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INTERLABORATORY COMPARISON OF THE PV MODULE ENERGY RATING STANDARD IEC 61853-3

M. R. Vogt[1,13,+,*], S. Riechelmann[2,+], A. M. Gracia-Amillo[3,+], A. Driesse[4,+], A. Kokka[5], K. Maham[5], P. Kärhä[5], R. Kenny[3], C. Schinke[6,1], K. Bothe[1], J. C. Blakesley[8], E. Music[2,7], F. Plag[2], G. Friesen[9], G. Corbellini[9], N. Riedel-Lyngskær[10], R. Valckenborg[11], M. Schweiger[12], W. Herrmann[12]

[*]Corresponding author: m.vogt@isfh.de, +49 511/762-5505
[+]Member of the taskforce for analyzing the results and investigating the inconsistencies
[1]Institute for Solar Energy Research Hamelin (ISFH), Am Ohrberg 1, 31860 Emmerthal, Germany
[2]Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany
[3]European Commission, Joint Research Centre (JRC), Via E. Fermi 2749, Ispra, Italy
[4]PV Performance Labs, Freiburg, Germany
[5]Aalto University, Metrology Research Institute, Maarintie 8, 02150 Espoo, Finland
[6]Institute for Solid State Physics, Leibniz University Hannover (LUH), Appelstr. 2, 30167 Hannover, Germany
[7]Institut za mjeriteljstvo Bosne i Hercegovine (IMBiH), Augusta Brauna 2, BA-71000 Sarajevo, Bosnia and Herzegovina
[8]National Physical Laboratory (NPL), Hampton Road, Teddington. TW11 0LW. UK
[9]University of Applied Sciences and Arts of Southern Switzerland, SUPSI-PVLab, 6952 Canobbio, Switzerland
[10]Technical University of Denmark (DTU), Dept. of Photonics Engineering, Roskilde, Denmark
[11]TNO, High Tech Campus 21, Eindhoven, The Netherlands
[12]TÜV Rheinland Energy GmbH, 51101 Cologne, Germany
[13]Now with: Delft University of Technology, PVMD, Mekelweg 4, 2628CD Delft, The Netherlands

ABSTRACT: The IEC 61853 standard series “Photovoltaic (PV) module performance testing and energy rating” aims to provide a standardized measure for PV module performance, namely the Climate Specific Energy Rating (CSER). An algorithm to calculate CSER is specified in part 3 based on laboratory measurements defined in parts 1 and 2 as well as the climate data set given in part 4. To test the comparability and clarity of the algorithm in part 3, we share the same input data, obtained by measuring a standard photovoltaic module, among different research organizations. Each participant then uses their individual implementations of the algorithm to calculate the resulting CSER values. The initial blind comparison reveals differences of 0.133 (14.7%) in CSER between the ten different implementations of the algorithm. Despite the differences in CSER, an analysis of intermediate results revealed differences of less than 1% at each step of the calculation chain among at least three participants. Thereby, we identify the extrapolation of the power table, the handling of the differences in the wavelength bands between measurement and climate data set, and several coding errors as the three biggest sources for the differences. After discussing the results and comparing different approaches, all participants rework their implementations individually and compare the results two more times. In the third intercomparison, the differences are less than 0.029 (3.2%) in CSER. When excluding the remaining three outliers, the largest absolute difference between the other seven participants is 0.0037 (0.38%). Based on our findings we identified four recommendations for improvement of the standard series.
Keywords: Energy Rating, PV Module, Energy Performance.

1 INTRODUCTION

The IEC 61853 standard series “Photovoltaic (PV) module performance testing and energy rating” was completed in 2018 with the publication of parts (3 and 4) [1], [2]. The series aims to provide a standardized measure for PV module performance, namely the Climate Specific Energy Rating (CSER) in Part 3. For this purpose, reference climate data are specified in Part 4 of the standard. The CSER relates the module efficiency in the reference climates to the module efficiency under Standard Testing Conditions (STC: 25°C, 1 kW/m², AM1.5)[3] and thus aims to be a more realistic measure of a module’s outdoor performance. The standard also defines a procedure for the calculation of CSER in Part 3. However, the specific implementation of the calculation is left to the user, and some steps in the procedure leave room for interpretation. This may lead to deviations between different implementations. To date, there is no reference parameter set available to the PV community, which could be used to verify the correct implementation of the CSER calculation.

This interlaboratory comparison of CSER calculation, with results from ten different institutions, is in the process of providing such a reference parameter set for the community, removing errors from the individual implementations and establishing best practices for the calculation steps that are not clearly defined in the standard. Among the participants, there are different programming languages used for implementation, namely Python 3.7 by four participants, Matlab by two participants, and JSL by one participant. At least one participant provides the code as open source[4].

2 ENERGY RATING ACCORDING TO IEC 61853-3

IEC 61853 was completed in August of 2018 to provide a new standardized measure for PV module performance, the Climate Specific Energy Rating (CSER). Part 3 [1] deals with the calculation algorithm (see Fig. 1) combining the measured module parameters (parts 1 & 2) [5], [6] with the reference climate data (part 4) [2].

The climate reference data [2] contains six different climates: Subtropical arid (sub. ari.), subtropical costal (sub. cos.), tropical humid (tro. hum.), temperate continental (tem. con.) and high elevation (hig. ele.). Each of the six climate data set contains hourly values of the following parameters: Ambient temperature, wind speed and sun incidence angle, for one whole year. In terms of irradiance part 4 provides: Horizontal as well as in-plane irradiance for global and direct broadband irradiance, and horizontal as well as in-plane spectrally resolved global irradiance integrated in 29 bands.

The first step of the calculation algorithm (see Fig. 1) is correcting the in-plane irradiation for the angular losses of the PV module. For this purpose, the model of Martin and Ruiz [7], [8] is used, which characterizes the PV modules angular response based on a single parameter: the angular loss coefficient a_r.

The second step is spectral correction [6] of the angular corrected irradiance $G_{corr,AOI,j}$ for the mismatch between the spectrally resolved global irradiance given in the climate data set and AM1.5G reference spectrum [9]. The result is the corrected global irradiance $G_{corr,j}$.

The third step is the calculation of the module temperature $T_{mod,j}$, for which the Faiman model is used [10].

The fourth step is the calculation of the module power output for the given hour. For this purpose, the module power is measured according to [5] at different module temperatures (15°C-75°C) and irradiances (100 W/m^2-1100 W/m^2). The results form the so called power matrix consisting of 22 power values. The power matrix is then divided by the irradiance to obtain module efficiency $\eta(G,T)$ values. Two-dimensional bilinear interpolation is then used to determine the module efficiency at the corrected global irradiance $G_{corr,j}$ and the module temperature $T_{mod,j}$ values. Afterwards the obtained module efficiency value is used to calculate power output $P_{mod,j}$ for the given hour j and the process (Step 1-4) is repeated for every hour of the year.

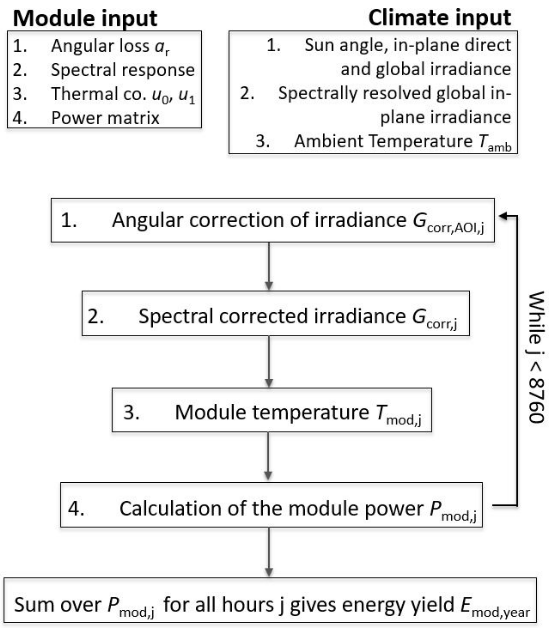

Figure 1: Main steps and input parameters for each step of the IEC61853-3 algorithm[1].

CSER is yearly efficiency in the climate relative to STC efficiency. It is calculated according to

$$CSER = \frac{E_{mod,year}/H_{p,year}}{P_{max,STC}/G_{ref,STC}}, \quad (1)$$

where $E_{mod,year}$ is the energy produced by the module over one year according to the algorithm of IEC 61853-3, $H_{p,year}$ is the total yearly irradiation in the module plane, $P_{max,STC}$ is the module's maximum power under STC and $G_{ref,STC}$ =1kW/m² the irradiance under STC. A CSER of 1 means that the PV module operates as efficient in the climate as under STC, while CSER values below 1 indicate lower efficiency in the reference climate and CSER values above 1 indicate higher efficiency in the reference climate than under STC.

3 INTERCOMPARISON

TÜV Rheinland experimentally determined the input parameters required for the CSER calculation and provided them to the other participants. Each participant then calculate the CSERs without knowledge of the other participant's results. The resulting CSER values as well as important intermediate results of the calculation procedure from each participant available to the consortium afterwards. The relative differences for each calculation step are analyzed and discussed.

3.1 Phase 1: Initial blind intercomparison

Fig. 2 shows the initial CSER value for all six climate profiles as defined in the standard. Differences between the results of up to 0.133 are observed, showing the importance of validation. Participants E1 or H1 had the highest CSER for all climate profiles, while I1 had the lowest values. However, the order is not the same in every profile. Please note, that J1 was excluded due to the use of input parameters from a different module.

Table 1 lists the standard deviations and the absolute difference between the CSER values. For all phases the tropical humid profile had the highest values for both, which is 0.133 for absolute difference and 0.039 as the standard deviation in phase 1.

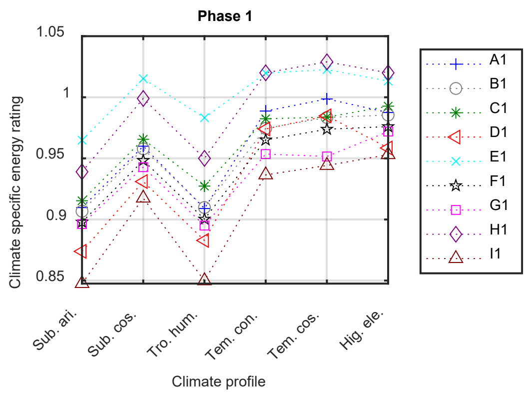

Figure 2: Initial CSER values show differences of up to 0.133 in CSER. Please note, that J1 was excluded due to the use of input parameters from a different module.

Despite the differences in CSER, an analysis of intermediate results revealed differences of less than 1% at each step of the calculation chain among at least three participants. Thereby, we identify the extrapolation of the power matrix, the handling of the differences in the wavelength bands between measurement and climate data set, and several coding errors such as misplaced brackets or signs as the three biggest sources for the differences.

Table 1: The standard deviation and the absolute difference of CSER values for each climate profile for all three phases.

	Absolute CSER difference			**CSER Standard deviation**		
Climate profile	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 1**	**Phase 2**	**Phase 3**
Subtropical arid	0.117	0.014	0.013	0.034	0.004	0.003
Subtropical coastal	0.098	0.016	0.016	0.031	0.005	0.004
Tropical humid	0.133	0.029	0.029	0.039	0.008	0.008
Temperate continental	0.084	0.019	0.017	0.028	0.006	0.005
Temperate coastal	0.085	0.024	0.023	0.028	0.007	0.006
High elevation	0.067	0.012	0.007	0.023	0.003	0.002

3.2 Impact of the angular correction

The angular loss coefficient a_r is obtained by fitting it to the measured IAM(θ) as defined in [6] and shown in Fig. 3. However, the mathematical fit method is not specified in the standard. Five participants performed least square fits, resulting in an a_r = 0.14571, while other participants used other methods such as the mean absolute deviation approach or simply fitting the model by hand. Other approaches resulted in higher a_r values than least square fit. The impact of these differences is about 0.002 in CSER. Consequently, we recommend that the a mathematical fit algorithm should be defined by future versions of part 2 [6] and that angular loss coefficient should be given with an accuracy offive digits to reduce the impact of the fitting and rounding in CSER calculation.

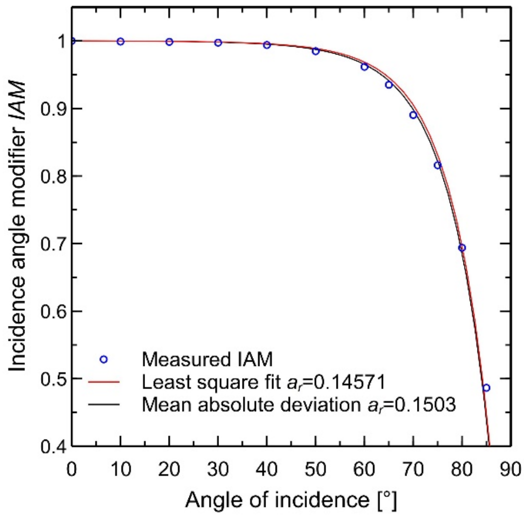

Figure 3: Measured IAM(θ) and fitted angular loss model for least square and mean absolute difference method.

3.3 Phase 2: Intercomparison with identical angular modifiers

For phase two of the intercomparison, the consortium decided to use a_r =0.14571 in all implementations to remove this fitting difference and focus on other steps. Additionally, participants have access to all the results of phase 1 to improve their implementations.

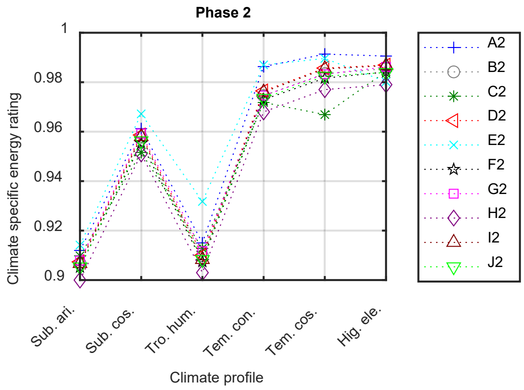

Figure 4: CSER values of phase 2 show differences of up to 0.29 in CSER, which is an improvement by a factor of more than four.

Figure 4 shows the CSER values of phase 2. The biggest change is actually signified by the change in the y-axis range, which is due to the four-fold reduction of the absolute difference to 0.029. The difference was driven by the four outliers, A2, C2, E2 and H2. After excluding those four outliers the largest absolute difference between the other six participants is 0.0042.

3.4 Impact of spectral correction

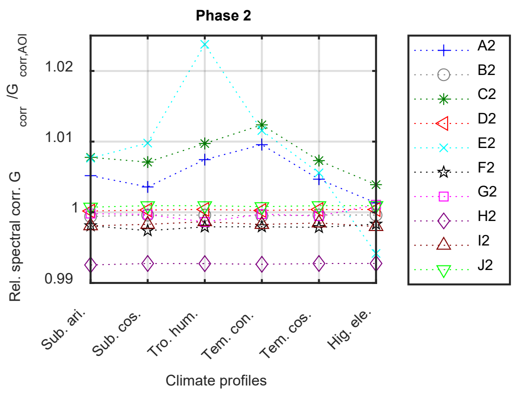

Figure 5: The spectral corrected yearly irradiance G_{corr} divided by the AOI corrected irradiance $G_{corr,AOI}$ of each participant relative to the median of all participants.

Figure 5 shows the spectral corrected yearly irradiance G_{corr} divided by the AOI corrected irradiance $G_{corr,AOI}$ of each participant relative to the median of all participants. This metric essentially evaluates a participant's mean annual spectral correction. The results of participants A2, C2, E2 and H2 clearly deviate. Moreover, the absolute mean difference in CSER follows (see Table 1) a similar trend as Figure 5 indicating, that the agreement in phase 2 is limited by spectral correction step.

One reason for the differences is that one has to numerically integrate over three different curves without a clearly defined method in the spectral correction step. Additionally, the three values (AM1.5g reference spectrum, module spectral response (SR) and spectrally resolved global irradiance) in the integrals have different spectral resolutions and definition ranges. Thus interpolations are required before the integrals can be solved numerically. This gives the users freedom within the standard, leading to the variations in the results.

3.5 Phase 3: Intercomparison after discussion of spectral correction methods

For phase three of the intercomparison, the consortium decided to use a_r =0.14571 again and additionally use linear interpolation to generate points at band edges and then determine band value with trapezoidal rule for both AM1.5G and SR.

Figure 6 shows the CSER values of phase 3. Participant H3 improves his calculation to join the other six participants, A3, C3 and E3 still have large differences in the spectral correction. Compared to phase 2 the absolute difference is reduced for four of six climates. The difference is driven by the three outliers A3, C3 and E3. After excluding those three outliers the largest absolute difference between the other seven participants is 0.0037.

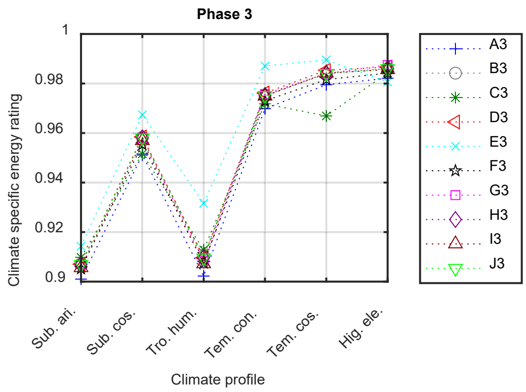

Figure 6: CSER values of phase 3. Compared to phase 2 the absolute difference is reduced for four of six climates.

3.6 Module temperature calculation

For the module temperature calculation step the results reveal no differences between the participants, which originate from this step. However, we noticed an inconsistency between part 2 [6] and part 3 [1] with regards to whether the uncorrected global irradiance (part 2) or angle of incidence corrected irradiance $G_{corr,AOI,j}$ (part 3) should be used in the Faiman model [10]. Our group has the recommendation to make them consistent. We believe that it is more logical from a physics point of view to use the angle of incidence corrected irradiance $G_{corr,AOI,j}$ as specified in part 3, since it is absorbed broadband irradiance after reflections, which impacts the module temperature. However, this may not be as practical from the perspective of part 2.

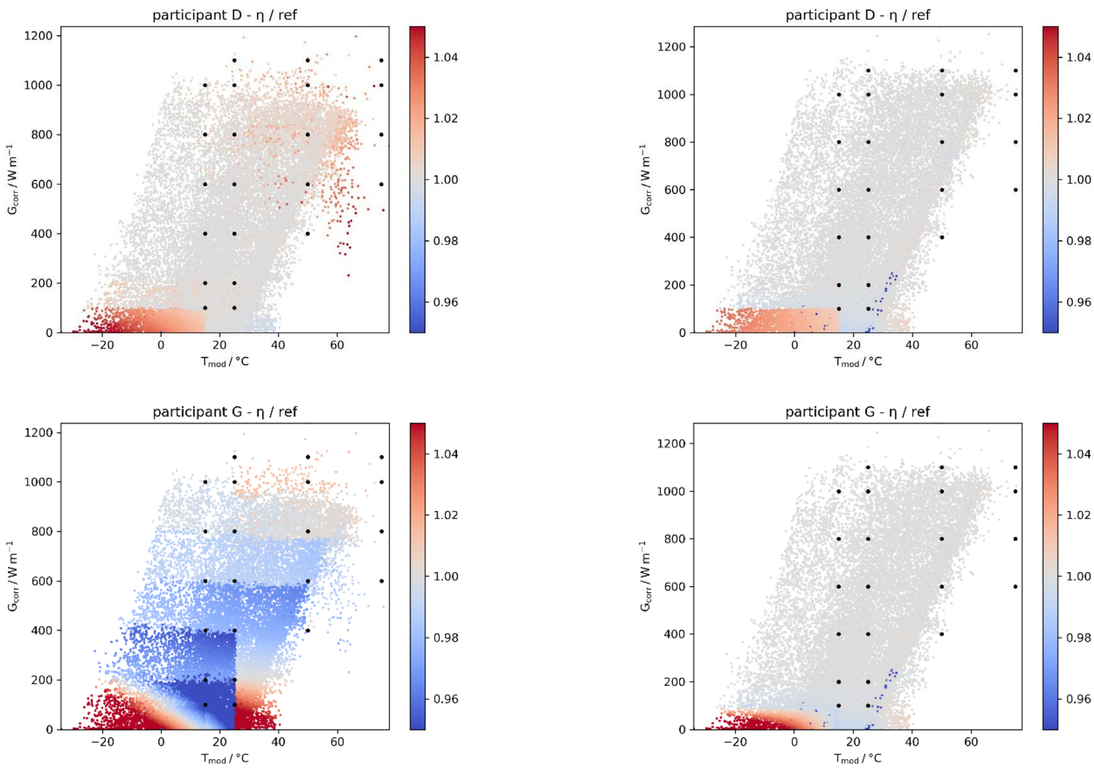

Figure 7: The efficiencies relative to the reference of the initial phase (left) are compared to the third (right). The black points are the measured values used for inter and extrapolation. While differences for interpolation are present in phase 1, phase 3 only shows differences for extrapolation, which is mostly relevant for low irradiances.

3.7 Impact of power matrix inter- and extrapolation

Another calculation, which introduces differences is the extrapolation of the power matrix. We analyze the implementation of the power matrix interpolation and extrapolation via the following steps:

1. Combining the results for all six climate data sets to a big dataset for each participant.
2. Dividing module power output by the spectrally corrected irradiance G_{corr} giving the efficiency values.
3. Choosing a reference efficiency dataset: In case of phase 3 the average dataset across all results of the phase while participants A1, C1, E1 and G1 where outliers and thus excluded as from the phase 1 reference.
4. Dividing each participant's efficiency values by reference efficiency values

Selected participants results are shown in Fig. 7. These scatter plots show the distribution of the relative efficiency values in relation to the corrected irradiance on the x-axis and the module temperature on the y-axis. The results of the initial phase (left) are compared to the third (right). The black points are the measured values from the power matrix, which are used as the basis for inter- and extrapolation. While differences for interpolation are present in phase 1, phase 3 only shows differences for extrapolation, which is mostly relevant for low irradiances.

One reason, why the these differences remain mostly for low irradiances is that the extrapolation is only explicitly defined for two following two cases:

i) $T_{mod} > 75°C$ and $G_{corr} > 1100$ W/m^2

ii) $T_{mod} > 75°C$ and 100 W/m$^2 < G_{corr} < 1100$ W/m^2

None of these cases deals with low irradiances (< 100 W/m^2) or temperatures (< 15°C), thus giving the users some freedom in transferring the extrapolation method to these cases, which are actually the most frequent extrapolations done in the reference climates [11]. We are currently in the process of comparing different extrapolation approaches such as [12] and plan to conduct another phase to evaluate the results.

4 CONCLUSIONS AND RECOMENDATIONS

The practical implementation of IEC 61853-3 is more complicated than one might expect as demonstrated by the initial comparison with differences of 0.133 (14.7%) in CSER. In the third phase of the intercomparison, the differences are less than 0.029 (3.2%) in CSER. After excluding the remaining three outliers the largest absolute difference between the other seven participants is 0.0037 (0.38%).

We identified four recommendations for improvement of the standard series:

First, we suggest that the mathematical fit algorithm for determining the angular loss coefficient should be defined by future versions of part 2 [6] and that angular loss coefficient should be given with an accuracy of five digits to reduce the impact of the fitting and rounding in CSER calculation.

Second, we suggest that a procedure for interpolating and numerically integrating in the spectral correction step is defined in the standard.

Third, the module temperature calculation equation should be consistent between parts 2 and 3. It is more logical from a physics point of view to use the angle of incidence corrected irradiance $G_{corr,AOI,j}$ as specified in part 3.

Fourth, the bilinear interpolation/extrapolation procedure of the power matrix values should be defined explicitly for all cases surrounding the matrix, especially for the more frequent ones such as low irradiance and low temperature situations.

4.1 Acknowledgment

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