PRECISE MEASUREMENT OF SOLAR CELL PERFORMANCE IN PRODUCTION

Wilhelm Warta, Jochen Hohl-Ebinger, Astrid Ohm, Katinka Kordelos
Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstrasse 2, 79110 Freiburg, Germany
Phone: +49 761 4588 5192, Fax: +49 761 4588 9250, Email: wilhelm.warta@ise.fraunhofer.de
Stefan Winter, Physikalisch Technische Bundesanstalt PTB, Braunschweig
Ralf Adelhelm, Detlev Berger, Berger Lichttechnik, Pullach, Germany
Hans-Peter Hartmann, Dirk-Holger Neuhaus, Deutsche Cell, Freiberg, Germany
Manfred Wald, Thomas Kieliba, Bosch Solar Energy AG, Erfurt, Germany
Horst Albert, HALM, Frankfurt, Germany
Britta Hund, Jörg Isenberg*, Q-Cells, Bitterfeld-Wolfen, Germany
Henning Nagel, Joachim Fölsch, Schott, Alzenau Germany
Peter Grabitz, Wolfgang Lattwein, Solarwatt Cells, Heilbronn, Germany

ABSTRACT: The economical relevance of a shift of several percent in the produced output of a PV factory is obvious. Basic for the assessment of cell performance in the cell sorter measurements at the end of a production line are calibrated references. We report on the leading-edge achievements of a co-operation project between most relevant German cell and test equipment manufacturers with Fraunhofer ISE CalLab PV Cells and the PTB in this research field. A significant reduction in the uncertainty of the calibration of large area industrial cells without cell inter-connectors has been achieved. Uncertainty in the short circuit current was reduced from previously 2.5 % to now 1.8 %. A series of measures to assure long term comparability of calibration results was established. Criteria for the selection of reference cells were agreed upon. Optical features of industrial cell testers were assessed on the basis of a complete uncertainty calculation for the attribution to a simulator class. Some progress steps in the complex metrology of a light sensitive device are exemplified in the paper.

Keywords: Calibration, production testing, solar cells, accuracy

1 INTRODUCTION

Solar cells are returning income in proportion to their performance data. The accuracy of performance measurements in production at standard test conditions STC (IEC 60904-3) is thus an economic factor of enormous financial impact, in particular with increasing competition and pressure on the margins. Cell calibration as a research topic, however, is still not generally recognised. Thus, this paper shall also contribute to foster awareness of the fundamental difference between a simple IV-measurement and the requirements to establish and maintain a high precision traceable calibration in production.

In support of the continuous improvement of quality control done within each company, a consortium of most major German manufacturers of silicon solar cells and the two major manufacturers of performance measurement equipment cooperated with Fraunhofer ISE CalLab PV Cells and the PTB, Braunschweig within the past three years to improve the accuracy of performance measurements in production. The cooperation rendered improvements all along the calibration chain starting with the special packaged reference cells calibrated as primary standards at PTB, the transfer to industrial production cells at ISE CalLab PV Cells and the use of the calibrated industrial cells to realize standard irradiation conditions in production.

The most critical links in any calibration chain are the transition points between different types of detectors, a fact which is well known in metrology. In our case, this transfer occurs at two instances: (i) at the PTB from the radiometric unit represented by a cryoradiometer (uncertainty < 0.01 %) via a transfer normal (uncertainty about 0.1 %) to 2 x 2 cm² silicon solar cells packaged with temperature sensor and electric connectors in a WPVS-type housing (see e.g. [1]) and (ii) at ISE CalLab PV Cells where large area bare industrial solar cells suitable for use in an industrial cell sorter are calibrated against these small primary calibrated devices. At the first link, the PTB has succeeded to improve the calibration uncertainty of the short circuit current of WPVS-type devices to < 0.7 %. A central part of the further improvement work was done at ISE CalLab PV Cells in order to precisely determine and reduce the uncertainty components involved in step (ii). Basis was an in-detail analysis of uncertainty contributions, including a determination of the uncertainty of the current mismatch factor using a random walk approach.

Hardware to assess irradiation spectra and lateral uniformity of simulators was developed and characterized in depth. In particular, the uncertainty of the classification of a simulator according to IEC 60904-9 was elaborated, which is a non-trivial task for such an integral quantity. A range of industrial cell classifiers was inspected at the sites of the partners. This provides the basis for improvements to be realized, e.g. by the equipment manufacturers. The analysis of this component of the chain confirms, that the main uncertainty in the classifying process is introduced by the reference cell

*present address: centrotherm photovoltaics technology GmbH, Blaubeuren, Germany

and the irradiation spectrum, if not well matched calibrated cells are employed. Selection of reference cells according to agreed criteria minimizes this uncertainty.

2 UNCERTAINTY OF INDUSTRIAL CELL CALIBRATION AT ISE CALLAB PV CELLS

The complete uncertainty budget for the cell calibration at ISE CalLab PV Cells was put on an actual basis. Major contributions were found to be the uncertainty of the primary reference and the current mismatch correction. The current mismatch is corrected by taking into account the differences between simulator spectrum and standard spectrum on the one hand and spectral response of the test cell and the reference cell on the other hand. Thus, uncertainty determination was needed (i) for the spectral response measurement of the test cell, (ii) for the measurement of the simulator spectrum and (iii) the propagation of these uncertainties into the mismatch correction factor. For (i) spectral dependent factors in the spectral response measurement like the filter non-uniformity or the extent of blocking had to be considered [2]. The spectral response of the test cell is usually measured with a differential spectral response (DSR) measurement setup. We have investigated different approaches for measuring the spectral response of non-linear solar cells. The aim was here to simplify the differential spectral response method in order to determine the spectral response at STC with just one DSR measurement and estimate the uncertainty added by this simplification. The White Light Response (WLR) method solved this task [3] and is used routinely meanwhile.

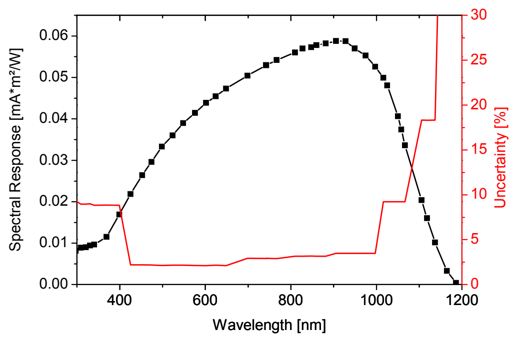

Fig. 1: Spectral response and individual uncertainty of an example test cell. At CalLab PV Cells wavelength dependent uncertainties are determined routinely in a filter monochromator measurement using the DSR-method.

For the measurement of simulator spectra a diode-array spectroradiometer was analyzed in great depth. This enabled us to determine the spectral dependent uncertainty for such a measurement even for flash simulators, where the timing is a critical point [4]. Experience was transferred to the industrial partners in workshops on spectroradiometer calibration. The propagation of the various uncertainty components via the integral calculation of the mismatch factor was treated with a random walk calculation [5] extending the pioneering work of Field and Emery [6].

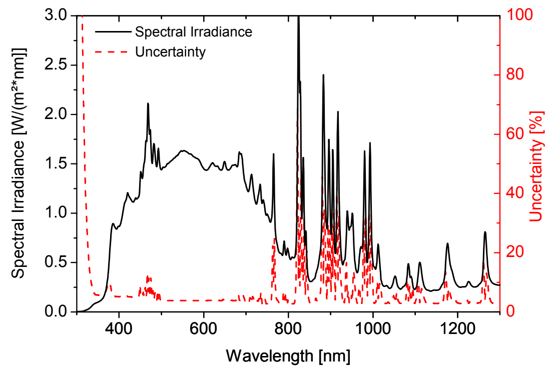

Fig. 2: Example for the measured spectral distribution of a steady state simulator. Also for this measurement wavelength dependent uncertainty is routinely determined.

An important outcome was, that in ill-defined constellations of reference and measured device the mismatch factor itself may appear to be quite small and thus uncritical, the uncertainty, however, indicates that an error of up to 2 % may be introduced within uncertainty margins. Suitable selection of a reference cell thus results not only in a small current mismatch, but also in a low uncertainty of the mismatch factor. It is thus important to keep in mind, that a low mismatch factor by itself does not guarantee, that also the uncertainty of this mismatch factor is low.

As a main result of the project, the expanded uncertainty (k = 2, coverage probability 95 %) given for large area cell calibration at ISE CalLab PV Cells are reduced to U_{Isc} = 1.8 %; U_{Voc} = 0.3 %; U_{FF} = 0.7 %; Uη = 2.0 %. The respective margins at the begin of the project had been U_{Isc} = 2.5 %, U_{Voc} = 0.5%, U_{FF} = 1.0%, U_η = 3.0 %. ISE CalLab PV Cells is meanwhile accredited by the Deutsche Kalibrierdienst DKD according to ISO 17025 to perform the calibration of large area industrial solar cells with these uncertainties.

3 MEASURES TO SECURE LONG-TERM COMPARABILITY OF RESULTS

The achieved error margins for reference solar cell calibration values are, although already quite demanding from the viewpoint of a calibration lab, highly problematic for industry: An offset in efficiency of 4 % between two calibrations, which is possible within uncertainty, should clearly be prevented. We therefore worked out a series of additional measures which are aiming to relax this conflict between state-of-the-art calibration and industry needs.

3.1 Primary reference cell development and quality control

The primary calibrated references are a main uncertainty component. The WPVS-type packaged reference cells underwent several improvement cycles. Aims were long temporal stability, low reflectivity, options to realize various spectral response and manufacturability. Effects like an unexpected high current collection from the surrounding of the actual silicon cell had to be detected [7], [8] and ruled out for the present package design. On the basis of the actual design the reference cell basis and thus the significance of in-house inter-comparisons is further improved.

3.2 Primary calibration of large area cells

A side branch of the main traceability chain is established based on primary calibration of large area industrial cells. A package design for mounting large area cells with good thermal contact and built-in temperature sensor was developed. Special emphasis was put on long-term stability. Work at PTB within the project concentrated on establishing the ability to do primary calibration with the DSR (differential spectral response) method on such mounted large area cells. The related improvements of the DSR calibration facility are nearly completed. A drastic reduction of the previous uncertainty for the short circuit current of these cells to ± 1.3 % is anticipated.

3.3 Absolute Spectral Response

The analysis and related improvements on the DSR measurement apparatus at ISE CalLab PV Cells did not only allow us to obtain an individual wavelength-dependent uncertainty, in addition the resulting SR values can now be taken as absolute ones. Integrated over the standard spectrum, they can be directly compared to the short circuit current measurement under the solar simulator. This allows us a control of the calibrated short circuit current in reference to a second independent traceability chain (provided different primary calibrated cells are used for IV and SR-measurement).

3.4 Pool of large industrial reference cells at ISE CalLab

Calibrations have to be done against primary calibrated cells, which are by nature not identical in spectral response to a specific industrial cell, a significant current mismatch correction may apply. As a result of the co-operation in the project, a set of previously calibrated industrial cells is kept at ISE CalLab PV Cells, which are representative of the production for all contributing cell manufacturers. The respective cells are used as a further comparison means in successive calibrations.

4 SELECTION OF REFERENCE CELLS AND MEASUREMENT CONDITIONS IN INDUSTRY

Criteria for the selection of solar cells to be used as references have been compiled based on the experience of the partners:

- cells should be from the bin which represents the centre of the performance distribution for a specific technology;
- cells should be stable, i.e. pre-degraded at the manufacturer;
- planar cells give optimum thermal contact on the chuck (no interconnectors at back).
- spectral response should be as linear as possible;
- current non-uniformity should not be too pronounced;
- optical non-uniformity should be small;
- for the calibration at ISE CalLab a parallel resistance R_P > 2000 Ωcm² is optimum.

These target-settings may not be realisable for a production, but shall serve to indicate, what can be done to support the efforts in the calibration lab, to reduce the related uncertainty contributions.

At an industrial classifier used in the PVTEC at Fraunhofer ISE tests of several quality criteria were done. Criteria were reproducibility, influence of reference cell type on the uncertainty etc. [9].

Main result was that the uncertainty introduced by the reference cell is dominating, as long as spectrally well matched cells are used as references. An example of the spreading of mismatch factors versus power classes is given in Fig. 3.

An important issue is to have the determination of the fill factor reproducible between different measurement setups. Criteria for the error associated with different contact pin configurations were evaluated [10]. Although a standardization of contacting schemes is desirable, it was found, that this task requires considerable additional effort.

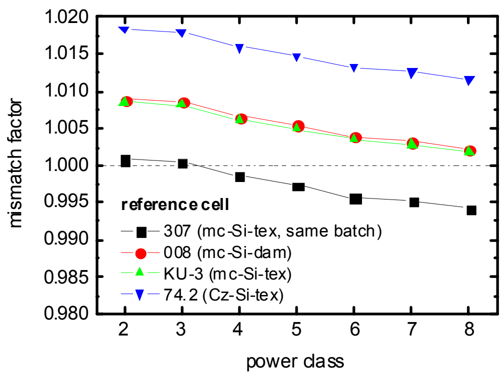

Fig. 3: Influence of different reference cells and the spread, if a close matched cell is used.

How critical the selection of a reference cell for a close match to the test cells is, depends on how close the spectrum of the simulator is to the standard spectrum. Criteria for classification of simulator spectra into classes A, B, C are defined in IEC 60904-9. We evaluated this for a series of industrial simulators at the partner's sites. While irradiation uniformity was generally good, improvement potential was identified for the spectral distribution in some cases. Here again it was important, to develop firstly the ability to assess the uncertainty of the measurement of the spectral distribution itself. A second difficult step was to determine the deviation of a spectrum from the standard with a well-defined uncertainty. The deviation is assessed with normalised integral ratios Vi within wavelength intervals i, see Fig. 4, as standardized in IEC 60904-9. This involves once more an integral uncertainty evaluation, which we solved again with a random walk treatment. An example is given in Fig. 4.

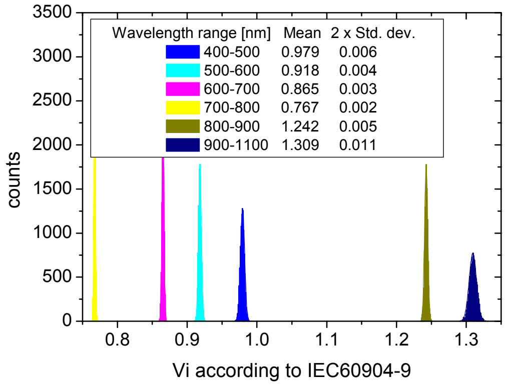

Fig. 4: Example for the assessment of a simulator spectrum against the standard spectrum. The widths of the distributions give the uncertainty of the deviation ratios Vi obtained for a specific measured spectral distribution.

For the example, the spectrum evaluated with the results depicted in Fig. 4 is clearly class B outside uncertainty margins: Class A requires $0.75 \leq Vi \leq 1.25$.

The calculation of the uncertainty for the current mismatch allows us to differentiate the impact of deviations between simulator and standard spectrum on the current mismatch for different wavelength ranges. Fig. 5 exemplifies the frequent observation, that several wavelength regions contribute to the spectral mismatch with opposing impact.

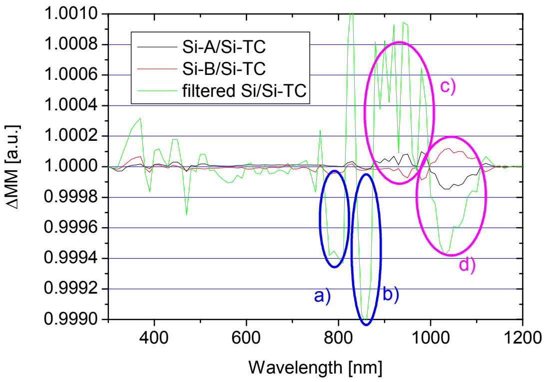

Fig. 5: Sensitivity analysis of the MM factor for three combinations of spectral response curves. Si-TC denotes a typical industrial cell, which is compared against Si-A and Si–B, which denote two different WPVS-type cells, and filtered-Si, a WPVS-type cell filtered to match a typical a-Si spectral response.

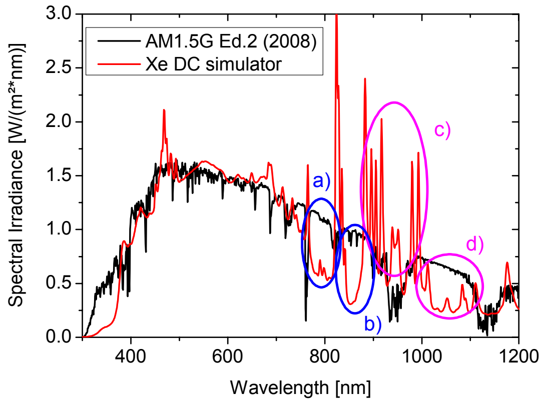

Fig. 6: Solar simulator spectral distribution in comparison to the AM1.5G standard spectrum. Spectral regions contributing to the MM are marked as in Fig. 5.

The spectral analysis capability in turn allows the design of adapted filters on the basis of a prediction of the importance of the modifications reached by a filter curve for a specific combination of reference and test cell spectral response.

5 SUMMARY

With the reduction of the uncertainty of the short circuit current calibration of bare industrial cells to ± 1.8 % ISE CalLab PV Cells is able to suit industrial needs in a much improved way. In-depth physical analysis was essential to understand and minimise limiting factors. Additional measures to secure long term comparability of the calibration results will allow a still improved control in order to prevent discontinuities between different calibrations. Further achievements were guidelines for the selection of reference cells, qualification of industrial cell testers at the partner's sites and harmonised spectroradiometer performance between institutes and industry. The excellent open co-operation between the project partners provided an indispensable prerequisite for this success.

The ability to calculate the effect of spectral changes on the current mismatch for specific wavelength regions including uncertainty margins will be highly useful for "spectral engineering": Filter design for the optimisation of an irradiation source for a specific purpose will find extended application e.g. also to the case of thin film multi-junction devices.

6 ACKNOWLEDGEMENTS

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