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THE RESULTS OF THE SECOND WORLD PHOTOVOLTAIC SCALE RECALIBRATION

S. Winter[1)], J. Metzdorf[1)], K. Emery[2)], F. Fabero[3)], Y. Hishikawa[4)], B. Hund[5)], H. Müllejans[6)] , A. Sperling[1)], W. Warta[5)]

[1)] PTB, 38116 Braunschweig, Germany
[2)] NREL, Golden, USA
[3)] CIEMAT, 28040 Madrid, Spain
[4)] AIST, Ibaraki 305-8568, Japan
[5)] ISE Fraunhofer-Institut für Solare Energiesysteme, 79110 Freiburg, Germany
[6)] ESTI, I - 21020 Ispra (VA), Italy

ABSTRACT

The World Photovoltaic Scale (WPVS) is used as a world-wide reference value for terrestrial PV performance measurements of I_{STC}, the short-circuit current under Standard Test Conditions. The WPVS has already been established in 1997 based on an international comparison where a set of 20 transfer/travelling standards were circulated between 11 national laboratories [1]. After the first recalibration carried out at NREL in 1999 [2], the PTB acted as pilot laboratory for the second recalibration, i.e. the 2003/04 intercomparison. It was performed as an international star-like comparison with 43 reference solar cells as reference standards, where 25 reference solar cells were made in accordance with the WPVS reference cell package design [3]. Nine institutes have participated: AIST(Japan), BGNSEC (Israel), CIEMAT (Spain), ESTI (EU), Fraunhofer ISE (Germany), NREL (USA), PTB (Germany), Sandia (USA), TIPS (China). The measurements of the pilot laboratory were carried out between August 2003 and January 2004. Summarizing the main result of the comparison, the deviations of the calibration values obtained by the pilot laboratory and by the participants are, in general, within ±2%.

In addition to the results of the comparison, typical stability and linearity test results of some reference cells as well as reproducibility of the DSR calibration facility of the pilot laboratory are described and discussed.

Finally, the recommendations of a working group concerning the future development of the WPVS are presented.

INTRODUCTION

The objective of this paper is to present and compare the calibration results of all participants as a whole (i) without allowing the identification of individual cells or participants and (ii) not yet discussing the determination of a new or modified reference value and degree of equivalence, because some data are still missing.

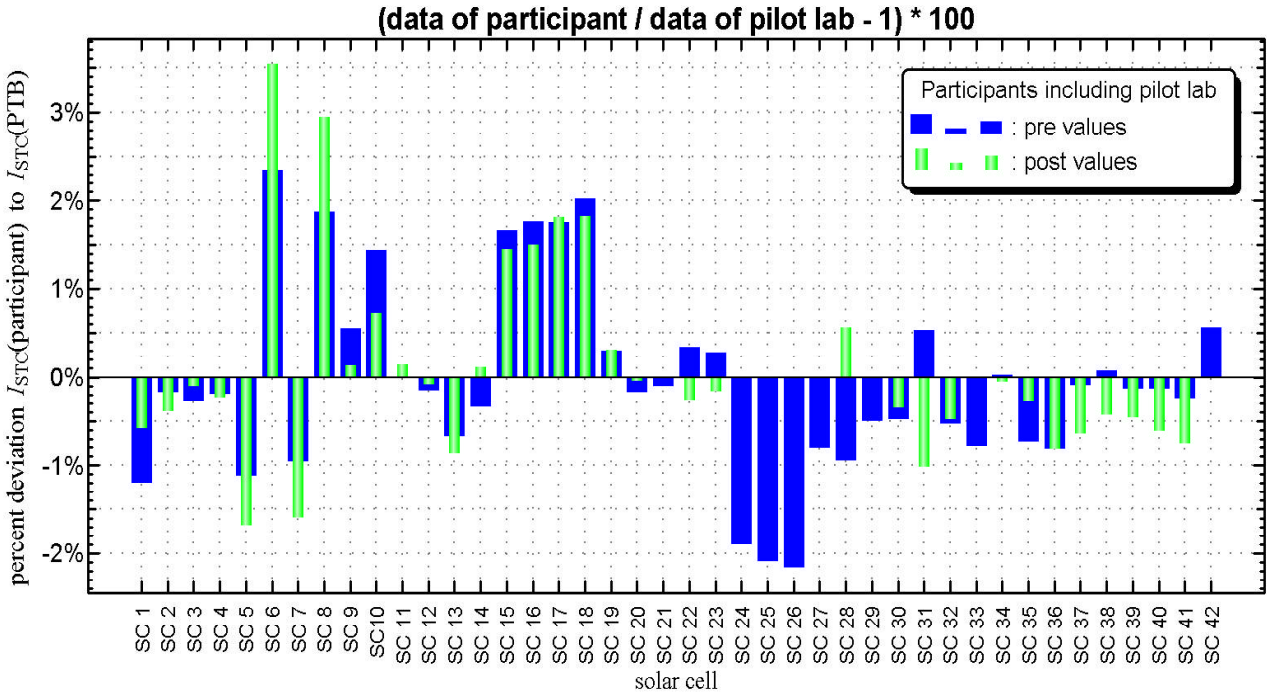

Fig. 1. Deviation between I_{STC}(participant) before and after the calibration at the pilot lab and I_{STC}(Pilot lab).

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The WPVS

The WPVS was already established in 1997 based on an international comparison of reference cell calibrations performed by 11 participating national laboratories between 1993 and 1996 [1]. Every laboratory determined the short circuit current I_{sc} under Standard Test Conditions of 20 solar cells (STC: Global reference spectrum according IEC 60904-3, 1000 W/m² and 25°C). The following rigorous procedure was used to qualify the WPVS calibrations and laboratories. First, it was decided that only primary calibration methods (methods, which does not rely on calibrated reference cells) should be allowed to contribute to the WPVS. The results of all the primary calibrations (of 7 participants) were used to calculate the arithmetic mean of the calibration values of the 20 different reference cells used to establish the WPVS. Second, any laboratories with 50 % or more of their data deviating more than 2 % from the respective mean were excluded. This criterion resulted in the removal of three more laboratories. The normalized calibration values were than recalculated (and two individual data with an offset of more than 2 % were removed). The remaining (78) normalized data of the 4 institutes meeting the requirements were averaged to obtain the final WPVS reference value. Thus, the WPVS is presently based on the calibration results of NREL, JQA/ETL/AIST, PTB and TIPS. There were three more laboratories (ISE, Sandia, IACS), that satisfied the 2% criteria, but they didn't use a primary calibration method.

In order to maintain the WPVS, additional intercomparisons, i.e. so-called recalibration campaigns are carried out. The first recalibration was performed at NREL in 1999. The main purpose was to update the calibration values of the existing WPVS solar cells and to include new solar cells. The second recalibration was organized by the PTB, where a further purpose was to transfer the WPVS to additional laboratories.

DSR calibration facility of the pilot laboratory

The PTB uses the Differential Spectral Responsivity Method (DSR [4]) to determine the short circuit current under Standard Test Conditions according to IEC 60904-3. The calibrations are performed with varying bias radiation E_{Bias} including a linearity test. Both the relative and the absolute spectral responsivities of a reference solar cell are determined to obtain I_{STC}:

$$I_{\mathrm{STC}} = \int_0^\infty s_{\mathrm{abs}}(\lambda, E_{\mathrm{STC}}) \cdot E_{\mathrm{AM1.5},\lambda}(\lambda)\, \mathrm{d}\lambda \qquad (1)$$

A dual-beam optical arrangement is used to measure the DSR spectrums of a solar cell at a series of discrete operating points that are set with different steady-state bias radiations at levels between 0.001 E_{STC} and 2 E_{STC}. The chopped monochromatic radiation behind a double grating monochromator is measured with lock-in technique where a monitor photodiode is calibrated against standard detectors not exposed to the bias radiation and traceable to SI units via cryogenic radiometers. To scale the relative DSR, the absolute DSR at discrete wavelength(s) is measured at one of the (low) bias levels using a filter monochromator without imaging optics to produce uniform spectral irradiance all over the cell area of up to 250 cm^2 [5].

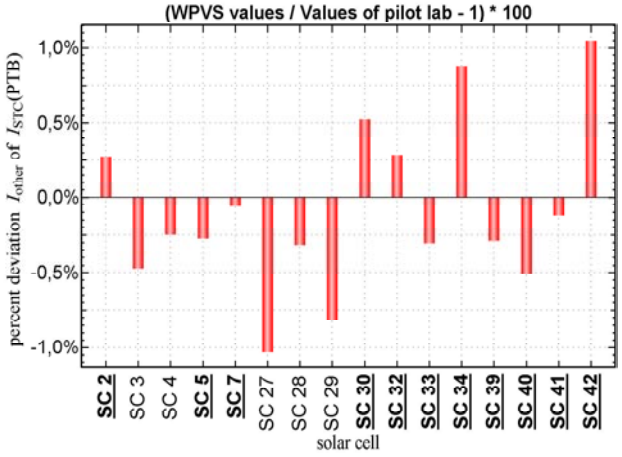

Fig. 2. Deviation of the calibration values of the pilot lab to the WPVS reference values. The underlined solar cells are WPVS cells of the initial intercomparison. The others were added at the recalibration campaign 1999.

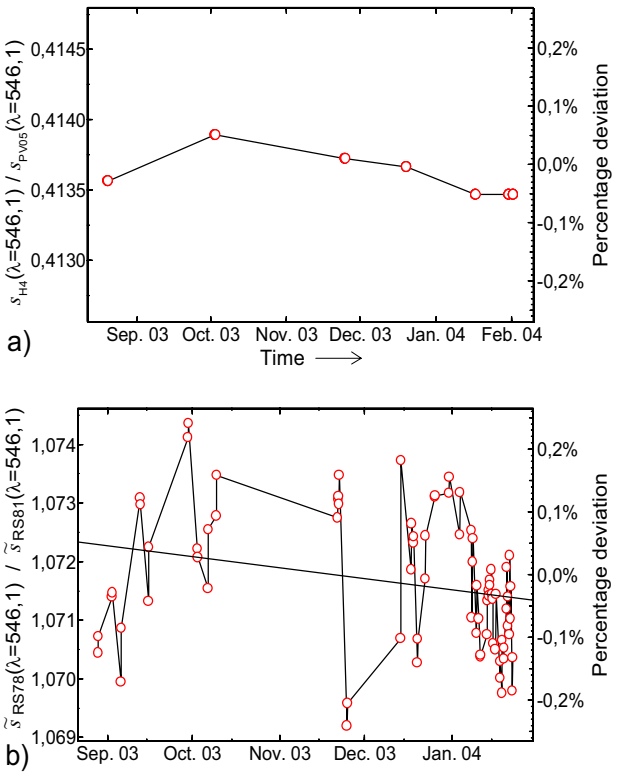

Fig. 3. Long-term stability and reproducibility of the DSR facility of the pilot laboratory (PTB): a) by comparing two photodiodes and b) by comparing two solar cells measured against each other.

Results

Fig. 1 shows the relative deviation of the calibration values I_{STC} of all reference cells determined once by the pilot lab (PTB) and twice by the participants before and after the PTB calibration. The data of the four qualified WPVS labs that could be used for a new realization of the reference value are not yet indicated. It is noted that the reference value of the PTB used in Fig. 1 is not identical with the WPVS and a reference value of the comparison, respectively. The post values of SC24-27,29 and 33 are still missing; SC42 was damaged before the post calibration.

Fig. 2 shows the relative deviation of the calibration values of the initial WPVS cells (1993-96) and of the WPVS cells added during the recalibration campaign 1999, illustrating that the PTB calibration values of 2003/04 are within ±1% of the former calibration values.

Fig. 3 illustrates the long-term stability and reproducibility of the DSR facility of the PTB. The variation of the values of two photodiodes is about ±0.05 %, the variation of the values obtained from two solar cells is about ±0.2 % (the standard deviation of a single value is 0.1% and of the mean value 0.012%), including the effect of exchanging several components of the DSR facility during the measurement campaign requiring several new alignment procedures.

Finally, Fig. 4 illustrates the AM1.5-weighted non-linearities of all reference cells by comparing the DSR values obtained under a bias irradiance of about 1000 W/m² to that under two different low bias irradiances. The resulting non-linearities are, in general, below 1% and thus are tolerable.

Recommendations of the WPVS working group and discussion

Four recommendations are presently under discussion aiming at an improvement of the evaluation/realization, maintenance and dissemination of the WPVS, which – strictly speaking – is not a scale but a reference value that should be valid and used world-wide for terrestrial PV calibrations (similarly to the WRR).

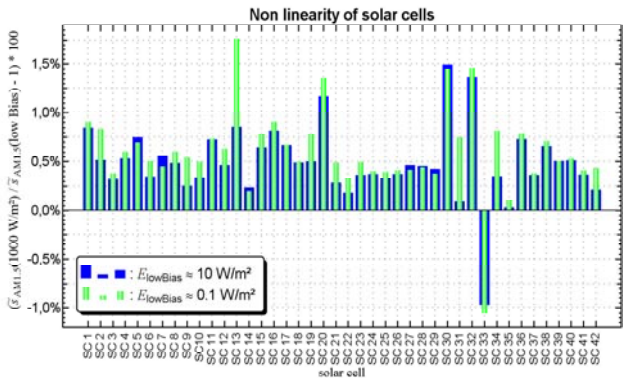

Fig. 4. Non-linearity of all solar cells measured by the pilot lab. Only the two filtered solar cells (SC14 and SC35) are almost perfectly linear. A negative non-linearity usually indicates a high series resistance (SC33).

Qualified WPVS labs:

The WPVS, i.e. the world-wide PV reference value, is presently based on the calibration values of only four so-called qualified WPVS labs. Therefore, it is desirable to increase the number of qualified WPVS labs, realizing, maintaining and disseminating the PV reference value.

Only those calibration labs performing primary calibrations which are directly traceable to the SI units via radiometric standards (including that of the WRR) can become qualified WPVS labs. It has been shown that the World Radiometric Reference lies almost exactly at the SI scale realized by cryogenic radiometers [6]. Qualified WPVS labs should own and use a group of at least 3 calibrated WPVS cells (see also the requirements for secondary WPVS labs) and at least 4 WPVS cells must be compared (at least 2 of them blind) and calibrated at least at 2 other qualified WPVS labs (already established), where the deviation of the data must be less than ±1%. If the calibration values are out of a ±1% band, the calibration at an additional qualified WPVS lab is needed, where the deviation off all data must not exceed 2% from the mean value of the data of the respective qualified labs. The calibration values have to include an uncertainty budget according to the GUM; the standard deviation of repeated calibrations should not exceed 1 %.

Finally, the need of a qualification (requalification) of future (established) qualified WPVS labs is pointed out if considerable changes of equipment and/or calibration procedure have been made.

Secondary WPVS labs:

It is obviously desirable to increase the number of labs maintaining and disseminating the WPVS although not being prepared to realize the WPVS (using a primary calibration method).

All secondary WPVS labs should own and use a group of at least 3 calibrated WPVS cells, because they are needed to maintain and disseminate the WPVS. The calibration results of a secondary WPVS lab traceable to qualified WPVS lab and determined within an intercomparison may have an offset to the WPVS of only up to ±2%. The minimum requirements for a transfer of the WPVS to another calibration lab should be based on the comparison of at least 3 WPVS reference cells, where both primary and secondary calibrations are allowed; the calibration values have to include an uncertainty budget according to the GUM; the standard deviation should not exceed 1 %.

Secondary WPVS labs must guaranty a minimum quality standard that has to be defined (e.g., spectral corrections, uncertainty budget and comparison results against at least 1 qualified WPVS lab).

It is noted, that the role of the Qualified WPVS labs is similar to that of the participants of a CIPM key comparison (Comité International des Poids et Mesures) determining the respective reference value KCRV (Key Comparison reference value). Furthermore, the role of a

Secondary WPVS lab is similar to that of a participant of the corresponding RMO key comparison (Regional Metrology Organizations) which are linked to the respective CIPM key comparison without affecting the KCRV, because it is only transferred to the RMOs [7].

Modifications of the WPVS:

There was an agreement among the participants of the meeting that slight changes / modifications of the WPVS maintained by the existing WPVS reference cells (which may not be stable enough or which may degrade or may be damaged) are realistic, possible and allowed. Knowledge of the reference solar cells and the measurement techniques improves over time. Within the final report, the pilot lab (PTB) will present a proposal and options of how to determine reference values and how to eventually modify the WPVS based on the results of the present WPVS recalibration/intercomparison.

Fig. 5. Picture of solar cell with WPVS design

WPVS cells (with WPVS design!):

It is desirable to increase the number of WPVS reference cells, because only 11 out of the 20 initial reference cells are presently available, which, moreover, are without standardized package.

WPVS cells (with WPVS design!) must be calibrated at least at 2 qualified WPVS labs (already established), where the deviation of the data must be less than ±1%. If the calibration values are out of a ±1% band, the calibration at an additional qualified WPVS lab is needed, where the deviation off all data must not exceed ±2%.

It was pointed out that a documentation of the "calibration history" of each WPVS cell is necessary in future (including visual and stability checks, duration of measurements especially outdoor measurements and sunlight dose). It was noted that a WPVS cell must not be used as a working standard for routine calibrations. Some rules must be written down concerning this matter (after the end of the current comparison, a discussion regarding the procedure for these rules should be started).

Requirements for international equivalence

It is noted, moreover, that international equivalence is generally based on two requirements, where the first one is crucial/indispensable: 1) international equivalence is based on the results (with reference value, degree of equivalence value and uncertainty) of a successful international comparison and 2) international equivalence is based on the establishment of a quality system within the respective calibration labs, i.e. for example on the laboratory accreditation according to ISO 17025, where one has to distinguish between testing and calibration. In practice, the second requirement is of little use without the first requirement! In this connection it is noted that the participating labs have still to decide whether they will require the additional laboratory accreditation in future, which was not required in the past.

CONCLUSIONS

The measurements of the recent WPVS intercomparison with relatively many cells and participants have been completed. This intercomparison can be used as a basis (i) for a new realization of the PV reference value called WPVS and (ii) for an increase of the number of reference cells and WPVS laboratories, both of which are needed to maintain and disseminate the WPVS reference value, where details have not yet been decided.

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