VALIDATION OF PROPOSED PHOTOVOLTAIC ENERGY RATING STANDARD AND SENSITIVITY TO ENVIRONMENTAL PARAMETERS

Jyotirmoy Roy1, Thomas R. Betts1, Ralph Gottschalg1, Stefan Mau2, Shokufeh Zamin2, Robert P. Kenny2, Harald Müllejans3, Gabi Friesen4, Sebastian Dittmann5, Hans Georg Beyer4, Andri Jagomägi6

1Centre for Renewable Energy Systems Technology (CREST), Loughborough University, Loughborough, LE11 3TU, UK, Tel.: +44 1509 635311, Email: J.Roy2@lboro.ac.uk
2Arsenal Research, Vienna, AT; 3ESTI, JRC, Ispra, IT; 4ISAAC-SUPSI, Canobbio, CH; 5 Institut fuer Elektrotechnik, Hochschule Magdeburg-Stendal, Germany; 6 Department of Materials Science, Tallinn University of Technology

ABSTRACT: PV devices are currently compared on the basis of the power measurements, which might not be as meaningful as a comparator as the energy yield. The energy rating standard proposed by the IEC promises to overcome this shortcoming. It has been implemented in three institutes and the issues with the current drafts are evaluated.

The data required as the input for the energy rating is normally not available and synthetic datasets will have to be used or parts need to be estimated for validation studies. The validation against outdoor data shows that the uncertainty of the input data, specifically the angular distribution of the diffuse irradiance, makes the energy prediction part virtually not applicable for energy yield calculations. The validation effort shows a reduction of the standard deviation in the measurements, indicating that all environmental effects are considered. The evaluation of the originally proposed standard days shows that there is little information to be gained in their application as they are not representative of realistic conditions; they are enveloping the possible environments. This will in some cases over-emphasise the importance of certain effects, as their contribution to the overall energy yield might be negligible.

Overall, the proposed standard represents an important advance on power rating. The standard is able to identify differences in device technologies. Further work might be required to make the output more relevant to a wider variety of users, though.

Keywords: Energy rating, PV modules

1 INTRODUCTION

Photovoltaic (PV) modules today are rated, compared and sold virtually exclusively on the basis of a power rating, which is measured at Standard Test Conditions (STC). In contrast to this, the expectation at a module or rating, which is measured at Standard Test Conditions and sold virtually exclusively on the basis of a power and a bridge between these two is required. This is done by energy prediction methodologies developed by a number of institutes [12] but this is not necessarily used as a device comparator as it is not standardised and different methodologies do not necessarily result in representative results. A way to create a device comparator is to extend energy prediction to energy rating, i.e. using a standardised environment, standardised baseline measurements and a standardised energy prediction methodology to create a universal device comparator.

There are a number of requirements on such a comparator. It must be:

- relevant, i.e. the outcome must give information useful to the user of the standard
- a fair comparator between different technologies, i.e. not neglect effects that might favour certain device categories
- accurate to be able to represent the differences in energy yield

complex enough to not neglect device idiosyncrasies but simple enough to enable a cost effective implementation for a large number of different devices

The IEC (International Electrotechnical Commission) has been working to develop an energy rating standard for PV devices, currently limited to PV modules only. The draft standard in its current form is anticipated to consist of four parts [1-4]. Parts one and two focus on the standardised measurements, part three focuses on standardised energy prediction and part four on the required standard environments. Currently, two standards have been submitted for comments to national standards bodies and the parts three and four are in different stages of the drafting process. The overall methodology is based on many years of experience of researchers but to the knowledge of the authors, no rigorous validation of the completed methodology has been carried out to date.

The paper presents the required validation effort this standard, which is carried out collaboratively at several institutions. The potential pit-falls and difficulties in the implementation are reported to support a smooth adoption once it is instated. The paper will firstly review the current state of the standard (and it should be stated that this might still be very different from the final version, as the voting procedure might result in drastic changes), report on the implementation efforts undertaken for three different PV technologies, relevance of methodology and a sensitivity analysis for the different device classes
2 REVIEW OF STANDARD

This standard gives the tools for an energy rating as outlined in the introduction. The contents of each standard are outlined below, to allow an appraisal of the complexity of the work.

2.1 Part 1 – Irradiance and Temperature Effects

This part deals with the measurements required for the effects of evaluation of the effects of irradiance and temperature. This is carried out by taking measurements of the short-circuit current, open-circuit voltage and maximum power at a number of different irradiances and temperatures. The measurement conditions are outlined in Figure 1 below, where the different measurements are overlaid on a visualisation of the energy production of an ensemble of 21 PV-plants situated in Belgium, Germany, Italy, Japan, Sweden and Switzerland, collected by IEA-PVPS-Task2. Each color represents 20% of the total AC-energy. The dots characterize the irradiance and temperature conditions for the standard days as defined in the draft standard.

Figure 1: Energy for hourly measurements at different irradiance and temperature conditions in relation to the measurements prescribed by the G-T matrix in the part 1 of the standard

The standard allows inter/extrapolation as outlined in [14] and it is immediately clear from Figure 1, that this will be required as a significant amounts of energy will be produced at irradiances below the minimum measurement temperature. It should, however, also be noted that interpolation tends to have more accurate results than extrapolation [12, 13] and thus there clearly was a compromise in the choice of thermal conditions, to enable people to measure outdoors (where lower temperatures are virtually impossible to achieve for accurate measurements at higher irradiances).

2.2 Part 2 – Spectral and Angle of Incidence Effects, Module Operating Temperature

This part describes the measurements required to assess spectral and angle of incidence (AoI) effects. The standard to date is explicitly limited to single junction devices. This involves measurement of the transmitted light in dependence of angles for the AoI effect and measurement of the spectral response for the modules as illustrated in Figure 2. The proposed standard also describes the measurements required to estimate the device operating temperature in the calculations.

Figure 2: Measured spectral response for the crystalline silicon modules in the study.

The aim of the first two parts is to provide all the measurements which are required to allow the energy prediction calculation in part 3.

2.3 Part 3 – Energy prediction methodology

This part gives the standardised energy prediction methodology, which is required for the energy rating. An overview of the proposed procedure is given in Figure 3.

Figure 3: Elements of the proposed energy rating procedure with the module specific measurements on the left, the input environment on the right and the actual calculations in the centre column.

The left column in Figure 3 shows the input parameters measured in part 1 and 2. The right column describes the environmental input parameters, while the centre column lays out the calculation methodology.

The environmental input is quite involved as it requires the beam- and diffuse irradiance as well as the angular distribution of the latter, also information of the incident spectrum is required. Furthermore the wind speed and the ambient temperature need to be known.

The environmental inputs are quite involved, and it is clear that not many datasets with all this information will exist. Also some measurements are typically associated with rather high uncertainties as e.g. spectral measurements in the UV region or the wind speed. This
might make this methodology unwieldy as an energy prediction methodology and the usefulness of this for a standardised comparison will obviously depend on the relevance of the overall dataset chosen.

It should be noted that the effective direct and diffuse irradiance is required for the calculations, which requires the diffuse irradiance to be distributed across the celestial sphere and the $G_{cmul}$ is the integration of the irradiance at each sky patch multiplied with a transmission modifier. This is pointed out here as it affects the availability of real data for applying this standard for validation.

2.4 Part 4 – standard input data

This part to date is the least developed and no draft exists for this data. An earlier version of the standard, which was not acceptable due to length and complexity of the document, suggested six reference days [1] to cover extreme combinations of ambient temperature and irradiance to estimate the energy yield of the module. The utilisation of these obviously depends on their relevance but they lend themselves as a perfect framework to implement and test the calculation procedure as suggested in part 3 [4].

These reference days are tabulated with irradiance, ambient temperature, wind speed, angle of incidence and spectral distribution over each day, with the cases labelled as:

- HIHT (High irradiance, high temperature)
- HILT (High irradiance, low temperature)
- MIMT (Medium irradiance, medium temperature)
- MIHT (Medium irradiance, high temperature)
- LILT (Low irradiance, low temperature)
- NICE (Normal Irradiance, cool environment)

This might be one of the most controversial parts of an energy rating standard as the environment needs to be relevant to the users of the standard: similar to average fuel consumption for cars not being measured at speeds of 200 mph, the standard datasets need to relate to the energy output to ‘standard’ sites. Otherwise one might have an excellent performance at LILT but it might hardly contribute to the annual energy production and thus the information is not relevant to any user. In this context, these days are used here to

- Implement the standard and ensure comparability between laboratories
- Investigate the impact of different effects, i.e. how much does the complexity really add to the overall accuracy of the result
- Investigate the relevance of the days themselves, i.e. do they relate to operating conditions found in the real world and are the combinations useful, e.g. it is the understanding of the authors that the spectra were simulated and these might disagree with realistic spectra, which in turn makes the spectral correction doubtful.

3 STANDARD IMPLEMENTATION

The calculations were implemented as well as the measurements at several laboratories across Europe. Three different materials were chosen to cover the range of device technologies on the market at the moment and commercial and experimental measurement setups were utilized to generate the data required for the calculations.

3.1 Investigated samples

Two sets of samples were investigated. The first one described in Table 1 is set of small crystalline silicon (c-Si), amorphous silicon (a-Si) and copper indium gallium selenide (CIGS) modules already described in [7]. The second set, summarised in Table 2, consist of 3 standard c-Si modules monitored over 1 year under real outdoor conditions [9].

<table>
<thead>
<tr>
<th>Device</th>
<th>Area [m^2]</th>
<th>$I_{sc}$ [A]</th>
<th>$V_{oc}$ [V]</th>
<th>$P_{max}$ [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>c-Si M1</td>
<td>1.663</td>
<td>7.41</td>
<td>36.42</td>
<td>191.6</td>
</tr>
<tr>
<td>a-Si M2</td>
<td>1.643</td>
<td>7.64</td>
<td>39.66</td>
<td>208.1</td>
</tr>
<tr>
<td>CIGS M3</td>
<td>1.277</td>
<td>4.77</td>
<td>43.24</td>
<td>147.7</td>
</tr>
</tbody>
</table>

Table 1: Set 1 module parameters at STC

<table>
<thead>
<tr>
<th>Device</th>
<th>Area [m^2]</th>
<th>$I_{sc}$ [A]</th>
<th>$V_{oc}$ [V]</th>
<th>$P_{max}$ [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>c-Si M1</td>
<td>1.663</td>
<td>7.41</td>
<td>36.42</td>
<td>191.6</td>
</tr>
<tr>
<td>a-Si M2</td>
<td>1.643</td>
<td>7.64</td>
<td>39.66</td>
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</tr>
<tr>
<td>CIGS M3</td>
<td>1.277</td>
<td>4.77</td>
<td>43.24</td>
<td>147.7</td>
</tr>
</tbody>
</table>

Table 2: Three different c-Si module parameters at STC (set2)

3.2 Characterization of modules

Indoor measurement of I-V curves are made by JRC (Ispra, Italy) (set 1) and ISAAC (set 2) in a pulsed solar simulator according to the proposed IEC draft standard [2] at irradiance level of 100 to 1100 W/m^2 and module temperature of 15°C to 75°C settings. All spectral response measurements have been done by JRC, the angle of incidence dependencies by Arsenal (Vienna, Austria) as described in [7] and the thermal coefficients of set 1 and set 2 were determined Arsenal and ISAAC respectively.

3.3 Implementation of algorithms

The module measurement data and the weather data of each reference days from the proposed standard are then analysed for power and energy calculation in Arsenal, ISAAC and CREST. In a number of iterations, it was ensured that the output of all algorithms is in agreement. The aim was to identify areas in the standard where possible interpretations can affect the results in the end. The outcome of this is discussed as the final sections were issues with the overall standard are reviewed.

4 VALIDATION OF ENERGY RATING

The final step in this implementation is to evaluate the validity of the proposed standard. The aim is to see how well the proposed standard works as an energy prediction methodology, how significant certain parts of the standard are and how relevant the standards days are in realistic conditions.

4.1 Agreement with realistic measurements

The first step is to use verify that the energy rating methodology is able to reproduce realistic operation, which has been carried out for a set of three different crystalline silicon modules operating at ISAAC for a full year.

4.1.1 Generating useful data samples

The first problem in applying the suggested energy rating methodology is on how to generate the required inputs. The module specific data is well defined in part 1
and part 2 of the standard, but the meteorological data is difficult to obtain. There is hardly any site available that measures global beam and (angularly distributed) diffuse and solar spectrum. ISAAC data measurement data needs to be modified to generate the angularly distributed diffuse irradiance, which is done by implementing the anisotropic model by Klucher [11]. Unfortunately, this introduces a significant uncertainty into the methodology, as all methods to calculate the angular dependence of the diffuse irradiance do not necessarily achieve better accuracy as isotropic sky models.

4.1.2 Agreement between measurements and calculations

Results are here shown for the two c-Si modules ‘c-Si M1’ and ‘c-Si M3’ measured in Lugano which demonstrated respectively the highest and lowest annual energy output of the silicon modules listed in Table 2. A difference in kWh per Wp real power of 5.7% was observed over 1 year in between the two modules (see also Table 4).

The validation was limited to days where full and validated spectral data was available, resulting in a total of 116 days with approximately 10 days for each month of the year.

The red lines in Figure 4 illustrates how the days were attributed to the standard operating regimes (related to the standard days). To differentiate these operating regimes from the standard days small letters were used (hiht, hilmnt, etc.) instead of the capital denoting standard days. The energy output is calculated for all 116 days and then for the entire year. The absolute energy prediction error is calculated for both modules as well as the predicted difference for the two modules. The validation was here done on one-minute data instead of hourly data. A higher accuracy is so reached as indicated that the model is not appropriate or that a systematic error was introduced during the modelling. It could be that the simplified Kings-model interpolation used here, contributed to the deviations, as it is known not to be ideal for low light behaviour. The introduction of a systematic error means that the energy prediction is not of noticeable accuracy, but another important aim of this standard is to allow distinction between the energy yield of different modules and the answer here is that clearly shows, as the kWh/kWp values in Table 4 demonstrate.

Table 4: absolute energy rating error for two c-Si modules in kWh.

<table>
<thead>
<tr>
<th>n°of days</th>
<th>Ecalc-Emeas (M1)</th>
<th>Ecalc-Emeas (M3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg</td>
<td>St.Dev</td>
</tr>
<tr>
<td>hiht 12</td>
<td>-3.7%</td>
<td>4.1%</td>
</tr>
<tr>
<td>hint 26</td>
<td>-1.9%</td>
<td>3.5%</td>
</tr>
<tr>
<td>hiht 3</td>
<td>2.1%</td>
<td>2.9%</td>
</tr>
<tr>
<td>milht 7</td>
<td>-1.1%</td>
<td>4.1%</td>
</tr>
<tr>
<td>mint 29</td>
<td>-4.9%</td>
<td>8.0%</td>
</tr>
<tr>
<td>milht 17</td>
<td>0.8%</td>
<td>5.7%</td>
</tr>
<tr>
<td>limit 7</td>
<td>-25.8%</td>
<td>2.5%</td>
</tr>
<tr>
<td>liht 13</td>
<td>-23.5%</td>
<td>5.4%</td>
</tr>
<tr>
<td>all days  114</td>
<td>-3.54%</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: absolute energy rating error for two c-Si modules.

Table 4 shows the difference in the measured and calculated energy of the two modules as well as the standard deviation achieved in each of the operating regimes. It is noticeable that the agreement for the low irradiance days is quite low, with the deviation being in order of magnitude that the real measurement is outside the 3-k interval of the simulations, which would indicate that the model is not appropriate or that a systematic error was introduced during the modelling. It could be that the simplified Kings-model interpolation used here, contributed to the deviations, as it is known not to be ideal for low light behaviour. The introduction of a systematic error means that the energy prediction is not of noticeable accuracy, but another important aim of this standard is to allow distinction between the energy yield of different modules and the answer here is that clearly shows, as the kWh/kWp values in Table 4 demonstrate.

The author’s feeling is that the complexity of the standard is actually not beneficial for an accurate energy prediction, as it requires data which is actually normally not known (angular distribution of the diffuse irradiance) and the generation of this for in plane irradiance seems to affect the overall agreement more than it would be without this complicated step.

4.2 Relevance of standard days

In order to produce a relevant energy rating, the standard days must be in operating regimes which somehow reflect realistic conditions. This is verified for three sites, Lugano, CH in Figure 4, Tallinn, Estonia in figure 5 and for Loughborough, UK, in Figure 6.
The conclusions are that the days are not particularly relevant for any of the sites. This is on top of the fact that no wind data or spectral matches were attempted at all, which would have reduced the overall overlap even more.

There is no site which has anything close to the HILT or LILT. Another idiosyncrasy is that the daily irradiance of the MIMT and the LILT are very comparable (negligible) while the MIHT has nearly three times as much irradiance.

There is a general agreement within the PV community about the need to use representative meteorological data for an energy rating, but it is questionable if these standard days are the way forward. The standard days are a good tool to validate an implementation of part 3, but if they provide useful information which goes beyond the common power rating is not certain from the above evaluation.

The days present somewhat the envelope of possible operating environments as such not representative. Given the sensitivity analysis in the next section, e.g. it would appear that the silicon module would be a worse module due to its rather high loss in low irradiance conditions but this effect would be marginal when operating at the majority of sites.

One could imagine to extend the concept of standard days not to energy rating but to evaluate what parts of an energy rating standard needs to be carried out. As such an example, a sensitivity analysis is demonstrated below, and one could imagine that one carries out a test with an extensive dataset to identify which effects need to be considered for detailed calculations and then only carry out the entire rating procedure for an annual data set representative for the different climatic zones.

4.3 Sensitivity analysis

In order to evaluate the importance of the different steps in this rather complex standard, an impact analysis against irradiance, temperature, AOI and spectrum is carried out based on daily conversion efficiency and daily energy generation of each reference day using different samples outlined in Table 1 as set 1.

Influence of irradiance has been analysed to see the importance of considering the variation of efficiency with irradiance. This sensitivity was carried out based on operating efficiency rather than power, as the main effect would otherwise have been due to the increase of input power. The efficiency of a simulation where each hour had an irradiance of 1000W/m² has been carried out and the percentage change compared to the normal irradiance is shown in Figure 7. This is equivalent to only moving along the T-axis in the G-T matrix.

Strong deviation has been found for the low irradiance days MIMT and LILT. Specifically the c-Si module is affected, showing an increase of 20%-25% if it would be operating at 1000W/m² all the time. Given that this particular module is known to have a rather bad low light behaviour, this is reasonable. However, this looks horrific, but how much would this contribute in a realistic operation to the absolute energy production in the course of a year? The a-Si module is also not working as well as sometimes assumed but that might have to do with the assumed spectra at these days and with the fact...
that it has seen 7 years of outdoor operation before the calibration used for this paper.

The effect of temperature on the energy yield is shown in Figure 8, here a fixed temperature of 25 degrees was chosen. Again, the c-Si module shows the most significant effect, more than ±10% influence for HIHT and LILT respectively, followed by CIGS and a-Si.

![Figure 8: Deviation in daily energy generation at unmodified and modified with fixed temperature at STC value condition.](image)

Similarly AOI and spectral influence has been analysed based for relative changes in energy generation for each day which is depicted in Figure 9 and Figure 10 respectively.

![Figure 9: Relative change of daily energy at actual and fixed at normal AOI. (this figure needs to be change, I am working on it)](image)

There is a 2-5% effect visible for the various technologies, which is not as big an effect as seen for the other two effects. Surprisingly, there is a very significant change between the HIHT and the HILT for the a-Si material, which is due to very different incident spectrum. Also the results represent what one would expect from experience.

![Figure 10: Relative change of daily energy at actual and fixed at spectrum AM 1.5](image)

The angle of incidence is in the range of 2-4%, depending on the material, thus an effect can be represented.

5 ISSUES IDENTIFIED

The implementation and validation exercise reported above has flagged up some issues, which should be resolved to make this standard more user friendly.

5.1 Data related issues

The input into the calculations is rather complex and the uncertainty of these is not known. The repeatability and accuracy of the AoI measurements is at the moment unknown and not easy to evaluate. Similarly, the accuracy of the different regions needs to be evaluated, it is well known for c-Si at STC, but how accurate is it at different conditions and how does this uncertainty filter into the results of the energy yield.

In terms of validation, it is required to understand the accuracy of the incident spectra or the spectra themselves. In the standard days, it is not known how accurate the spectra used in the standard data sets are.

The data in the measurements does not cover the range required for the simulation of the standard days, which results in having to employ extrapolation which in turn has a tendency to increase uncertainty. Example for this is the thermal coefficients at high wind speed categories or the lack of low temperatures in the power matrix.

The application of the height correction for the wind speed results in several values being exactly equal to a class border value which is not specified in the standard how to deal with it (the equal sign needs to be added to one side of the range definition).

5.2 Implementation and calculation related issues

The aim of a standard is that if two people perform the same calculation, the result should match. This was not always the case, largely due to changes in the resolution and the interpolation. The spectral resolution e.g. of the AM1.5 is given in 0.5 nm steps, spectral response in the standard days is given in 10 nm steps. Interpolation to 1 nm steps gave different results than using the 10 nm resolution. Similarly, the integration for the diffuse irradiance, where there the interval should be fixed to 1 degree steps. Differences were also observed when applying the Isc-T-P matrix, were the choices are between choosing the closest measurements or apply an
interpolation for each time step. There is also a lack of clarity what interpolation strategy is to use when as e.g. the transmission data could be fitted for all modules tested nearly perfectly using the Fresnel equations which would minimise the influence of the scatter in the measurements rather than to enhance them.

The lack of angularly distributed diffuse irradiance makes the energy rating nearly impossible to use. This is enhanced by relatively high uncertainties in the measurement of irradiance (global and diffuse), especially at low irradiance levels. There is a high likelihood that realistic, measured data does not agree with the required data, e.g. the spectral range of many spectroradiometers is up to 1000nm and the wavelength required for spectral corrections is wider, and no guidance is given on how to calculate the spectral correction is given.

6 CONCLUSIONS

The entire draft standard has been implemented and some issues have been identified. The standard represents a significant improvement over the angular use of power rating for comparing devices. The measurement standards, i.e. part one and part two, provide essential information required for developing a device comparator for different PV technologies, although sections of part 2 might only be of importance for some technologies and glass structures. The new measurements and the different signal strengths requires a careful investigation of measurement uncertainty to ensure the required data quality. Also, there are some minor issues with the data ranges prescribed in the standard. Furthermore a large number of measurements are required, and the necessity for all of them is not proven for all technologies.

The calculation part of the standard is very complex with some question marks over the quality of data required to do the energy prediction. Overall the energy rating is able to give accurate results for the days tested here, with accuracies not worse than those of other methodologies. Currently, in the tests reported here, there appears to be a systematic error in the measurement, but the overall statistical fluctuations are reduced. The main issue for the validation or use as energy predictor is the unavailability of the required input data is the biggest problem for an accurate good validation study. The agreement between measurements and simulations for low light conditions is rather low indicating a need for enhancing of data quality.

Finally, the standard days are of questionable relevance for an energy rating, as the information that could be gained from them is not necessarily of relevance for any user of the standard. It might be useful to show differences with amounts of data in a simulation that are manageable, albeit the results might be very misleading as we deal with non-representative days.

The main point would be that for a relevant energy rating, a longer and more representative time scale than the reference days would need to be chosen, which would need a model for the data required (e.g. spectral input) to keep data to a manageable amount.

7 ACKNOWLEDGEMENTS

The work has been supported through EU FP6 project ‘Performance’ (contract no SES-019718) as well as EPSRC Grant EP/D07843/1. It reflects only the author’s views; the Community is not liable for any use that may be made of the information contained therein.

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