	2.2%	1.6%	2.8%	-2.3%			
Mono-Si	Linearity Deviation for Irradiance (W/m ²)						
	1100	1000	800	600	400	200	100
Linearity deviation of I_{sc} for irradiance at 100-1100 W/m ² irradiance range and a single temperature of 25°C (allowed limit: < 2%)	1.0%	0.7%	0.4%	2.1%*	0.8%	3.6%	-5.6%
Linearity deviation of V_{oc} for irradiance at 100-1100 W/m ² irradiance range and a single temperature of 25°C (allowed limit: < 5%)	-0.2%	-1.0%	-1.2%	4.6%	-1.3%	-1.4%	0.6%
* Seems to be a slight experimental/processing error as the device meets the linearity requirement at above 600 W/m ² and at 400 W/m ² (or it can be neglected due to measurement uncertainty)							

P_{max} Matrix Generation With Mesh Screen Placed 2 Inches Above Module Surface

The P_{max} matrix data for all the four module technologies were obtained using one of the four procedures (Procedure 1, 2, 3, or 4). The translation method of each procedure is briefly explained in the Appendix (Figures A3 and A4) (Marion et al., 2004) (IEC, 2009). This study required 8 to 23 reference I-V curves, depending on the procedure. The reference curves were obtained using calibrated screens, maintaining an optimum distance of 2 inches between screen and module surface, and keeping the reference cells outside the screens. Figure 9 shows the reference/measured conditions used for c-Si. Table 10 shows an example of P_{max} data obtained for mono-Si from actual measured conditions to reporting conditions of IEC 61853-1. The reference curves used for the other three technologies are shown in the Appendix (Figures A5 through Figures A7). Figure 10 shows the P_{max} matrix obtained for each of the four technologies using all the four procedures. The validation (translated vs. measured) of each procedure is presented in the next section.

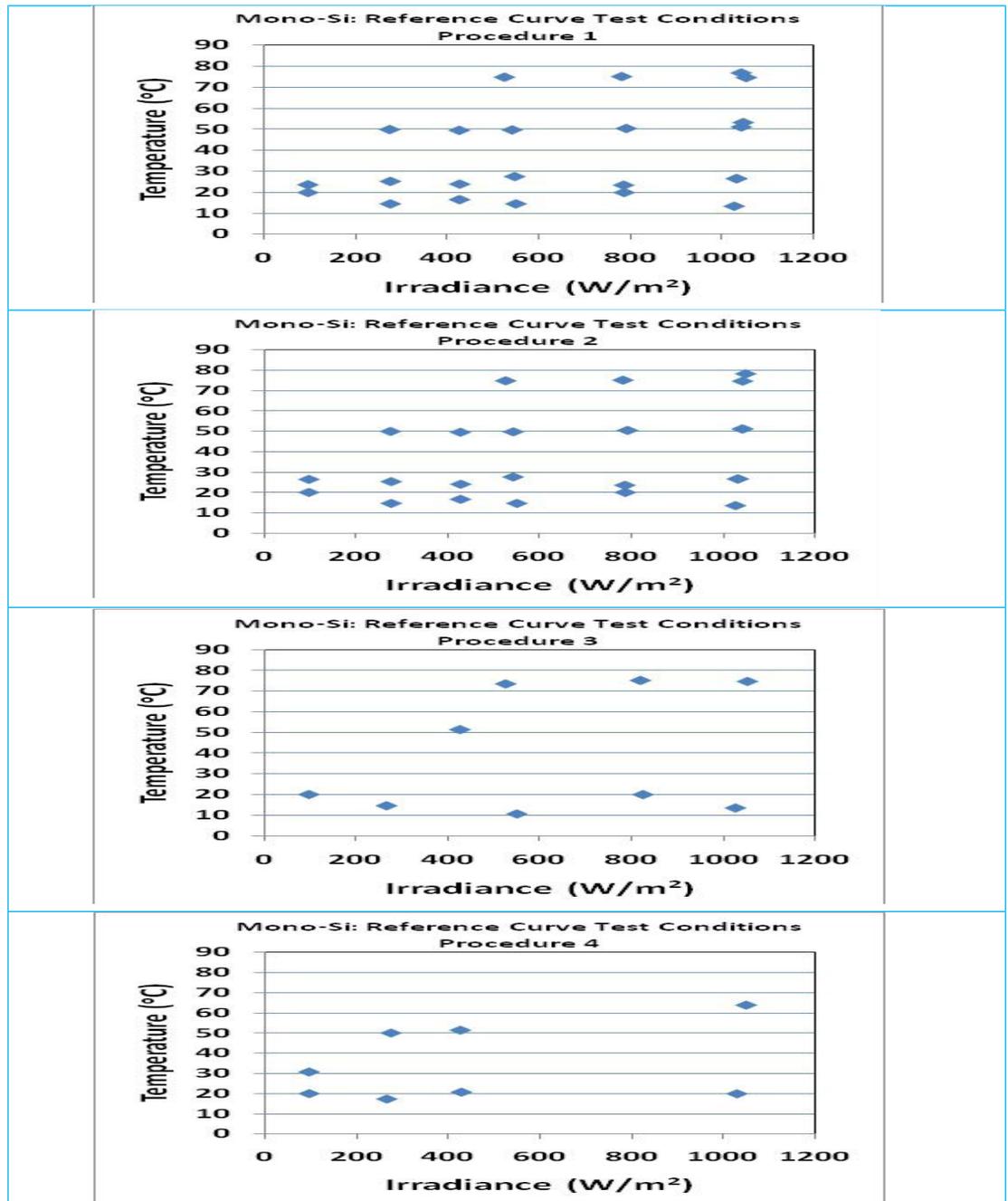
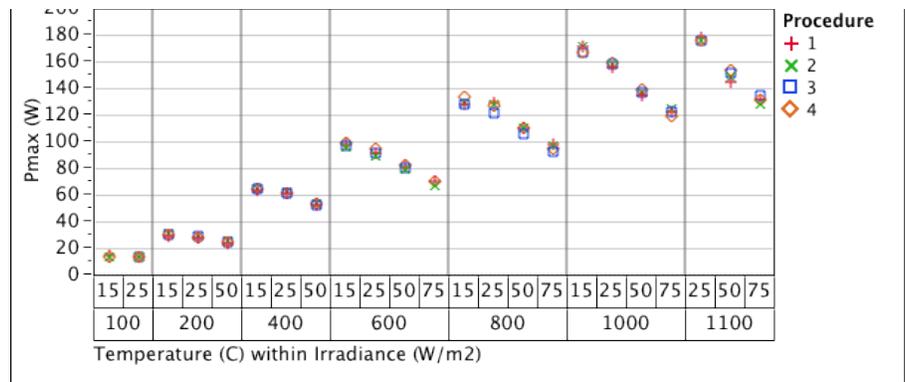


Figure 9. Test conditions used for c-Si to obtain reference curves for each procedure.

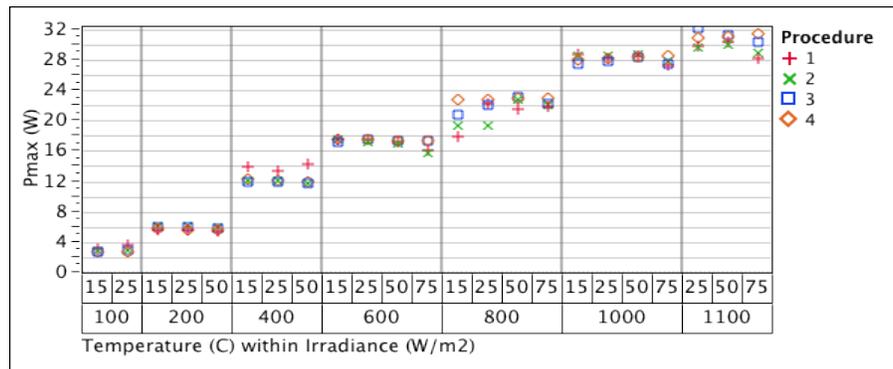
TABLE 10
 Example of P_{max} Data Obtained for Mono-Si From Actual Measured
 Conditions to Reporting Conditions of IEC 61853-1

Measured			Translated (Procedure)		
Irradiance (W/m ²)	Temp (°C)	P_{MAX} (W)	Irradiance (W/m ²)	Temp (°C)	P_{MAX} (W)
97	20.0	13.3	100	15	14.0
97	23.7	12.8	100	25	13.2
277	14.6	41.6	200	15	28.8
277	25.3	39.4	200	25	27.4
275	50.0	33.5	200	50	23.3
428	16.6	68.2	400	15	63.5
428	24.0	65.9	400	25	61.1
427	49.6	56.1	400	50	52.1
551	14.6	88.7	600	15	97.4
548	27.6	82.9	600	25	90.7
542	49.8	72.5	600	50	80.9
526	74.9	60.2	600	75	69.6
787	20.0	129.2	800	15	128.0
786	23.5	125.6	800	25	129.1
792	50.5	109.1	800	50	110.1
782	75.2	95.0	800	75	97.3
1027	13.5	173.7	1000	15	170.6
1032	26.6	162.8	1000	25	155.7
1043	51.2	142.2	1000	50	134.7
1054	74.7	128.9	1000	75	122.1
1032	26.6	167.9	1100	25	177.5
1046	53.3	140.5	1100	50	144.0
1042	76.9	126.5	1100	75	131.5
<i>Measured irradiance is within 100 W/m² from target irradiance</i> <i>Measured temperature is within 5°C from target temperature</i>					

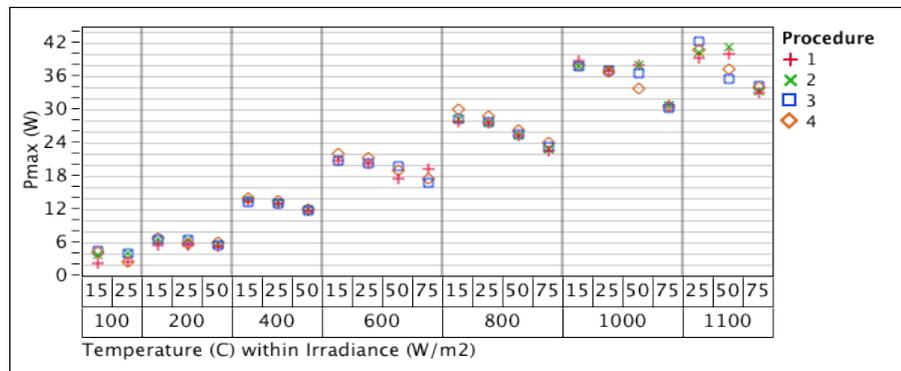
Pmax Matrix: Mono-Si



Pmax Matrix: CIGS



Pmax Matrix: a-Si



Pmax Matrix: CdTe

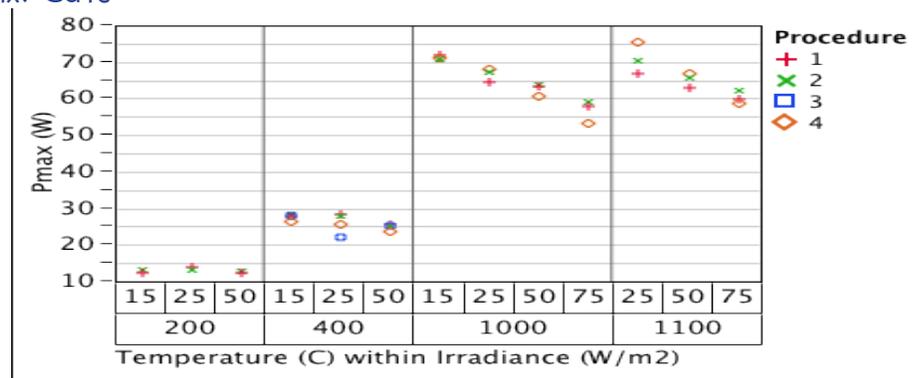


Figure 10. Pmax data of all four technologies at different temperatures and irradiance levels (Procedure-1: IEC60891; Procedure-2: IEC60891; Procedure-3: IEC60891; Procedure-4: NREL Method).

Validation of Current-Voltage Translation/Interpolation Procedures

The goal in using all four I-V curve translation and interpolation procedures is to fill up the 23-element performance matrix with the highest accuracy using the least number of measured/reference I-V curves. Procedure 1 requires the highest number of reference curves (as high as 23 curves) as the allowed irradiance deviation from target curves is less than 20%. Procedures 3 and 4 require the least number of reference curves (as low as 3-4 curves). The required number of reference curves for Procedure 2 falls between these two extremes. The major disadvantage of Procedures 1 and 2 (translation procedures) is the accurate determination of correction factors. The issue related to the accurate determination of correction factors can be minimized if the data processing is completely automated or the measured curves are obtained closest to the 23 target curves. The major disadvantage of Procedures 3 and 4 (interpolation procedures) is the difficulty in accurately accounting for the fill factor change between high and low irradiance ranges. The issue related to the fill factor change can be minimized if two sets of reference curves are obtained (one set of 3 to 4 curves at low irradiance range and the other set of 3 to 4 curves at high irradiance range). In order to execute Procedures 1 and 2, it is necessary to determine the correction parameters (see Figure A3 in the Appendix). It may be necessary to make a comment on the determination of proper single value for each of the correction parameters (a, R_s , or k) for the translation from any measured (reference) irradiance-temperature condition to any other measured (target) irradiance-temperature condition.

For the determination of proper value, the standard (IEC 60891) requires that the P_{max} deviation between reference and target curves shall be within 0.5%. It is possible to meet this requirement if the best fit individual correction value is used for each reference test condition rather than a single value for all the reference conditions (or use multiple narrow translation ranges rather than a single large translation range)

In order to determine the accuracy of each of these four translations and interpolation procedures, the validation approach used by NREL Method was adopted in this work (Marion et al., 2004). Because the translation and interpolation procedures are more sensitive to the irradiance ranges than to the temperature ranges, the sensitivity of each translation procedure was verified at four irradiance ranges (approximate): A (within 1% of target irradiance), B (400-1000 W/m²), C (100-400 W/m²), and D (600-1000 W/m²). We selected a large number of measured curves for this validation work. Some of the selected curves were treated as reference curves and the others were treated as target curves. As an example, 25 measured curves of mono-Si module were selected for the validation Procedure 4B (see Table 11). Out of these 25 measured curves, eight curves were treated as reference curves and the other 17 curves were treated as target curves.

The temperature and irradiance ranges of the target curves of only two technologies (mono-Si and CIGS) are presented in Table 11 as examples. The validation results of each procedure for P_{max} are provided in Figure 11A (average error in %) and Figure 11B (RMSE in %). Because the irradiances of reference and target curves of Procedures 1A and 2A are within 1%, they are expected (and found) to be very accurate as evidenced in Figures 11A and 11B. As shown in Figure 11, all the ranges (A, B, C, and D) in all the procedures agree with each other and are within about a 3% average error from the actual measured data. As suspected, among all the irradiance ranges considered, the low irradiance range (100 to 400 W/m²) in all the four procedures tend to have the highest average error. The meta-stable nature of the thin-film technologies may also contribute to the errors for a-Si, CdTe, and CIGS technologies. We concluded that the general agreement between the translated/interpolated P_{max} data and the actual measured data for all four module technologies (within 3% average error) is remarkably good.

TABLE 11

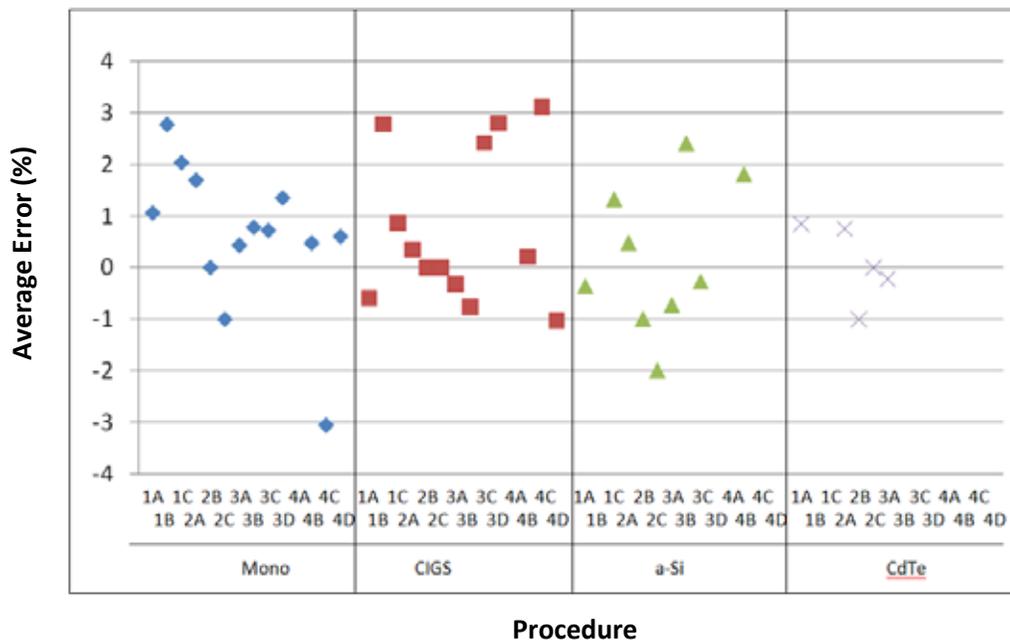
Irradiance and Temperature Ranges of Target I-V curves
Used for the Validation of Four Procedures

Procedure 1	Procedure 2	Procedure 3	Procedure 4
Number of reference I-V curves used = 23	Number of reference I-V curves used = 5-21	Number of reference I-V curves used = 9	Number of reference I-V curves used = 8
<p><i>Data 1: Target & reference irradiance difference (%); Data 2: Target & reference temperature difference (°C);</i> <i>Data 3: Number of target I-V curves used for validation; Data 4: Irradiance range/limit of target I-V curves used for translation or interpolation (W/m²)</i></p>			
Mono-Si			
Procedure 1A: 0.1 %; 4°C; 26 I-Vs; Irrad. range not applic.	Procedure 2A: < 1 %; < 4°C; 26 I-Vs; Irrad. range not applic.	Procedure 3A: NA; < 10°C; 17 I-Vs; < 200 W/m ²	Procedure 4A: NA
Procedure 1B: < 25 %; 6°C; 6 I-Vs; 426-1054 W/m ²	Procedure 2B: < 31 %; < 4°C; 13 I-Vs; 428-1054 W/m ²	Procedure 3B: NA; 9-74°C; 14 I-Vs; 428-1029 W/m ²	Procedure 4B: NA; 20-64°C; 17 I-Vs; 426-1050 W/m ²
Procedure 1C: < 37 %; 6°C; 10 I-Vs; 97-428 W/m ²	Procedure 2C: < 37 %; < 4°C; 7 I-Vs; 266-429 W/m ²	Procedure 3C: NA; 9-51°C; 6 I-Vs; 97-528 W/m ²	Procedure 4C: NA; 17-50°C; 9 I-Vs; 97-275 W/m ²
Procedure 1D: Not applicable (NA)	Procedure 2D: Not applicable	Procedure 3D: NA; 14-75°C; 6 I-Vs; 526-1051 W/m ²	Procedure 4D: NA; 14-58°C; 11 I-Vs; 542-1046 W/m ²
CIGS			
Procedure 1A: 0.4 %; 3°C; 12 I-Vs; Irrad. range not applic.	Procedure 2A: < 4 %; < 4°C; 33 I-Vs; Irrad. range not applic.	Procedure 3A: NA; < 10°C; 17 I-Vs; < 200 W/m ²	Procedure 4A: NA
Procedure 1B: < 28 %; 4°C; 6 I-Vs; 429-793 W/m ²	Procedure 2B: < 28 %; < 4°C; 13 I-Vs; 429-798 W/m ²	Procedure 3B: NA; 9-51°C; 6 I-Vs; 432-1034 W/m ²	Procedure 4B: NA; 11-75°C; 17 I-Vs; 432-1034 W/m ²
Procedure 1C: < 39 %; 3°C; 9 I-Vs; 262-433 W/m ²	Procedure 2C: < 39 %; < 4°C; 7 I-Vs; 262-432 W/m ²	Procedure 3C: NA; 9-51°C; 6 I-Vs; 104-564 W/m ²	Procedure 4C: NA; 17-50°C; 9 I-Vs; 104-564 W/m ²
Procedure 1D: NA	Procedure 2D: Not applicable	Procedure 3D: NA; 9-45°C; 6 I-Vs; 566-1030 W/m ²	Procedure 4D: NA; 9-45°C; 11 I-Vs; 566-1030 W/m ²

a) Procedure Validation: % Error

TYPICAL TRANSLATION RANGE/LIMIT

A: Within 1% of target irradiance; B: 400-1000 W/m²; C: 100-400 W/m² (very sensitive range); D: 600-1000 W/m²



b) Procedure Validation: % RMSE

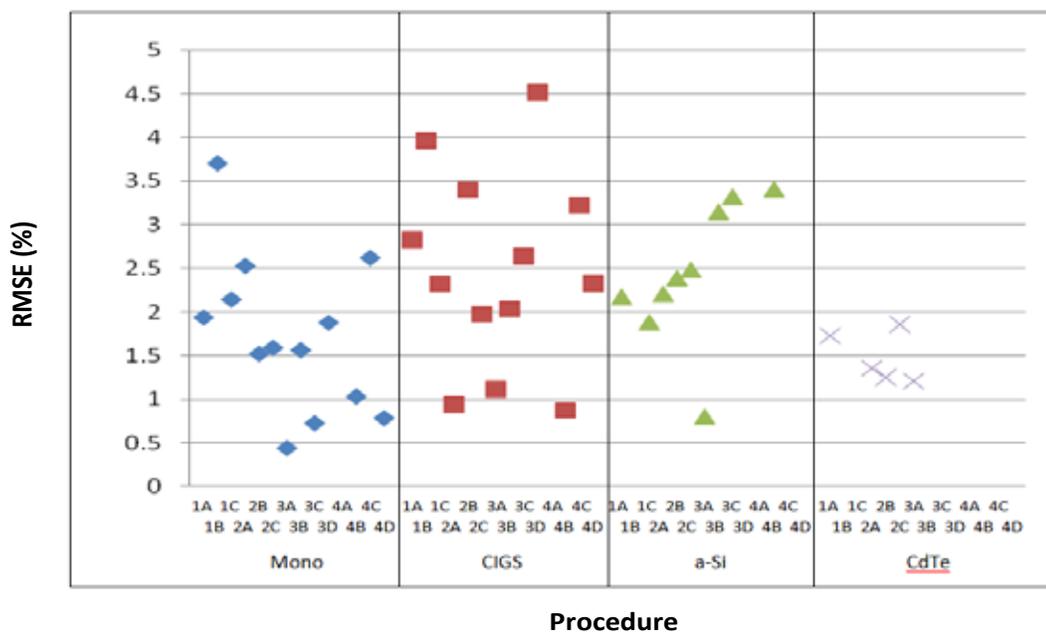


Figure 11a) Average (%). b) RMSE (%) errors of P_{max} of all four technologies at different temperature and irradiance ranges.

CONCLUSIONS

We carried out two rounds of power rating measurements. In the round one (2009) measurements, the distance between the screen and test module or small reference cell was kept at 0-inch distance. The round one measurements with 0-inch distance between test device and screen demonstrated that the P_{\max} measurements are repeatable within only about 6%—higher than the acceptable limit of 1 to 2%. Based on the round one study, we conclude that the P_{\max} matrix using natural sunlight can be acceptably repeated if:

- The measurements are carried out on clear sunny days when the air mass is less than 2.5.
- A matched reference cell technology is used to monitor the irradiance level.
- A calibrated mesh screen is used with the reference cell kept outside the screen.
- A minimum distance of 1.5 inch is maintained between the test module and the mesh screen.

In the round two (2010) measurements, the distance between the screen and test module was kept at a 2-inch distance and the reference cell was kept outside the screen. None of four technologies qualifies for the use of “Simplified Translation Procedure” of IEC 61853-1, because they all fail to meet the linearity requirement of IEC 61853-1. For I_{sc} , V_{oc} , and P_{\max} , all four module technologies, excluding a-Si at 50°C, were determined to be linear, as per IEC 60904-10, with respect to temperature for a wide range of temperature (15 to 75°C). For V_{oc} , all four technologies, excluding CIGS at 1100 W/m² and a-Si at 600 W/m², were determined to be linear, as per IEC 60904-10, with respect to irradiance for a wide range of irradiance (100 to 1000 W/m²). For the short-circuit current versus irradiance, the devices met the linearity requirement (2% deviation limit) for irradiance levels above 200 W/m² but they surprisingly showed a higher deviation for the irradiance levels below 200 W/m². This higher deviation was evidently attributed to some minor experimental errors related to the calibration of low transmittance mesh screens under natural sunlight.

The required P_{\max} matrix of IEC 61853-1 was successfully filled for all four module technologies using the four translation/interpolation procedures of IEC 60891 and NREL Method. With two narrow ranges of irradiance (typically 100 to 400 W/m² and 400 to 1100 W/m²), all four procedures were validated using the measured reference and target I-V curves of all four technologies. The translation procedure validation work demonstrated that the translated/interpolated P_{\max} data could be remarkably matched with the actual measured data for all of the procedures within an average error of about 3%, provided these procedures were applied with a minimum of two ranges of irradiance (for example, 100 to 400 W/m² and 400 to 1100 W/m²).

The Procedures 1 and 2 have the potential to lower the number of I-V measurements as compared to Procedures 3 and 4, but they require the determination of two temperature coefficients and up to three correction factors. The determination of proper correction parameters of Procedures 1 and 2 (translation procedures) for the 23 power rating conditions of IEC 61853-1 using a trial and error method would be very time consuming. Unless an extreme attention is paid or commercial test laboratories automate the data processing, the translation procedures (1 and 2) are more prone to human errors than the interpolation procedures (3 and 4). However, Procedures 1 and 2 would work extremely well if multiple narrow irradiance ranges are used with individual set of correction values for each narrow irradiance range or multiple/variable set of correction values are used for a single wide irradiance range.

REFERENCES

International Electrotechnical Commission. (2011). IEC 61853-1, *Photovoltaic (PV) module performance testing and energy rating*.

International Electrotechnical Commission. (2009). IEC 60891 (ed.2). *Photovoltaic devices—Procedures for temperature and irradiance corrections to measured I-V characteristics*.

Marion, B., Rummel, S., & Anderberg, A. (2004). Current-voltage curve translation by bilinear interpolation, *Progress in Photovoltaics, Res. Appl.* 12, 593-607.

Lad, R. (2010). Outdoor performance rating and spectral effects of photovoltaic modules. (Master's thesis). Arizona State University.

Paghasian, K. (2010). Power Rating of Photovoltaic Modules: Repeatability of Measurements and Validation of Translation Procedures. (Master's thesis). Arizona State University.

International Electrotechnical Commission. (2009) IEC 60904-10 (ed. 2). *Photovoltaic devices—Methods of linearity measurement*.

Herrmann, W. (2007). *The I-V curve translation: The new IEC 6891 draft*. European Performance Project Meeting, Freiburg, Germany.

APPENDIX

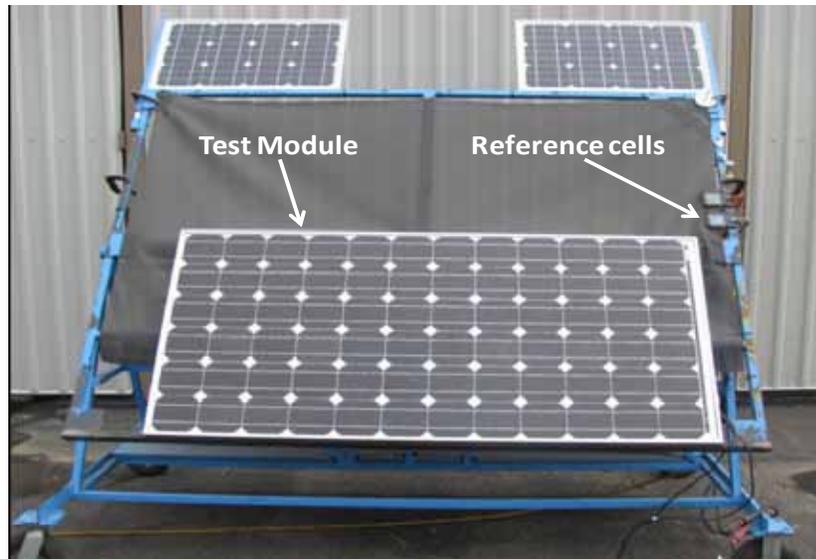


Figure A1. Outdoor performance measurements setup using a manual 2-axis tracker.

Screen Manufacturer: Phifer Incorporated Tuscaloosa Alabama	
Model Number of Manufacturers	Screen Designation of ASU
Sheer Weave (2100)	S-100
Shear Weave (3000)	S-200
Fiber Glass (20x20)	S-400
Fiber Glass (18x14)	S-600
Fiber Glass (Vent mesh)	S-800

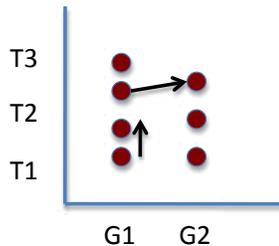


Figure A2. Mesh screens (100"x50") used in this investigation.

IEC 60891:Procedure 1

$$I_2 = I_1 + I_{sc} (G_1/G_2 - 1) + \alpha (T_2 - T_1)$$

$$V_2 = V_1 - R_s (I_2 - I_1) - \kappa I_2 (T_2 - T_1) + \beta (T_2 - T_1)$$



Procedures 1 and 2

Legend:

I_2, V_2 = Target current and voltage
 I_1, V_1 = Measured current and voltage
 G_2, T_2 = Target irradiance and temperature
 G_1, T_1 = Measured irradiance and temperature

Module Parameters:

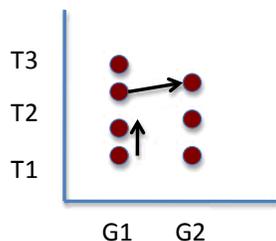
α = temp coeff I_{sc} (A/°C)
 β = temp coeff V_{oc} (V/°C)
 R_s = series resistance (Ω)
 κ = curve correction factor ($\Omega/^\circ\text{C}$)

NOTE: Temperature coefficients, series resistance and curve correction parameters are required for this procedure. The difference between the measured and target irradiances should be within 20%.

IEC 60891:Procedure 2

$$I_2 = I_1 * (1 + \alpha_{rel} * (T_2 - T_1)) * G_2/G_1$$

$$V_2 = V_1 + V_{oc1} * (\beta_{rel} * (T_2 - T_1) + a * \ln(G_2/G_1)) - R'_s * (I_2 - I_1) - \kappa' * I_2 * (T_2 - T_1)$$



Procedures 1 and 2

Legend:

I_2, V_2 = Target current and voltage
 I_1, V_1 = Measured current and voltage
 G_2, T_2 = Target irradiance and temperature
 G_1, T_1 = Measured irradiance and temperature

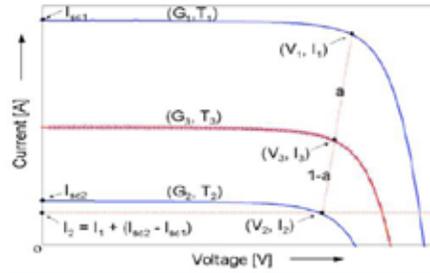
Parameter constants of module

α_{rel} = relative temp coeff I_{sc} (1/°C)
 β_{rel} = relative temp coeff V_{oc} (1/°C)
 R'_s = series resistance (Ω)
 κ' = curve correction factor ($\Omega/^\circ\text{C}$)
 a = Irradiance correction factor

NOTE: Temperature coefficients, series resistance and curve & irradiance correction parameters are required for this procedure. The difference between measured and target irradiances can be higher than 20%.

Figure A3. IEC 60891—Procedures 1 and 2.

IEC 60891: Procedure 3



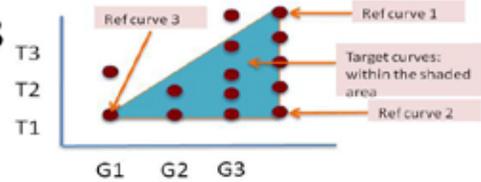
Irradiance Correction

$$V_3 = V_1 + a * (V_2 - V_1)$$

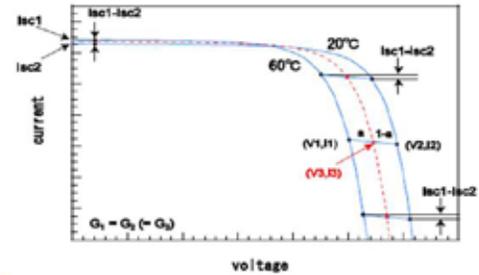
$$I_3 = I_1 + a * (I_2 - I_1)$$

NOTES: "a" is the constant for interpolation:
 $0 < a < 1$; The pair of (V_1, I_1) and (V_2, I_2) should be chosen such that: $I_2 = I_1 + (I_{sc2} - I_{sc1})$

Source: PV Performance Project Meeting (2007)



Procedure 3 (3 reference curves)



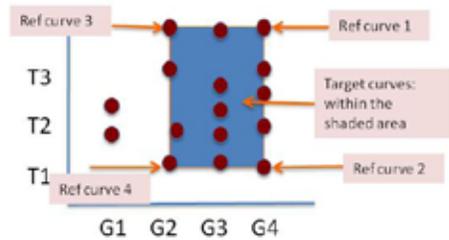
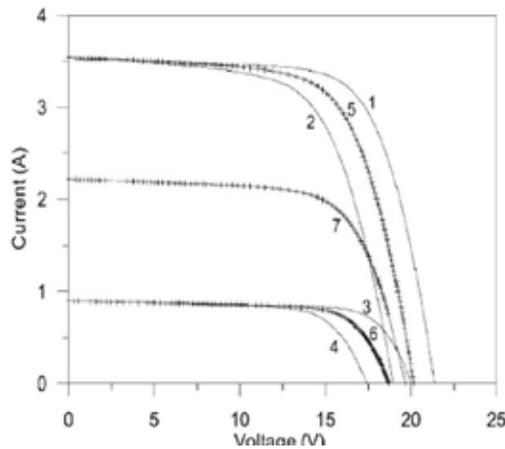
Temperature Correction

$$G_3 = G_1 + a * (G_2 - G_1)$$

$$T_3 = T_1 + a * (T_2 - T_1)$$

NREL: Procedure 4

Bilinear Interpolation



Procedure 4 (4 reference curves)

NREL method requires four measured reference I-V curves with conditions below:

$$G_1 = G_2 = G_H, G_3 = G_4 = G_L$$

$$T_1 = T_3 = T_L, T_2 = T_4 = T_H$$

With

G_H = higher irradiances

G_L = low irradiances

T_H = high temperatures

T_L = low temperatures

Figure A4. IEC 60891 Procedure 3 and NREL Method Procedure 4.

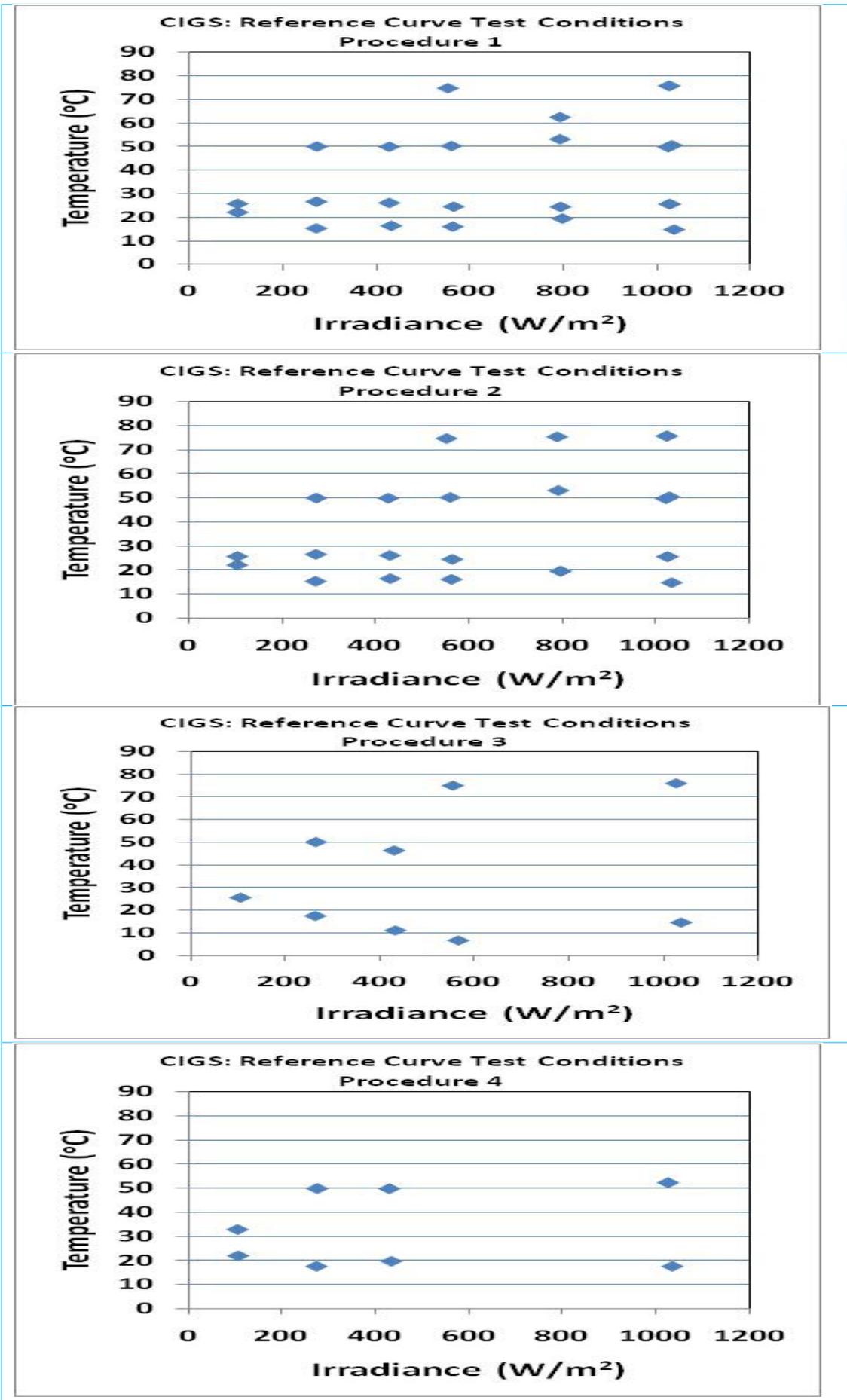


Figure A5. Test conditions to obtain reference curves—CIGS.

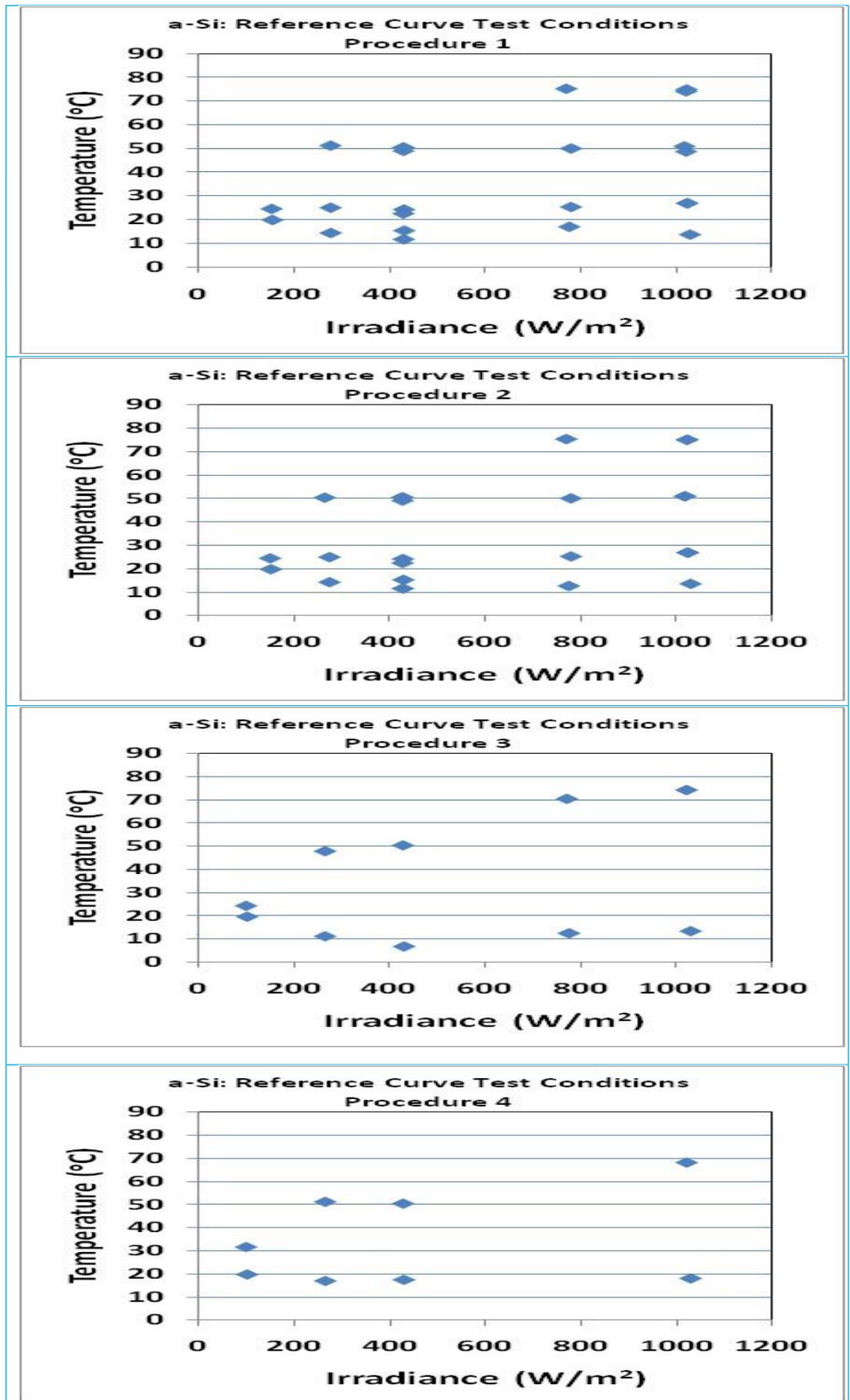


Figure A6. Test conditions to obtain reference curves—*a-Si*.

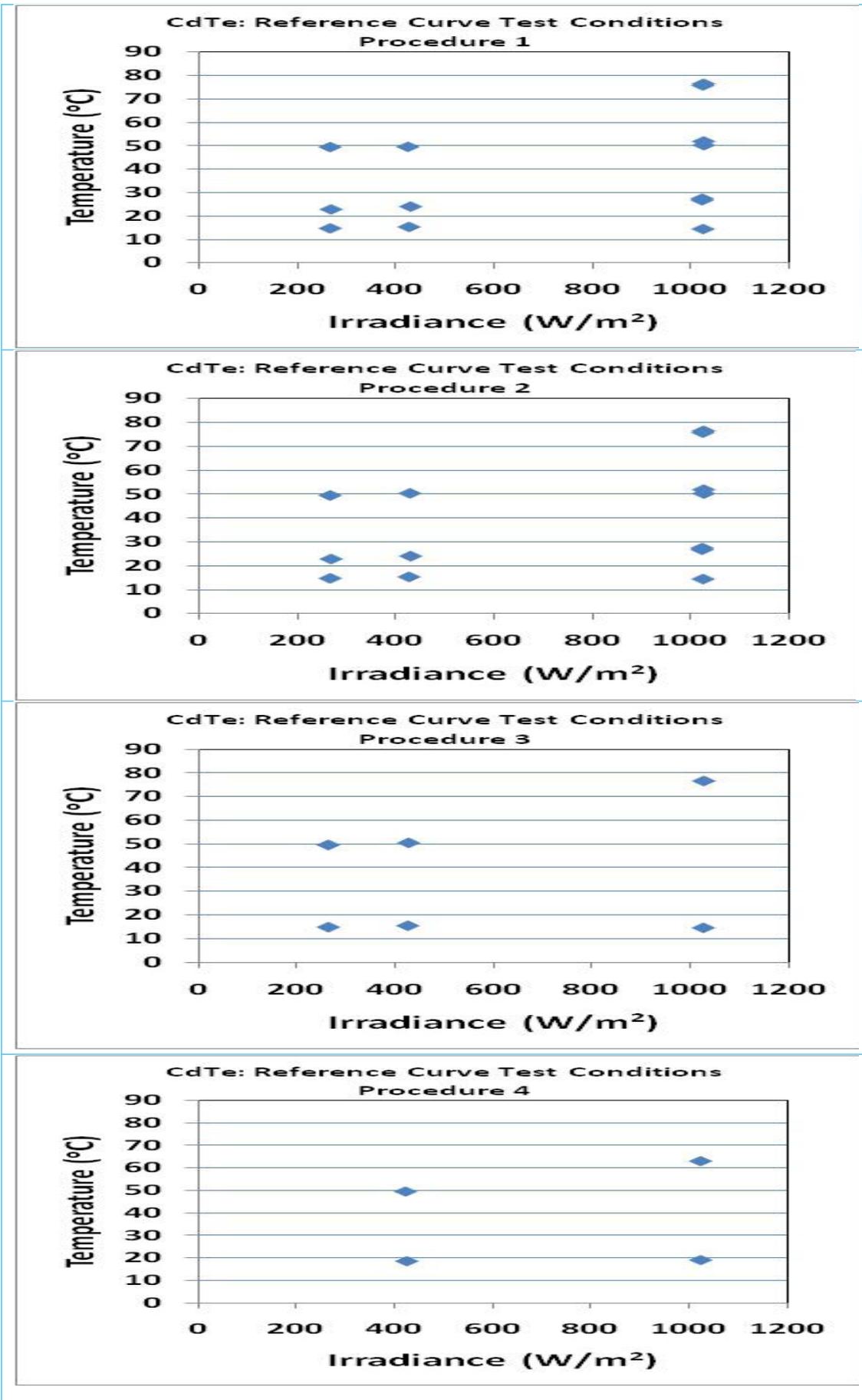


Figure A7. Test conditions to obtain reference curves—CdTe.

TABLE A1

Temperature Coefficients of All Four Technologies at Each Specific Irradiance Level

Technology	Irradiance (Approximate)	I_{sc} (A/°C)	V_{oc} (V/°C)	I_{max} (A/°C)	V_{max} (V/°C)	P_{max} (W/°C)
Mono-Si	1000	0.0021	-0.1667	-0.0009	-0.1744	-0.8230
	800	0.0024	-0.1671	0.0004	-0.1763	-0.6264
	600	0.0019	-0.1669	0.0000	-0.1673	-0.4627
	400	0.0005	-0.1727	-0.0002	-0.1793	-0.3378
	200	-0.0004	-0.1798	-0.0007	-0.1719	-0.1768
	100	0.0015	-0.1781	0.0012	-0.1724	-0.0382
a-Si	1000	0.0008	-0.4182	0.0008	-0.2133	-0.0745
	800	0.0005	-0.4170	0.0004	-0.2140	-0.0740
	600	0.0005	-0.4027	0.0004	-0.2203	-0.0490
	400	0.0002	-0.4015	0.0005	-0.2839	-0.0390
	200	0.0000	-0.3774	0.0000	-0.2022	-0.0212
	100	0.0000	-0.3671	0.0002	-0.3506	-0.0087
CIGS	1000	0.0004	-0.0912	0.0035	0.0193	0.0876
	800	-0.0003	-0.0923	0.0025	0.0334	0.0898
	600	-0.0001	-0.0978	0.0007	0.0190	0.0352
	400	-0.0003	-0.0993	0.0002	0.0057	0.0082
	200	-0.0010	-0.1075	-0.0007	-0.0077	-0.0140
	100	-0.0001	-0.1093	-0.0002	-0.0190	-0.0073
CdTe	1000	0.0008	-0.1222	-0.0001	-0.0590	-0.0914
	800	0.0001	-0.1341	0.0000	-0.0576	-0.0190
	600	0.0001	-0.1406	0.0000	-0.0576	-0.0182
	400	-0.0003	-0.1578	-0.0003	-0.0634	-0.0341
	200	0.0006	-0.1982	0.0006	-0.1126	-0.0078
	100	0.0000	-0.2049	0.0000	-0.1198	-0.0189

TABLE A2

Linearity Checking of Test Modules As Per IEC 60904-10
 (the red highlighted data do not meet the linearity deviation limit)

CIGS	Linearity deviation for temperature (°C)						
	15	25	50	75			
Linearity deviation of I_{sc} for temperature at 15-75°C temperature range and a single irradiance of 1000 W/m ² (allowed limit: < 5%)	0.2%	-0.4%	0.6%	-0.2%			
Linearity deviation of V_{oc} for temperature at 15-75°C temperature range and a single irradiance of 1000 W/m ² (allowed limit: < 5%)	0.8%	-0.8%	-0.4%	0.4%			
Linearity deviation of P_{max} for temperature at 15-75°C temperature range and a single irradiance of 1000 W/m ² (allowed limit: < 5%)	0.0%	1.0%	-1.9%	1.0%			
CIGS	Linearity deviation for irradiance (W/m ²)						
	1100	1000	800	600	400	200	100
Linearity deviation of I_{sc} for irradiance at 100-1100 W/m ² irradiance range and a single temperature of 25°C (allowed limit: < 2%)	-2.0%	-3.0%*	-0.9%	0.4%	-3.0%*	-1.9%	-7.9%
Linearity deviation of V_{oc} for irradiance at 100-1100 W/m ² irradiance range and a single temperature of 25°C (allowed limit: < 5%)	8.1%**	-3.6%	-3.4%	-1.4%	-3.1%	3.5%	-0.2%
	* Seems to be a slight experimental/processing error as the device meets the linearity requirement at above 600 W/m ² and at 400 W/m ² ; ** Could be due to the series resistance issue of this device						

TABLE A3

Linearity Checking of Test Modules As Per IEC 60904-10
 (the red highlighted data do not meet the linearity deviation limit)

a-Si	Linearity deviation for temperature (°C)						
	15	25	50	75			
Linearity deviation of I_{sc} for temperature at 15-75°C temperature range and a single irradiance of 1000 W/m ² (allowed limit: < 5%)	0.7%	0.0%	1.9%	0.2%			
Linearity deviation of V_{oc} for temperature at 15-75°C temperature range and a single irradiance of 1000 W/m ² (allowed limit < 5%)	0.4%	-0.3%	-0.5%	0.4%			
Linearity deviation of P_{max} for temperature at 15-75°C temperature range and a single irradiance of 1000 W/m ² (allowed limit: < 5%)	1.1%	2.5%	-8.3% *	4.8%			
a-Si	Linearity Deviation for Irradiance (W/m2)						
	1100	1000	800	600	400	200	100
Linearity deviation of I_{sc} for irradiance at 100-1100 W/m ² irradiance range and a single temperature of 25°C (allowed limit: < 2%)	-2.2% **	-2.3% **	-0.5%	1.0%	-0.8%	-2.9%	-13.3%
Linearity deviation of V_{oc} for irradiance at 100-1100 W/m ² irradiance range and a single temperature of 25°C (allowed limit: < 5%)	3.9%	-4.5%	-2.0%	6.9% *	-3.9%	-3.5%	3.1%
* Seems to be an experimental error as the device meets the requirement at below 50°C and at 75°C or at below/above 600 W/m ² ; ** Neglected from deviation due to measurement uncertainty							

TABLE A4

Linearity Checking of Test Modules As Per IEC 60904-10
 (the red highlighted data do not meet the linearity deviation limit)

CdTe	Linearity Deviation for Temperature (°C)						
	15	25	50	75			
Linearity deviation of I_{sc} for temperature at 15-75°C temperature range and a single irradiance of 1000 W/m ² (allowed limit: < 5%)	-0.3%	0.0%	1.0%	-0.4%			
Linearity deviation of V_{oc} for temperature at 15-75°C temperature range and a single irradiance of 1000 W/m ² (allowed limit: < 5%)	0.6%	-1.0%	0.7%	-0.2%			
Linearity deviation of P_{max} for temperature at 15-75°C temperature range and a single irradiance of 1000 W/m ² (allowed limit: < 5%)	-3.3%	4.5%	-1.1%	-0.2%			
CdTe	Linearity Deviation for Irradiance (W/m ²)						
	1100	1000	800	600	400	200	100
Linearity deviation of I_{sc} for irradiance at 100-1100 W/m ² irradiance range and a single temperature of 25°C (allowed limit: < 2%)	-2.2%*	-2.6%*	NA	NA	-1.4%	-3.9%	NA
Linearity deviation of V_{oc} for irradiance at 100-1100 W/m ² irradiance range and a single temperature of 25°C (allowed limit: < 5%)	1.7%	-1.6%	NA	NA	-0.3%	0.3%	NA
* Neglected from deviation due to measurement uncertainty; NA = module broke during measurements							

ACRONYMS

ASTM	American Society for Testing and Materials (formerly the American Society for Testing and Materials)
AM	air mass
a-Si	amorphous silicon
CdTe	cadmium telluride
c-Si	crystalline silicon
CIGS	copper indium gallium diselenide
G	global
I_{sc}	short-circuit current
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
I-V	current-voltage
NREL	National Renewable Energy Laboratory Method
P_{max}	maximum power
PV	photovoltaic
RMSE	root mean square error
V_{max}	voltage at maximum power
V_{oc}	open circuit voltage



Solar America Board for Codes and Standards

www.solarabcs.org