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Citation: KRAWCZYNSKI, M. ... et al. 2010. Influence of spectral irradiance measurements on accuracy of performance ratio estimation in large scale PV systems. IN Proceedings of the 25th European Photovoltaic Solar Energy Conference and Exhibition (EUPVSEC) and 5th World Conference on Photovoltaic Energy Conversion (WCPEC 5), València, pp. 4710 - 4714.

Additional Information:

• This is a conference paper.

Metadata Record: [https://dspace.lboro.ac.uk/2134/9217](https://dspace.lboro.ac.uk/2134/9217)

Version: Accepted for publication

Publisher: © WIP Wirtschaft und Infrastruktur GmbH & Co Planungs KG

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INFLUENCE OF SPECTRAL IRRADIANCE MEASUREMENTS ON ACCURACY OF PERFORMANCE RATIO ESTIMATION IN LARGE SCALE PV SYSTEMS

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ABSTRACT: Understanding the quality of irradiance measurements is an essential part of PV monitoring. For precise estimation of solar radiation all of its properties must be considered. There are two different ways to describe irradiance – broadband and spectral. Broadband irradiance measurements are by far the most commonly applied technique and can be undertaken by the use of pyranometers or calibrated reference cells. Broadband measurements give integrated power over a specified bandwidth. Spectral irradiance describes not only the integrated energy of the sunlight, but also its distribution by wavelength. PV modules are strictly wavelength selective devices. Their spectral sensitivity depends mostly on the cell material technology. Spectral effects can be observed at their most extreme for thin-film a-Si modules. Knowing the accurate intensity and spectral distribution of the sunlight may have a significant influence on accurate prediction of the available energy for different types of PV device.

Keywords: spectral response, solar radiation, performance

1 INTRODUCTION

Recovery of the spectral irradiance from broadband irradiance measurements, based on the standardised terrestrial solar spectrum with correction for the atmospheric path length traversed and the solar angle of incidence (caused by Sun’s position and site’s geographic location and orientation), may not be sufficiently precise. The majority of the influencing parameters such as cloudiness, reflected irradiance, air pressure, humidity and pollution in the atmosphere have a stochastic character and cannot be applied with confidence to spectral simulation models. To introduce precise spectral characterisation of the irradiance, spectroradiometer measurements are essential [1]. PV modules are strictly wavelength selective devices. Their spectral sensitivity depends mostly on the cell material. Spectral effects can be observed at their most extreme for thin-film a-Si modules, which have the widest band gap [2]. Despite this, spectral irradiance measurements are almost always omitted in PV monitoring systems. This is due to the relatively high cost of the spectroradiometers and the large amount of data that must be stored and processed. This paper discusses utilisation of spectral irradiance data in photovoltaic monitoring systems. Based on real measurements of the environmental conditions (irradiance, spectral irradiance, ambient temperature, relative humidity) initial analysis of the spectral influences on different module technologies has been performed. The EQE responses of the different modules were taken under consideration and were used together with the spectral irradiance measurements to calculate current density available for a specific module. Photon Utilization Ratio (PUR) has been introduced to express the influence of spectral variations for a given module type.

2 APPROACH

In theoretical considerations light is described as a wave – particle called a photon. The energy of a photon depends only on its frequency (1).

\[ E(\lambda) = h \nu = \frac{hc}{\lambda} \]  

Where \( h \) is Planck’s constant, \( c \) is the speed of light in vacuum, \( \nu \) is the frequency in Hertz and \( \lambda \) is the wavelength in \( \mu m \).

Broadband irradiance sensors measure radiant power, which is the sum of spectral irradiance received from the light source over the specified bandwidth (2).

\[ H = \int_{\lambda_1}^{\lambda_2} E(\lambda) d\lambda \left[ \frac{W}{m^2} \right] \]  

Where \( E(\lambda) \) is spectral irradiance.

The same radiant power may be received by broadband sensor as a result of interaction with different amounts of photons, depending on their energy (i.e. different spectral distributions). Radiant power does not provide accurate information on the number of photons that interact with a sensor.

Generation of electron-hole pairs depends on the absorption coefficient of the material, the number of interacting photons and thickness of the material (3).

\[ G = \alpha N e^{-\alpha x} \left[ \frac{1}{m} \right] \]  

Where \( \alpha \) is the absorption coefficient, \( N \) is the number of photons and \( x \) is the depth in the material.

If the photon energy is equal to or greater than the band gap of a semiconductor, a photon can excite an electron-hole pair. In a conventional solar cell one photon can generate only one electron. Photon energy greater than the band gap is wasted, as the excited electron will thermalize down to the band gap edge. Although a new concept of multi-excitation generation in organic materials has been proposed, it is still far from application [3].

For currently available photovoltaic devices it is important to know the number of photons that are able to generate carriers instead of the sunlight’s radiant power. Spectral irradiance describes the distribution of a radiant power over the spectrum. If the radiant power is known
for a defined wavelength interval, photon flux can easily be calculated (4).

\[ \phi(\lambda) = \frac{E(\lambda)}{E_s(\lambda)} \left( \frac{\text{photons}}{s \cdot m^2 \cdot \mu m} \right) \]  

(4)

Where \( \phi(\lambda) \) is the photon flux, \( E(\lambda) \) is the spectral irradiance and \( E_s(\lambda) \) is the energy of a photon in Joules (\( 1J = 6.24150974 \times 10^{18} \text{eV} \)).

The spectral response of a photovoltaic cell can be described by an external quantum efficiency (EQE). External quantum efficiency is a ratio between the number of carriers collected outside of the device to the number of photons of given energy incident on the device (5).

\[ \text{EQE}(\lambda) = \frac{\text{electrons} / s}{\text{photons} / s} \]  

(5)

By combining photon flux \( \phi(\lambda) \) with EQE(\( \lambda \)) the spectral current density of a cell can be calculated.

\[ J(\lambda) = \text{EQE}(\lambda) \cdot \phi(\lambda) \left( \frac{A}{m^2 \cdot \mu m} \right) \]  

(6)

Integrating \( J(\lambda) \) through the wavelengths under a given spectral photon flux gives the resultant density of the current available from the cell (7).

\[ J = \int J(\lambda) d\lambda \left( \frac{A}{m^2} \right) \]  

(7)

Moreover, if the same type of cross-calibrated spectral irradiance sensor has been used to characterize module/cell EQE(\( \lambda \)) and to measure spectral irradiance \( F(\lambda) \), the absolute calibration accuracy of the sensors will not have a significant influence on the accuracy of the photocurrent calculation.

To demonstrate the influence of the spectral irradiance on the density of current generated by modules, the photon utilization ratio (PUR) is introduced (8).

\[ \text{PUR} = \frac{N_s}{N_{\text{AM1.5}}} = \frac{\int \text{EQE}(\lambda) \cdot E(\lambda) d\lambda}{\int \text{EQE}(\lambda) \cdot E_{\text{AM1.5}}(\lambda) d\lambda} = \frac{J}{J_{\text{AM1.5}}} \]  

(8)

Where \( N_s \) is the ratio between the number of photons that generate carriers in the device to the total number of photons reaching the device under the experienced spectrum. \( N_{\text{AM1.5}} \) is the ratio between the number of photons that would generate carriers in the device under AM1.5 illumination to the total number of photons reaching the device under AM1.5 illumination. In terms of current, PUR can be described as the ratio between the current density under the experienced spectrum for a given device (\( J \)) to the current density available under the experienced spectrum for an ideal device (\( J_{\text{AM1.5}} \)), normalized by the ratio of the current density under AM1.5 illumination for the given device (\( J_{\text{AM1.5}} \)) to the current density available under AM1.5 illumination for the ideal device (\( J_{\text{AM1.5}} \)).

3 EXPERIMENTAL SETUP

Three similar sets of reference irradiance sensors were installed in various locations. Each of the sets contained two second class broadband pyranometers, a VIS spectroradiometer, up to five different PV modules (working in a short circuit mode), module temperature sensors, ambient temperature and humidity sensors and a wind speed and direction sensor.

The VIS spectroradiometers were installed in the plane of the arrays to provide accurate reference spectral irradiance measurements for installed modules. Spectral irradiance measurements should allow an increase in the accuracy of prediction of the energy available for a variety of PV device.

Dedicated short-circuited modules were used for non-biased reference measurements. Such a module has the same angular and spectral response as the modules that are generating power. It will also degrade in a similar way. Short circuit current varies more or less linearly with irradiance, so it can be used as a measure of reference irradiance. For each of the investigated technologies, one dedicated reference short circuited module was installed.

A module’s temperature has an influence on most of its electrical parameters. Thermal energy transport between the module and environment depends on mounting structure, irradiance, ambient temperature, humidity, wind speed and direction. All those parameters were monitored to provide an accurate reference for system performance analysis.

Detailed PV plant specification and all measurements were stored in a database to provide an effective method of data analysis. Most of the analyses were performed by custom developed software, with the help of statistical packages.

A simplified layout of the measuring system is shown in Figure 1.
ANALYSIS

The main motivation for the analysis reported here was to establish to what extent irradiance measurements can be improved to allow more accurate estimation of the performance ratio (PR) of a photovoltaic system. The used irradiance sensors were manufactured by different companies. To avoid influences of the manufacturer’s specific calibration, the spectroradiometer and reference module responses were calibrated with the broadband pyranometer. The pyranometer was used as an absolute reference for two reasons: it is classified and calibrated in accordance to ISO standards (ISO 9060 and ISO 9846) and it is used as a reference sensor for irradiance measurements by module manufacturers. Moreover, the pyranometer sensitivity does not significantly depend on wavelength (within its sensitivity range), radiation intensity, ambient temperature and time.

4.1 Spectroradiometer cross-calibration.

Records used for absolute calibration were chosen on criteria given by standard test conditions (H=995-1005 W/m$^2$ and $T_{ambient}=25^\circ$C. From selected spectra, the mean spectral response of the spectroradiometer under STC was calculated. Spectral irradiance measurements were taken over the range of 300-1150nm. In calculations a range of 350-1050nm was used due to high measurement uncertainty outside of this interval. Measured spectra were integrated over the range of 350-1050nm and compared with the corresponding relative fraction (74%) of the integrated AM1.5 spectrum. The ratio between the measured and standard integrated spectral irradiance was used to scale the spectroradiometer measurements. Figure 3 shows a spectrum measured under STC before and after recalibration, in comparison to the AM1.5 spectrum.

As shown, non-calibrated spectroradiometer measurements correspond to approximately 12% lower irradiance than the reference AM1.5 spectrum specifies. Such a large error in absolute calibration was verified during spectroradiometer indoor tests [4]. In [4] the authors have demonstrated that the shape of the spectrum measured by the type of spectroradiometer used here follows the spectrum of a calibrated reference lamp within 2% difference in a given interval. Moreover, variations observed in Figure 3, between measured and AM1.5 spectra shapes could have been caused by site-specific environmental conditions (i.e. pollution).

If an external quantum efficiency (EQE) for a given module technology is known, the current of the device can be calculated for a given spectrum. Figure 4 presents spectral photon flux calculated from the AM1.5 spectrum and external quantum efficiency of standard module technologies.

![Figure 4: Photon flux density and EQE of the photovoltaic modules used in this study.](image)

By integrating spectral current density through the band of 300nm to 1200nm, STC current densities for the investigated module types was calculated and compared with data from manufacturers’ datasheets. (Table I)

<table>
<thead>
<tr>
<th>Tech</th>
<th>EQE</th>
<th>Datasheet</th>
</tr>
</thead>
<tbody>
<tr>
<td>mono-Si</td>
<td>366.5</td>
<td>371.0</td>
</tr>
<tr>
<td>a-Si</td>
<td>142.4</td>
<td>-</td>
</tr>
<tr>
<td>CIS</td>
<td>262.5</td>
<td>260.0</td>
</tr>
<tr>
<td>multi-Si</td>
<td>337.8</td>
<td>333.3</td>
</tr>
<tr>
<td>AM 1.5</td>
<td>464.5</td>
<td>464.5</td>
</tr>
</tbody>
</table>
Table I: Current density for different cell technologies under standard test conditions.

The measurement range of the used spectroradiometer lays between 350 – 1050nm. Current densities shown in Table I were recalculated for that bandwidth (Table II).

<table>
<thead>
<tr>
<th>Technology</th>
<th>J[A/m²] EQE based</th>
<th>Spectral Irradiance based</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>mono-Si</td>
<td>341.78</td>
<td>341.5</td>
<td>-0.08</td>
</tr>
<tr>
<td>a-Si</td>
<td>143.1</td>
<td>143.1</td>
<td>1.41</td>
</tr>
<tr>
<td>CIS</td>
<td>260.9</td>
<td>261.3</td>
<td>0.15</td>
</tr>
<tr>
<td>multi-Si</td>
<td>325.0</td>
<td>324.7</td>
<td>-0.9</td>
</tr>
<tr>
<td>AM 1.5</td>
<td>409.24</td>
<td>409.24</td>
<td>0</td>
</tr>
</tbody>
</table>

Table II: Current density for different cell technologies under standard test conditions.

Table II shows that an estimation of the current density (for conditions close to STC) based on module EQE and measured spectral irradiance gives similar results to estimates based on module EQE and reference AM1.5 spectral irradiance. This validates the spectroradiometer calibration.

4.2 Reference module calibration

For most of the used reference modules, the manufacturer’s flash data were available. Flash tests are performed with solar simulators. The parameters of the light emitted by the simulators does not fully correspond to the parameters of sunlight. Module short circuit current (I_sc) was measured outdoors at STC to check if the manufacturer’s parameters corresponded with those measured under broadband reference irradiance. In most cases standard test conditions do not correspond with real operating conditions (i.e. temperature of the loaded module under STC irradiance of 1000W/m² will be rarely equal to 25°C, especially in southern locations). Depending on site specific conditions, different methods of short circuit current extrapolation should be used. For this analysis the northern method was used. Conditions applicable for record extraction are given in Table III.

<table>
<thead>
<tr>
<th>Device Description</th>
<th>H [W/m²]</th>
<th>T_ambient [°C]</th>
<th>T_module [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference module</td>
<td>995-105</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>(southern country method)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reference module</td>
<td>950-1050</td>
<td>X</td>
<td>24-26</td>
</tr>
<tr>
<td>(northern country method)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table III: Record extraction condition for I_sc extrapolation.

Table IV presents short circuit currents extrapolated from outdoor broadband irradiance measurements at STC and manufacturer supplied flash test data.

<table>
<thead>
<tr>
<th>Module type</th>
<th>I_sc (flash)</th>
<th>I_sc (extracted)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>µa-Si</td>
<td>2.20</td>
<td>2.192</td>
<td>0.36</td>
</tr>
<tr>
<td>m-Si</td>
<td>5.79</td>
<td>5.651</td>
<td>2.40</td>
</tr>
<tr>
<td>p-Si (1)</td>
<td>8.37</td>
<td>8.069</td>
<td>3.60</td>
</tr>
<tr>
<td>p-Si (2)</td>
<td>8.07</td>
<td>8.027</td>
<td>0.53</td>
</tr>
<tr>
<td>CIS</td>
<td>2.39</td>
<td>2.408</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Table IV: Short circuit current for different modules (manufacturer specified vs. measured at STC).

4.4 Photon utilization ratio

The main idea tested by this work is that, since module output current depends on the spectral characteristics of the illumination, spectral measurements could be applied to plant monitoring to provide more accurate predictions of reference irradiance. This parameter has the most significant influence on the accuracy of PR estimation.

The spectral characteristics of sunlight vary over the course of a day as well as with the time of the year. These variations happen due to the thickness of atmosphere that the light has to travel through overcast conditions and aerosols contained in the atmosphere. Figure 6 shows measured mean spectra for two different months and for a specific day.

As shown in Figure 6, differences in spectral characteristics can be significant and will have an influence on module performance. To demonstrate this, current densities for different module technologies were calculated under spectra experienced during the measurement campaign. To quantify utilization of the spectrum by a specified technology PUR was introduced (8). Daily distributions of PUR were calculated for different days and are shown in Figure 7 (clear day) and Figure 8 (fully overcast day).
Spectral effects can be observed for photovoltaic devices. However at the present time it is relatively difficult to use spectroradiometers by themselves as reference irradiance sensors for PV systems. This is due to a lack of classification and calibration standards that spectroradiometers could be manufactured to. Additional calibration based on standardised broadband irradiance sensors had to be followed to achieve accurate absolute spectral measurements.

Short circuited reference modules seem to be a good alternative for spectral irradiance measurements. When the sensing and generating devices are of the same technology spectral effects should be automatically compensated. It was shown that module parameters specified by manufacturers are not always precise. Without additional calibration reference modules will not provide accurate estimation of available irradiation. Moreover each technology to be monitored requires a separate reference module or cell.

To quantify the influence of spectral irradiance on a module the photon utilization ratio has been introduced. It allows presentation of the utilization of the measured spectrum by different types of modules in relation to the AM1.5 spectrum. It does not depend on the absolute value of irradiance and presents the spectrally dependant response of the module as a singular number.

The largest spectral influences were observed for a-Si modules. Amorphous silicon has a relatively wide band gap, which makes its spectral response correspondingly narrow. Due to this, variations in the spectral irradiance have a stronger influence on this technology than on any of the others reported here.

6 REFERENCES