ROUND ROBINS OF SOLAR CELLS TO EVALUATE MEASUREMENT SYSTEMS OF DIFFERENT EUROPEAN RESEARCH INSTITUTES

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ABSTRACT: Determination of the solar cell efficiency and internal quantum efficiency are standard characterization methods used by the majority of research institutes. Random errors can be assessed by institutes themselves by repeated measurements, but systematic deviations cannot be assessed without comparisons with other institutes. The comparisons were performed for illuminated IV, spectral response and reflection measurements. The results were split into systematic differences between the partners and random differences within an institute for a single measurement session. The total differences are: Jsc: 0.27 A, Voc: 8.5 mV, FF: 2.4 %, η: 0.6%, spectral response: 0.14 A/W and reflection: 0.08. For all measurement methods, the systematic differences exceeded the random differences. The major component for the systematic differences is likely the reference device, but also temperature control, contacting scheme and setup differences play a part.
Keywords: Characterisation, Solar Cell Efficiency, Spectral Response

1 INTRODUCTION

The defining characteristic of a solar cell is its efficiency. Accurate measurements of the solar cell's electro-optical characteristics are of paramount importance.

The most accurate measurements are carried out by the independent calibration laboratories, such as AIST, ESTI, ISE, NREL and PTB. Calibration institutions regularly ship solar cells to each other for measurements in a so-called round robin to ensure a good agreement of the measured parameters and to gain an additional input for their uncertainty calculations. As a matter of fact, these round robins are a prerequisite for the calibration certificate which the calibration laboratories per definition possess [1].

The three measurements involved in the round robins described here are the illuminated IV parameters under standard conditions (STC: 25 °C, 1000 W/m^2, AM1.5G spectrum) [2,3,4], the spectral response under bias light [5] and the reflection [6].

The first two measurements are specific to solar cells. Together they are necessary to determine an accurate short circuit current. The spectral response is needed to carry out a mismatch correction [7] to account for the spectral differences between the solar simulator and the desired AM1.5G spectrum.

Spectral response measurements and reflection measurements together are used to calculate the internal quantum efficiency which can be used to assess at which wavelength photons are less efficiently utilized than desired.

In this paper the results of round robins across ten partners are shown. The aim was to carry out a cross-check of the different measurement set-ups used by the different research partners in Europe and to distinguish the random and systematic differences for each partner.

2 EXPERIMENTAL

Fourteen industrial untabbed p-type H-pattern multicrystalline solar cells with a firing through full Al BSF of 156x156 mm^2 were used for the illuminated IV and the spectral response round robins. The solar cells were supplied by one of the partners.

Reflection measurements are typically done locally on spots of a few centimetres in diameter. A comparison of the reflectance curves of full size multicrystalline solar cells would increase the uncertainty because the replication of the exact measurement spot is important. Therefore two full size monocrystalline solar cells and six small (30x30 mm^2) multicrystalline samples were used. The small samples had an acid texturing and SiN_x coating like the solar cells, but no metal pattern.

All samples were measured independently at the different set-ups of the participants.

3 ILLUMINATED IV RESULTS

3.1 Measurements

All participants used their own reference cells to calibrate their solar simulator. IV results of the fourteen cells are given in Figure 1. Most results are adjusted for mismatch, except those of partner 3 and 5. Partner 5 did measure the mismatch, and decided it was negligible.

A significant spread between the partners in all measured parameters can be seen.

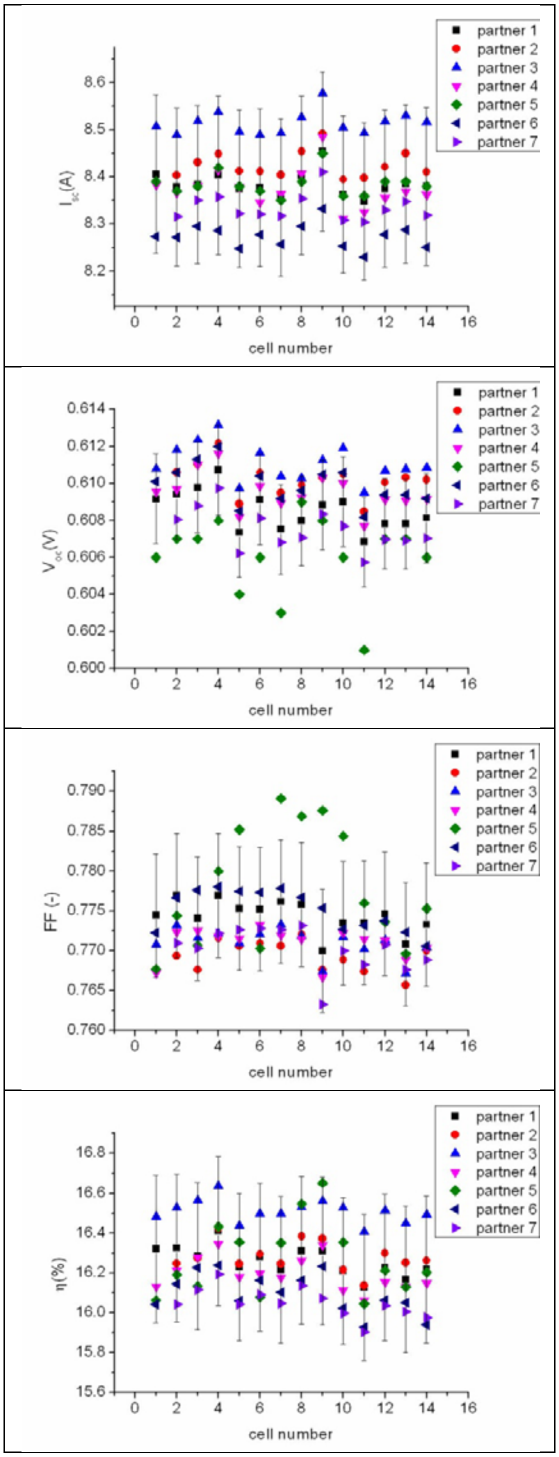

Figure 1: Illuminated IV results of the solar cells with error bar of partner 1 included

The observed maximum spread (the difference between maximum and minimum values) in the absolute values between the different partners for measurements on the same cells is:

- J_{sc}: 0.27 A (~1.1 mA/cm^2)
- Voc: 8.5 mV
- FF: 2.4 %
- η: 0.6%

These values correspond well to the earlier results of the Crystal Clear project [8].

Viewing the raw data, partner 3 stands out for its relatively high short circuit current and corresponding high efficiency, but still within the uncertainties. Also, because partner 3 did not perform mismatch corrections, this could have led to a certain systematic deviation, depending on the particular reference cell used. Partner 5 is notable for the low open circuit voltage in a number of cells and the large scatter in fill factors, both outside the uncertainty of a single partner

The uncertainty limits of the parameters (at 2 sigma) are given by some of the participants in Table I. Only those of partner 1 are included in the graphs for readability. The uncertainty limits for I_{sc} are dominated by the reference cells' uncertainty given by the calibration institutes. Thus the majority of the systematic deviation of partners observed in the results can be attributed to the different reference cells.. Note that partner 5 gives a large uncertainty of the fill factor, which is reflected in the raw data.

Table I: Uncertainty limits as given by the partners

	Isc (%)	Voc (%)	FF (%)	eta(%)
Partner 1	2.00	0.40	1.00	2.27
Partner 2	1.90	0.30	0.70	2.05
Partner 5	2.79	0.34	6.26	6.86
Partner 7	2.56	0.37	1.00	2.77

2.2 Analysis

The systematic deviation (offset) from the median and random error (scatter) for each parameter can be assessed by calculating the average deviation from the median and the standard deviation therein. Using the median instead of the average eliminates the outliers which are present in the current samples. In the graphs in Figure 2 we show the systematic deviation from the median and the random error for the parameters of the illuminated IV.

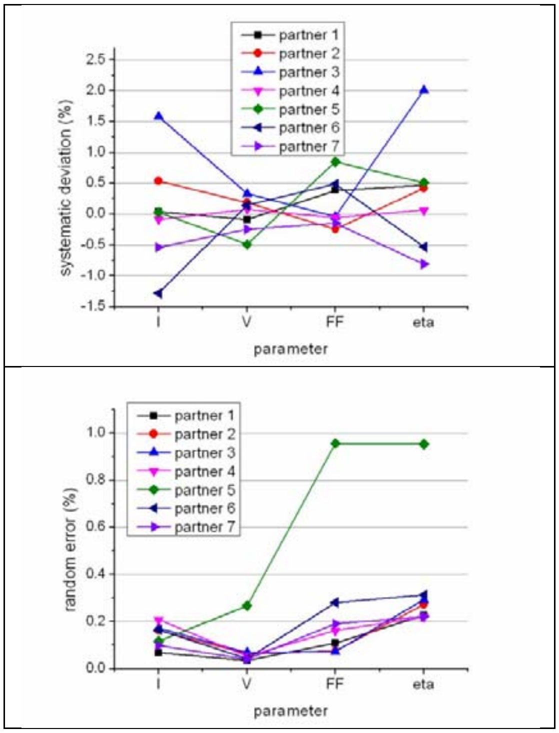

Figure 2: Systematic deviation from the median (offset) and random error (scatter) for each parameter respectively, all in relative values

It should be noted that the systematic deviation from the median does not imply any value is more correct than any of the others, as the real value remains an unknown.

Comparing Table I and Figure 2, it is seen that the partners who supplied an uncertainty estimate seem to be well aware of the quality of their measurements, as in most cases their uncertainty estimate agrees with the assessment of errors given here. The only point at which the two do not conform is the voltage for partner 5, which seems to hold more scatter than the partner was aware of.

3 SPECTRAL RESPONSE RESULTS

3.1 Measurements

All spectral response measurements were of the relative, differential type, in which under bias illumination the increase in current for each measured wavelength is recorded. In this round robin, the cells used were linear, and therefore the differential spectral response equalled the absolute spectral response. An example of a typical spectral response curve from the round robin can be seen in Figure 3. Some partners supplied an uncertainty with the measurements, and these values are also found in Figure 3.

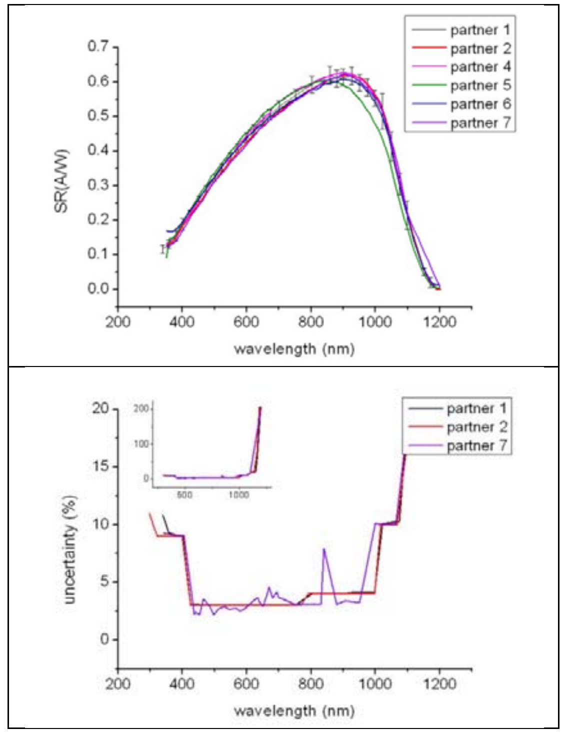

Figure 3: Example of a typical spectral response, with the uncertainty of partner 1 as error bar and below the uncertainties as given by the partners. The small inset is a full zoom out, with a scale an order of magnitude higher than the zoom in

All but partner 5 lie within the uncertainty limits of partner 1. As no uncertainty analysis of partner 5 was performed, we cannot tell whether or not these results lie within each other's uncertainty.

3.2 Analysis

Selection of the wavelengths can be done by filters or grating monochromators. The first option gives no opportunity to select the wavelengths, other than at the building of the setup. The inclusion of filtered spectral response setups in the round robin with disparate filters means that comparisons between the spectral responses of the cells are not straightforward because the wavelength intervals are neither homogeneous nor all identical to each other. By assuming the spectral response is a smooth curve, intermediate values can be calculated by cubic spline calculations.

The method to separate systematic deviations and random errors also works in principle on spectral measurements, except that each spectral response measurement consists of numerous measurements, and the determination of systematic deviation and random error should be performed for all points.

As the uncertainties in the spectral response are given in percentages, the graphs for systematic deviations and random errors follow that convention. However, because at higher wavelengths (~1200 nm) the spectral response reduces to almost zero because of the band gap of silicon, the error in percentages tends to be very large. This has been demonstrated by all partners performing uncertainty calculations on the spectral response measurements. Calibration laboratories supply a similar uncertainty curve.

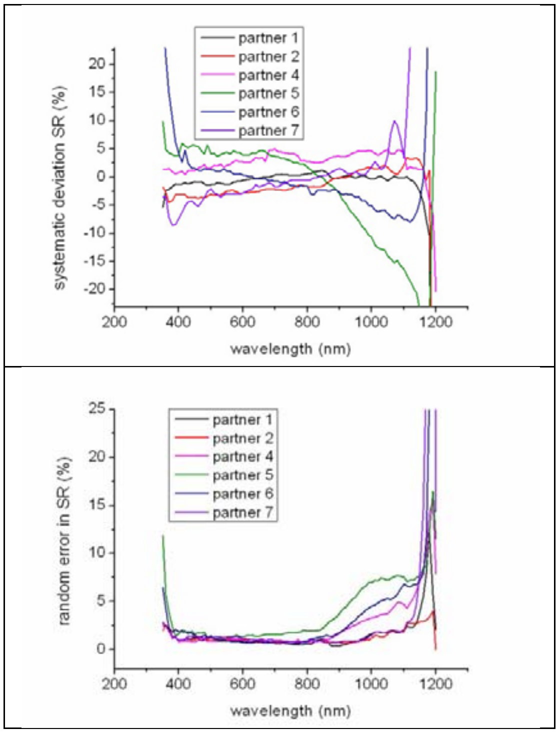

Figure 4: Systematic deviation from the median and random error in spectral response measurements

The maximum of the error scales reaches up to $200\%_{rel}$ at 1200 nm, but a zoom out to that level flattens out all features on other wavelengths, as can be seen from the inset of Figure 3. Note that partner 7 seems to have a high systematic deviation above 1100 nm. This is an artefact caused by lack of data between 1100 and 1200 nm of that partner as this partner is using a filter monochromator system with no filters in that range.

For the three partners supplying uncertainty margins, we note that their random error is within the uncertainty margins given.

4 REFLECTION RESULTS

4.1 Measurements

Measurement setups ranged from component systems to integrated systems of various make. The measurement samples were a mc-Si wafers of 9 cm^2, which was measured in the middle with a measurement spot of at least 1 cm^2. Using the same samples as for IV and spectral response would have yielded additional uncertainties, because it is more difficult to reproduce the exact spot on a larger sample and multicrystalline silicon varies locally strongly in reflectance. To see the effects of the metallization, monocrystalline solar cells were used, which are very homogeneous in reflectance. Each institute used their own reference sample for calibration. Uncertainties of reflection setups were not given by the vast majority of partners. An example of the reflection of the monocrystalline samples is shown in Figure 5.

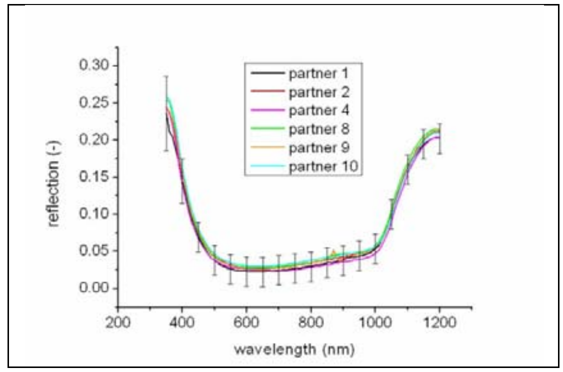

Figure 5: Example of the reflection of a monocrystalline solar cell. The error bar is from partner 1

Every partner has delivered reflection curves within the uncertainty of a single partner.

4.2 Analysis

The wavelength interval of the different setups differed between 0.5 nm and 10 nm. Although additional data could be generated by cubic splines, the maximum wavelength interval is so small that the choice has been made to use the common interval of 10 nm, of which all participants had measured data. As the curves are smooth, this presents no problems.

For each data point of each of the graphs a systematic and random deviation was calculated in an analogous way as for the spectral response graphs. However, the commonly used uncertainty notation of the reflection curve is in absolute values, whereas for the spectral response (as for illuminated IV measurements) commonly relative notation is used. This distinction is kept here.

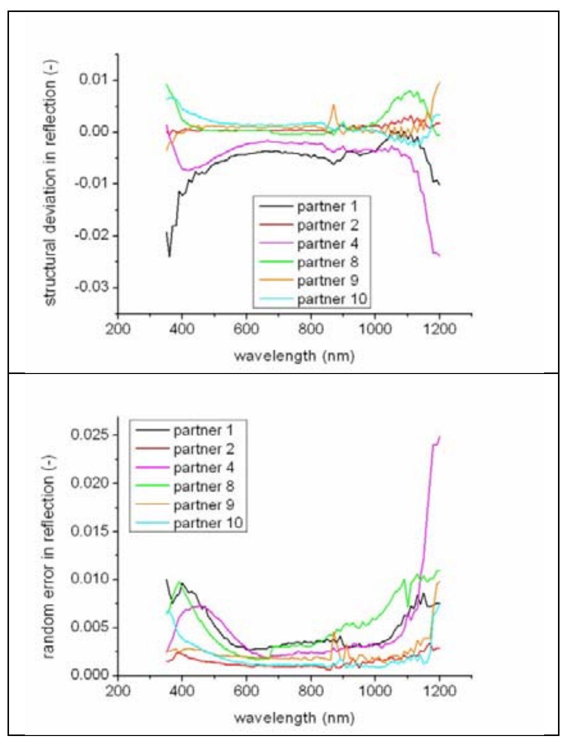

Figure 6: Systematic deviation from the mean and random error for reflection measurements

The random error is for almost all wavelengths below $1\%_{abs}$ reflection. The structural differences are quite a bit larger, between $1\%_{abs}$ at the minimum and almost $4\%_{abs}$ at maximum between the minimum and maximum values given for each separate wavelength.

5 DISCUSSION

5.1 Illuminated IV measurements

The differences in IV measurements are largely due to systematic differences instead of random differences, indicating a good reproducibility within the institutes themselves.

The short circuit current is mostly influenced by the settings of the solar simulator, which in turn is mostly influenced by the reference cell. Using the same reference cell will strongly decrease the systematic differences [8]. Four partners actually have given nearly the same short circuit current.

The voltage of a solar cell is an independent measurement which should be measured with sufficient accuracy by a good voltmeter. The external factor with the most influence on the voltage is the temperature. The temperature control is commonly excellent, even if the different absolute values of the cell are not always identical. Different absolute values may arise because the temperature control can be executed on the cell by a probe contact or a pyrometer, or by temperature control of the chuck.

Systematic differences in fill factor may arise because of different contacting schemes. Most contacts are established by multiprobe configurations, but the number of probes is not identical. The higher random component in the fill factor indicates that the reproducibility of the contacting may be an issue at times. Possible reasons for problems with the repeatability may be inconvenient views of the contact situation, lack of physical aids for cell positioning, insufficiently stiff probe holder and wear and tear of the probes for example. Another possible source of uncertainty in the measured FF is the lack of temperature correction in case the cell was not at exactly 25 °C during the measurement.

An obvious factor in the random error of all measurement parameters is the noise in the electrical system.

5.2 Spectral response measurements

The differences between partners are mostly due to systematic differences, which can be attributed to several causes.

The reference cell is the first and most obvious reason for systematic differences, as the current of the sample cell at each wavelength is compared to the reference cell.

Another cause of systematically differing spectral responses are fundamental differences in setup, to do with the filter or monochromator types. Partners 1, 2 and 7 possess setups of the former type, partners 4, 5 and 6 of the latter. A view of the systematic differences (Figure 4) shows that indeed the measurements sets can be split in two groups: a group with a positive slope (filter) and a group with a negative slope (monochromator).

Systematic differences may also arise from strong deviations in temperature control.[9] The short circuit current which is measured in spectral response is not as sensitive to temperature as the open circuit voltage, but the response to different wavelengths does change with the temperature; the infrared response decreases with lower temperatures [10].

Random errors are quite small compared to the systematic differences. Again we observe a difference between the monochromator and the filter setups. In the former there is an increase in the scatter of the data for the infrared part. Sources of scatter in spectral response data are insufficient control of temperature or irradiance and general noise in the electrical setup.

5.3 Reflection measurements

Calibration in reflectance measurements is generally done by measuring a reference sample. It is possible to have the reference sample calibrated by a certified institute, but manufacturers may deliver their own reference samples as well, which are generally not certified.

The differences between the partners are mostly systematic. The reference sample is also in this case the first culprit of systematic differences. Soiling and dust may diminish the reflectivity of the reference sample, leading to lower reflectance curves. Another source of systematic differences is the setup which is not identical for all participants. It should be noted however, that also setups of different make can give reflection results very close together, and as such the setup is a source of secondary differences only.

Random error is strongly concentrated upon the high and low wavelength regions. High wavelength regions are measured with a different detector than the low and mid wavelength regions, and by nature these detectors have a higher uncertainty in counts. The accuracy of the low wavelengths may depend on the light intensity of the illuminating lamp at those wavelengths. Not every lamp used for reflection has a high UV component, both for safety reasons and practical reasons, but as a consequence the noise level of the measurement suffers in the UV region.

6 SUMMARY AND OUTLOOK

Round robins for illuminated IV, spectral response and reflection are held among ten institutes in Europe. Fourteen mc-cells were used for the illuminated IV and spectral responses, and dedicated samples for the reflection round robin.

For the illuminated IV, a spread of J_{sc} of 1.1 mA/cm^2, a spread of 8.5 mV in V_{oc} and a spread of 2.4% in fill factor were found. These spreads are mostly due to systematic differences in equipment of the partners, rather than random errors; in other words, the reference cell and the absolute temperature of the measured cell are likely origins of the deviations. The fill factor is notably less stable per partner than the short circuit current and the open circuit voltage, indicating that repeatable contacting is not easy to accomplish.

The spectral response suffers mostly from systematic differences. This may arise from differences in the reference cell. We also see a slight effect of the type of spectral response setups. Both the systematic deviations and the random error increase at high and low wavelengths, at which points the spectral response is minimal. Slight differences in the reference cell get enlarged here, and at low signal the noise of the setup is largest.

Also for the reflectance samples, the systematic differences between the partners are dominant, mostly caused by differences in the reference sample, and only secondary by differences in the setup.

The European project SOPHIA financed the round robins for the larger parts, although also partners outside SOPHIA have participated. Additional round robins are planned within SOPHIA regarding carrier mobility measurements and illuminated IV measurements regarding bifacial cells with single sided illumination.

7 ACKNOWLEDGEMENTS

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