INTERLABORATORY COMPARISON OF VOLTAGE SWEEP METHODS USED FOR THE ELECTRICAL CHARACTERIZATION OF ENCAPSULATED HIGH-EFFICIENCY C-SI SOLAR CELLS

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ABSTRACT: This work presents the comparison of measurement results for four types of encapsulated high efficiency (HE) c-Si solar cells measured by ten laboratories based in Asia, Europe and North America utilizing a wide range of voltage sweeping methods, which include well-established procedures that represent good industry practice, as well as recently introduced ones that have not been verified yet. A proficiency test was employed to examine the consistency of results and their corresponding uncertainties. The results of all participant laboratories generally remained well within [−1; 1], thus indicating consistency between the measured values and the reference values within stated measurement uncertainties. A preliminary analysis revealed that differences remained within ±1.15% in P_{MAX} and within ±0.35% in V_{OC} for all participants and methods applied. Essentially this work forms the basis to validate all applied methods and their stated measurement uncertainties.

Keywords: round-robin, interlaboratory comparison, high-efficiency c-Si photovoltaic module, electrical performance, characterization

1 INTRODUCTION

The power measurements of high efficiency (HE) c-Si technologies have been a challenge for both production lines and calibration laboratories for over two decades [1-3]. HE c-Si devices exhibit measurement deviations due to their slow response causing hysteresis in IV measurements in particular in pulsed solar simulators. Such deviations are attributed to the diffusion capacitance of c-Si devices, which derives from the redistribution of charge carriers in the depletion region under forward bias. HE c-Si have longer diffusion lengths for minority carriers, and hence would also have a higher inert diffusion capacitance than conventional solar cells giving rise to measurement artefacts. Such deviations have been previously reported for both solar simulator and outdoor measurements. [1-6].

Recent developments in HE c-Si technologies (such as *p*-type PERC, *n*-type PERT, HJT and IBC) have popularized these devices in the market and made the accuracy of their calibration increasingly important. In parallel advances in measurement systems have opened new possibilities for characterization [7-11] compared to proven standard procedures involving long-pulse solar simulators, the multi-flash method and steady-state conditions such as those provided by natural sunlight.

The aim of this work is to examine the comparability of measurements of different laboratories utilizing different procedures for the measurement of HE solar cells with particular focus on voltage sweeping methods. The sweeping methods utilized by the participants of the round-robin are: 1. linear sweep rate, 2. non-linear sweep rate, 3. hysteresis measurement and correction, 4. voltage-stepping and correction and 5. voltage-irradiance modulation and correction. Furthermore, the work aims to compare different methods and laboratory setups used between ISO/IEC 17025 accredited calibration and testing as well as industrial laboratories that have processes and procedures in place in accordance with IEC 60904-1. In this context a HE encapsulated solar cell round-robin was initiated. A preliminary analysis is presented in the following paragraphs.

2 METHODOLOGY

2.1 Participant laboratories, measurement uncertainty and setups

A round-robin was realized between ten laboratories based in Asia, Europe and North America. The participants were five ISO/IEC 17025 accredited laboratories (three for calibration and two for testing) and five industrial laboratories. Namely the participant laboratories were: AIST (Japan), Berger Lichttechnik (Germany), JRC ESTI (Italy), h.a.l.m. Electronic (Germany), ISFH (Germany), Kyoshin Electric Co., Ltd. (Japan), Pasan, Meyer Burger (Switzerland), SIMIT, CAS (China), Sinton Instruments (USA), TÜV Rheinland (China). The participant laboratories employed one or more of the above-mentioned sweeping methods to electrically characterise the devices under test (DUTs). Table I lists information related to the accreditation, but also the method and the sweeping procedure that each of the participant laboratories employed.

Measurement uncertainty in HE PV devices are driven by device hysteresis and reference irradiance. As both effects can impact the I_{SC}, P_{MAX} and V_{OC} of the DUTs, it is desirable to design an experiment which can isolate the influence of reference irradiance calibration, so measurement deviations can be directly associated with device hysteresis and consequently the voltage sweeping strategy employed. In order to do so, predetermined I_{SC} values were assigned to each of the DUTs by the initiator and communicated to all participants in advance. The randomly assigned values were within ±3% of the measured I_{SC} value at STC. All laboratories were then asked to perform IV characterization of the DUTs so that the I_{SC} matches the predefined value while controlling device temperature at (25±1) °C. All participants employed four-terminal connections, while the contact points at voltage and current terminals were clearly marked, so one may also assume that deviations due to contacting played a secondary role.

Table I: List of participant laboratories, methods and IV sweeping procedures employed in the round-robin.

Lab. Participants	Accreditation	Illumination (Min. Pulse Length)	IV Sweeping Method
AIST (Japan)	17025 for calibration	Long-pulse solar simulator (>100ms)	Linear sweep
Berger Lichttechnik (Germany)	None	Pulse solar simulator (>10ms)	Linear step-like
CAS, SIMIT (China)	17025 for testing	Long-pulse solar simulator (>100ms)	Linear step-like
JRC ESTI (Italy)	17025 for calibration	Steady-state solar simulator (>1s)	Linear sweep
h.a.l.m. Electronic (Germany)	None	Pulse solar simulator (>110ms)	Advanced Hysteresis [11]: 1. 2×16ms (hysteresis) 2. 2×24ms (hysteresis) 3. 2×50ms (hysteresis) 4. 2×110ms (hyst. /multiflash) 5. 2×2500ms (hyst./multiflash)
ISFH (Germany)	17025 for calibration	Steady-state solar simulator (>10s)	Linear sweep
Kyoshin Electric Co., Ltd. (Japan)	None	Pulse solar simulator (>20ms)	1. Multiflash 2. Photo and dark analysis (hysteresis) [10] 3. Fast and versatile (non-linear sweep)
Meyer Burger, Pasan (Switzerland)	None	Pulse solar simulator (>10ms)	1. *Dragonback*® (non-linear voltage stepping) [9] 2. Smart Sweep (non-linear sweep)
Sinton Instruments (USA)	None	Pulse Solar simulator (multiple flashes of >1ms)	Voltage-irradiance modulation [7]
TÜV Rheinland (China)	17025 for testing	1. Pulse solar simulator A (>10ms) 2. Pulse solar simulator B (>80ms)	Dynamic IV (non-linear voltage stepping) [8]

In this context a comparison of P_{MAX} and V_{OC} (as I_{SC} was almost identical for all participants) could reveal deviations arising from device hysteresis, due to the different voltage sweeping strategies employed without influence from irradiance traceability and spectral mismatch. This strategy effectively allows to isolate and quantify measurement artefacts due to device hysteresis. The measurement uncertainty contributions (UCs) for the electrical parameters at predefined I_{SC} values are reported in Table II.

Table II: Laboratory measurement uncertainty contributions (UCs) of electrical parameters at predefined I_{SC} values (k=2). For laboratories, which practiced measurements with multiple methods, the name of the method is indicated next to the laboratory name.

	PMAX	VOC
AIST	0.30%	0.30%
Berger Lichttechnik	0.70%	0.50%
JRC ESTI	0.75%	0.20%
h.a.l.m., 2x16ms	0.60%	0.40%
h.a.l.m., 2x24ms	0.60%	0.40%
h.a.l.m., 2x50ms	0.60%	0.40%
h.a.l.m., Multiflash, 2x110ms	0.60%	0.40%
h.a.l.m., Multiflash, 2x2500ms	0.70%	0.50%
ISFH	0.70%	0.35%
Kyoshin Electric, FAV*	0.59%	0.30%
Kyoshin Electric, Multiflash	0.52%	0.30%
Kyoshin Electric, PDA**	0.55%	0.30%
Pasan, *Dragonback*®	0.70%	0.50%
Pasan, Smart Sweep	1.50%	0.50%
Sinton Instruments	1.20%	0.70%
SIMIT, CAS	1.20%	0.70%
TÜV Rheinland	1.11%	0.40%

* FAV: Fast, Accurate, and Versatile method
** PDA: Photo and Dark Analysis method

2.2 Devices under test (DUTs)

The DUTs were four types of encapsulated HE c-Si solar cells (two types of *p*-type PERC and two types of *n*-type HJT) with initial aperture solar cell efficiencies varying between 20.5% and 23.1%. In total 11 single-cell encapsulated devices were used in the round-robin, seven of which were measured by all participants, while four were kept by the initiator in a controlled environment of temperature, humidity and light and were used as control cells (one per type). More details about the test specimens are given in Table III. Prior to any measurements all samples were subject to (15-25) kWh/m^2 light soaking in accordance with the stabilization procedures listed in IEC 61215-2. Therefore, all devices were sufficiently stabilized prior to the round robin.

2.3 Interlaboratory comparison Approach and Project Timeflow

The interlaboratory comparison took place from June 2018 to July 2020. The round-robin approach was employed here, i.e. the test samples were measured in turn by each participant and shipped to the subsequent laboratory. The agreed test protocol required electrical characterization, so the I_{SC} of the DUT matches its predetermined value at 25°C. Optionally EL measurements were also required for all samples, as long as the laboratory was qualified to do so. A timeflow of the round-robin is shown in Table IV. The identity of participants is not disclosed to ensure the confidentiality of results. Participant laboratories are rather identified with capital letters A-J assigned by order of testing. Due to shipment issues the initiator laboratory (A) repeated its final measurements before laboratory (J) concluded the round-robin.

Table III: List of the encapsulated cells used in the round-robin together with their constructional characteristics.

Sample No.	Use	Cell Technology	Initial Aperture Solar Cell Efficiency*	Soldering/Dimensions
HJT-1 #1	Round-Robin	*n*-type HJT	~21.6%	double soldered per +/- terminal; 20 x 20 cm
HJT-1 #2	Round-Robin			
HJT-1 #3	Control			
HJT-2 #1	Round-Robin	*n*-type HJT	~23.1%	double soldered per +/- terminal; 38 x 38 cm
HJT-2 #2	Round-Robin			
HJT-2 #3	Control			
PERC-1 #1	Round-Robin	*p*-type PERC	~21.6%	double soldered per +/- terminal; 30 x 30 cm
PERC-1 #2	Control			single soldered per +/- terminal; 30 x 30 cm
PERC-2 #1	Round-Robin	*p*-type PERC	~20.5%	double soldered per +/- terminal; 30 x 30 cm
PERC-2 #2	Round-Robin			double soldered per +/- terminal; 30 x 30 cm
PERC-2 #3	Control			single soldered per +/- terminal; 30 x 30 cm

(*) Initial aperture solar cell efficiency is calculated based on the initial nominal power after stabilization assuming the total projected area of the solar cell under test (which were at all cases ~15.6 x 15.6 cm), but excluding its surrounding area. It is given here indicatively of the total conversion solar cell efficiency. It is noted that the actual solar cell total conversion efficiency would be lower. As the surrounding area far exceeded the actual cell dimensions, there is a non-negligible part of light, which is being redirected towards the cell from its surroundings due to multiple internal reflections inside the glass, which rises the aperture solar cell efficiency.

Table IV: Time flow of measurement in the round robin between participant laboratories (A-J) highlighted with different colour code; different measurements sets performed by the initiator laboratory are marked with a number. Inter-laboratory shipment time is indicated with arrows and highlighted in grey.

Year	2018							2019					
Month	6	7	8	9	10	11	12	1	2	3	4	5	6
Lab.	A1			→	B	→ C	→	D	→ E		→ F	→	G

Year	2019					2020							
Month	7	8	9	10	11	12	1	2	3	4	5	6	7
Lab.	→ H			→		I	→		A2		→		J

2.4 Methods for statistical analysis

The consistency of the results was first verified by employing the E_n number proficiency test according to ISO/IEC 17043 against ISO/IEC 17025 calibration laboratories (i.e.. AIST, ESTI and ISFH). Consensus values were then assigned based on the weighted (by measurement uncertainty) average of all values of accredited calibration and qualifying testing laboratories. This approach has been previously used successfully in other interlaboratory comparisons [12, 13] and represents the state of the art, as it provides a higher weight to measurement values, which measured with a lower uncertainty.

The disadvantage of such an approach is that it depends on each laboratory's stated uncertainties, but also on the metastability of the DUTs. A reliable uncertainty estimate requires firstly traceability (i.e. an unbroken chain of prior measurements to international standards), secondly a rigorous analysis of all possible contributions in the measurement itself and thirdly a stable device which would allow the direct interlaboratory comparison of measurements practiced by different laboratories. Furthermore, some devices exhibited metastabilities, which limited the usefulness of the interlaboratory comparison. When a DUT showed metastability, the consensus values were assigned directly by accounting the weighted average of all testing and calibration laboratories omitting the E_n number proficiency test, as the test does not provide useful information for the laboratory method and procedure. These cases will be discussed in more detail in section 3.1.

2.4.1 Electrical performance analysis

A validity and consistency of all results was firstly tested in order to identify and, if necessary, eliminate outliers. For this purpose the values submitted by all participants were compared with a reference value, which was chosen as the weighted (by inverse square measurement uncertainty) average of all participant calibration laboratories according to ISO/IEC 17025. A proficiency test was performed employing E_n numbers in accordance with ISO/IEC 17043 [14], as:

$$E_{n\,i} = \frac{x_i - \bar{x}}{\sqrt{{U_{95}}_i^{\,2} + \bar{U}_{95}^{\,2}}} \tag{1}$$

E_{n_i} is the E_n number of the i^{th} participant laboratory, x_i is the measurement value corresponding to a measurement uncertainty U_{95_i} of the i^{th} participant laboratory. $\bar{x}$ is the reference value with a measurement uncertainty $\bar{U}_{95}$. An agreement between results within stated UCs is obtained when the E_n number is between -1 and 1; the results do not agree with the reference, and therefore the UCs are to be revised (or some cause for an erroneous measurement has to be identified), in case the E_n number is above 1.

The weighted mean for each electrical parameter (either V_{OC}, or P_{MAX}) is used here as its reference value. In addition, corrections were applied to consider multiple results submitted by a single laboratory. In particular, laboratory A measured twice all the modules. Therefore, a formula accounting for both reliability weights (i.e. measurement uncertainty) and frequency weights (i.e. number of independent measurements submitted per laboratory) was employed. Specifically, the weighted mean, $\bar{x}^*$,of measurements was derived as follows [15, 16]:

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

with weights w_i defined as:

$$w_i = \frac{1}{N_{lab} \cdot {U_{95}}_i^{\,2}} \tag{3}$$

and x_i is a measurement with expanded measurement uncertainty (k=2), U_{95} [17]. In eq. (2) N_{lab} is the number of independent measurement sets submitted by each laboratory. The notation n represents the total number of independent measurements submitted by all participants in the round-robin. The derived values are considered as the best estimate of the physical true value of the electrical parameters.

The uncertainty of the weighted mean can then be expressed as [18]:

$$\bar{U}_{95} = \frac{1}{\sqrt{\sum_{i=1}^{m} \frac{1}{{U_{95}}_i^{\,2}}}} \tag{4}$$

The notation m represents the number of participant testing or calibration laboratories, i.e. five in our case.

Inter-laboratory deviations were then expressed in terms of their deviation from the weighted mean as defined above. This is a more conservative approach as compared to the maximum absolute laboratory differences, because it accounts for the dispersion of measurements, and therefore can provide a more comprehensive estimate of laboratory agreement. The weighted deviation was used rather than the standard deviation, which gives statistical weight to differences measured with lower uncertainty. As the sample size was relative small (<30), the unbiased estimator correction was used for the population variance [19]:

$$\bar{s}_w = \sqrt{\frac{\sum_{i=1}^{n} w_i (x_i - \bar{x}^*)}{\sum_{i=1}^{n} w_i - \frac{\sum_{i=1}^{n} w_i^{\,2}}{\sum_{i=1}^{n} w_i}}} \tag{5}$$

3 PRELIMINARY RESULTS

A preliminary analysis of the results is discussed in the following paragraphs in terms of the metastability of the reference samples and interlaboratory deviations for the electrical performance parameters. A more comprehensive analysis will be presented elsewhere.

3.1 Drift or metastability of test samples

As device metastability or drift would directly affect the outcome of the round-robin, it is important to minimize its impact. When this is not possible it is equally important to be able to quantify any performance changes, to isolate artefacts deriving from device hysteresis from metastability or drift in general. In the following paragraphs, the metastable behaviour or drift is discussed.

DUT HJT-2 #2 sustained damage in its electrical termination while in laboratory I. The damage was significant, as an electrical terminal was completely cut-off (Figure 1), which changed the measured P_{MAX} on average by approximately 2.0 % (see Figure 2). For this reason, the results of DUT HJT-2 #2 will not be analysed further in the following paragraphs.

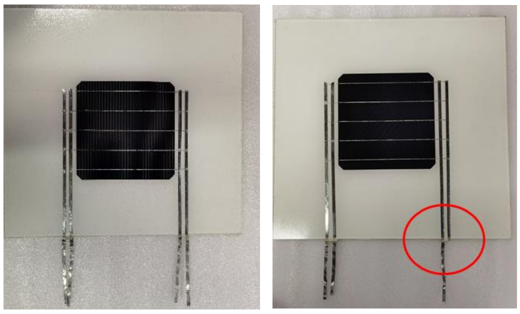

Figure 1: Sample HJT-2 #1 (left) and HJT-2 #2 (right) carrying double soldered electrical terminations. The sample HJT-2 experienced damage in its exterior terminations during the round-robin.

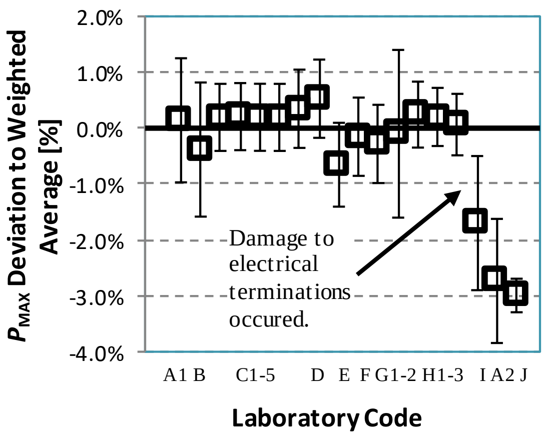

Figure 2: Maximum power deviation for DUT HJT-2 #2 as measured blindly by each laboratory at predefined I_{SC} condition at 25°C in respect to the weighted average of all measurements before any damage occurred. The measurements of the last three laboratories was not accounted in the weighted average calculation. X-axis denotes the test laboratory code in chronological order of testing. The estimated values of uncertainty (k=2) are shown by error bars for each laboratory. The figure indicates the drift shown after an electrical termination was accidentally cut-off.

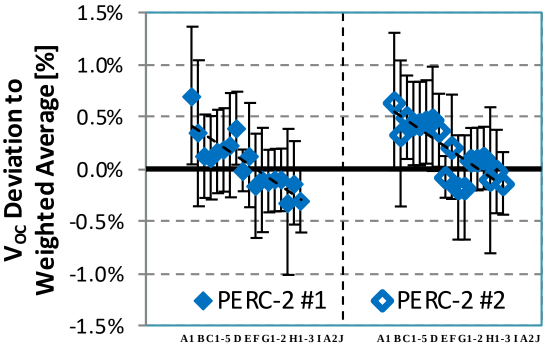

Figure 3: Open-circuit voltage deviation for samples PERC-2 #1 and #2 as measured blindly by each laboratory at predefined I_{SC} condition at 25°C in respect to the weighted average of all measurements. X-axis denotes the test laboratory code in chronological order of testing. The estimated values of uncertainty (k=2) are shown by error bars for each laboratory. The figure shows that samples PERC-2 #1 and #2 exhibited a linear metastable behaviour during the course of round-robin. Dashed lines have been added as a guideline to show the linear regression of open-circuit voltages measured over time.

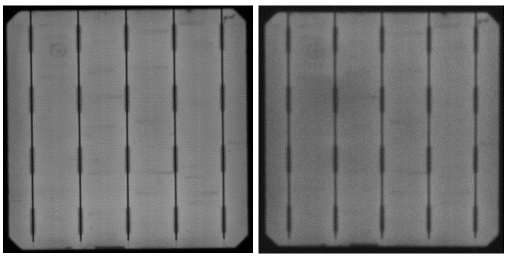

Figure 4: Sample PERC-2 #1 as measured by laboratory B on the 25th October 2018 and laboratory A on 26th April 2020. A minor darkening of the image was observed, which indicates a decrease of minority carrier lifetime.

Samples PERC-2 #1 and #2 also exhibited moderate systematic metastable behaviour, which became notable in P_{MAX} and V_{OC} (as shown in Figure 3). Specifically, for device PERC-2 #1 P_{MAX} degraded approximately 1.10% and V_{OC} approximately 0.84%, while device PERC-2 #2 degraded approximately 0.75% in P_{MAX} and 0.67% in V_{OC}. The estimates provided were based on the differences seen between initial and final measurements carried out by the initiator laboratory at STC (not predefined I_{SC}). The effect was also noticeable when comparing the EL images of this cell taken at the beginning and the end of the round-robin (as shown in Figure 4), which generally indicates an increase of series resistance or a decrease in the minority carrier lifetime. The increase of series resistance was ruled out, because a reduction in V_{OC} was also observed, but also because a comparison of EL images of the cell at higher and lower injection still showed a darkening of these cells. Therefore, it is assumed that minority lifetime changes influenced the metastability of cells PERC-2 #1 and #2. Interestingly, the control samples (which were stored in a dark environment) have not shown similar behaviour, pointing out that exposure to light may have had an impact in the metastability of the samples. Indeed the control sample PERC-2 #3 was remeasured higher at STC by the initiator laboratory and its values changed by +0.23% in I_{SC} and +0.33% in P_{MAX}; suggesting either a minor increase in performance, or an influence from laboratory reproducibility. As the effects seen were rather moderate (approx. within 1%) it was decided to include the solar cells in the round-robin examination, but exclude them from E_n proficiency test. Generally, the results of PERC-2 should be read with a caution.

3.2 Proficiency Test - E_n Numbers

The results of the proficiency verification are expressed with the E_n numbers for P_{MAX} and V_{OC} in tables V and VI respectively. The results presented here correspond to all samples whose behaviour did not show systematic metastabilities, or drift over the course of the round-robin. A single outlier was observed in the E_n numbers among all participants for P_{MAX}. Specifically, the measurement of laboratory E for device PERC-1 #1 is associated with an E_n number of 1.30. No outlier was observed for V_{OC}. The results of all participant laboratories generally remained well within [−1; 1], thus indicating consistency between the measured values and the reference within the declared UCs for all measurement procedures and laboratories.

Table V: E_n numbers for P_{MAX} for the participant laboratories at predefined I_{SC} condition at 25°C.

Laboratory	HJT-1 #1	HJT-1 #2	HJT-2 #1	PERC-1 #1
A1	0.53	0.22	0.59	0.28
B	0.08	0.09	-0.18	0.32
C1	0.29	0.17	0.43	0.54
C2	0.26	0.12	0.41	0.47
C3	0.25	0.09	0.37	0.45
C4	0.21	0.07	0.35	0.49
C5	0.33	0.13	0.39	0.46
D	0.83	0.94	0.84	0.73
E	-0.58	-0.53	-0.77	-1.30
F	0.39	0.38	-0.34	0.99
G1	0.32	0.02	-0.19	0.06
G2	0.09	0.24	-0.18	0.51
H1	0.59	0.97	0.67	0.64
H2	0.39	0.64	0.40	0.54
H3	0.18	0.51	0.42	0.54
I	0.60	0.48	0.99	0.14
A2	0.02	-0.12	-0.04	0.05
J	-0.10	-0.15	-0.04	0.16

3.3 Electrical Performance Parameters Comparison

Interlaboratory deviations in the electrical performance parameters P_{MAX} and V_{OC} are shown in Figure 5 and Figure 6 respectively.

Since I_{SC} values were predefined, the weighted deviation for I_{SC} stayed below 0.06% (k=2) for all modules, which shows that all calibrations have been carried out correctly for all modules. The worst case agreement in I_{SC} has been -0.30%, which was measured by laboratory D for DUT PERC#2-1. This would introduce an error contribution of the same size to P_{MAX}.

The calculated uncertainty of the consensus value of P_{MAX} varied between ±0.63% and ±0.80% (k=2) depending on the DUT. The weighted deviations of DUTs varied between 0.79% and 1.12% (k=2) in P_{MAX}. These

Table VI: E_n numbers for V_{OC} for the participant laboratories at predefined I_{SC} condition at 25°C.

Laboratory	HJT-1 #1	HJT-1 #2	HJT-2 #1	PERC-1 #1
A1	0.35	0.33	0.49	0.56
B	0.13	0.05	0.10	0.33
C1	0.34	0.04	0.55	0.71
C2	0.34	0.08	0.55	0.50
C3	0.40	0.14	0.58	0.36
C4	0.40	0.11	0.55	0.64
C5	0.38	0.25	0.55	0.49
D	0.62	0.74	0.71	0.94
E	-0.46	-0.47	-0.63	-0.53
F	-0.11	-0.01	-0.05	0.46
G1	-0.21	-0.43	-0.65	-0.25
G2	0.21	0.15	-0.31	0.02
H1	0.43	0.66	0.66	0.47
H2	0.41	0.44	0.33	0.47
H3	0.35	0.59	0.62	0.54
I	0.15	0.01	0.20	0.14
A2	0.48	0.38	0.54	0.50
J	0.26	0.18	0.45	0.11

values indicate good agreement between laboratories. Worst case agreement in P_{MAX} was seen in the first measurement of laboratory A for DUT PERC#2-1, where the laboratory deviation to the consensus value was higher by 1.21%. The difference is largely attributed to the metastable behaviour of this device, which drifted in P_{MAX} over time (see also Figure 5). Another noticeable difference is the value measured by laboratory I for sample HJT-2 #1, which deviated by 1.15% in P_{MAX} to the consensus value. Lastly, laboratory E measured sample PERC-1 #1 by -1.04% lower than the consensus value of P_{MAX}. The last two deviations are most likely single events, which are difficult to explain, as the deviations in the associated values of V_{OC} were less than 0.2% of the consensus values. Lastly, sweep time and temperature control are critical parameters as they can affect P_{MAX}, but the errors reported in this work do not show any systematic under- or overestimation of P_{MAX}, which point towards the directions that the employed methods and procedures are valid.

Laboratory weighted deviations in V_{OC} remain within 0.35% to 0.56% (k=2) for all samples, while the uncertainty of the consensus values of V_{OC} stayed between ±0.29% and ±0.48% (k=2). Generally, these values are encouraging and indicate a high level of agreement observed amongst the participant laboratories. Worst case agreement in V_{OC} from the consensus values were the values recorded in the first measurements of laboratory A for devices PERC-2 #1 and #2, which deviate by 0.70% and 0.66% respectively. These errors are consistent with the P_{MAX} measurement of the laboratory, which was also overestimated by 1.21% and 0.86% for devices PERC-2 #1 and #2 respectively. As previously discussed, the PERC-2 devices exhibited a linear degradation in P_{MAX} and V_{OC} during the round-robin. The reported values agree well on the reported linear trend of degradation for devices PERC-2 #1 and #2, which degraded by 1.10% and 0.84% approximately in V_{OC} during the round-robin (see also Figure 4). It is also noted that laboratory D systematically overestimated V_{OC} for all DUTs by 0.21% - 0.37% higher to the consensus values, but the reported values were within the uncertainties stated. Since no significant systematic overestimation or underestimation was recorded, it is assumed that all employed methods and procedures are valid.

Generally, in this round-robin interlaboratory comparison no significant deviations for any of the four devices, which were considered stable (HJT-1 #1, HJT1 #2, HJT-2 #1 and PERC-1 #1), were observed. In total 144 measurement results were reported, and only one outlier has been reported. The latter implies that the stated uncertainties are more conservative, as statistically one would expect at least five outliers for every 100 measurements practiced at a 95% level of confidence. Specifically, the results obtained utilizing the following methods: linear, non-linear sweep rate, hysteresis measurement and correction, voltage-stepping and correction and voltage-irradiance modulation and correction, are comparable within ±1.00% (k=2) for P_{MAX} and within ±0.40% (k=2) for V_{OC} with the results of established methods such as long-pulse, and multiflash. Therefore, this investigation leads to the conclusion that hysteresis artefacts are countered sufficiently well by all practiced methods and procedures. It is noted that a round-robin has been conducted in the past, which also examined the magnitude of capacitive artefacts on full-sized PV modules [13], the reported level of agreement has been ±0.90% (k=2) for P_{MAX} and ±0.33% (k=2) for V_{OC}, which are quantitatively similar with the values reported in this round-robin.

4 CONCLUSIONS

A round-robin interlaboratory comparison was realized between ten laboratories based in Asia, Europe and North America. The participants were five ISO/IEC 17025 accredited laboratories (three for calibration and two for testing) and five industrial laboratories. The scope of this work was to examine the comparability of measurements made by different laboratories utilizing different procedures on the measurement of HE solar cells with particular focus on voltage sweeping methods. The sweeping methods examined in this work are: 1. linear sweep rate, 2. non-linear sweep rate, 3. hysteresis measurement and correction, 4. voltage-stepping and correction and 5. voltage-irradiance modulation and correction. Furthermore, the work aimed to compare different methods and laboratory setups used between ISO/IEC 17025 accredited calibration and testing as well as industrial laboratories that have processes and procedures in place in accordance with IEC 60904-1.

A proficiency test was employed to examine the consistency of results and their corresponding uncertainties, but also isolate possible outliers. For all stable devices the results of all participant laboratories generally remained well within [−1; 1], thus indicating consistency between the measured values and the reference within the declared UCs for all measurement procedures and laboratories. A preliminary analysis revealed that the maximum measured deviations varied for all stable samples within ±0.67% to ±1.15% for P_{MAX} and within ±0.21% to ±0.35%, for V_{OC}. The weighted deviations per sample type ranged within ±0.79% to ±1.12% (k=2) for P_{MAX} and ±0.35 to ±0.56% (k=2) for V_{OC}, which can be seen as a conservative estimation of

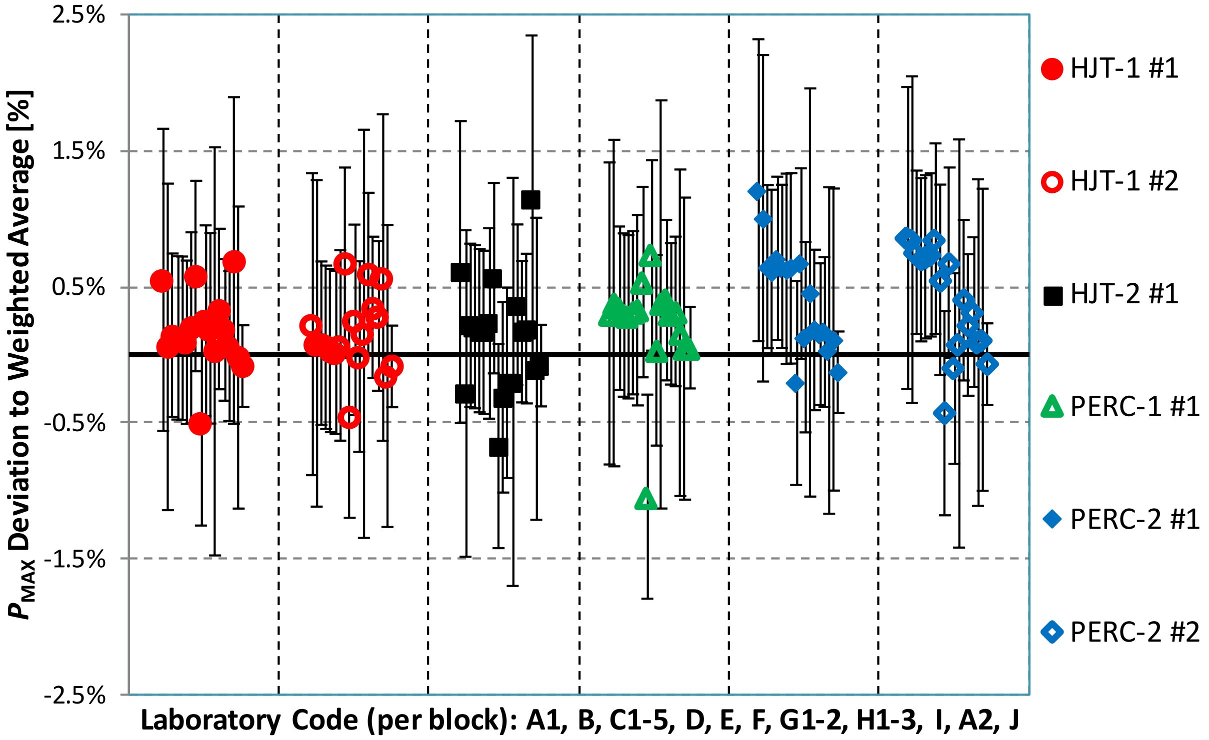

Figure 5: Maximum power point deviations to the weighted mean for all modules as measured blindly by each laboratory at predefined I_{SC} condition at 25°C. The estimated values of measurement uncertainty (k=2) are shown as error bars for each laboratory.

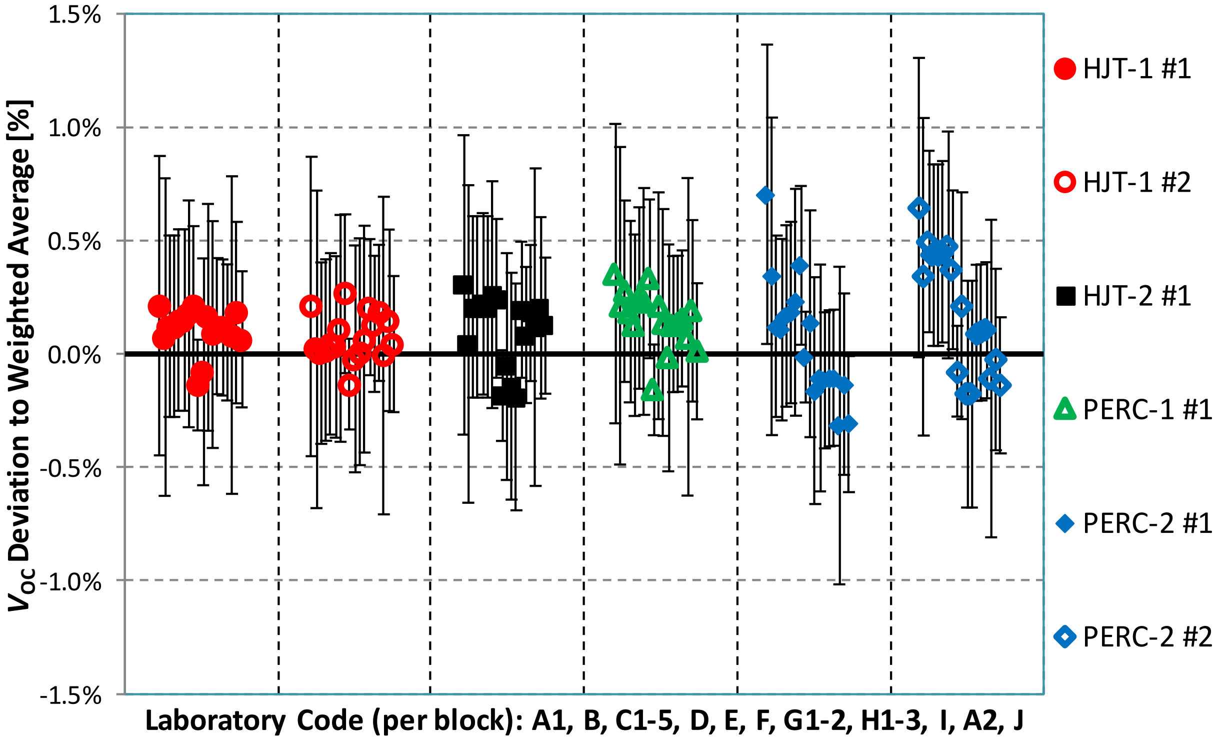

Figure 6: Open-circuit voltage deviations to the weighted mean as measured blindly by each laboratory at predefined I_{SC} condition at 25°C. The representations used are the same as in Figure 5.

interlaboratory agreement of this round-robin. These numbers are encouraging and indicate good agreement for all participants.

Essentially this work validated all applied methods and their stated measurement uncertainties. A more comprehensive analysis of the results will be presented elsewhere.

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