INTER LABORATORY COMPARISON OF INDOOR PERFORMANCE TESTS ON CRYSTALLINE SILICON SOLAR PV MODULES

Lawrence Pratt[1], Manjunath Basappa Ayanna[1], Siyasanga May[1], Kittessa Roro[1],
Jacqui Crozier McCleland[2], and Qaphela Zikhali[3]

[1] CSIR, Meiring Naude Road, Pretoria, South Africa; Phone: +27 12 841 2055; E-Mail: lpratt@csir.co.za

[1] CSIR; E-mail: MBasappaAyanna@csir.co.za, SMay@csir.co.za, KRoro@csir.co.za

[2]PVinsight- Nelson Mandela University; E-mail: jcrozier@mandela.ac.za;

[3]ARTsolar; E-mail: qaphela@artsolar.net

Abstract

The paper presents results from an inter laboratory comparison (ILC) of crystalline silicon PV module performance measurements from three different institutions within South Africa. The analysis quantifies the differences in power, current, and voltage measurements and compares power to the stated uncertainties for the measurements. The paper also explains the basics of PV module performance measurements, the link to PV module nameplate ratings, and describes the sources of uncertainty in the measurements.

The results of the 2019 ILC I-V measurements among three South African institutions show differences of +/- 2.0% or less for maximum power measurements of crystalline PV modules, relative to the CSIR results. These differences are within the stated uncertainty for the measurements but greater than the +/- 0.5% differences among international reference labs reported in a 2017.

Keywords: inter laboratory comparison, round robin, IV curve, sun simulator, nameplate ratings

1. Introduction

Solar photovoltaic (PV) systems are rated according to nameplate power of the individual modules. Accurate measurements of PV module power is essential to accurate yield predictions and financial returns for any given PV project. This paper will describe the basics of PV module power measurements and share results from an inter laboratory comparison of three crystalline silicon modules.

In 2018, the CSIR commissioned a new indoor solar simulator with integrated thermal chamber for testing PV modules across a broad range of irradiance and temperature settings. In preparation for the ISO 17025 accreditation, the CSIR must conduct an inter laboratory comparison for PV module performance. The collection and reporting of results from an ILC require considerable resources, and the results should be valuable to the broader South African PV industry.

2. PV Module Performance Measurements

2.1. IEC Standards

The International Electrotechnical Commission (IEC) published the IEC 60904-1 standard for the “Measurement of photovoltaic current-voltage characteristics” in 2006, which defines the procedures for performance measurements under natural and artificial light. The IEC published nine additional standards under the IEC 60904 series on topics related to performance and characterization of the solar PV modules. The topics range from requirement for the measurement equipment to techniques for correcting measurement for spectral mismatch and temperature deviations.

2.2. The current – voltage curve

The IEC 60904-1 [1] describes the basic procedures for measurement of the current-voltage (IV) curve for cells and modules. The standard covers measurements under natural sunlight using a dual-axis tracker, a reference device, and a means to control the module temperature or by use of shade. An alternative approach to outdoor measurements of PV modules is described in the Sandia Array Performance Model which monitors the performance of PV modules on dual axis trackers over a period of one or two weeks and derives model coefficients from linear regression models [2].

The standard also describes I-V measurements using artificial sunlight from pulsed and steady state light sources that must meet the requirements described in IEC 60904-9 [3]. Methods for setting the irradiance on the test plane are critical to accurate measurements on PV modules. Three methods are described using reference devices which may be of different sizes than the device under test and reference modules that should be of the same size as the device under test. Considerations for temperature control, non-uniformity of irradiance, and high capacitance modules are also presented.

All measurement methods produce an I-V curve from which the maximum power is extracted. Fig. 1 shows an I-V curve for the ARTsolar module 18023-01 with key points identified.

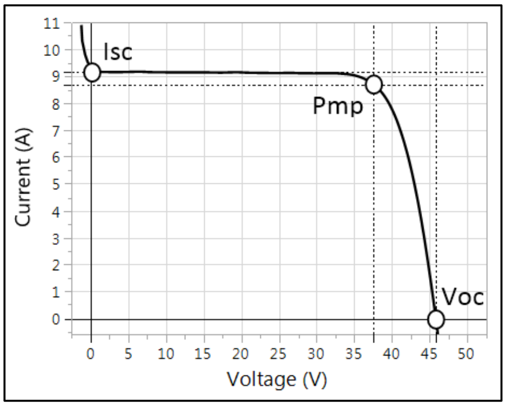


Fig. 1. I-V curve of ARTsolar module

The maximum power point (Pmp) is the point along the curve at which the product of current and voltage is maximized. Voltage at maximum power (Vmp) and current at maximum power (Imp) are then determined by the corresponding points along the voltage and current axes. Open-circuit voltage (Voc) and short-circuit current (Isc) are defined where the I-V curves crosses the voltage and current axes, respectively. The small portion of the I-V curve to the left of the current axis shows current flowing through the bypass diodes. Care must be taken to ensure the bypass diode current does not skew the estimate of Isc. Finally, the fill factor (FF) represents the ratio of two rectangles defined by the dotted lines with the bottom left coordinates at the origin (0,0) and the top right coordinates at the intersection of Imp and Vmp (Pmp) and the intersection of Isc and Voc, respectively.

2.3. Module nameplate ratings

Module nameplate ratings are fixed to each module before it leaves the PV module factory. The nameplate ratings represent the electrical characteristics of a class of modules, not the I-V characteristics of the specific module as stated on the nameplate. The nameplate ratings include the following: maximum power (Pmp), voltage at open circuit (Voc), voltage at maximum power (Vmp), current at short circuit (Isc), and current at maximum power (Imp). Fig. 2 shows the nameplate label from the ARTsolar module measured as part of this ILC.

18023–01

ARTsolar™
LOCAL | POWERFUL | GUARANTEED

ART320-72
320Wp

Current		Voltage	
Short Circuit	9.50A	Open Circuit	46.0V
Max Power	8.53A	Max Power	37.5V
Reversed	16.0A	Max System(DC)	1000V

Connectors	MC4	Dimensions 1956x992x40mm	
Weight	21Kg	SA201712071770	

Einnova Solarline

Product of RSA

ARTsolar (Pty) Ltd. Unit 11 124 Escom Rd, New Germany, South Africa. Conditions tested at 1000W/m2 and 25℃ with 5% tolerance. Read manual before installation, servicing or operating. Non-standard mounting methods, removing the frame, junction box, or connectors will result in loss of warranty.

Danger High Voltage!
Do not connect or disconnect under load.
Multiple modules produce lethal voltage.

www.artsolar.net

Fig. 2. ARTsolar nameplate

The power rating on each module is determined by the binning strategy of the manufacturer. ARTsolar declared a “5% tolerance” on the actual Pmp of the 320 W module sold the label shown in Fig. 2. Other manufacturers may bin on maximum power with a tolerance of “+/- 5 W”, for example, so that a large batch of modules should have an average power output equal to the Pmp on the nameplate label. Others may adopt a positive binning strategy of so that the minimum output from a large batch would be equal to the nameplate rating. In 2018, researchers at ESTI published an interesting paper showing trends in the difference between measured Pmax and nameplate ratings with the difference decreasing over the period from 1982 to 2014 [4]. Nameplate ratings are based on binning strategy and the condition of the factory test equipment at the time of binning. There are many factors that can impact the performance measurement of a module and the associated uncertainty of the measurement.

2.4. Sources of Uncertainty

The IEC 60904-1 standard also provides some guidance for minimizing the measurement uncertainty of the IV curve. The quality and intensity of the irradiance is critical to determine PV module current output. Temperature control of the reference device and the device under test is critical to determine the PV module voltage output.

The European Solar Test Institute (ESTI) provided technical assistance to the CSIR for estimating the measurement uncertainty for the HALM sun simulator. The components of measurement uncertainty are described in detail by researchers from ESTI [5].

The CSIR adopted the ESTI method to enumerate and quantify the components of overall uncertainty in the measurement. There are five groups of components: temperature, reference device, optical, fill factor, and electrical. The standard deviation of each component is estimated individually, and then each component is combined for the relevant subgroup. The root-mean-sum-of-squares (RMSE) is used to combine the squared value of each component within subgroup and then take the square root again to get back to estimates of the standard deviation. Each subgroup is then combined using RMSE to derive a combined uncertainty estimate for Isc, Voc, Pmp, and Fill Factor.

Fig. 3 shows the individual components and subgroups of measurement uncertainty for the HALM at the CSIR. Components with large standard deviations (stddev) have greater impact on the overall uncertainty than components with smaller standard deviations. The spectral mismatch and non-uniformity of irradiance are major drivers for the combined uncertainty estimate.

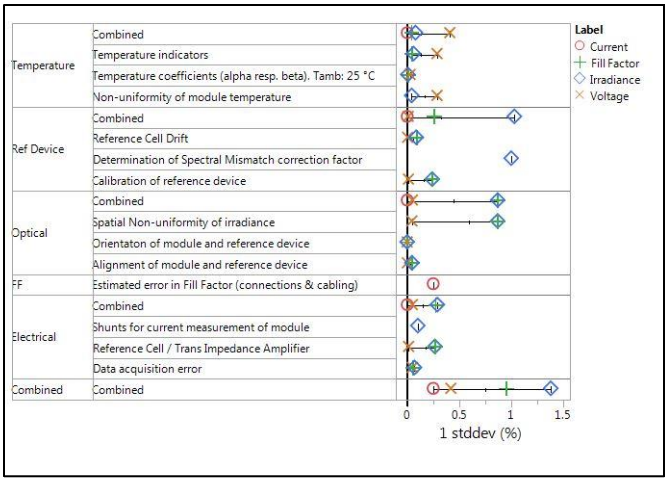


Fig. 3. Components of measurement uncertainty for the HALM

Table 1 shows the absolute uncertainty of measurement for each of the simulators participating in the ILC. The estimated uncertainties for Pmp are similar for each piece of equipment. The LED based simulator has a lower uncertainty for Isc and a higher estimate for Voc compared to the two Xenon based systems. In all cases, the uncertainty for Isc is the largest source of uncertainty for the measurement of Pmp. All values in Table 1 report a coverage factor of k=2. The combined estimates of uncertainty described above results in an estimate of one standard deviation, so k=2 is an estimate of two (2) standard deviations. The k=2 coverage factor doubles the width of the interval and therefore increases the confidence that the wider interval contains the true value for Pmp. The Gaussian probability distribution provides some intuition for the increased confidence associated with the wider interval. Under a Gaussian distribution, 67% of the area lies within one (1) standard deviation of the mean and 95% of the area lies within two (2) standard deviations. Thus, the k=2 coverage factor is interpreted as a 95% prediction interval for the true value.

Term	HALM Xenon	NMU-PVI Xenon	NMU-PVI LED	ART
Isc	+/- 2.8	+/- 2.4	+/- 2.0	TBD
Voc	+/- 0.84	+/- 1.1	+/- 1.7	TBD
FF	+/- 0.5	+/- .5	+/- .5	TBD
Pmp	+/- 3.0	+/- 2.8	+/- 3.0	TBD

Table 1. Absolute measurement uncertainties, k=2

2.5. 2017 International Round Robin

Inter-laboratory comparisons are common in the PV industry. The comparisons provide a means for labs to check one another and validate the uncertainty of measurements. A recent ILC of reference labs across the northern hemisphere reported a difference of +/-0.5% for Pmp of crystalline silicon modules [6]. Reference labs have the highest standards of measurements, as they are also responsible for providing reference cells and reference modules to test institutions in South African and the rest of the world. The results from the international ILC provides a benchmark for comparison of the ILC results presented in this paper.

3. Experimental design

3.1. Participating Labs and Equipment

Two South African and two European institutions were recruited to participate in the inter-laboratory comparison (ILC). ARTsolar is a PV module manufacturer and testing facility based in Durban. The Photovoltaics Testing Laboratory at Nelson Mandela University, (trading as PVinsight) is a SANAS ISO 17025:2017 accredited PV test lab based in Port Elizabeth. The European Solar Test Institute (ESTI) is a reference laboratory for calibration of PV reference devices based in Italy. TUV Rheinland is a multi-disciplinary company, including solar PV testing and certification services, based in Germany with offices throughout South Africa.

Due to unforeseen complications at ESTI, the European measurements will not be included in this report as anticipated. We do plan to present the international results when the data become available.

3.2. Methodology

Two sets of modules were used for this ILC. One set of modules was used for the domestic round of testing and another set of modules was used for the European round of testing. The 'hub and spoke' approach to ILC is effective at reducing shipping costs and timelines, as both legs of the testing can be done in parallel. However, not all modules are measured at all sites. All modules were measured at the CSIR, and the CSIR measured values were used for the reference values when comparing the results of other participants.

Three crystalline silicon modules were measured for the ILC among South African institutions. One 60 cell multi-crystalline module from ARTsolar was measured at ARTsolar in February 2018 on a Pasan sun simulator. The same module was measured at the CSIR in October 2018 and again in August 2019 on the HALM. One 60 cell and one 72 cell modules were measured at PVinsight in March 2019 and at the CSIR July 2019. PVinsights measured both modules on two separate systems: the Optosolar sun simulator with a xenon lamp and the MBJ mobile tester with LED light.

Table 2 shows key characteristics of the indoor sun simulators used at the three South African institutions. The class indicates the quality of sun simulator per the IEC 60904-9 standard. The standard defines the criteria for Class A, B, and C grades, and the industry has adopted the use of 'A+' for metrics that are at least twice as good as Class A. In order, the letters refer to the quality of light for spectral matching, spatial non-uniformity of irradiance, and temporal stability. The Pmp absolute uncertainty was taken from Table 1 above. The Pmp relative uncertainty describes the repeatability of measurement within a lab, excluding all the bias terms that contribute to the absolute uncertainty of measurement. The relative uncertainty is estimated from day to day measurements of the same module over a period of weeks or months.

Name	Class	Light Source	Pmp abs. uncertainty	Pmp rel. uncertainty
CSIR	A+ A+ A+	Xenon	+/- 3.0 %	+/- 0.5%
PVI	AAA	Xenon	+/- 2.8 %	+/- 0.5%
PVI	A+ A+ A+	LED	+/- 3.0 %	+/- 0.2%
ART	Pasan - TBD	Xenon	TBD	TBD

Table 2. Characteristics of South African sun simulators

Fig. 4 shows data related to the spectral quality of the HALM sun simulator light source. The spectral distribution of the HALM sun simulator (orange) and the ASTM G173-03 reference spectrum (blue) are presented. Ideally, the spectrum of the indoor light source matches exactly that outdoor spectrum, but this is never the case. The HALM uses a Xenon arc lamp as the light source, and other Xenon based sun simulators will have a similar spectrum. The xenon spectrum matches the shape of the reference spectrum reasonably well up to 1100 nm, however the variability of the xenon spectrum increases above 700 nm.

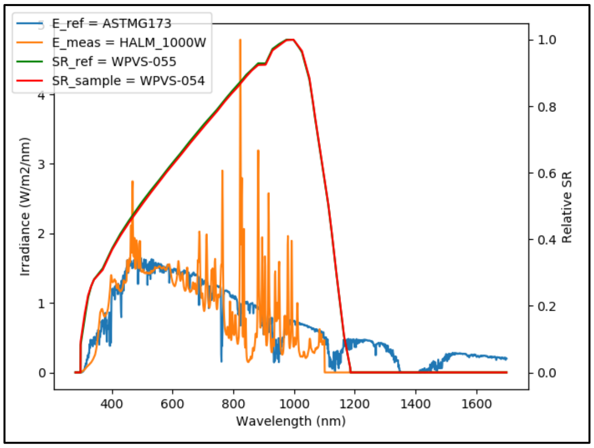


Fig. 4. Spectral distribution of the HALM (orange) and the ASTM G173 reference spectrum (blue). Relative spectral responds of the two difference c-si reference cells (red, green).

Fig. 4 also includes the relative spectral response of two crystalline silicon reference cells. The spectral response measures the current output of the cell at a given wavelength relative to the power of the light incident on the cell at that wavelength. The spectral response of the silicon cell reaches peak output near the bandgap of silicon at 1.12 eV. A silicon reference cell is used to set the irradiance of the HALM when measuring silicon modules. The matched spectral response between the reference cell and the device under test compensates for the mismatch in the xenon spectrum and the reference spectrum. When the spectral response of the reference cell is different from that of the device under test, a spectral mismatch correction is required for accurate measurements of the current generated by the device under test. Spectral mismatch corrections will not be covered in this paper.

Fig. 5 shows the spectral distribution of the LED based sun simulator at the NMU-PVI lab. The ASTM reference spectrum is shown in red and the LED light source in black. Both the xenon spectrum shown in Fig. 4 and the LED based light source vary significantly from the reference spectrum at any given wavelength. The IEC 60906-9 rating for Class A, however, is based on integrated irradiance over six intervals of 100 nm and 200 nm bins. The percentage of total irradiance in any bin must be within 25% of target for each bin. For example, 18.4% (+/- 25%) of total irradiance from the light source must be in the range of 400-500 nm. All remaining bins must also meet the target (+/- 25%) to be rated Class A. By convention, Class A+ must meet target (+/-12.5%) for all six intervals.

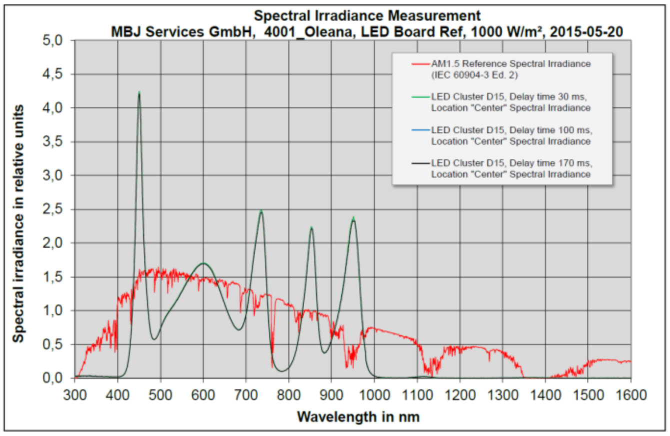
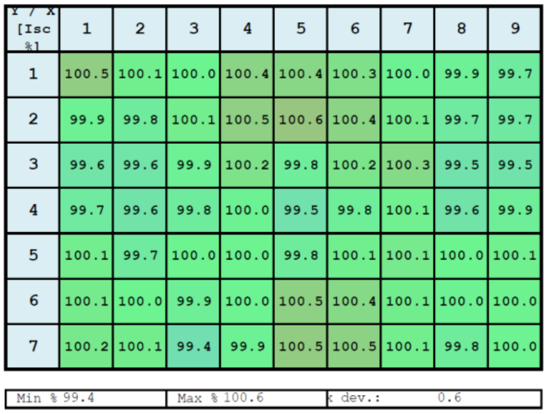


Fig. 5. Spectral distribution of the MBJ LED based sun simulator

Fig. 6 shows the non-uniformity of irradiance for the CSIR sun simulator. Each square represents the relative irradiance as measured by a standard silicon cell of dimensions 156 mm x 156 mm. The cell is moved around in a 9 x 7 grid, measured, and corrected relative to the irradiance as measured in a fixed position. The non-uniformity of irradiance is then calculated per the IEC 60690-09 as (max – min) / (max + min). A class 'A' sun simulator must have non-uniformity of irradiance less than 2% per the standard, and by convention a Class A+ must have non-uniformity of irradiance less than 1%. In the figure shown below, the non-uniformity of irradiance is (100.6 – 99.4) / (100.6 + 99.6) = 0.006 = 0.6%.



Y / X [Isc %]	1	2	3	4	5	6	7	8	9
1	100.5	100.1	100.0	100.4	100.4	100.3	100.0	99.9	99.7
2	99.9	99.8	100.1	100.5	100.6	100.4	100.1	99.7	99.7
3	99.6	99.6	99.9	100.2	99.8	100.2	100.3	99.5	99.5
4	99.7	99.6	99.8	100.0	99.5	99.8	100.1	99.6	99.9
5	100.1	99.7	100.0	100.0	99.8	100.1	100.1	100.0	100.1
6	100.1	100.0	99.9	100.0	100.5	100.4	100.1	100.0	100.0
7	100.2	100.1	99.4	99.9	100.5	100.5	100.1	99.8	100.0

Min % 99.4	Max % 100.6	dev.: 0.6

Fig. 6. CSIR HALM non-uniformity of irradiance

Fig. 7 shows the trend of Pmp normalized for two control modules over ten months at the CSIR. The values are normalized to the average values as measured over the first two weeks. Each day before a measurement session begins, two control modules are measured and compared against the normalized historical data to ensure the system is stable. The trend shows reference lines for the relative measurement uncertainty (+/- 0.5%) and the absolute measurement uncertainty (+/- 3.0%) The repeatability of measurement is well within the absolute uncertainty of measurement and stable over the course of the ILC study. Stability of measurement is important for accuracy and repeatability of measurement. The CSIR also conducts reliability stress testing of PV modules, so stability of measurement is essential to assess the degradation before and after stress tests.

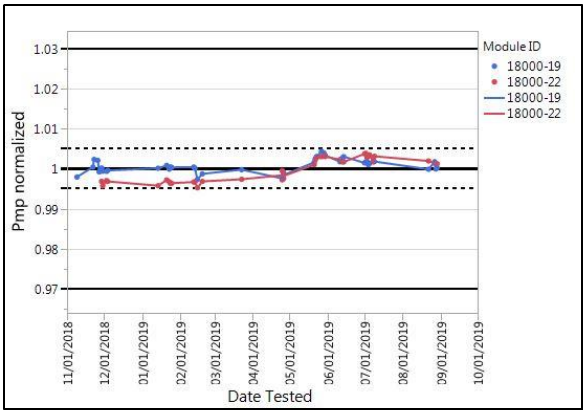


Fig. 7. Trend of Pmp normalized for two control modules

4. Experimental Results

Fig. 8 shows the measured differences between CSIR and ARTsolar on one module, relative to the CSIR average. ARTsolar sent one module to the CSIR in February of 2018 to assist with the commissioning of the new sun simulator at the CSIR, which was completed in August 2018. In October 2018, the module was measured at the CSIR over four consecutive days, after standard operating procedures were in place. The CSIR measured the same module again over two consecutive days in August 2019. The plot shows six summary values from the I-V curves relative to the CSIR average values. The one outlier measured at the CSIR was from 07 August 2019. The Pmp measured 1.6% higher at ARTsolar compared to the CSIR average, correlating primarily to the difference in voltage at maximum power (Vmp).

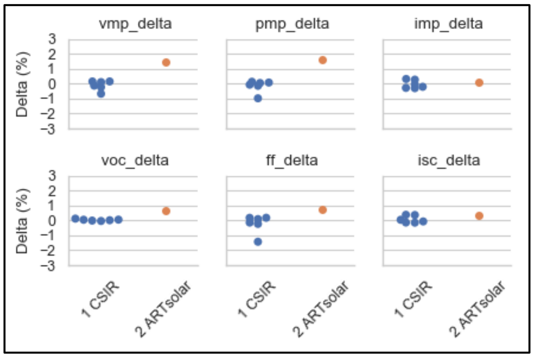


Fig. 8. CSIR – ARTsolar differences in I-V characteristics as measured on one module

Fig. 9 shows the measured differences between CSIR and PVinsight, relative to the CSIR. In this comparison, two different modules were measured on three different systems: CSIR HALM, PVinsight Optosolar with xenon light source, and PVinsight MBJ with LED light source. In this case, the module Pmp measured 1-2% lower on the Optosolar system and 1-2.5% lower on the MBJ system, relative to the measurements at CSIR. The difference in Pmp correlates primarily to the difference in current at maximum power (Imp) as measured on both PVinsight systems.

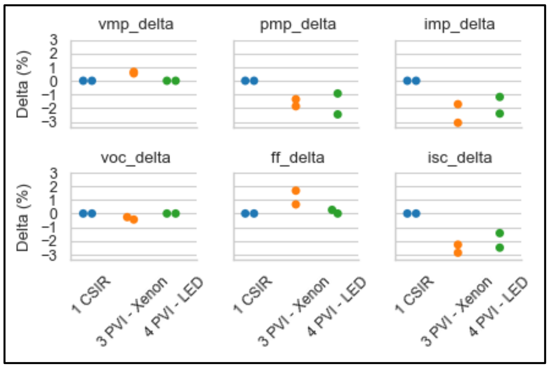


Fig. 9. CSIR – PVinsight differences in I-V characteristics as measured on two modules

5. Conclusion

The results of the 2019 ILC of I-V measurements among three South African institutions was concluded on three crystalline silicon PV modules. The range in measured Pmp was 4%, or +/- 2.0%. The difference in Pmp measurements between the CSIR and ARTsolar was driven by differences in voltage. The difference between CSIR and PVinsight was driven by current.

Acknowledgements

The CSIR acknowledges ARTsolar and Nelson Mandela University-PVinsight for contributing modules and I-V measurement data to this ILC. The CSIR also acknowledges support from Tony Sample at the ESTI for calibration of three WPVS reference cells and for guidance in the calculation of measurement uncertainty.

References

[1] “IEC 60904-01 Measurement of photovoltaic current-voltage characteristics (eng-french).pdf.” .
[2] B. H. King, C. W. Hansen, D. Riley, C. D. Robinson, and L. Pratt, “Procedure to Determine Coefficients for the Sandia Array Performance Model (SAPM),” SAND2016-5284, 1256510, Jun. 2016.
[3] “IEC 60904-09 Solar simulator performance requirements (eng-french).pdf.” .
[4] J. Lopez-Garcia and T. Sample, “Evolution of measured module characteristics versus labelled module characteristics of crystalline silicon based PV modules,” *Solar Energy*, vol. 160, pp. 252–259, Jan. 2018.
[5] H. Müllejans, W. Zaaiman, and R. Galleano, “Analysis and mitigation of measurement uncertainties in the traceability chain for the calibration of photovoltaic devices,” *Measurement Science and Technology*, vol. 20, no. 7, p. 075101, Jul. 2009.
[6] E. Salis *et al.*, “Improvements in world-wide intercomparison of PV module calibration,” *Solar Energy*, vol. 155, pp. 1451–1461, Oct. 2017.