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Realistic Power Output Modeling of CPV Modules

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Abstract. In this work, we introduce a new model called YieldOpt, which calculates the power output of CPV modules. It uses SMARTS2 to model the spectral irradiance, a ray tracing program to model the optics and SPICE network simulation to model the electrical characteristic of triple-junction (3J) cells. The calculated power output is compared to data measured of five CPV modules operating in Freiburg, Germany during a period from October 2011 to March 2012. Four of the modules use lattice-matched 3J cells; one of these modules has also reflective secondary optics. In one of the five modules novel metamorphic 3J cells are used. The agreement of the predicted power output calculated by YieldOpt with the measured data is quantified using the normalized root mean square error. A good agreement between simulation and measurement is achieved. Moreover, the predicted energy yield derived from the new model is compared with the measured energy yield. A good agreement between the measured data and simulated data is achieved. In addition, a high accuracy in predicting the energy yield of different CPV modules is demonstrated. Finally, the new model is compared with three empirical models.

Keywords: CPV module, modeling, SPICE, optics, SMARTS2, energy yield.
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INTRODUCTION

The prediction of the power output and energy yield of CPV modules is still challenging. In literature different approaches are discussed to predict the power output or energy yield [1,2]. In general, the power output of CPV modules is influenced by several components. First of all the power output is affected by the spectrum and intensity of the sunlight, which is altered by the Earth's atmosphere due to aerosols and precipitable water as well as by the path length of the sun ray through the atmosphere. Furthermore, the power output is influenced by the optics which concentrates the sunlight onto a triple-junction (3J) cell. The alignment of the module on the tracker and the alignment of the tracker to the sun are also important for the power output modeling of CPV modules. Several of the described influencing factors on the power output of a modul can be already modeled. For example, the spectrum of the sunlight is calculated by SMARTS2 [3]. The optics of the module is modeled by ray tracing [4] and the IV characteristic of the 3J solar cells can be calculated using a SPICE network model [5,6]. In this work we combined these modeling approaches to create a new model which allows to calculate the output power and enery yield of CPV modules. We call this new model YieldOpt. In the paper we shortly introduce the basics of this model. Thereafter, YieldOpt is used to predict the power output of five CPV modules. The outdoor operating IV characteristic of these five modules had been measured each five minutes in Freiburg, Germany. Additionally, several sensors monitor the ambient weather and irradiance conditions. Based on the data from these sensors YieldOpt is able to calculate the power output of different CPV modules with good precision. Moreover, we show that YieldOpt predicts the power output of CPV modules with a good agreement with measured data. Furthermore, an energy yield forecast of the CPV modules is possible with high accuracy.

MEASUREMENT SETUP

The measurement station at Fraunhofer ISE's rooftop in Freiburg, Germany allows an automated sun tracking of several CPV modules [7]. The IV characteristics of these CPV modules are measured each five minutes. Simultaneously, a Pyrheliometer detects the direct normal irradiance (DNI), a Z-Sensor based on component cells quantifies the impact of the spectrum [8] and a multifilter rotating shadowband radiometer allows the determination of the aerosol optical depth (AOD) as well as of the precipitable water (PW). Moreover, a tracking accuracy sensor measures the alignment of the tracker to the sun and a weather station protocols ambient temperature and wind speed. In this work five modules are used to validate the agreement of the modeled power output with the measured data. Some details of the modules are listed in Table 1. All modules consist of Fresnel lenses with a size of 40x40 mm² and cells of a size of 5 mm². One of these modules is a mono-module consisting of only one lens and one lattice matched triple-junction cell (3JLM). This mono-module ISE069T has two temperature sensors to monitor the temperature of the lens and of the cell. Additionally, three modules (ISE047T, ISE049T, ISE059T) with six series connected 3JLM cells and one with metamorphic

3J cells (ISE064T) developed at Fraunhofer ISE [9] are used. One of the three 3JLM modules is equipped with reflective secondary optics (ISE049T). Each cell has a bypass diode which is connected in parallel. All cells in the modules are connected in series. The modules and the sensors are cleaned every month.

TABLE 1. Overview of used CPV modules

Label of module	Number of cells	Cell type	Reflective Secondary?
ISE069-T	1	3JLM	No
ISE059-T	6	3JLM	No
ISE047-T	6	3JLM	No
ISE049-T	6	3JLM	Yes
ISE064-T	6	3JMM	No

AMBIENT CONDITIONS

The measurement of the CPV modules was carried out from October 2011 until March 2012. The ambient conditions in this measurement period were subject to constant change. The period contained cloudy sky, clear sky and also days with many cirrus clouds. The measured DNI during this period had a maximum of approximately 900 W/m² and the mean value of approximately 750 W/m². The ambient temperatures in this period were between -10°C and 30°C. Most of the time the spectral parameter Z indicated a more red rich spectrum compared to the AM1.5d ASTM spectrum. The alignment of the tracker, measured by a tracking accuracy sensor, was in maximum 1° of axes and in average 0.1° of axes.

MODEL DISCRIPTION

The new model YieldOpt, introduced in this paper, combines modeling approaches of the spectral irradiance on Earth by SMARTS2 [3], of the Fresnel lens by ray tracing [4] and of the cell using a SPICE network model [5,6]. The combination of these modeling approaches allows the creation of a realistic model for the power output and energy yield of CPV modules. This model can also be used to optimize the performance of CPV modules by introducing different cells or optics. As input parameters for YieldOpt we need measured data of DNI, AOD and PW at the location where the modules are installed. AOD and PW are used as input parameters for SMARTS2. SMARTS2 calculates a spectral irradiance, which represents the sunlight illuminating the Fresnel lens on the front side of the modules. The calculated spectral irradiances are normalized using the measured DNI. Spectral optical efficiencies are calculated via ray tracing. The temperature effect for Silicon-on-Glass Frensel lenses are included in our model by considering the deformed lens structure via the finite element method (FEM). The optical efficiencies are multiplied with the calculated spectral irradiance to get the spectral conditions under which the solar cell operates [10]. In order to model the cell, a typical spectral response at room temperature is used as input [11]. The dependences of the sub cells band gaps on temperature presented by Varshni [12] is used to calculate the spectral response at operating cell temperature within the module. The current densities of the sub cells are determined by multiplying the spectral response of the corresponding sub cell with the calculated spectral irradiance. The calculated current densities need to be modified due to effects originating from the alignment of the tracker to the sun and from the alignment of the module on the tracker. Acceptance angle measurements of each module provide the response of the module on the alignment of the tracker to the sun. In this manner we determined the ratio of short circuit current density of the module depending on the elevation and azimuth of the tracker alignment to the maximum current density achievable (J_{SC}(Elevation,Azimuth)/$J_{SC,Max}$). The elevation and azimuth of the tracker alignment is provided by the tracking accuracy sensor mounted on the tracker. J_{SC}(Elevation,Azimuth)/$J_{SC,Max}$ is multiplied with the calculated current densites of each sub cell. The current densities and the dark saturation currents of each sub cell are used as input parameters for the SPICE network model. The calculation of the dark saturation currents of the 3J solar cell is described in [13]. In our case we neglect the spatial distribution of the solar cell. Therefore, the solar cell is modeled by two diodes and a current source per sub cell. One lumped series resistance completes the network model. The IV curve of the solar cell is then calculated by a LTSPICE [5]. The maximum power output is derived from the IV curve and multiplied by the number of solar cells within the modules and by a fit parameter. This fit parameter has to be determined from measurement data and is the only fit parameter used in the YieldOpt model. As a benchmark for YieldOpt in respect to the agreement between the model and measurement data, three empirical models are used. These empirical models are based on multi-linear regression methods to obtain fit parameters from measured data. The first model, called “DNI-Model”, is a polynomial function of the third order having DNI as input parameter and three fit parameters. The second one is called “Z-ISC-VOC-Model” and uses DNI, spectral parameter Z and ambient temperature $T_{Ambient}$ as input parameters. The dependence of I_{SC}, V_{OC} and FF on DNI, Z and $T_{Ambient}$ is modeled separately. The maximum power of the modules is calculated by multiplying short circuit current I_{SC}, open circuit voltage V_{OC} and fill factor FF. The third model named “Z-IMPP-VMPP-Model” is similar to the “Z-ISC-VOC-Model” but uses only data of the current at maximum power point I_{MPP} and voltage at maximum power point V_{MPP} in order to derive its fit parameter for the calculation of power output.

MODEL APPLICATION

For the application of YieldOpt, the measurement period was devided into two periods, one is the month of October 2011and the other from November 1st 2011 until March 20th 2012. The first period is used to determine the fit parameters needed for the three empirical models and the one fit parameter for YieldOpt. The second period is used to prove the accuracy of the output power prediction of the different models. The agreement between measurement and model is quantified with a normalized root mean square error (NRMSE). In this paper we define the agreement between measured and modeled data as follows: i) very good: the NRMSE is 0-2 %; ii) good: the NRMSE is 2-3.5 %, iii) satisfactory: the NMRSE is 3.5-5 %, iv) adequate: the NRMSE is 5-7 %, v) bad: the NRMSE is > 7 %. Figure 1 and Figure 2 show an exemplary comparison of measured power output to calculated power output on two days using YieldOpt. Figure 1 shows a very good agreement with a NRMSE of 1.2 %. Figure 2 shows a still satisfactory agreement with a NRMSE of 4.6 %. The reason for the deviation between measurement and simulation at the day 16-03-2012 are differences in the calculated and measured short-ciruit current of the module.

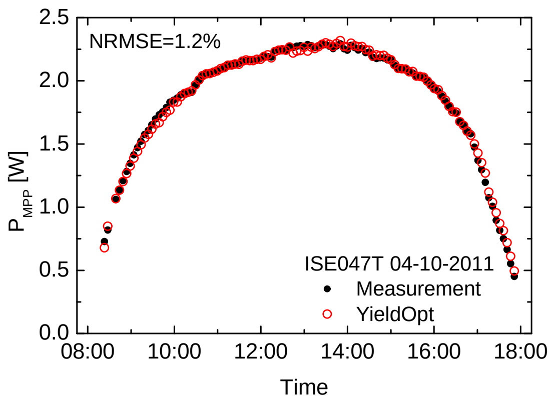

FIGURE 1. Maximum power output of the module ISE047T over one day. The power output calculated with YieldOpt shows a very good agreement with the measured power output. This is reflected by a NRMSE of 1.2 %.

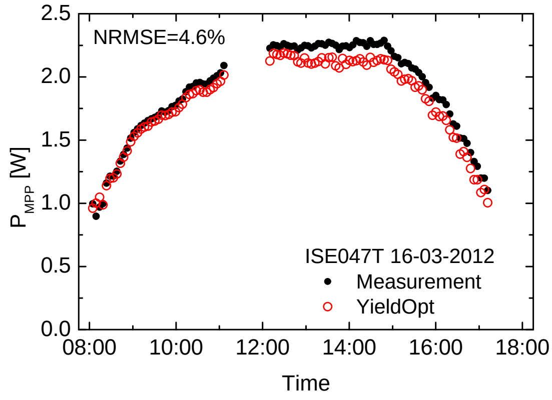

FIGURE 2. Maximum power output of the module ISE047T over one day. The power output calculated with YieldOpt shows a satisfactory agreement with the measured power output. This is reflected by a NRMSE of 4.6 %.

Figure 3 presents the NRMSE of YieldOpt and of the three empirical models. The white bars in Figure 3 represent the NRMSE calculated based on the DNI-Model. The NRMSE of the DNI-Model is between 4 % and 6 % for the five modules. This indicates a satisfactory to adequate agreement with the measurement. The NRMSE of the Z-based Models are between 3 % and 5 %, which shows a good to satisfactory agreement of these two models with the measurement. YieldOpt shows a good agreement with the measured data indicated by a NRMSE between 2.5 % and 3.2 %. The best agreement of YieldOpt is achieved for the lattice-matched module ISE059T with a NRMSE of approximately 2.5 %. A still good agreement is achieved for the module ISE049T using reflective secondary optics and also for the module ISE064T using metamorphic 3J cells.

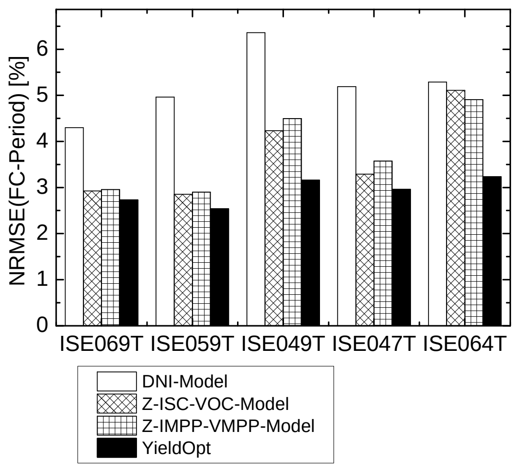

FIGURE 3. The figure shows the NRMSE calculated for five CPV modules using the three empirical models and YieldOpt in the period between November 2011 and March 2012. The NRMSE quantifies the agreement of the predicted power output of YieldOpt or of the empirical models with the measurement. The NRMSE of YieldOpt is between 2.5 and 3.2 %, which corresponds to a good

agreement. The NRMSE values of up to 6 % for the DNI-Model and of up to 5 % for the Z-based models show a weaker agreement than YieldOpt.

Figure 4 presents the deviation of the predicted energy yield from the measured energy yield of the five modules for the three empirical models and for YieldOpt. The deviation from the measured energy yield is between -4 % and 4 % for the DNI-Model. Therefore, the DNI-Model is showing a satisfactory accuracy to predict the energy yield of the used modules. The deviation from measured energy yield for the two Z-based models is better and between -1 % and +0.5 % and for YieldOpt between +2 % and -0.25 %. Therefore, the Z-based models and YieldOpt show a good accuracy to predict the energy yield of the used CPV modules, even for the module ISE049T using secondary optics and ISE064T using metamorphic triple-junction cells.

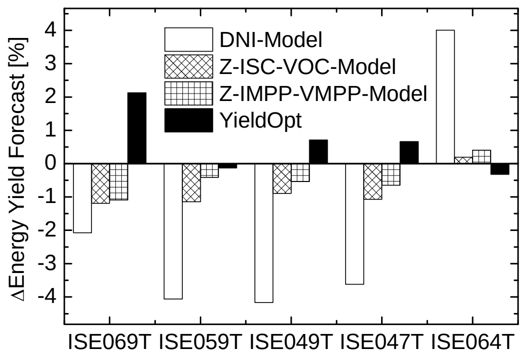

FIGURE 4. Deviation of the predicted energy yield by YieldOpt from the measured energy yield for five CPV modules in the period between November 2011 and March 2012. The DNI-Model shows the lowest accuracy to predict the energy yield of 4 %. The Z-based models and YieldOpt achieve similar accuracy between 2 and 0.25 %.

CONCLUSION

In this paper a new model called YieldOpt has been introduced. The approach used for YieldOpt is motivated to model the power output of a CPV module based on the underlying physical principles. It was shown that YieldOpt is able to predict the power output of five different CPV modules during a period between November 2011 and March 2012 in Freiburg, Germany. Three empirical models were used to benchmark YieldOpt. The agreement of the predicted power output of these four models with the measured data was quantified by the calculation of a normalized root mean square error (NRMSE). The NRMSE of YieldOpt was between 2.5 % and 3.2 % for all five modules, which indicates a good agreement with the measurement. The three empirical models show notably higher NRMSE of up to 6 % for the DNI-based model and of up to 5 % for the Z-based models. The comparison of measured energy yield to predicted energy yield of YieldOpt reveals a high accuracy of 2 % to -0.25 %. The Z-based models show a similar accuracy as YieldOpt. The DNI-based model has the highest deviation from measured energy yield of about 4 %.

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