NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Improvements in Module Calibration and Their Impact on World-Wide Intercomparisons

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Dean Levi 2018 PV Systems Symposium Albuquerque, NM May 1, 2018

Outline

- **2011-2012 world wide inter-comparison**
- **Advances in NREL measurement methods**
- **2015-2017 world wide inter-comparison**

Overview: 2011-12 Worldwide Inter-Comparison

Participating Calibration labs

Fraunhofer Institute for Solar Energy Systems ISE
European Commission–Joint Research Centre, European Solar Test Installation (ESTI)
National Renewable Energy Laboratory (NREL)
National Institute of Advanced Industrial Science and Technology (AIST)

Why Compare calibration labs?

- Calibration laboratories provide traceable module calibrations that are used to determine Pmax
- Pmax under standard test conditions (STC) is the price-setting quantity for PV modules
- Lower uncertainties and consistency of measurements reduces financial uncertainty = reduced cost
- Thus, good worldwide comparability of measurements is required in a global PV market.
- Intercomparisons help to establish best practices, contributing to better agreement, and to standards

Progress in photovoltaic module calibration: results of a worldwide intercomparison between four reference laboratories, D Dirnberger, U Kräling, H Müllejans, E Salis, K Emery, Y Hishikawa and K Kiefer. , Meas. Sci. Technol. 25 (2014) 105005 (17pp), DOI 1Q: 10.1088/0957-0233/25/10/105005/

Overview: 2011-12 Worldwide Inter-Comparison

Modules tested for inter-comparison

Table 1. PV modules calibrated within the comparison. Electrical parameters are the calculated weighted mean of all laboratories. M1, M2 and M3 were stabilized (operation at V_{OC}) for roughly 20 kWh prior to the intercomparison, M4, M6 and M7 for 112 kWh. M5 was not light soaked.

Sample ID	Technology	Size in m^2	Cells	I_{SC} in A	V_{OC} in V	P_{MPP} in W	FF in %
M1	High eff.	1.610 × 0.860	Honeycomb	7.355	43.30	239.8	75.30
M2	Poly c-Si	1.970 × 0.990	72 / 6 inch	8.286	44.29	272.9	74.34
M3	Poly c-Si	0.771 × 0.665	36 / 6 inch	3.936	21.74	64.6	75.69
M4	a-Si single	1.300 × 1.100	106 / stripes	1.480	93.98	90.7	65.32
M5	CdTe	1.200 × 0.600	116 / stripes	1.206	93.04	76.3	67.25
M6	a-Si/μ-Si	1.408 × 1.008	180 / stripes	3.299	59.63	121.0	62.45
M7	a-Si/a-Si	1.308 × 1.108	56 / stripes	6.758	24.18	108.3	66.37

Traceability chains for each lab

	NREL	ESTI	AIST	CalLab PV Modules
Electrical	NIST via in-house	UKAS via in-house	AIST traceable	DAkkS
Temperature	NIST via in-house	UKAS via in-house	AIST traceable	DAkkS
Reference cell	NREL (via in-house, WRR for cavity radiometer)	SI units and WRR via in-house	SI units and WRR	PTB (SI units)
Spectral irradiance	NIST lamps, in-house calibration	NPL via in-house	AIST lamps	PTB via in-house calibration
Spectral response	NIST (in-house, NIST calibrated detectors)	PTB via in-house	Electrically calibrated pyroelectric detector (NIST), standard detectors (AIST)	DAkkS via CalLab PV cells

NIST—National Institute of Standards and Technology, US; UKAS—United Kingdom Accreditation Service; DAkkS—Deutsche Akkreditierungsstelle, Germany's national accreditation body; PTB—Physikalisch-Technische Bundesanstalt, Germany's NMI; WRR—World Radiometric Reference [37]; NPL—National Physical Laboratory, UK's National Metrology Institute (NMI)

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2011-2012 Inter-comparison: Measurement Methods

Measurement methods applied at each lab

Table 3. Information on measurement and evaluation methods of all participants.

	NREL	ESTI	AIST	ISE/CalLab
Light source	Continuous	Natural sunlight	Long-pulse xenon lamps	Pulsed xenon lamp
Spectrum	Fixed	Close to AM1.5 G but variable	Adjustable at 13 wavelength bands	Fixed
Pulse width	Not applicable	Not applicable	100– 1000 ms	10 ms
Maximum measurement time	3 s (variable)	1 s with typically 900 ms between I_{SC} and V_{OC}	800 ms	180 ms
IV sweep	Hysteresis check, T and V_{OC} measured before and after IV. Sweep forward to reverse bias	Single linear voltage sweep from I_{SC} to V_{OC}	Single linear voltage sweep with hysteresis check ($I_{SC} \rightarrow V_{OC}$ and $V_{OC} \rightarrow I_{SC}$) at various sweep speed	Hysteresis and section measurement, i.e. $I_{SC} \rightarrow V_{OC}$ and $V_{OC} \rightarrow I_{SC}$, sections
Temperature sensors	1 × Pt100 in center of module	1 × Pt100 in center of module behind cell	9 × Pt100	4 × Pt100
Correction methods	Mismatch correction prior to IV, no correction for T. Current corrected to constant intensity value (correction less than 2%)	Translation of IV curve to STC (IEC 60891, Ed. 2, $R_S = 0$) considering spectral mismatch (IEC 690904–7), no correction for temperature	Correction for irradiance (IEC60891 Ed. 2; correction less than 1%) considering spectral mismatch. No correction for temperature	Correction to STC according to (IEC60891, Ed. 2 k, $R_S = 0$)
Final result calculation	Single IV curve	Mean of 3 IV curves	Single IV curve	Mean of 3 IV curves

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2011-2012 Inter-comparison: Relative Uncertainties

Relative uncertainties for each lab and each measurand

Table 4. Relative uncertainty indicated per measurand and measurement object by the participating laboratories.

	I_{SC}	V_{OC}	P_{MPP}	FF		I_{SC}	V_{OC}	P_{MPP}	FF
NREL					ESTI				
M1	3.7%	1.2%	3.9%	1.2%	M1	1.3%	1.4%	2.0%	0.72%
M2	3.7%	1.2%	3.9%	1.2%	M2	1.3%	1.4%	2.0%	0.72%
M3	3.7%	1.2%	3.9%	1.2%	M3	1.3%	1.4%	2.0%	0.72%
M4	3.7%	1.2%	3.9%	1.2%	M4	1.3%	1.4%	2.0%	0.72%
M5	3.7%	1.2%	3.9%	1.2%	M5	1.3%	1.4%	2.0%	0.72%
M6	5.0%	2.0%	5.0%	5.0%	M6	1.3%	1.4%	2.8%	2.0%
M7	5.0%	2.0%	5.0%	5.0%	M7	1.3%	1.4%	2.8%	2.0%
AIST					CalLab				
M1	2.1%	0.3%	2.1%	1.1%	M1	1.7%	0.6%	2.2%	1.6%
M2	2.1%	0.3%	2.1%	1.1%	M2	1.3%	0.6%	1.6%	1.2%
M3	2.1%	0.3%	2.1%	1.1%	M3	1.3%	0.6%	1.6%	1.2%
M4	2.9%	0.3%	2.9%	1.0%	M4	1.4%	0.6%	1.8%	1.2%
M5	2.9%	0.3%	2.9%	1.0%	M5	2.5%	0.7%	2.9%	1.7%
M6	3.2%	0.3%	3.2%	3.2%	M6	5.1%	0.7%	5.5%	1.9%
M7	3.2%	0.3%	3.2%	3.2%	M7	6.1%	0.7%	6.4%	2.3%

k=2 (~95% coverage factor)

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2011-2012 Inter-comparison; results for c-Si modules

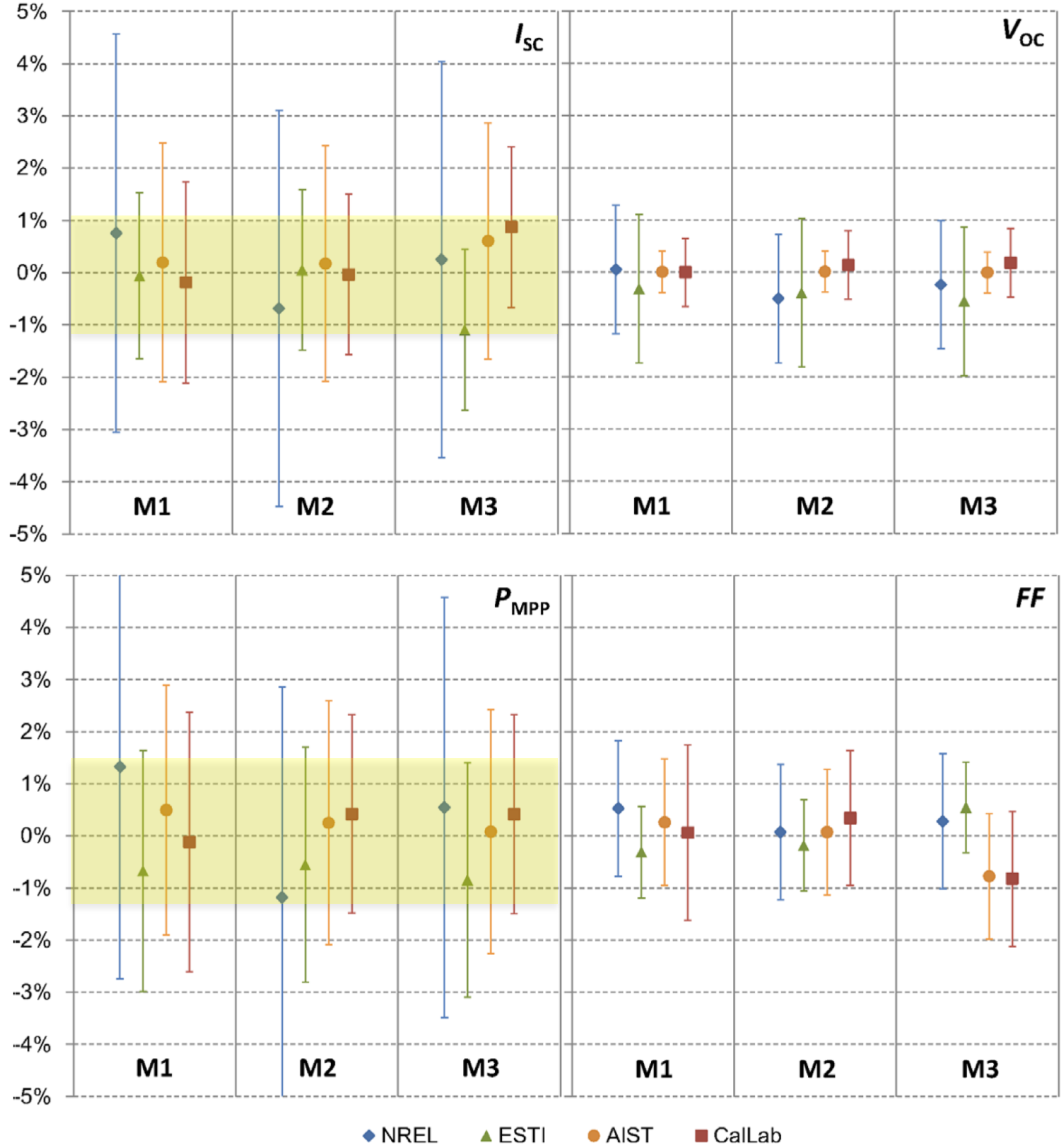
Expressed in terms of deviation from weighted average, scaled by uncertainty

$$\bar{x} = \frac{\sum_{i=1}^{n} w_i \, x_i}{\sum_{i=1}^{n} w_i} = \frac{\sum_{i=1}^{n} \frac{x_i}{\sigma_i^2}}{\sum_{i=1}^{n} \frac{1}{\sigma_i^2}}$$

with $w_i = \frac{1}{{\sigma_i}^2}$, and $\sigma_i = \frac{UC95\%(k=2)}{2}$.

Error bars crossing the x-axis within half their length indicate good agreement of the respective result with the weighted mean.

Error bars not crossing the x-axis indicate measurements with non-satisfying agreement.



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2011-2012 Inter-comparison; results for thin film modules

Expressed in terms of deviation from weighted average, scaled by uncertainty

$$\bar{x} = \frac{\sum_{i=1}^{n} w_i \, x_i}{\sum_{i=1}^{n} w_i} = \frac{\sum_{i=1}^{n} \frac{x_i}{\sigma_i^2}}{\sum_{i=1}^{n} \frac{1}{\sigma_i^2}}$$

$$\text{with } w_i = \frac{1}{\sigma_i{}^2}, \text{ and } \sigma_i = \frac{UC95\%(k=2)}{2}.$$

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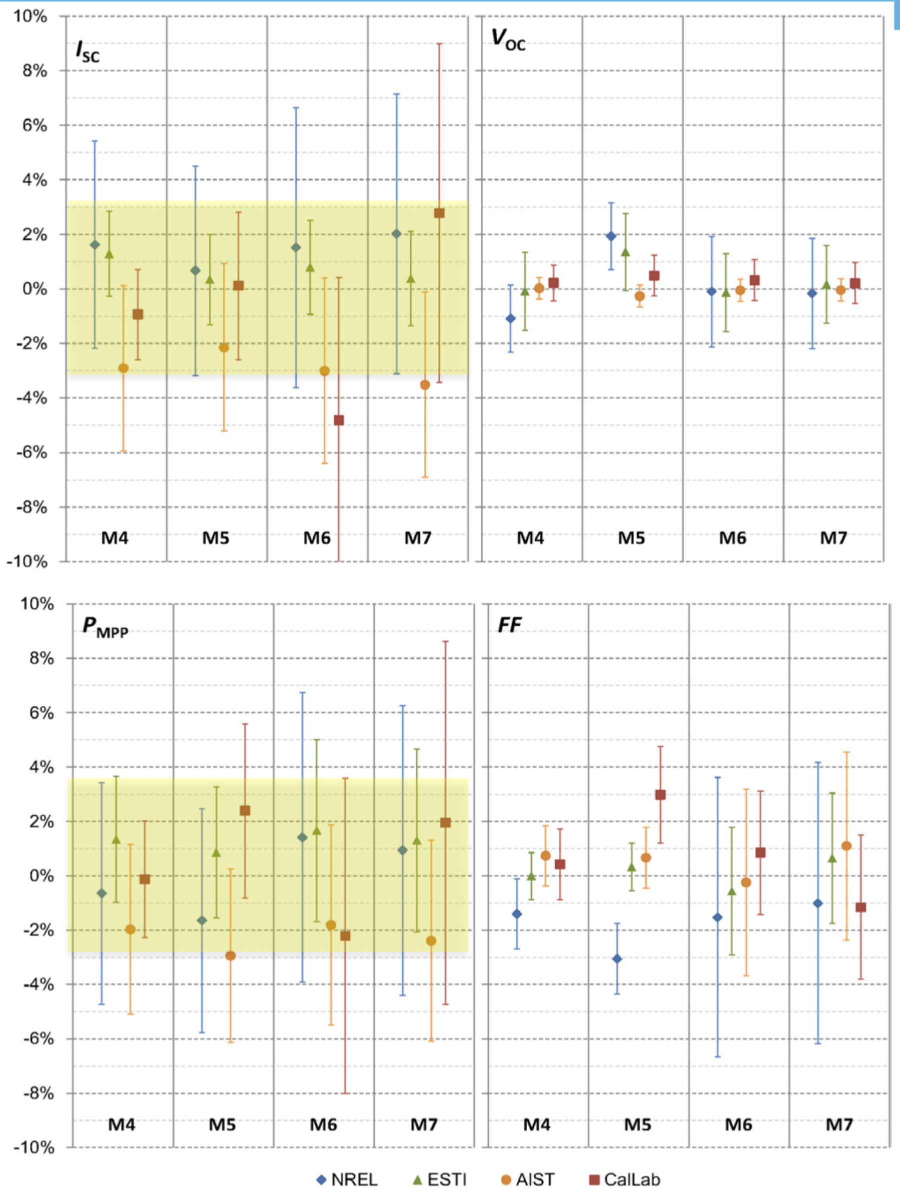

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Conclusions of 2011-2012 inter-comparison:

- The overall evaluation, based on accepted statistical methods, revealed that 98% of all z scores were smaller than 2
- The fact that 98% instead of the expected 95% of all scores are smaller than 2 indicates that the laboratories tend to slightly overestimate measurement uncertainty.
- Based on these results, it is expected that the uncertainty calculations can be revised and lead to slightly smaller uncertainty values for future measurements.

Outline

- **2011-2012 world wide inter-comparison**
- **Advances in NREL measurement methods**
- **2016-2017 world wide inter-comparison**

NREL module test lab

Measurements are performed on 3 Different Module Test Beds

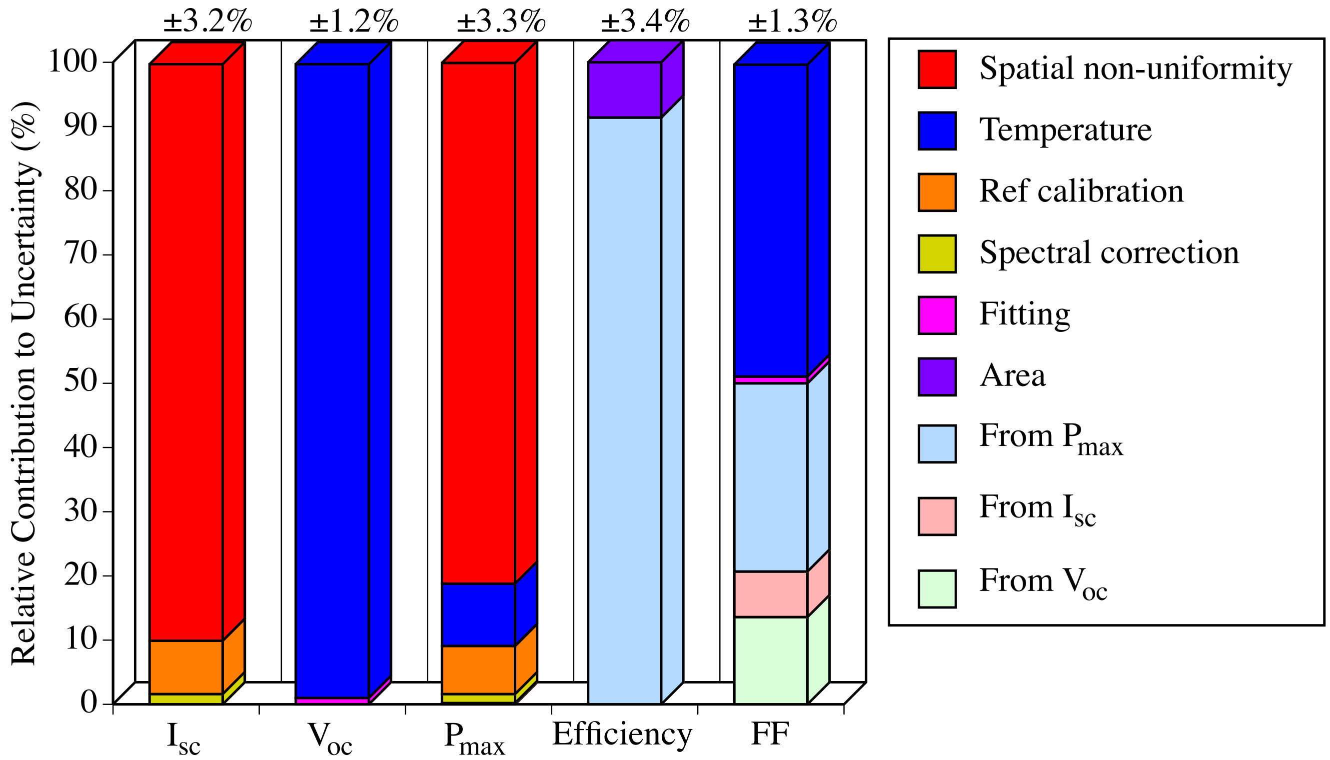
- Spire 5600 flash simulator
- Outdoor test bed using natural sunlight
- Spectrolab X200 large area continuous simulator

Test bed strengths and weaknesses

Test Bed	Strength	Weakness
Spire 5600 Flash Simulator	Minimal module heating due to its 100 ms flash duration, which enables accurate measurement of voltage in thermal equilibrium at 25°C	Short flash can distort I-V curve when measuring high capacitance modules
Outdoor Ted Bed	Natural sunlight is highly uniform, providing minimal uncertainty in I_{SC}	Irradiance is rarely at exactly 1000 W/m^2, requiring scaling of I-V curve, which introduces undesirable uncertainties
Spectrolab X200 Continuous Simulator	Continuous light source at 1000 W/m^2 enables accurate measurement of I-V curve	Spatial non-uniformity of ± 3.0% directly contributes to large I_{SC} uncertainty

Self-Reference Procedure to Reduce Uncertainty in Module Calibration, D.H. Levi, C.R. Osterwald, S. Rummel, L. Ottoson, A. Anderberg, Proceedings 44th IEEE PVSC, Washington, DC, 2017.

Uncertainty factors for X200 large area continuous simulator



- Spatial non-uniformity of this simulator for modules > 0.9 m^2 in area is ± 3.0%, (dominates uncertainty in both Isc and Pmax)
- Temperature uncertainty of ± 2.0C dominates Voc uncertainty
- Efficiency and fill factor are derived parameters with uncertainties dominated by Isc, Voc, and Pmax.

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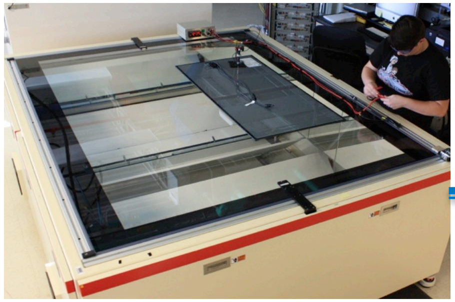
Module Self-Reference (MSR) Procedure

Spire flash simulator



Thermal equilibrium T = 25°C
Minimal heating during flash

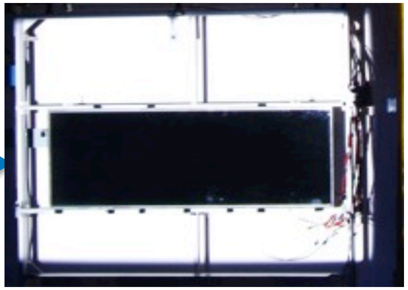
Voc (25°C) →

outdoor test bed

Non-uniformity ~ 0.2%
Measurement at 25°C

Isc →

Large area continuous simulator



Use module Isc to set simulator intensity, eliminates effects of non-uniformity and spectral correction

Strategic Combination of Module Test Beds

<u>Step 1</u>: The first step is measurement of V_{OC} vs. irradiance in thermal equilibrium within±0.2°C of 25°C using the flash simulator. Because voltage is very sensitive to temperature this provides a very sensitive measure of junction temperature for subsequent measurements.

<u>Step 2:</u> The module is cooled to ~ 15°C, then mounted on the outdoor test bed. V_{OC} is monitored until the module is at ~ 24.5°C and the I-V curve is measured. This provides a measure of I_{SC} with very low uncertainty due to the high uniformity of sunlight.

<u>Step 3:</u> The module is then mounted in the continuous simulator and the value of I_{SC} from the outdoor test bed is used to set the simulator intensity. This eliminates errors due to spatial non-uniformity and spectral mismatch. The module is again cooled, allowed to heat to ~ 24.5°C and the final I-V curve is measured.

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Uncertainty in Voc and Isc from flash simulator and outdoor test bed

Uncertainty in V_{oc} from flash simulator

$$U_{95}\left(V_{OC}\right) = ku\left(V_{OC}\right)$$

$$= k\left[\left(\frac{u\left(V_{LT}\right)}{1}\right)^2 + \left(\frac{U\left(V_{5600}\right)}{2}\right)^2 + \left(\frac{u\left(\ln\left(E\right)\right)}{1}\right)^2\right]^{1/2}$$

$$= (2)\left[\left(0.162\right)^2 + \left(\frac{0.25}{2}\right)^2 + \left(0.183\right)^2\right]^{1/2} = \pm 0.27\%$$

Term	Uncertainty Component	Value (%)
$U(V_{LT})$	Long term V_{oc} stability of Spire 5600	0.162
$U(V_{5600})$	Uncertainty of V measurement	0.25
U(ln(E))	Uncertainty of ln(E) fit	0.183

Uncertainty in I_{SC} from outdoor test bed

Calibration Equation

$$I_{0,TD} = I_{TD}\frac{I_{0,RC}}{I_{RC}}\frac{1}{M\left(T_{TD},T_{RC}\right)}$$

RSS calculation of U_{95} uncertainty

$$u\left(I_{0,TD}\right) = \begin{bmatrix} \left(U_{95}\left(M\right)/2\right)^2 + \left(U_{95}\left(I_{0,RD}\right)/2\right)^2 + \\ u^2\left(S\right)/3 + u^2\left(PM_{TD,RD}\right)/3 + u^2\left(I_{T,TD}\right)/3 + \\ u^2\left(R_{RD}\right) + u^2\left(R_{TD}\right) + \sigma^2\left(I_{SC0,RD}\right) + \\ \sigma^2\left(I_{SC0,TD}\right) + u^2\left(VM_{RD}\right) + u^2\left(VM_{TD}\right) \end{bmatrix}^{0.5} = 0.342\%$$

$$U_{95}\left(I_{0,TD}\right) = k \times u\left(I_{0,TD}\right) = \left(2\right)\left(0.342\right) = \pm 0.684\%$$

Term	Uncertainty Component	Value (%)
M	T-dependent spectral mismatch correction	0.3
$I_{0,RD}$	Primary reference device calibration	0.422
S	Spatial non-uniformity of irradiance	0.25
$PM_{TD,RD}$	Planar misalignment of test and reference devices	.242
$I_{T,TD}$	Current error due to temperature change during I-V sweep	0.0185
R_{RD}	Current sense resistor for reference device	0.0074
R_{TD}	Current sense resistor for test device	0.024
$I_{SC0,RD}$	Fit of I-V data for reference device I_{SC}	0.0678
$I_{SC0,TD}$	Fit of I-V data for test device I_{SC}	0.0623
VM_{RD}	Voltmeter for reference device current sense resistor	0.0141
VM_{TD}	Voltmeter for test device current sense resistor	0.0139

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Uncertainty in PMAX from continuous simulator

Term	Uncertainty Component	Value (%)
$V_{OC,0}$	Calibrated V_{OC} at 25°C, 1000 W/m² (from Spire measurement)	0.27
$V_{V,TD}$	Voltage error due to temperature change during I-V sweep	0.0018
$VM_{V,TD}$	Voltmeter error for voltage measurement	0.0088
$I_{0,TD}$	Calibrated I_{SC} from outdoor measurement	0.342
$I_{T,TD}$	Current error due to temperature change during I-V sweep	0.0382
$VM_{I,TD}$	Voltmeter error for current measurement across current sense resistor	0.0173
R_{TD}	Current sense resistor for test device	0.5
$I_{SC,TD}$	Fit of I-V curve for test device I_{SC}	0.0759
I-V	Maximum bounds of I-V distortion from spatial non-uniformity	0.2075
$P_{MAX,TD}$	Uncertainty of P_{MAX} curve fit using prediction intervals	0.034

$$u(P_{MAX}) = \begin{bmatrix} u^2(V_{OC0}) + u^2(V_{T,TD})/3 + u^2(VM_{V,TD}) + \\ u^2(I_{0,TD}) + u^2(I_{T,TD})/3 + u^2(VM_{I,TD}) + \\ u^2(I\text{-}V)/3 + \sigma^2(I_{SC,TD}) + \sigma^2(P_{MAX,TD}) + \\ u^2(R_{TD}) \end{bmatrix}^{0.5} = 0.572\%$$

$$U_{95}(P_{MAX}) = k \times u(P_{MAX}) = (2)(0.572) = \pm 1.14\%$$

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2015-2017 Inter-comparison

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Fraunhofer Institute for Solar Energy Systems ISE
European Commission–Joint Research Centre, European Solar Test Installation (ESTI)
National Renewable Energy Laboratory
National Institute of Advanced Industrial Science and Technology (AIST)

Seven photovoltaic modules of different technologies were measured

Modules were standard modules purchased on open market

- 2 standard crystalline silicon
- 2 high-efficiency crystalline silicon
- 2 cadmium telluride
- CIGS

Module list. The value reported for each electrical parameter is the nominal value given by the manufacturer, except for the modules M1 and M2 for which the results of the previous intercomparison are listed (Dirnberger et al., 2014).

Device	Technology	Cells No./type	Size [m × m]	I_{SC} [A]	V_{OC} [V]	P_{MAX} [W]	*FF* [%]
M1	High efficiency c-Si	240/Honeycomb	1.610 × 0.860	7.355	43.30	239.8	75.30
M2	Poly c-Si	72/6 in.	1.970 × 0.990	8.286	44.29	272.9	74.34
M3	High efficiency c-Si	96/5.1 in.	1.559 × 1.045	6.2	64.7	318	79.3
M4	Poly c-Si	60/6 in.	1.650 × 0.990	8.37	37.2	240	77.6
M5	CI(G)S	170/stripes	1.256 × 0.976	2.2	112	170	67.0
M6	CI(G)S	104/stripes	1.586 × 0.670	3.11	58.5	120	66.0
M7	CdTe	154/stripes	1.200 × 0.600	1.99	60.5	87.5	72.7

Improvements in world-wide intercomparison of PV module calibration, E. Salis, D. Pavanello, M. Field, U. Kräling, F. Neuberger, K. Kiefer, C. Osterwald, S. Rummel, D. Levi, Y. Hishikawa, K. Yamagoe, H. Ohshima, M. Yoshita, H. Müllejans, Solar Energy 155 (2017) 1451–1461, http://dx.doi.org/10.1016/j.solener.2017.07.081

2015-2017 Inter-comparison

Relative uncertainties for each lab and each measurand

Stated UCs for all the measurands and every laboratory.

CalLab					ESTI				
Device	I_{SC} [%]	V_{OC} [%]	P_{MAX} [%]	FF [%]	Device	I_{SC} [%]	V_{OC} [%]	P_{MAX} [%]	FF [%]
M1	1.5	0.6	2.2	2.0	M1	0.8	1.4	1.8	0.72
M2	1.3	0.6	1.6	1.4	M2	0.8	1.4	1.8	0.72
M3	1.3	0.6	1.6	1.4	M3	0.8	1.4	1.8	0.72
M4	1.3	0.6	1.6	1.4	M4	0.8	1.4	1.8	0.72
M5	2.5	0.8	3.2	2.1	M5	0.8	1.4	1.8	0.72
M6	2.5	0.8	3.2	2.1	M6	0.8	1.4	1.8	0.72
M7	2.5	0.7	2.9	1.7	M7	0.8	1.4	1.8	0.72
NREL					AIST				
Device	I_{SC} [%]	V_{OC} [%]	P_{MAX} [%]	FF [%]	Device	I_{SC} [%]	V_{OC} [%]	P_{MAX} [%]	FF [%]
M1	0.7	0.6	1.1	1.4	M1	1.4	0.4	1.5	0.8
M2	0.7	0.6	1.1	1.4	M2	1.4	0.4	1.5	0.8
M3	0.7	0.6	1.1	1.4	M3	1.4	0.4	1.5	0.8
M4	0.7	0.7	1.2	1.5	M4	1.4	0.4	1.5	0.8
M5	3.2	0.6	3.2	1.2	M5	1.4	0.6	1.7	0.9
M6	3.2	0.6	3.2	1.2	M6	1.5	1.1	1.8	1.2
M7	3.2	0.7	3.2	1.2	M7	1.6	0.6	1.9	0.9

k=2 (~95% coverage factor)

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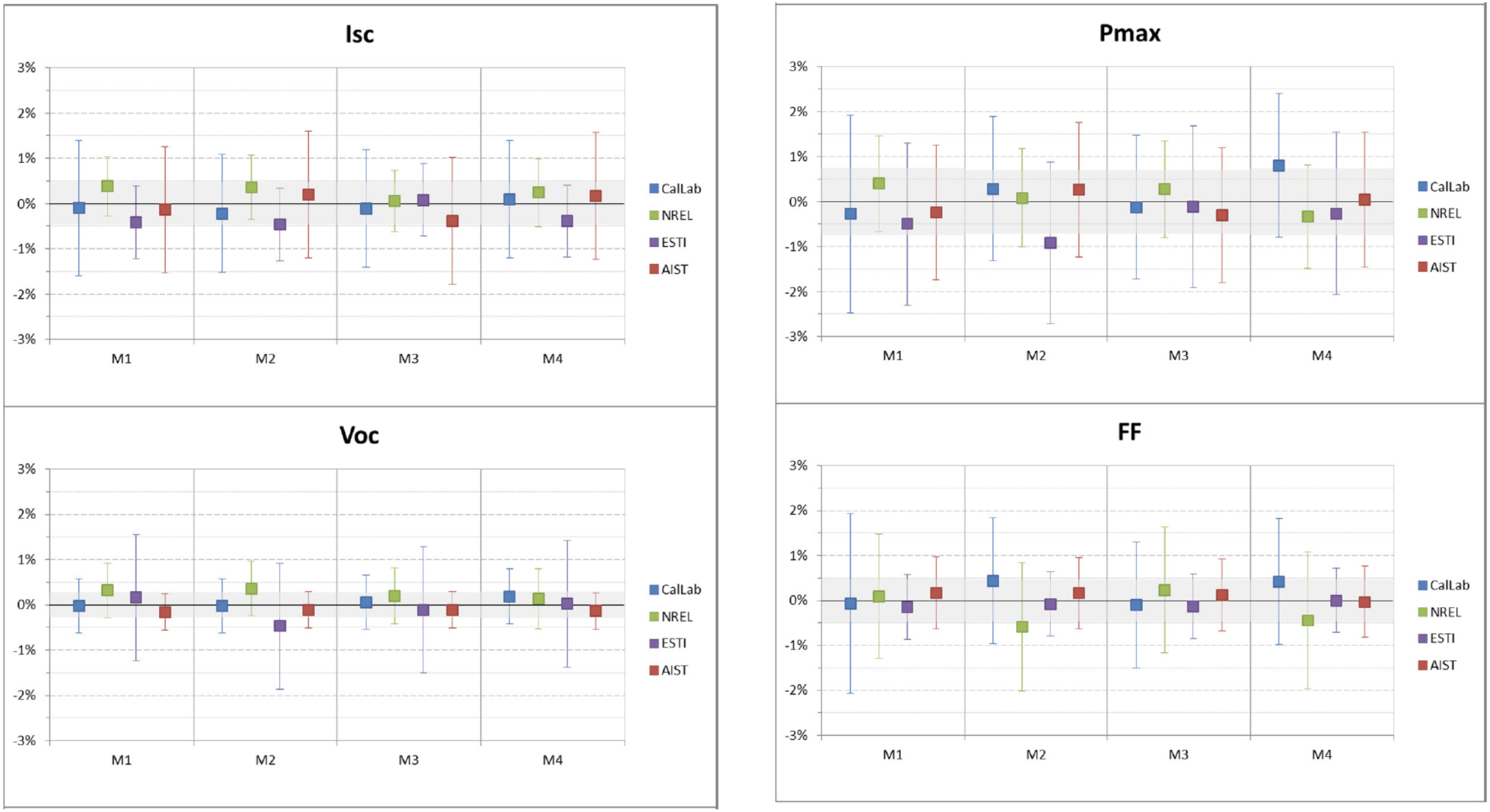
2015-2017 Inter-comparison; results for c-Si modules



$$\bar{x} = \frac{\sum_{i=1}^{n} w_i \, x_i}{\sum_{i=1}^{n} w_i} = \frac{\sum_{i=1}^{n} \frac{x_i}{\sigma_i^2}}{\sum_{i=1}^{n} \frac{1}{\sigma_i^2}}$$

$$\text{with } w_i = \frac{1}{\sigma_i{}^2}, \text{ and } \sigma_i = \frac{UC95\%(k=2)}{2}.$$

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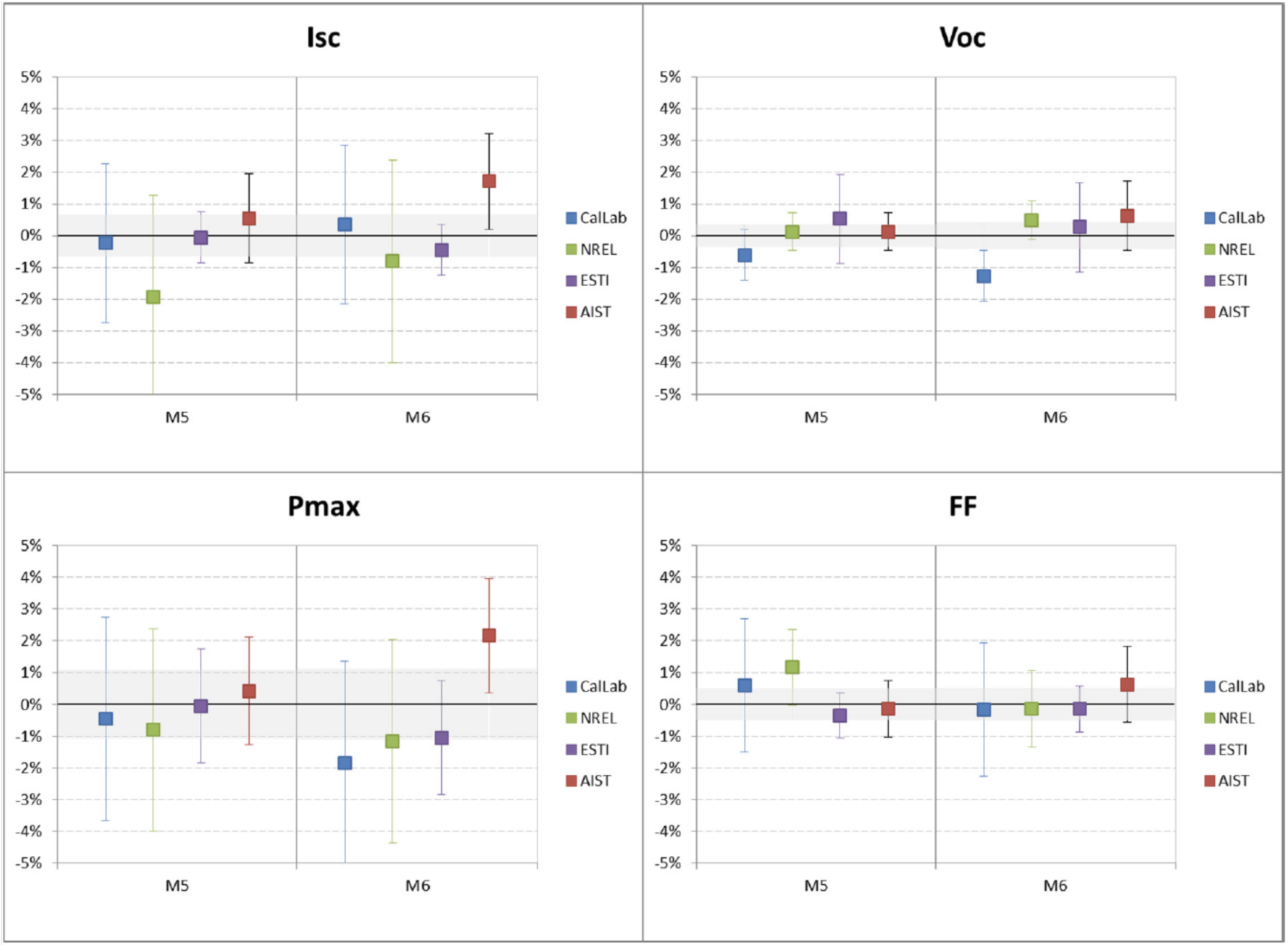
2015-2017 Inter-comparison; results for CIGS modules



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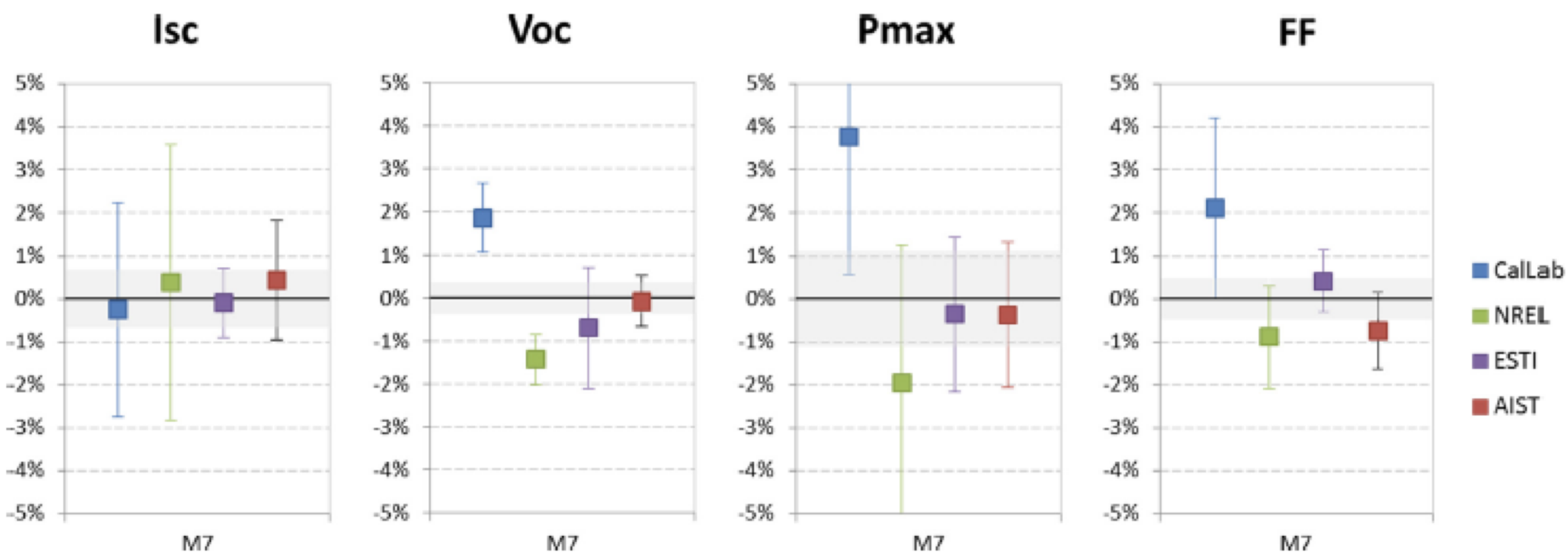
2015-2017 Inter-comparison; results for CdTe module



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