Presented at the 20th European Photovoltaic Solar Energy Conference and Exhibition,
Barcelona, Spain, 6-10 June 2005

COMPARISON BETWEEN LARGE REFERENCE CELLS CALIBRATED BY ESTI-JRC, NREL AND PTB, PERFORMED AT ECN

Arvid van der Heide[1,2], Stefan Winter[3], Tom Moriarty[4], and Wim Zaaiman[5]
[1]Energy research Centre of the Netherlands, Westerduinweg 3, 1755 LE Petten, Netherlands
[2]Now at Photovoltech, Grijpenlaan 18, 3300 Tienen, Belgium, email: arvid.vanderheide@photovoltech.be
[3]Physikalisch-Technische Bundesanstalt, Bundesallee 100, D-38116 Braunschweig, Germany, email: stefan.winter@ptb.de
[4]National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, CO 80401-3393, USA, email: tom_moriarty@nrel.gov
[5]Joint Research Centre of the European Commission, Via E. Fermi 1, I-21020 Ispra, Italy, email: willem.zaaiman@jrc.it

ABSTRACT: Calibrations of large area reference cells performed at ESTI-JRC, NREL and PTB were compared at ECN. The cells that constitute the so-called World Photovoltaic Scale (WPVS) are only 4 cm^2 in size. In this study for the first time large area cells (100 cm^2, 156 cm^2, 225 cm^2) have been used for intercomparisons between the leading calibration institutes. The short circuit current calibrations at ESTI-JRC and NREL were performed in a solar simulator, including a spectral mismatch correction. PTB uses absolute spectral responsivity curves at different bias levels for calibration. For the calibration comparison at ECN a 156 cm^2 cell calibrated at NREL was used as a reference to determine the (mismatch corrected) short-circuit currents for all other cells in the ECN solar simulator. The differences between specified calibrated short circuit currents and measurements at ECN were found to be <1% for 156 cm^2 cells. The largest deviation for all cells, after correction for beam non-uniformity was found to be 1.3%, for a 225 cm^2 cell. The conclusion is that the variation of calibrations performed by the three calibration institutes for cells upto 225 cm^2 is within +/- 2% error margin that is specified for the small WPVS cells.
Keywords: Characterisation, Solar Cell Efficiencies, Spectral Response.

1 INTRODUCTION

The most difficult factor in determining the correct efficiency of a solar cell is the measurement of the short-circuit current at standard test conditions. At the beginning of the nineties, the leading calibration laboratories agreed to establish a World Photovoltaic Scale (WPVS) [1,2] as a worldwide reference for the short-circuit current calibration of primary reference cells, since at that time no international standard was available. This was based upon the same philosophy as the World Standard Group of Pyrheliometers (located at the PMOD in Davos, Switzerland) determining the World Radiometric Reference (WRR).

After the 1st WPVS round robin [1], 4 laboratories qualified to maintain the WPVS: the National Renewable Energy Laboratory (NREL, USA), the Physikalisch-Technische Bundesanstalt (PTB, Germany), the Japan Quality Assurance Organisation (JQA) jointly with the Electrotechnical Laboratory (ETL, Japan) and the Tinanjin Institute of Power Sources (TIPS, China). In October 2004, also ESTI-JRC qualified.

The cells used in the WPVS comparisons between laboratories are 4 cm^2 in size. Until now no comparisons for larger sized cells have been published, which would be very relevant since all industrial cells are larger.

The purpose of this work is to present results of the comparison between calibrations performed at different institutes for large mc-Si solar cells, up to 225 cm^2 in size. The laboratories that calibrated the cells were NREL, PTB and ESTI-JRC. The calibration comparison was independently performed at ECN.

2 APPROACH

For the comparison, several multi-crystalline silicon solar cells made at ECN were used. Cells with a high shunt resistance have been selected to reduce possible inaccuracies in the determination of the short-circuit current density. Most of these cells were mounted onto 0.5 mm copper plates because they are used as reference cells for the solar simulator at ECN. To enable mounting of the cells, silver is evaporated on them and a conductive adhesive containing silver particles is used to glue the cells onto the plates. To avoid damage to the busbars due to frequent use as reference cells, tabs have been soldered on top of the busbars. A picture of one of the reference cells is shown in Fig.1.

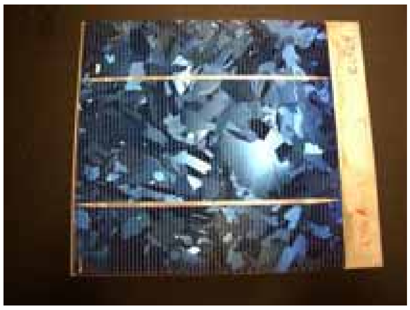

Figure 1: One of the reference cells used in the comparisons; it is glued on the metal mounting plate, this cell is 156 cm^2 in size.

The number of cells sent to each institute is listed in Table I, only one cell (a 100 cm^2 sized cell) has been sent to two institutes, the total number of cells is 9.

Institute	100 cm^2	156 cm^2	225 cm^2
ESTI-JRC	2	2	1
NREL	1	2	-*
PTB	-	1	1

Table I: Cells used in the calibration comparison. The * indicates that the cell was damaged during transport.

The standard practice to determine the short circuit current of a solar cell at standard test conditions (STC) is by using reference cells [3]. The STC have been defined to be a total light intensity of 1000 W/m^2, a reference solar spectral irradiance distribution called AM1.5 Global [4] (the combination of this intensity and spectrum is often summarised by using the phrase 'one sun'), a nearly perpendicular incidence of the irradiation on the cell surface and a cell temperature of 25 °C.

The intensity of the solar simulator is adjusted so that the short-circuit current flowing through the reference cell equals the calibration value. Then the current of the sample of interest is measured, and this value is divided by a spectral mismatch factor [5] to correct for differences between the lamp and the sun. To calculate the spectral mismatch, the spectrum of the solar simulator and the relative spectral responsivity [6] of both reference cell and sample of interest have to be measured.

To be able to use the procedure described above, in the end primary reference cells have to be calibrated using primary standards. Two different approaches are used for this purpose, namely outdoor measurements (e.g. at NREL and ESTI-JRC) and absolute spectral responsivity measurements (PTB). Within this intercomparison, primary standards were only available at NREL and PTB; at ESTI-JRC reference cells were used with WPVS calibration value. Since January 2005, also ESTI-JRC has primary standards available, but that was after the measurements for this paper.

The details of the NREL primary reference cell calibration are described in [7]. The solar spectrum is measured (relatively) with a spectroradiometer, at the same time an absolute cavity radiometer is used to convert the relative spectrum into an absolute one. Using another measurement set-up the relative spectral responsivity of the cell is determined. Finally, using the absolute spectrum, the relative spectral responsivity and the measured outdoor short-circuit current, the value of the short-circuit current for STC is calculated.

The other approach, used at PTB, is to determine the differential spectral responsivity curve for different bias levels with a high degree of accuracy [8], using a spectral response set-up that is partly shown in Fig. 2.

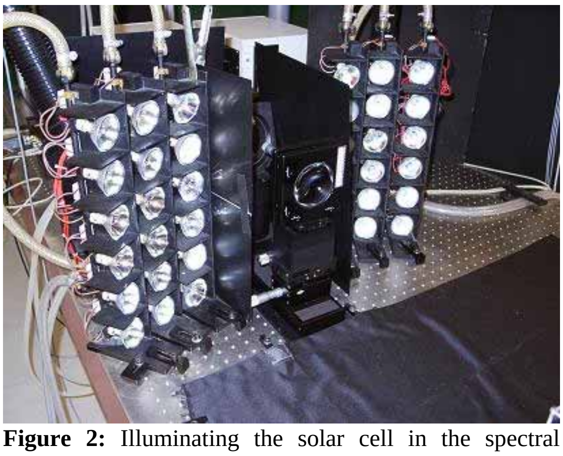

Figure 2: Illuminating the solar cell in the spectral responsivity setup at PTB: 36 halogen lamps are used for a uniform bias illumination, inbetween is the lens that projects the chopped monochromatic light onto the cell.

The short-circuit current is calculated by summing the current contributions produced at every wavelength, that are obtained by multiplying the irradiance in the AM1.5 spectrum with the spectral responsivity at that particular wavelength. To obtain an accurate result, it is important to use a spectral responsivity that has been averaged in a certain way over the biases between 0 and 1 sun, because the spectral responsivity curves of solar cells can be strongly bias-dependent. When using the absolute spectral responsivity for calibrations it has to be measured very accurately. This contrasts with the measurement of the spectral responsivity only for spectral mismatch correction and measuring the short-circuit current in a solar simulator. In that case relatively large inaccuracies in the spectral responsivity can be accepted. Only PTB has proven to be capable to perform the calibration using only spectral responsivity measurements with sufficient accuracy to meet the WPVS requirements.

In the set-up at PTB, a Xenon lamp is used as the source for the wavelengths up to ~600 nm, while a tungsten filament lamp is used for the longer wavelengths. To compensate for changes in lamp intensity, a monitor photodiode is used that monitors the intensity within the monochromatic beam via a beam splitter. Two lock-in amplifiers are used to be sure that the measurement of the solar cell signal and the monitor photodiode signal are performed exactly at the same moment. Two monochromators in series are used to filter the light, the step size used in the measurement is only 2 nm. To obtain a uniform bias illumination up to 36 halogen lamps can be used. Cell sizes up to 225 cm^2 mm can be measured using the set-up. The calibration of large cells does involve many reference measurements at different positions within the monochromatic beam since the used primary reference cells, that have been calibrated internally at PTB are only 4 cm^2 in size. Since the system is fully automated this is not a major problem, but a calibration of a large cell will of course take some days of measurement time.

Finally, all calibrated cells have been compared with the solar simulator at ECN, one of the 156 cm^2 cells is taken as the reference for all the other cells. The solar simulator is home-built at ECN around a Spectrolab X-10 Xenon light source, which is class A up to cell size 225 cm^2. Class A means a non-uniformity of the integrated irradiation <±2%, temporal instability <±2% and the deviation of the energy in certain wavelength intervals from the standard spectrum <±25%. The ECN solar simulator has a non-uniformity just below ±2%, and the temporal lamp instability is around ±0.5%. But even for these small changes in intensity a correction in cell current is made, using data from a small monitor solar cell located next to the measurement table. To have a good uniformity also at larger cell sizes, the current set-up at ECN will be replaced by a new one at the end of this year, that will enable measurement of solar cells up to 900 cm^2 in size.

A picture of the current set-up at ECN is shown in Fig. 3, with the box containing the 1000 W Xe lamp clearly visible on top of the set-up.

Figure 3: Solar simulator at ECN, used to measure the J-V curves for solar cells up to 225 cm^2 in size.

To enable spectral mismatch correction, spectral responsivity measurements at a bias level of 0.5 sun were made with the filter monochromator set-up at ECN (see Fig. 4), using the PTB calibrated cells as reference cells.

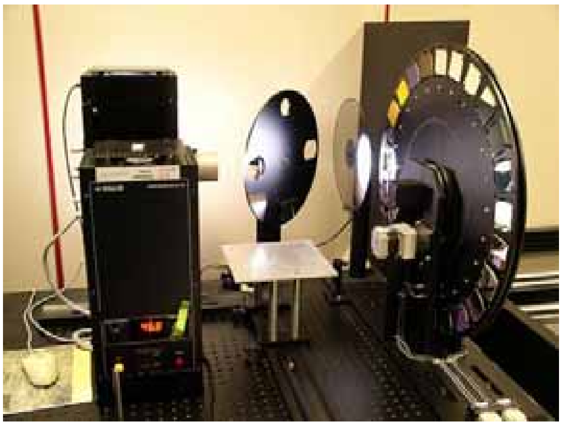

Figure 4: Filter monochromator setup at ECN. Above the measurement table (positioned outside the picture) a mirror is mounted to enable horizontal cell mounting.

In the filter monochromator set-up, around 30 filters with wavelenghts between 340 and 1200 nm are used to filter the light emitted by the 1000 W xenon lamp. The measurement itself takes around 3 minutes per solar cell, and is performed on the full cell area, for cells up to 225 cm^2 in size.

The spectrum of the solar simulator is calibrated every three months with a spectroradiometer from Instrument Systems, the light is collected with an integrating sphere and transported to the instrument via a glass fiber. To enable correction for the transmission of the combination of integrating sphere and glass fiber, before every solar simulator calibration first the precisely known spectrum from a calibrated halogen lamp is measured. This lamp has been primary calibrated at the National Institute of Standards and Technology (NIST) in the USA.

3 RESULTS

The differential spectral responsivity curves measured by PTB for different bias levels are shown for the 156 cm^2 cell in Fig. 5.

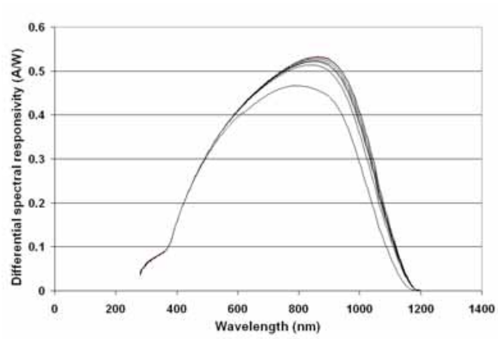

Figure 5: Absolute differential spectral responsivities for the 156 cm^2 cell at different bias levels. The levels are (in suns) 0.00001, 0.005, 0.052, 0.11, 0.38, 1.02 and 1.14, the spectral responsivity curves increase with bias level.

For the 225 cm^2 cell the curves are shown in Fig. 6.

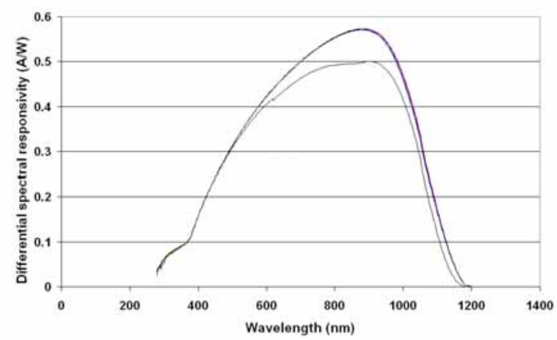

Figure 6: Absolute differential spectral responsivities for the 225 cm^2 cell at different bias levels. The levels are (in suns) 0.00001, 0.004, 0.041, 0.10, 0.26, 0.70 and 0.80, the spectral responsivity curves increase with bias level.

It is clear that the absence of any bias results in a spectral responsivity curve that deviates strongly from the spectral responsivity curve for standard test conditions, this is due to trapping. Therefore, always a bias level that is high compared with the monochromatic irradiance is required to get a well defined spectral responsivity curve.

It is interesting to note that there is quite a difference in bias dependence for the two cells. Apart from the measurement with negligible bias, the 225 cm^2 cell does not depend on bias, while the 156 cm^2 cell is quite bias dependent. This is probably related to a difference in material quality between the cells, because there were no significant differences in the fabrication process.

From the curves shown, the calibrated values of the short-circuit current $I_{sc,\mathrm{cal}}$ were determined for both cells. At ESTI-JRC and NREL, $I_{sc,\mathrm{cal}}$ values were determined with a solar simulator, using their own reference cells and a spectral mismatch correction. The values they found are given in the table below. Also given are the values of $I_{sc,\mathrm{ECN}}$ determined at ECN with cell 125-C as the reference cell, including spectral mismatch correction and a beam non-uniformity correction for the 100 cm^2 and 225 cm^2 cells. This beam non-uniformity correction takes into account that the intensity near the centre is somewhat higher than near the edges, so that a cell <156 cm^2 will experience a slightly higher intensity, and cells >156 cm^2 will experience a somewhat lower intensity than the reference cell. By measurements of the intensity with a 4 cm^2 cell at several locations in the beam it was calculated that the measured currents for the 100 cm^2 cells should be lowered by about 0.3%, the measured currents of the 225 cm^2 cells should be increased by about 0.9%. The principle of the correction is just the comparison of the average intensities for the different cell sizes. Note that only the 100-B was calibrated at two institutes (NREL and ESTI-JRC), all the other cells were calibrated once.

Cell	Calibrated	$I_{sc,\mathrm{cal}}$	$I_{sc,\mathrm{ECN}}$	ΔI (%)
100-A	ESTI 2002	3.020 ± 1.9%	3.032	+0.1
100-B	ESTI 2002	3.006 ± 1.9%	3.019	+0.1
100-B	NREL 2003	3.023 ± 2.0%	3.019	-0.4
125-A	ESTI 2002	4.780 ± 1.9%	4.816	+0.8
125-B	ESTI 2002	4.731 ± 2.0%	4.716	-0.3
125-C	NREL 2004	5.311 ± 2.0%	5.311	---
125-D	NREL 2004	5.380 ± 2.0%	5.393	+0.2
125-E	PTB 2004	4.752 ± 2.9%	4.724	-0.6
150-A	ESTI 2002	6.858 ± 1.9%	6.808	+0.2
150-B	PTB 2004	7.247 ± 2.8%	7.122	-1.3

Table II: Results of the calibration comparison. All currents are indicated in A. ΔI is the difference $I_{sc,\mathrm{ECN}}$-$I_{sc,\mathrm{cal}}$ in % of $I_{sc,\mathrm{cal}}$. The solar cell 125-C, calibrated by NREL, was used as the reference cell at ECN. A beam non-uniformity correction was included in the values of the last column, for the cells that are not 156 cm^2 in size.

The largest difference between measured current and calibration value for the 156 cm^2 cells, for which no non-uniformity correction had to be used, is 0.8 %. This is well within the ± 2% interval allowed for the 4 cm^2 cells used within the WPVS. The 0.8% is also small compared to the errors specified by the institutes for the calibrations of the large area cells (see Table II).

For the cells that had a size differing from the size of the reference cell the maximum deviation was found to be 1.3% for one of the 225 cm^2 cells , which is also well below 2%.

4 CONCLUSIONS

In this paper it was shown by an experiment comparing calibrations from different institutes at ECN that also for large sized solar cells, the differences between the calibrated I_{sc} values are within the ± 2 % limit specified within the World Photovoltaic Scale. Within the group of 156 cm^2 cells, the maximum difference between measurement and calibration was only 0.8%, so well within the ± 2 % interval.

For the cells smaller/larger than 156 cm^2 a correction has been made for small differences in the average intensity experienced by these cells, compared to the cell used as reference. Including the correction, based on calculated average beam intensities, the largest deviation between measured current and calibration current was found to be 1.3%, well within the ± 2% error interval that is specified for the small WPVS cells.

It has therefore been shown that even for large area industrial solar cells, accurate comparisons between solar cells can be made using cells calibrated at the leading calibration laboratories in the world.

5 REFERENCES

[1] C.R. Osterwald, S. Anevsky, A.K. Barua, K. Buecher, P. Chaudhuri, J. Dubard, K. Emery, B. Hansen, D. King, J. Metzdorf, F. Nagamine, R. Shimokawa, Y.X. Wang, T. Wittchen, W. Zaaiman, A. Zastrow, J. Zhang, "The Results of the PEP'93 Inter-comparison of Reference Cell Calibrations and Newer Technology Performance Measurements: Final Report", National Renewable Energy Laboratory, Tech. Rep. NREL/TP-520-23477, 1998 (available at http://www.osti.gov/bridge)

[2] C.R. Osterwald, S. Anevsky, A.K. Barua, K. Buecher, P. Chaudhuri, J. Dubard, K. Emery, B. Hansen, D. King, J. Metzdorf, F. Nagamine, R. Shimokawa, Y.X. Wang, T. Wittchen, W. Zaaiman, A. Zastrow, J. Zhang, Progress in Photovoltaics: Res. Appl. **7** (1999) 287.

[3] IEC 60904-1: Measurement of photovoltaic current-voltage characteristics.

[4] IEC 904-3 or ASTM G-173 (they are almost equivalent, the ASTM is the most recent one).

[5] IEC 60904-7: Computation of spectral mismatch error introduced in the testing of a photovoltaic device.

[6] IEC 60904-8: Measurement of spectral responsivity of a photovoltaic (PV) device.

[7] C.R. Osterwald, K.A. Emery, D.R. Myers, R.E. Hart, Proceedings of the 21st IEEE Photovoltaic Specialists Conference, (1990) 1062.

[8] S. Winter, T. Wittchen, J. Metzdorf, Proceedings of the 16th European Photovoltaic Solar Energy Conference, (2000) 2198.