Spectrometric Outdoor Characterization of CPV Modules using Isotype Monitor Cells

G. Peharz[1], G. Siefer[1], K. Araki[2], A.W. Bett[1]
[1]Fraunhofer ISE, Heidenhofstrasse 2, 79110 Freiburg, Germany
[2]Daido Steel Co., Ltd, 2-30 Daido-cho, Minamiku, Nagoya, 457-8545 Japan

ABSTRACT

In this paper we present a method to investigate the impact of the solar spectrum on the output parameters of a CPV module equipped with triple-junction solar cells. The changes of the sun´s spectrum were monitored by using calibrated isotype solar cells. A correlation of the CPV module outdoor performance to changes in the sun spectrum has been determined. Experimental results of the spectral impact on the current of a Daido Steel CPV module are presented. Finally, a correction method is applied in order to derive the module's current under reference spectral conditions.

INTRODUCTION

Many of today's CPV modules are equipped with triple-junction solar cells made of III-V materials. These solar cells are usually optimized to be current matched for one reference spectrum. Under AM1.5d low AOD reference spectrum triple-junction solar cells achieve efficiencies >40 % [1]. However, if one considers changes in the spectrum, the currents of the subcells can change and the triple-junction solar cell's current can become mismatched [*2-5*]. Thus, the performance of CPV modules using triple-junction solar cells depends not only on the direct normal irradiance (DNI in [W/m²]) value but also on the spectrum of the direct sunlight [*6-8*].

Some years ago a measurement set-up was installed at the roof of the Fraunhofer ISE for measuring the IV curves of CPV modules and meteorological data (irradiance, temperature, humidity…) [*7, 9*]. From long term measurements the relative efficiency variations of CPV modules using multi-junction solar cells were found in general to be about ±15 %. The observed variations of the open circuit voltages of the modules can be explained by taking into account the solar intensity and the ambient temperature [*10*]. However, the variations of the short circuit currents (I_{SC}) of the modules cannot be explained sufficiently without considering the influence of the solar spectrum.

In order to monitor changes in the direct sun spectrum the measurement set-up was upgraded in October 2007. We mounted calibrated isotype cells which are sensitive for different bands of the solar spectrum. Isotype cells have the same internal structure as multi-junction solar cells, however, only one sub cell is electrically active. Changes in the solar spectrum can be quantified by comparing the measured I_{SC} of the isotype cells. Finally the changes in the solar spectrum were correlated to the performance of CPV modules.

EXPERIMENTAL

In order to monitor changes in the solar spectrum isotype cells were mounted at the outdoor CPV measurement set-up at the Fraunhofer ISE (Freiburg, Germany, 48.01° northern latitude; 7.83° eastern longitude). The isotype cells were encapsulated and mounted on the tracking system beneath collimator pipes with an opening angle of about ±2.5°. Consequently they receive only direct normal irradiation (DNI). A picture of the outdoor measurement set-up is shown in Fig. 1.

Fig. 1. Photograph of the CPV outdoor test set-up at the Fraunhofer ISE. The position of the three collimator pipes with underneath mounted isotype cells is marked with a circle.

The isotype cells have been calibrated at ISE CalLab. Therefore AM1.5d low AOD (G = 1000 W/m²) [*11*] was used as reference spectrum. The measured quantum efficiencies of a $Ga_{0.50}In_{0.50}P$ top isotype cell and a $Ga_{0.83}In_{0.17}As$ middle isotype cell are shown in Fig. 2. Please note that both isotype cells have practically the same internal structure as state of the art triple-junction solar cells. For the spectral monitoring this combination of isotype cells was chosen because of availability reasons. For the application of spectral monitoring we benefit from the fact that the spectral responses of the two isotype cells have almost no overlap (see Fig. 2).

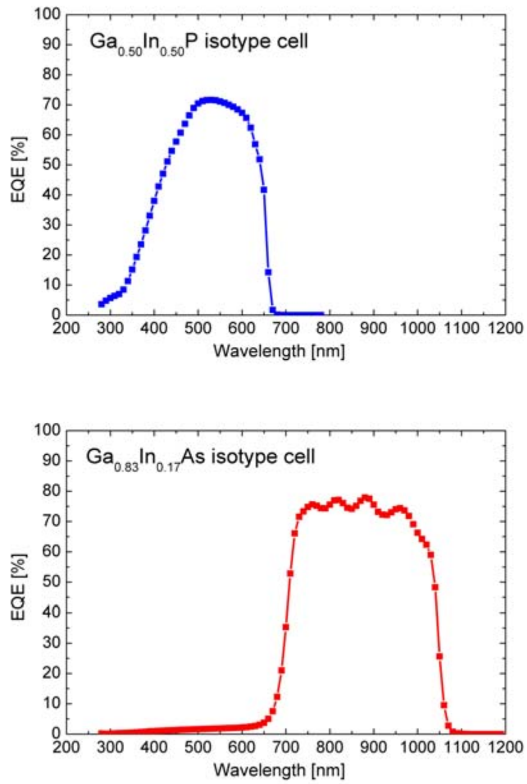

Fig. 2. Top: Measured External Quantum Efficiency (EQE) of the encapsulated Ga0.50In0.50P top isotype cell. Bottom: Measured EQE of the encapsulated Ga0.83In0.17As middle isotype cell.

The top isotype cell is sensitive for wavelengths > 300 nm and < 700 nm and the middle isotype cell is sensitive for wavelengths > 700 nm and < 1050 nm. The current signal of the isotype cells was monitored, in order to estimate the DNI in these two different spectral bands.

SPECTROMETRIC METHOD

For the analysis of the spectral condition the measured currents of the isotype cells are related to their calibrated current. The determined current ratios ($I_{SC,\ measured}$ / $I_{SC,\ calibrated}$) of each isotype cell are now plotted into a two-dimensional spectrometric plane. Fig 3 shows this spectrometric plane for the performed outdoor measurements in Freiburg from October 2007 until April 2008.

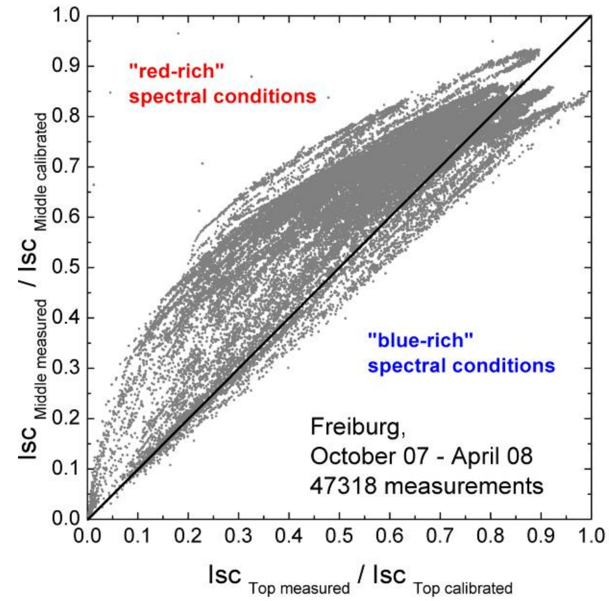

Fig 3. Spectrometric plane: The x-axis displays the ratio of the measured I_{SC} to the calibrated I_{SC} (AM1.5d low AOD (G=1000 W/m²) of the top isotype cell. The y-axis gives the same ratio for the middle isotype cell.

Using this method, every measured solar spectrum is represented by one unique point in the spectrometric plane. However, it is noteworthy that every combination of top and middle current ratios can be generated by an infinite number of solar spectra.

All data points which are located on a line through the origin correspond to spectra which generate the same relative current ratios of the top and the middle isotype cell. In other words: The (relative) current mismatch between the top and the middle isotype cell is the same for all points which are on the same line through the origin. For example, data points which are located on the line y=x correspond to spectra which generate the same relative current mismatch between the two isotype cells as the reference spectrum does.

In the spectrometric plane one can define a “red-rich” region: Spectra which are allocated in this region are generating relatively more current in the middle isotype cell than in the top isotype, if compared to reference conditions (y=x). In contrast the “blue-rich” region in the spectrometric plane corresponds to spectra which generate a “current gain” in the top isotype cell and a “current loss” in the middle isotype cell relative to the reference spectrum (see also Fig 3).

Let us define now a “spectrometric line” in the spectrometric plane [*2*] – as illustrated in Fig. 4. The definition of the spectrometric line is done in a way that the point (1;1) corresponds to solar spectra which generate the same current in the isotype cells as the chosen reference spectrum would generate. The sum of the current ratios for data points on the spectrometric line is asked to be constant – in the present case equal to 2. This definition implies: When moving along this spectrometric line the current ratio ($I_{SC, measured}$ / $I_{SC, calibrated}$) of one isotype cell increases Z*100% and simultaneously the current ratio of the other isotype cell decreases Z*100%.

In order to normalize the measured data points in the spectrometric plane shown in Fig. 4, they are projected onto the spectrometric line by using a line through the origin. The procedure of the data point projection is illustrated in Fig. 4.

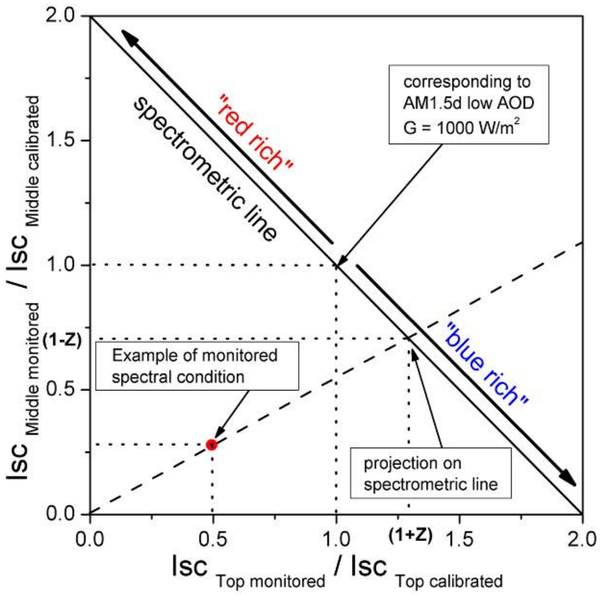

Fig. 4. The "spectrometric line" in the spectrometric plane is illustrated. Furthermore the projection of an arbitrary data point onto the spectrometric line is sketched.

For the analysis of the spectral impact on the module performance every point in the spectrometric plane is then projected on the spectrometric line using the procedure described above. Consequently the shift of every "measured" solar spectrum relative to reference conditions is described by a single spectral parameter Z. Positive values of Z correlate to a Z*100% increase of the top isotypes cell's current ratio and a Z*100% decrease of the middle isotype cell's current ratio. In other words: the parameter Z describes the current mismatch between the two isotype cells relative to their current mismatch under the underlying reference spectrum.

RESULTS

In order to investigate the impact of the solar spectrum on the performance of CPV modules, special attention was drawn to the I_{sc} of the modules. Furthermore, the DNI was measured with an Eppley NIP Pyrheliometer. Without any spectral or other impact the I_{sc} of a CPV module should depend directly on the received DNI. When normalizing the I_{sc} of a CPV module to a certain DNI, the normalized I_{sc} should ideally be constant. However, changes in the solar spectrum, tracking errors, Circum Solar Radiation (CSR), dust and water condensation have additional impacts on the I_{sc} of a CPV module using triple-junction solar cells.

From October 2007 until April 2008 we measured the I_{sc} of a CPV module manufactured by Daido Steel in Japan. This module uses dome shaped Fresnel lenses, homogenizers and state of the art triple-junction solar cells [*12*],[*13*]. The measured I-V curves of this module were analyzed. Only IV curves with measured fill factors (FF) in the range of 70% < FF < 90% and measured efficiencies of 10% < efficiency < 30% were considered for the evaluation.

The I_{sc} of the Daido Steel CPV module was normalized to a DNI of 850 W/m² for the spectral analysis. Fig. 5 shows the normalized I_{sc} of the module versus the spectral parameter Z, which was determined by a spectrometric analysis of the two monitored isotype cells.

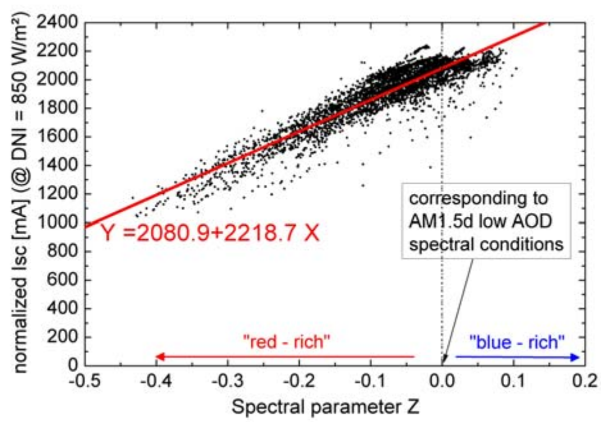

Fig. 5. The measured I_{sc} of a Daido Steel module was normalized to a DNI of 850 W/m². The relative normalized I_{sc} is plotted versus the spectral parameter Z, which was determined by the currents of the two isotype cells. Furthermore a linear regression of the data is shown.

The relative normalized I_{sc} of the module correlates to the spectral parameter Z (correlation coefficient = 0.91)[1]. A linear regression of the data delivers a slope of about 2219 mA. This slope describes the spectral sensitivity of the module's I_{sc}. A change of 10 % in the spectral parameter Z causes a change of about 222 mA in the normalized I_{SC}. This linear dependency can now be used to perform a spectral correction of the measured I_{sc}. Every normalized I_{sc} value can be corrected to a certain spectral parameter Z by using the slope of the linear regression line:

$$I_{SC,2} = I_{SC,1} - 2218.7 \cdot Z_1$$

Where $I_{SC,1}$ is the uncorrected value corresponding to

[1] Please note we expect the normalized I_{SC} to have a maximum at a certain value Z_{max}. For $Z > Z_{max}$ we expect the normalized I_{SC} to decrease linearly.

a spectral condition Z_1 and $I_{SC,2}$ is the corrected value to the spectral condition Z=0 (corresponding to the underlying reference condition). Fig. 6 shows a histogram of the relative normalized I_{sc} values, measured on the Daido Steel CPV module. Additionally the I_{sc} values which have been corrected to spectral conditions corresponding to Z=0, i.e. spectral conditions corresponding to the chosen reference spectrum, are plotted.

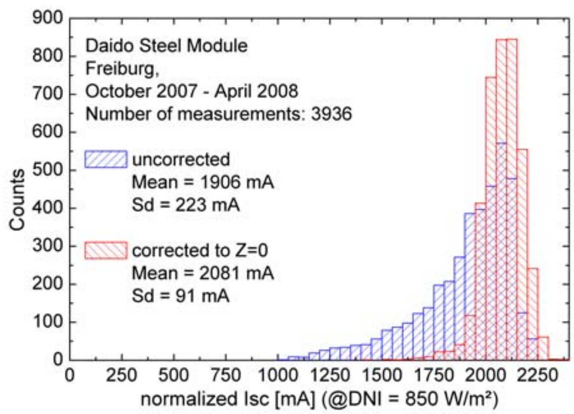

Fig. 6. A histogram of the CPV module's normalized I_{sc} is plotted. In one case the uncorrected values are shown. The other case illustrates the relative normalized I_{sc} corrected to spectral conditions corresponding to Z=0. Furthermore the mean values and the standard deviations (Sd) are shown.

By correcting the normalized I_{sc}, the mean slightly increases and the standard deviation (Sd) significantly decreases. Consequently also the uncertainty in the outdoor determination of the CPV module's I_{sc} is reduced by applying the described correction procedure. When determining the I_{sc} of a CPV module the impact of the solar spectrum can be determined and the current of the module can be determined more accurately.

CONCLUSION

We have shown that monitoring the spectrum with at least two calibrated isotype solar cells enables one to quantify the solar spectral impact on the CPV module performance. In the ideal case, isotype cells with a spectral response similar to those of the subcells in the triple-junction should be used. By applying a spectrometric analysis on the measured I_{sc} of the isotype cells a spectral parameter Z can be determined. The parameter Z describes the current mismatch between the two isotype cells relative to their current mismatch under the reference spectrum. We found that the (DNI) normalized I_{sc} of a CPV module using triple-junction solar cells correlates linearly to the spectral parameter Z.

We think that outdoor performed power rating procedures for CPV modules using multi-junction solar cells can benefit from the presented method of spectral monitoring. The spectral parameter Z can be easily determined with isotype cells or appropriate filtered reference cells and it describes the impact of shifts in the solar spectrum relative to the reference spectrum. For an outdoor rating procedure one should measure IV curves of a CPV module during at least one day. Additionally the spectral conditions during the IV-measurement should be monitored using isotype cells. Using these data the spectral sensitivity of the CPV module can be determined and now it is possible to rate the power of the module towards the reference spectral condition, i.e. the AM1.5d low AOD. This would allow a better comparison of the performance of CPV modules fabricated with different technologies even if they are not measured side by side.

ACKNOWLEDGEMENT

The authors would like to thank Raymond Hoheisel for the calibration of the isotype cells and Armin Bösch for his technical support. This work has been partly supported by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) under the ProKonPV project (contract 0327567). The authors are responsible for the content of this paper.

REFERENCES

[1] M. A. Green *et al.*, "Solar Cell Efficiency Tables (Version 31)", *Progress in Photovoltaics: Research and Applications* **16**, 61-67 (2008).

[2] M. Meusel *et al.*, "Spectral Mismatch Correction and Spectrometric Characterization of Monolithic III-V Multi-Junction Solar Cells", *Progress in Photovoltaics: Research and Applications* **10**, 243-255 (2002).

[3] K. Emery, D. Myers, S. Kurtz, "What is the appropriate reference spectrum for characterizing concentrator cells?" *Proceedings of the 29th IEEE Photovoltaic Specialists Conference*, 840-843 (New Orleans, Louisiana, USA; 2002).

[4] G. Siefer *et al.*, "Influence of the simulator spectrum on the calibration of multi-junction solar cells under concentration" *Proceedings of the 29th IEEE Photovoltaics Specialists Conference*, 836-839 (New Orleans, Louisiana, USA; 2002).

[5] K. Araki *et al.*, "Which is the best number of junctions for solar cells under ever-changing terrestrial spectrum?" *Proceedings of the 3rd World Conference on Photovoltaic Energy Conversion*, 307-310 (Osaka, Japan; 2003).

[6] W. E. McMahon *et al.*, "Fill factor as a probe of current-matching for GaInP2/GaAs tandem cells in a concentrator system during outdoor operation", *Progress in Photovoltaics: Research and Applications* **16**, 213-224 (2008).

[7] G. Siefer, A. W. Bett, K. Emery, "One Year Outdoor Evaluation of a FLATCON Concentrator Module" *Proceedings of the 19th European Photovoltaic Solar Energy Conference*, 2078-81 (Paris, France; 2004).

[8] K. Araki, M. Yamaguchi, "Influences of spectrum change to 3-junction concentrator cells", *Solar Energy Materials and Solar Cells* **75**, 707-714 (2003).

[9] G. Siefer, A. W. Bett, "Experimental comparison between the power outputs of FLATCON® modules and silicon flat plate modules" *Proceedings of the 31st IEEE Photovoltaic Specialists Conference*, 643-6 (Kissimmee, Florida, USA; 2005).

[10] G. Siefer, A. W. Bett, "Calibration of III-V Concentrator Solar Cells and Modules" *Proceedings of the 4th World Conference on Photovoltaic Energy Conversion*, 745-8 (Waikoloa, Hawaii, USA; 2006).

[11] C. A. Gueymard, D. Myers, K. Emery, "Proposed reference irradiance spectra for solar energy systems testing", *Solar Energy* **73**, 443-67 (2002).

[12] K. Araki *et al.*, "Development of concentrator modules with dome-shaped Fresnel lenses and triple-junction concentrator cells", *Progress in Photovoltaics: Research and Applications* **13**, 513-27 (2005).

[13] K. Araki, "500X to 1000X -R&D and Market Strategy of Daido Steel" *Proceedings of the 4th International Conference on Solar Concentrators for the Generation of Electricity or Hydrogen*, 73-6 (El Escorial, Spain; 2007).