Results of the Sophia module intercomparison part-1: stc, low irradiance conditions and temperature coefficients measurements of C-Si technologies

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ABSTRACT: The results of a measurement intercomparison between eleven European laboratories measuring PV energy relevant parameters are reported. The purpose of the round-robin was to assess the uncertainty analyses of the participating laboratories on c-Si modules and to establish a baseline for the following thin-film round-robin. Alongside the STC measurements, low irradiance conditions (200W/m²) and temperature coefficients measurements were performed. The largest measurement deviation from the median at STC was for HIT modules from -3.6% to +2.7% in $P_{\text{MAX}}$, but in agreement with the stated uncertainties of the participants. This was not the case for low irradiance conditions and temperature coefficients measurements with some partners underestimating their uncertainties. Larger deviations from the median from -5% to +3% in $P_{\text{MAX}}$ at low irradiance conditions and -6.6% to +18.3% for the $P_{\text{MAX}}$ temperature coefficient were observed. The main sources of uncertainties contributing to the spread in measurements were the RC calibration, mismatch factor and capacitive effects at STC and low irradiance conditions as well as the additional light inhomogeneity for the latter. The uncertainty in the junction temperature and the temperature deviation across the module were the major contributors for temperature coefficients measurements.

Keywords: Modules, Characterisation, Uncertainty.

1 INTRODUCTION

Module measurement intercomparisons are part of the quality control for established laboratories and one of the few ways to validate measurement uncertainties. The results of such intercomparisons provide an insight into the measurement capabilities and challenges in characterising PV devices. An outline of the results of key module round-robins is given below. An international module intercomparison between accredited laboratories finalised in 2006 was reported in [1]. There were differences in $P_{\text{MAX}}$ of [-4.4%:+3%] for mono-Si, [-3.5%:+1.7%] for a-Si, [-3.4%:+4.7%] for CdTe, [-4.5%:+7.9%] for CIS and around ±8% for multi-junction (MJ) devices. At a later stage, intercomparisons as part of the PERFORMANCE project in Europe reported similar results for different types of standard and high efficiency c-Si modules [-1.5%:+2.6%] [2] and higher spreads in $P_{\text{MAX}}$ for thin film modules: initially [-7%:+8%] for SJ thin film modules and then ±3% for SJ and ±6% for MJ thin film devices at a second intercomparison [3], [4]. At lower irradiance levels the results in general agreed to a lesser extent: ±4% for c-Si modules[4]. The result of a round-robin between 9 national laboratories in the Asian region measuring two mono c-Si and two multi c-Si modules are reported in [5]. The results were within ±3% in $P_{\text{MAX}}$.

As part of the European Sophia project, 11 laboratories conducted a c-Si module round-robin to critically assess their uncertainty estimations and to create a baseline for a thin-film round-robin aiming at improving the measurement practices for such devices. A larger variety of laboratories participated in the round-robin including: accredited and non-accredited laboratories, national laboratories, university research centres and commercial test houses. Measurements were carried both outdoors and indoors. Some performed mismatch factor corrections whilst others accounted for it in their uncertainty. A list of the participating partners is as follows:

• Austrian Institute of Technology (AIT), AT.
• Centre for Renewable Energy Systems Technology (CREST), UK.
• Energy Research Centre of the Netherlands (ECN), NL.
• Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), IT.
• National Electricity Corporation (ENEL), IT.
• Fraunhofer Institute for Solar Energy Systems (ISE), DE.
• National Solar Energy Institute (INES), FR.
• Joint Research Centre - European Solar Test Installation (JRC-ESTI), IT.
• Juelich Forschungszentrum, DE.
• Research on the Energetic System (RSE), IT.
• University of Applied Sciences and Arts of Southern Switzerland (SUPSI), CH.

Three types of modules were selected for the round-robin and two modules of each type were measured:

• Mono-crystalline silicon – Standard technology (referred to as Mono).
• Mono-crystalline silicon/a-Si Heterojunction – High performance hetero-junction technology (referred to...
as HIT).

- Back contact mono-crystalline silicon – High performance back contact module (referred to as BC).

All laboratories performed STC measurements. Not all partners were able to measure at Low Irradiance conditions (LIC), i.e. at 200W/m² or the Temperature Coefficients (TC) of modules. A number of laboratories measured electroluminescence and two laboratories measured the spectral responsivity of the modules. One partner measured the modules at the beginning and at the end of the round-robin and therefore there are twelve arbitrary ordered partners in the STC figures. The repeat measurements were within the reproducibility of that partner. There was no evidence of significant aging or deterioration, as supported by the repeated measurements and the electroluminescence images. All partners were asked to measure the modules according to their best practices and to report their measurement uncertainty alongside their results.

2 CORRELATION BETWEEN MEASUREMENTS

A key element of any intercomparison is the potential correlation between participants. The partners used reference cells with primary or secondary calibration from Physikalisch-Technische Bundesanstalt (PTB), ISE or ESTI with varying associated uncertainty. The majority of the cells were manufactured by ISE or by one of the solar simulator manufacturers. Three partners measured outdoors, whilst the other partners measured indoors. One partner used outdoor measurements for mismatch factor correction of its indoor measurements. From the eight partners that measured indoors, six used the same type of solar simulator and thus had similar light source spectra. However, there were variations in the load, age of lamps, measurement modes and software versions. For the low irradiance conditions, most partners used neutral density filters close to the light source. The temperature coefficients measurement setups were mostly bespoke, utilising different approaches in controlling the module temperature. It must be emphasised that there were no recognised correlating factors that affected all partners. Despite the correlations mentioned above between different subsets of partners, due to the large number of partners, the results reported below provide a unique perspective on the measurement capabilities and their uncertainties in Europe.

3 RESULTS

The choice of a reference value (mean, weighted mean, median etc.) is particularly important when the value itself and its uncertainty are the key outputs of the intercomparison (e.g. WPVS intercomparisons). The aim of the round-robin was to critically assess the uncertainty estimates of partners and provide a baseline for a further thin film round-robin. Any reference value could have been selected. The median was chosen, because it is more robust to uncorrected systematic errors such as those due to mismatch. Most partners were unable to measure the spectral responsivity of modules and thus were unable to apply corrections. All figures are normalised to the median.

3.1 Standard Test Conditions measurements

a) Short circuit current

In Figure 1 the Isc measurements of one of the standard mono c-Si modules are presented as the horizontal blue lines. The vertical black dotted lines with red markers represent the uncertainty of each partner with 95% confidence.

Figure 1: Normalised Isc measurements and stated uncertainties at STC for one of the mono c-Si modules.

As expected, partners that measured outdoors have lower uncertainties due to a closer match to the standard spectrum and assumed perfect homogeneity. Two partners did not provide uncertainty for their Isc measurements. Partner 5 measured consistently higher as can be seen in Figure 2. This is likely a systematic effect related to the reference cell used, its calibration and the lack of mismatch factor correction and or the inhomogeneity of the simulator. Note that the partner was still within the stated uncertainty for standard c-Si modules and only marginally outside the uncertainty of partners that measured outdoors for some of the other modules. All measurements were within -2.7% and +4.1% from the median. If a systematic effect is confirmed, excluding partner 5’s measurements and one possible outlier BC module outdoor measurement, the results are within ±1% for standard c-Si modules and within ±2% for the other technologies.

b) Open circuit voltage

Figure 2: Normalised Isc measurements at STC
All voltage measurements were within -1.6% and +1.1% from the median. Partner 10 had a newly developed outdoor measurement setup where controlling and estimating the temperature is more challenging and $V_{OC}$ measurement uncertainty is higher. As shown in Figure 3, the deviation from the median of partner 10 was random and most probably due to thermal transient effects. Excluding partner 10, voltage measurements for the standard mono modules were within ±0.6%.

Capacitive measurement artefacts indoors are well-known for HIT and BC modules (although affected to a lesser extend)[6]. These are mitigated via multi-point or multi-section measurements utilising multiple flashes. Partners 5 could not and Partner 7 did not use multi-section or multi-point mode for $V_{OC}$ and as expected underestimated the voltage as shown in Figure 4. Partner 5 provided a larger uncertainty to their measurements and Partner 7 used multi-section measurements for $P_{MAX}$ of HIT modules. Excluding the systematic effects outlined above, the rest of the partners were within ±0.8% for BC and HIT.

In Figure 5 the deviations from the median per partner are shown. There are no evident systematic effects, which are not explained in the previous sections. It is possible that partner 11 underestimated $P_{MAX}$ measurements for HIT modules, but not $V_{OC}$. This is currently being investigated further. All $P_{MAX}$ measurements were within -3.6% and +2.8% and within the stated uncertainties of the partners. There was no significant difference in the deviation with technology. The systematic overestimation of $I_{SC}$ by Partner 5 translates directly to $Impp$ and cancels out to an extent with the underestimation of $V_{mpp}$ due to the single sweep for BC and HIT modules. Note that the $V_{mpp}$ underestimation can be larger than that of $V_{OC}$.

### 3.2 Low irradiance condition measurements

Six partners measured at low irradiance conditions one of which measured outdoors. One partner measured twice at the beginning and at the end of the round-robin. All five partners measuring indoors used the same type of solar simulator. Four of them measured using similar neutral density filters placed near the light sources while one partner used a large area plastic neutral density filter placed near the module. These filters affect the spectrum and homogeneity of the light sources to a different extent and it has to be accounted for in the uncertainty estimation. None of the partners applied mismatch factor corrections for LIC measurements. The modified spectrum and higher inhomogeneity, in addition to the potential non-linearity of the reference cells, results in higher uncertainties than at STC conditions.

a) Short circuit current

Short circuit current measurements are presented in Figure 6. The maximum deviation in measurements from the median was from -5.8% to +8.4% for one of the BC modules. Interestingly the other BC module was within -1.4 to +2.5%, thus the deviation was not technology specific. Mono and HIT modules were within -2% and +8.3%. The four partners with very similar setups but different reference cells were within -2% and +3.5%.

Partner 5 was measuring systematically high, similar to STC measurements. However, they were in agreement with the other partners within their uncertainties with the exception of Partner 1 who most likely underestimates their uncertainty (see Figure 7). Partner 1 measured outdoors and was not in agreement with the other partners within its stated uncertainty for one module of each type. However, the partner was not consistently measuring high or low (see Figure 6). The most possible explanation is because LIC outdoors were measured...
outdoors without filters at higher air mass or during cloud cover and thus varying spectral conditions. In addition, correction was applied to translate exactly to 200W that introduces some additional uncertainty.

The high deviation for BC and even higher for HIT modules, compared to the standard mono c-Si modules and STC measurements would indicate that there was a deficiency in the way these modules are measured to mitigate the capacitive artefacts at low irradiance conditions. As mentioned before, partners 5 and 7 did not use section or multi-point measurements to measure \( V_{OC} \). Partners 3 and 12 used the same number of sections as for STC. It was shown at a later stage that this number was insufficient for the particular HIT modules at LIC to mitigate the capacitive artefacts. Thus partner 3 and 12 underestimated HIT results by approximately 0.5%.

c) Maximum power

The deviations of measurements from the median are within the following ranges: -5% to +3% for mono c-Si, -3.1% to +2.8% for HIT and -12.8% to +2.9% for BC. If the one very low measurement for one of the BC modules is considered as an outlier, the lower limit changes to -5% (see Figure 9).

Similar to LIC voltage measurements, partners 3 and 12 did not use sufficient sections for measurement and underestimated \( P_{MAX} \) by approximately 0.6% for HIT modules. Partner 7 used section measurements for HIT modules, but not for the BC modules. Partners 5 did not use section measurements. The systematically high \( I_{SC} \) cancels out with the underestimated voltage measurements for BC and HIT modules. At LIC the percentage error due to capacitive artefacts seems to be larger and HIT modules required a larger number of section or multi-point measurements than at STC.

3.3 Temperature coefficient measurements

Seven partners measured temperature coefficients, two of which were measured outdoors. Some partners measured only one module of each type. It is clear that a few partners underestimated their temperature coefficient’s uncertainty and thus the results were not in agreement within their stated uncertainties. A comprehensive analysis of the uncertainty of temperature coefficients can be found in [7].

a) Short circuit current TC – \( \alpha \)

The measurement deviations from the median for the
module with the larger spread from each technology were -51.2% to +56.3% for c-Si, -33.0% to +30.8% for HIT and -82.3% to +95.1 for the BC module. Partners were generally not in agreement within their stated uncertainties. While these deviations are extremely high in percentage terms it must be noted that $I_{SC}$ temperature coefficients are small in general and the impact of this on energy yield is limited. However with such high deviations, assuming a typical coefficient would be sufficient for some analyses.

From each technology was -6.4% and +14.4% for mono, -6.6% to +18.3% for HIT and -6.6% to +11.6% for BC modules.

In Table 1 a summary of all measurement deviations relative to the median are shown for the module with the larger spread from each technology at all conditions.

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**4 CONCLUSION**

The purpose of the round-robin was to assess the uncertainty analyses of the partners in order to check for potential limitations of their setups and to identify systematic errors. A round-robin such as this is part of the basic quality assurance that reputable laboratories carry out to ensure measurement quality. Although, a couple of the partners developed or re-assessed their uncertainty analyses for this round-robin, at STC, all partners were within their stated uncertainties. The majority of partners were in a much closer agreement (approximately half of the maximum deviation between measurements reported above). This however has to be considered in the context of the correlations between laboratories due to similar equipment and traceability chains.

The round-robin has allowed us to identify that there is room for improvement to achieve better agreement between all partners. In particular, outdoor correction procedures and/or better spectral responsivity...
measurements of large area modules, and consequently mismatch factor correction, could minimise the spread between partners.

The deviation between measurements was larger and the agreement with stated uncertainties was not as good for LIC and TC measurements indicating that there is scope for improvement. In particular, improvements in procedures and equipment can be made to mitigate the capacitive effects of high efficiency modules at lower irradiance, minimise errors due to the non-linearity of the reference device, apply mismatch factor correction with low uncertainty and improve the homogeneity at lower irradiance and the temperature control of the device-under-test. To mitigate the capacitive effects, the number of points or sections in multi-point or multi-section measurements has to be confirmed as sufficient at low irradiance conditions as well as at STC. This number is module specific.

The round-robin identified that partners underestimated as well as overestimated their uncertainties at non-STC measurements and in particular the uncertainty of temperature coefficients, however following the intercomparison the uncertainty estimation methodology has been harmonised between partners.

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6 REFERENCES:


