Software Modeling of FLATCON© CPV Systems

Tobias Gerstmaier[1], Sascha van Riesen[2], Andreas Gombert[2], André Mermoud[3], Thibault Lejeune[3], Eric Duminil[4]

[1]*Concentrix Solar GmbH, Bötzinger Str. 31, D-79111 Freiburg, Germany, phone +4976121410842, e-mail tobias.gerstmaier@concentrix-solar.de*
[2]*Concentrix Solar GmbH, Freiburg, Germany*
[3]*University of Geneva, ISE - Group Energy / FOREL, Switzerland*
[4]*zafh.net, Stuttgart University of Applied Sciences, Germany*

Abstract: This paper describes an approach of making the FLATCON® CPV technology compatible with standard photovoltaic simulation software like PVSYST and INSEL in order to facilitate yield estimations for potential power plant sites. Due to the use of triple-junction cells, the FLATCON® CPV module efficiency is more sensitive to changes in the solar spectrum than the efficiency of an average single-junction flat plate module. Besides that, the concentrating optics show a temperature dependency. These effects result in a non-linear component in the short circuit dependency on the direct normal irradiance. By means of introducing a "Utilization Factor", deduced from both measured data and theoretical considerations, these CPV peculiarities can be considered in standard software tools and transferred to other locations without the need of overly complex measurements or algorithms.

Keywords: CPV, modeling, DNI, spectrum, air mass, multi-junction cells
PACS: 88.40.fc, 88.40.jp, 42.79.Ek

INTRODUCTION

Within the maturing CPV market, Concentrix Solar has brought the FLATCON® CPV technology developed by the Fraunhofer Institute for Solar Energy Systems [1] from pilot assembly stage to fully automated, industry size production. FLATCON® modules are made up of a Fresnel lens plate and a glass base plate on which the high performance III-V multi-junction solar cells are mounted on metal heat spreaders.

In order to be able to fully compete with flat plate PV, CPV technology has to offer the same kind of predictability. Standard PV simulation programs like "PVSYST" developed by André Mermoud at the University of Geneva [2] assume that the short circuit current of a PV module is proportional to the irradiance received by the module. Yield estimations based on this assumption turn out to be sufficiently precise for single junction modules. But as can be seen from eight months of continuous outdoor measurements in Seville in figure 1, the deviation of the measured module short circuit current (dots) from the simulated current (line) is not negligible for the FLATCON® module. This deviation is caused by the inherent spectral dependency of the triple cells and by the non-constant temperature of the concentrating optics.

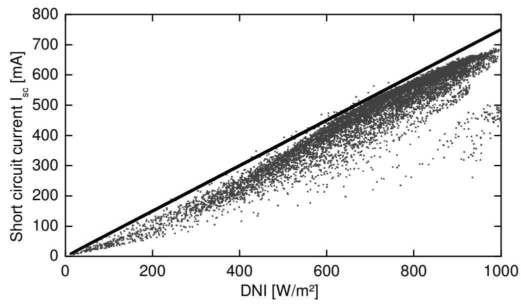

FIGURE 1: Measured (dots) and simulated (line) short circuit current of a FLATCON® module plotted against DNI.

The purpose of this paper is to present a way of considering the influence of the solar spectrum without the need for spectrally resolved direct normal irradiance (DNI) data, as this is measured only occasionally and cannot be derived from satellite data so far. Although less influential on energy yield, the temperature dependency of the concentrating optics shall be considered as well. Following the approach of the PVSYST software, the non-linear part of the short circuit current – DNI dependency shall be considered by means of a Utilization Factor ('*UF*') which allows for the calculation of the DNI fraction effectively usable for photocurrent generation [3].

INFLUENCE OF THE DNI SPECTRUM

The III-V multi-junction cells used in the FLATCON® modules consist of three monolithically stacked single cells showing an inherent spectral dependency. This is due to the serial interconnection of the three sub cells. The current of the stack is limited by the sub cell producing the lowest current. With the present stack design, the limiting cell can either be the top cell or the middle cell, depending on the spectral distribution of the incoming sunlight. The cell stack shows the highest efficiency when illuminated with sunlight of the ASTM G173 direct normal spectral distribution, as in this case the top and the middle cell produce the same current density. To be able to quantify the influence of the solar spectrum, an "EKO MS-700" spectrometer equipped with a collimator tube was installed in Seville in July 2008. The collimator tube was built according to the opening characteristics of the Kipp & Zonen "CH-1" pyrheliometer (half opening angle 2.5°) in order to measure the spectral distribution of the direct normal irradiance.

Quantification of the DNI spectrum

In order to correlate the DNI spectrum with the FLATCON® module behavior, it turns out to be helpful to express the 'red' or 'blue' emphasis of the measured spectra with a characteristic figure [4]. The photo current j of a cell can be calculated by multiplying the spectral irradiance $E_v(\lambda)$ with the transmission of the optical components $T(\lambda)$ and the cell's spectral response $SR(\lambda)$ and by integrating over the wavelength λ. R_{ASTM} shall be defined as the ratio of the top and middle cells' current densities when illuminated with light of the ASTM G173 spectral distribution:

$$R_{ASTM} = \frac{j_{top,ASTM}}{j_{mid,ASTM}} = \frac{\int E_{v,ASTM}(\lambda)T(\lambda)SR_{top}(\lambda)d\lambda}{\int E_{v,ASTM}(\lambda)T(\lambda)SR_{mid}(\lambda)d\lambda} \quad (1)$$

The corresponding ratio $R_{measured}$ is calculated for every measured DNI spectrum:

$$R_{measured} = \frac{j_{top,measured}}{j_{mid,measured}} = \frac{\int E_{v,measured}T(\lambda)SR_{top}(\lambda)d\lambda}{\int E_{v,measured}T(\lambda)SR_{mid}(\lambda)d\lambda} \quad (2)$$

Dividing the ratio $R_{measured}$ by the ratio R_{ASTM} results in the characteristic figure Y:

$$Y = \frac{R_{measured}}{R_{ASTM}} \quad (3)$$

Sunlight of the ASTM G173 spectral distribution results in $Y = 1$. Sunlight with a comparatively high short wavelength irradiance share (300nm – 600nm), hereinafter referred to as 'blue emphasized' is characterized by $Y > 1$. 'Red emphasized' sunlight with a higher irradiance share in the >600 nm region results in $Y < 1$. Figure 2 shows the diurnal variation of Y (line) and the short circuit current of a module divided by the DNI $I_{sc,scaled}$ (dots). The highest $I_{sc,scaled}$ values were measured under DNI spectra close to the ASTM G173 spectrum and hence close to $Y = 1$.

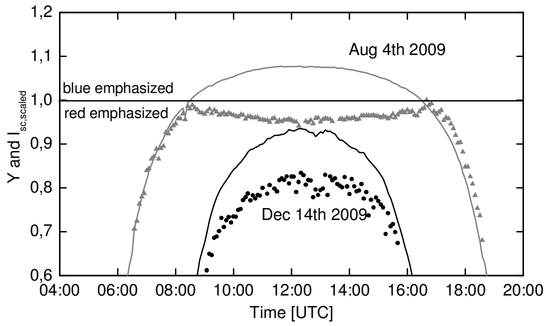

FIGURE 2: Y (lines) and $I_{sc,scaled}$ (dots) measured in Seville on Aug 04th 2009 (grey) and Dec 14th 2009 (black). The August $I_{sc,scaled}$ peaks coincide with sunlight spectra similar to the ASTM G173 spectrum ($Y = 1$).

Simulation of the DNI spectrum

Simulation based on the SMARTS2 model

On its way through the atmosphere the sunlight is changed in its spectrum by various processes like Rayleigh scattering, aerosol extinction and absorption by water vapor, ozone and nitrogen dioxide [5]. The Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS2) [6] was used to compute DNI spectra for the measuring site in Seville. The reference atmospheres "mid latitude summer" and "mid latitude winter" were used, the Air Mass was considered by entering time and coordinates. All other values were set to default. Figure 3 shows the measured (solid lines) and SMARTS2 simulated (dashed lines) DNI spectra for two different days. Although the December spectrum simulated by SMARTS2 slightly overestimates the spectral irradiance up to 600nm, the measured and the simulated spectra generally show a good agreement. For August 04th and December 14th hourly DNI spectra were simulated with SMARTS2 and the characteristic figure Y was calculated as shown in figure 5.

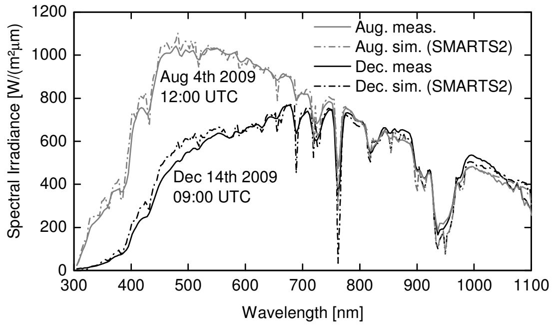

FIGURE 3: Measured (solid lines) and SMARTS2 simulated (dashed lines) spectra.

Again, measured (solid lines) and SMARTS2 simulated (dots) data shows a good agreement, thus it can be stated that for clear sky days with low circumsolar radiation the SMARTS2 model is very suitable for estimating the red and blue emphasis of the sunlight received by the FLATCON® modules. The SMARTS2 algorithm is a reasonable tool for a detailed assessment, but for preliminary assessments a simplified approach shall be evaluated.

Simulations based on a Y – Air Mass fit

The relative Air Mass (‘*AM*’) is the path length the sunlight takes under a certain elevation angle divided by the path length at normal incidence (i.e. sun elevation = 90°). Neglecting the height above sea level, trigonometry shows that *AM* only depends on the sun elevation angle. As extinction grows with the path length and Rayleigh scattering significantly increases for shorter (‘blue’) wavelengths, the red emphasis of the DNI spectrum increases as *AM* grows. To quantify this relation, *Y* was calculated for all 39’000 DNI spectra measured in five minute intervals in Seville throughout 2009 and plotted against *AM* (black and grey dots) in figure 4. The decrease of *Y* and thus growth of the red emphasis for higher *AM* is evident.

Before applying a linear fit, *Y* was DNI filtered in order to consider only values measured at DNI > 500 W/m² (black dots). The linear fit is marked with a white line.

$$Y = 1.17 - 0.10 \cdot AM \tag{4}$$

Using this fit the spectral emphasis can be estimated by simply calculating the air mass. The quality of this estimation shall be analyzed by comparing the resulting *Y* values to the measurements on August 04th and December 14th 2009. Figure 5 shows that the August simulation comes close to the measurements and that the December simulation overestimates the blue emphasis.

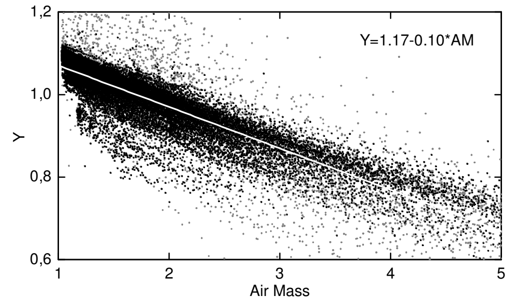

FIGURE 4: All *Y* values measured in Seville throughout 2009 (gray and black dots) plotted against *AM*. For the linear fit only the *Y* values measured at DNI > 500 W/m² were considered (black dots).

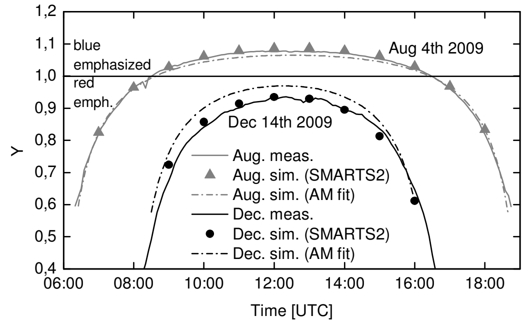

FIGURE 5: The characteristic figure *Y* calculated from measured DNI spectra (solid lines), from SMARTS2 simulated spectra (dots) and from an air mass fit (dashed lines).

INTRODUCTION OF A UTILIZATION FACTOR (UF)

As mentioned before, a Utilization Factor function (*UF*) shall be used to account for the influence of the spectrum and the temperature of the concentrating optics. For the FLATCON® system, *UF* shall be defined as the ratio of the short circuit current actually produced by the module to the simulated short circuit current. In order to make *UF* computable and thus the FLATCON® system yield predictable world wide, only measurements readily available shall be used to calculate *UF*.

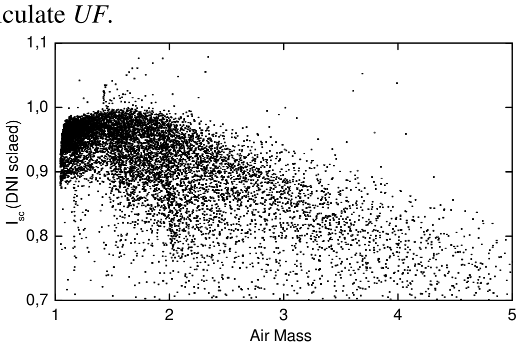

FIGURE 6: The short circuit current (DNI scaled) measured in Seville shows a maximum around AM = 1.7. From these values the piecewise function in figure 7 (top) was derived.

The Air Mass *AM* shall account for the spectral dependency. Figure 6 gives an example for the dependency of the DNI scaled short circuit current from the Air Mass which leads by means of error minimization to the piecewise function *uf(AM)* shown in figure 7 (top). The influence of the DNI and the ambient temperature T_{amb} on the concentrating optics is expressed in the equations *uf(DNI)* and *uf*(T_{amb}). The functions *uf(AM)*, *uf(DNI)* and *uf*(T_{amb}) add up to *UF(AM, DNI,* T_{amb}):

$$UF(AM, DNI, T_{amb}) = c_1 \cdot uf(AM) + c_2 \cdot uf(DNI) + c_3 \cdot uf(T_{amb}) \quad (5)$$

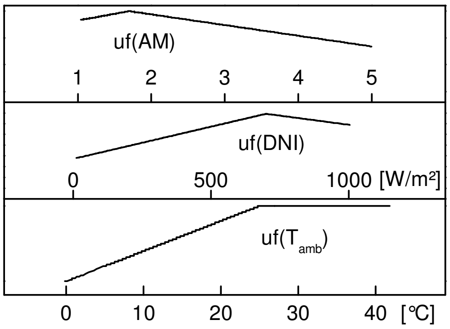

FIGURE 7: The three elements of *UF(AM, DNI,* T_{amb}) describe the deviation of the measured from the simulated short circuit current depending on Air Mass (top), DNI (middle) and ambient temperature (bottom).

uf(AM) is defined to be 1 for air mass 1.7, which can be seen in figure 6 and is a result of equation 4. The slopes before and after AM 1.7 are derived from the measured values.

uf(T_{amb}) is set to be 1 above an ambient temperature of 25°C as the measured values show that with the current module design the concentrating optics change only marginally above this temperature. This threshold temperature can be adjusted in the production process and therefore can be used to optimize the FLATCON® energy yield for certain environmental conditions.

uf(DNI) should theoretically be 1, but the measured values show that lower DNI values frequently coincide with higher circumsolar radiation values. High DNI values are often linked to blue emphasized spectra whose effect are only partially covered by the *uf(AM)* function. Both effects cause a lower short circuit current than simulated.

The coefficients c_1, c_2 and c_3 were adjusted by means of error minimization using more than 10’000 outdoor measurements from Seville. It is evident that the three *uf* functions do not describe independent phenomena, but that the short circuit current, *AM*, DNI and T_{amb} correlate in a complex way.

The aim of *UF* is not to give an overall physical description, but to provide a manageable way of achieving more precise yield predictions for CPV systems. By multiplying the DNI time series for any location with the values resulting from the Utilization Factor function, the CPV peculiarities can be considered in the yield prediction to a high degree. Figure 8 shows that a FLATCON® IV curve measured under “UF = 1” conditions can be modeled using a standard PV simulation software like INSEL with high accuracy.

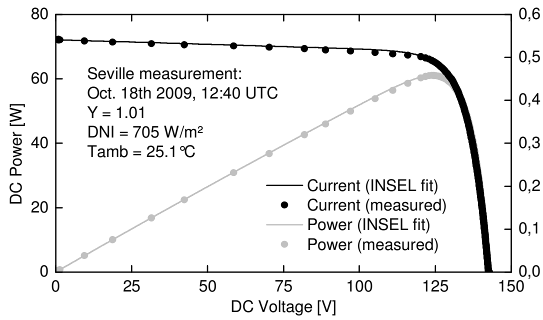

FIGURE 8: The measured IV values (dots) in this plot were gathered outdoors, with UF close to 1. This particular IV curve has been fitted with a two-diode model using the INSEL PV simulation software (lines).

ACKNOWLEDGMENTS

The authors would like to thank Gerhard Peharz from Fraunhofer ISE, Germany for his support. This work has been supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety through the funding of the CPVGen2 project (No. 0327662A).

REFERENCES

1. Bett, A.W. and Lerchenmüller, H., in: “Concentrator Photovoltaics”, edited by A. Luque and V. Andreev, Springer Series in Optical Sciences 130, (Springer-Verlag, Berlin, 2007), chap. 14.
2. http://www.pvsyst.com/
3. Mermoud, A. (2005). “Conception et Dimensionnement de Systèmes Photovoltaïques: Introduction des Modules PV en couches minces dans le logiciel PVsyst”, Internal final report, Centre Universitaire d'étude des problèmes de l'énergie, Université de Genève
4. Perharz, G., Siefer, G. and Bett, A. W. (2009). “A simple method for quantifying spectral impacts on multi-junction solar cells.” Solar Energy (83); pp. 1588-1598
5. Gueymard, C. (1995). "SMARTS, A Simple Model of the Atmospheric Radiative Transfer of Sunshine." Professional Paper FSEC-PF-270-95. Florida Solar Energy Center, 1679 Clearlake Rd., Cocoa, FL 32922.
6. Gueymard, C. (2001). "Parameterized Transmittance Model for Direct Beam and Circumsolar Spectral Irradiance." Solar Energy (71:5); pp. 325–346.