Diffuse and direct light solar spectra modeling in PV module performance rating

Blaz Kirn* and Marko Topic

University of Ljubljana, Faculty of Electrical Engineering

Trzaska cesta 25, 1000 Ljubljana, Slovenia

*Corresponding author

E-mail address: blaz.kirn@fe.uni-lj.si

Tel.: +38614768848

Abstract

To achieve higher accuracy in power rating of photovoltaic modules and systems we recently developed an advanced PV performance model that separately address the contribution of diffuse and direct solar irradiance. To further improve the accuracy, we upgraded the model in this study to include the influence of solar spectra on PV module conversion efficiency. We measured solar spectra in Ljubljana separately for diffuse and direct irradiances under different weather conditions. Compared to AM1.5 reference spectrum, we detected spectral losses for silicon PV module up to 23.9% for diffuse irradiance under clear sky and 3.5% in average for cloudy conditions. For direct irradiance we detected spectral gains, ranging from 0.8% to 10.3% for air mass values of 1.1 and 5.0, respectively. We modeled obtained results in a form of spectral correction factors in relation to the air mass for direct light solar spectra and the share of diffuse irradiance for diffuse light solar spectra. The spectral correction factors are applied to measured diffuse and direct irradiance which are then used as an input parameters of the developed PV performance model. We evaluated the increase of accuracy of the model with the spectral upgrade for one month and one year measurements of silicon PV module at outdoor monitoring test site in Ljubljana, Slovenia. For the month of June 2014 the root-mean-square error of the spectrally upgraded model was 2.3% compared to 2.7% without spectral correction. For the eight snowless month period in 2014 the error of evaluated performance model improved from 3.7% to 3.3% in the case of additional spectral corrections applied.

Keywords

PV performance model; Irradiance components; Solar spectra; Spectral response

1. Introduction

The accurate performance analysis of photovoltaic (PV) systems using various mathematical models (De Soto et al., 2006; Ding et al., 2012; Huld et al., 2010; King et al., 2004; Marion, 2002) is a key to maximize energy harvesting leading to improvement in the economical sustainability. Heuristic PV module performance models focus on modelling the PV module electric power based on outdoor measurements of maximum power at PV module test sites (Ding et al., 2012). Contrary, analytical models are achieving better results by evaluating the one- or two-diode model of solar cells within a PV module, separately calculating voltage, current and other output parameters (Almonacid et al., 2009; De Soto et al., 2006; King et al., 2004; Marion, 2008; Tsuno et al., 2009). Compared to heuristic models analytical models require higher degree of (indoor and outdoor) characterization of PV module, making them difficult to utilize. Basic heuristic models are easier to implement, since they consider only two input parameters, irradiance and temperature, usually irradiance in the plane of array (G_{poa}) and PV module operating temperature (T_{pv}). That limits the accuracy which is usually correlated to the complexity of the model, often defined by the number of fitting coefficients (Ding et al., 2012; Dittmann et al., 2010). Common approach to increase accuracy of heuristic models is to consider higher number of input parameters. In this respect, we have recently developed direct-diffuse-power-rating model (DDPR) both for crystalline silicon (c-Si) and thin film (TF) modules (Kirn et al., 2015). The DDPR model separately addresses diffuse and direct irradiances in the plane of the array (G_{poa_dif} and G_{poa_dir}) and also compensates losses at higher solar incident angles (θ_s). The diffuse light model (P_{model_dif}) for crystalline silicon (c-Si) PV modules is a simple linear function (Eq. 1), while the direct light model (P_{model_dir}) consist of a second order polynomial function (Eq. 2) multiplied by the solar incident angle loss factor F (Eq. 3). To obtain the output power of the module (P_{mpp}), direct and diffuse light powers are summed and linearly corrected for cell operating temperature of PV module (Kirn et al., 2015).

$$P_{model_dif}(G_{poa_dif}) = k_{dif1} \cdot G_{poa_dif} \quad (1)$$

$$P_{model_dir}(G_{poa_dir}, \theta_s) = [k_{dir1} \cdot G_{poa_dir} + k_{dir2} \cdot G_{poa_dir}^2] \cdot F(\theta_s) \quad (2)$$

$$F(\theta_s) = \left[1 - \frac{e^{\left(\frac{-\cos \theta_s}{a_r}\right)} - e^{\left(\frac{-1}{a_r}\right)}}{1 - e^{\left(\frac{-1}{a_r}\right)}} \right] \quad (3)$$

The proposed DDP model shares its properties with other heuristic models, being robust and easy to implement. However, compared to the basic performance models with two input parameters, the DDP model renders higher accuracy especially at lower irradiances in the mornings and evenings, when the share of diffuse irradiance is higher and direct irradiance arrives to the surface of the PV modules at higher incident angles. The other benefit of the DDP model is also the possibility to map the PV performance globally by directly applying the model to various weather databases which usually include the information of diffuse and direct irradiances in horizontal plane (Kirn and Topič, 2016).

To further improve the accuracy of performance models additional input parameters have to be considered, for example wind speed and direction (Kurnik et al., 2011) and snow (Marion et al., 2013). Solar spectra is also an important factor in PV module conversion efficiency. Many studies of spectral influence on PV module performance were carried on showing various spectral gains and losses for different PV module technologies at different weather conditions (Alonso-Abella et al., 2014; Duck and Fell, 2015; Galleano et al., 2013; Gracia Amillo et al., 2015; Martín and Ruiz, 1999; Nofuentes et al., 2014). The effect of solar spectra variation can be described with average photon energy APE (Jardine et al., 2002), blue fraction BF (Sutterlueti et al., 2011) or spectral mismatch factor MM (International Electrotechnical Commission, 2008). To include the influence of solar spectra into PV performance models, the air mass method by Sandia (King et al., 2004) and utilization factor UF by PVsyst are used ("PVsyst," 2016). Other approaches consider also precipitable water, rendering higher accuracies in spectral corrections (Lee and Panchula, 2016). While APE, BF and MM render lower deviation in spectral correction compared to air mass method (Louwen et al., 2016), they require spectral data to correct the power of the modules. On contrary, by the air mass method the correction coefficients are obtained at a specific location from a certain measurement set and can be applied later on without additional spectral measurements.

When applying spectral correction to PV performance models, ease of practical implementation as well as availability of data are important. For example, solar spectra are usually measured in the

horizontal plane, while the PV modules are tilted to maximize the energy yield. Additionally, solar spectra are often not available for specific locations what makes basic air mass correction the most widely used approach. In this study, we evaluated the spectral influence on c-Si PV modules at an outdoor test site in Ljubljana, Slovenia (Kurnik et al., 2008). We measured solar spectra in the plane of the array for both diffuse and direct irradiance separately and developed spectral correction methods for both irradiance components in order to be used with the spectrally upgraded DDPR performance model.

2. Experimental methods

To consider the solar spectrum influence on PV module performance an outdoor spectrophotometer measuring diffuse (with the use of a shading ring) and direct light solar spectrum (G_{λ}) in the plane of the array (south, 30° inclination) from 300 nm to 1100 nm was installed at our outdoor PV module test site in Ljubljana, Slovenia (Kurnik et al., 2008). Solar spectrum is periodically measured together with other weather data and an I - V curve sweep of the tested modules.

To interpret the influence of the solar spectrum to the conversion efficiency of c-Si PV module under various weather conditions, spectral response (SR) of the tested module is required. In order to obtain the spectral response, we laminated a reference c-Si solar cell following a typical commercial PV module manufacturing process omitting only the aluminum frame of the module. The measured spectral response of the reference cell from 300 nm to 1200 nm is shown in Fig. 1.

Fig. 1. Measured spectral response of the reference c-Si solar cell and AM1.5 solar spectrum

From measured G_{λ} and reference cell SR we calculated short-circuit current density (J_{sc}) using Eq. 4. The limits of integration (λ_1 and λ_2) were defined by the range of spectrophotometer being from 300 nm to 1100 nm, resulting in some negative error due to non-zero spectral response of the reference cell up to 1200 nm (Fig. 1). To evaluate the induced error we calculated J_{sc} at AM1.5 spectrum from 300 nm to 1100 nm as well as from 300 nm to 1200 nm (International Electrotechnical Commission, 2008). The results are shown in Table 1, indicating an error of -0.53% due to the limited wavelength range of the spectrophotometer.

Table 1. Calculated short circuit current density of the reference c-Si solar cell illuminated by AM1.5 spectrum for different wavelength ranges

J_{sc} from 300 nm to 1100 nm	J_{sc} from 300 nm to 1200 nm	Relative difference
---------------------------------	---------------------------------	---------------------

36.14 mA/cm ²	36.34 mA/cm ²	-0.53%
--------------------------	--------------------------	--------

$$J_{SC} = \int_{\lambda_1}^{\lambda_2} SR(\lambda) \cdot G_{\lambda} \cdot d\lambda \quad (4)$$

According to the philosophy of separating diffuse and direct irradiance by the DDPR model, we measured a set of solar spectra of diffuse and direct irradiance at different weather conditions. We measured the solar spectra of diffuse irradiances by manually covering direct sunlight from the glass dome of spectrophotometer using a shading ring. We calculated the direct irradiance spectrum by subtracting the diffuse spectrum from the total spectrum measurement, which we carried out immediately after the diffuse one. We normalized measured spectra to match the spectral irradiance of AM1.5 spectrum (1000 W/m²). Then we calculated the diffuse and direct spectral factor (S_{dif} and S_{dir}) as a relative difference between J_{SC} at the normalized diffuse and direct spectra ($J_{SC_dif@1000W/m^2}$ and $J_{SC_dir@1000W/m^2}$) and reference J_{SC} at the AM1.5 spectrum from 300 nm to 1100 nm (J_{SC_STC}), using Eq. 5 and 6. The spectral factors represent spectral loss or gain due to the deviation of the measured spectral density from AM1.5 reference. Using the J_{SC} relative difference in this case also reduces the error caused by limited range of the spectrophotometer.

$$S_{dif} = \frac{J_{SC_dif@1000W/m^2} - J_{SC_STC}}{J_{SC_STC}} \quad (5)$$

$$S_{dir} = \frac{J_{SC_dir@1000W/m^2} - J_{SC_STC}}{J_{SC_STC}} \quad (6)$$

Since the spectrophotometer is mounted in the plane of the array, the spectral factors can be directly used to correct measured diffuse and direct irradiances. The corrected irradiances ($G_{poa_dif_AM1.5}$ and $G_{poa_dir_AM1.5}$) are calculated using Eq. 7 and 8 and can be directly applied to the DDPR model instead of G_{poa_dif} and G_{poa_dir} in Eq. 1 and 2.

$$G_{poa_dif_AM1.5} = G_{poa_dif} \cdot (1 + S_{dif}) \quad (7)$$

$$G_{poa_dir_AM1.5} = G_{poa_dir} \cdot (1 + S_{dir}) \quad (8)$$

We validated the proposed spectral correction method using one-year (2104) outdoor measurements of 240 W multi-crystalline silicon (mc-Si) PV module in Ljubljana, Slovenia. We used measurements of month June to obtain the coefficients of the basic DDPR and spectrally upgraded S-DDPR models. To evaluate the accuracy gain of the S-DDPR model, we calculated root-mean-square-error (RMSE) of both performance models for different irradiances in 10 W/m² intervals using Eq. 9.

$$RMSE(G_{poa} \pm 5 \text{ W/m}^2) = \frac{\sqrt{\frac{1}{n} \cdot \sum_{i=1}^n (P_{mpp,i} - P_{measure,i})^2}}{\frac{1}{n} \cdot \sum_{i=1}^n P_{measure,i}} \quad (9)$$

3. Results and discussion

3.1. Results

In Fig. 2, typical measurements of diffuse light spectra, normalized to AM1.5 spectral irradiance (1000 W/m²) are shown. The diffuse light spectra on a sunny day are richer at shorter wavelengths, matching the blue color of the sky dome. During cloudy day, the shape of the diffuse light spectrum is closer to AM1.5 reference.

Fig. 2. Diffuse irradiance solar spectra normalized to AM1.5 spectral irradiance measured at various weather conditions in Ljubljana

From measured diffuse light spectra we calculated the diffuse light spectral factors, S_{dif} . The results are shown in Fig. 3 in relation to the share of diffuse irradiance in the total irradiance in the plane of the array ($r_{dif} = G_{poo_dif}/G_{poo}$). The negative value of S_{dif} indicates spectral losses of c-Si reference cell under diffuse irradiance. We detected the highest losses of 23.9% at clear sky conditions, when the share of blue color in diffuse light solar spectra was highest. On the other side, spectral losses were lowest at cloudy conditions, on average 3.5%. To characterize the diffuse light spectral factor S_{dif} , we used a third order polynomial equation with fitting coefficients s_{dif0} , s_{dif1} , s_{dif2} and s_{dif3} and the share of diffuse irradiance (r_{dif}) as an input parameter (Eq. 10).

$$S_{dif}(r_{dif}) = s_{dif3} \cdot r_{dif}^3 + s_{dif2} \cdot r_{dif}^2 + s_{dif1} \cdot r_{dif} + s_{dif0} \quad (10)$$

Fig. 3. Diffuse light spectral factor of the reference c-Si solar cell against the share of diffuse irradiance in the total irradiance in the plane of the array

In Fig. 4, measurements of direct light spectra, normalized to 1000 W/m² are shown. The direct light spectra were measured on a sunny day at different hours. Measured direct light spectra is richer at longer wavelengths, especially for the measurements in morning hours when the direct sunlight travels longer distance through atmosphere.

Fig. 4. Direct light solar spectra normalized to AM1.5 spectral irradiance measured at various weather conditions in Ljubljana.

Similar to diffuse light spectra we also calculated direct light spectral factors, S_{dir} . The results are shown in Fig. 5 in relation to the air mass (m) at the time of measurements. Contrary to diffuse light spectra, the S_{dir} is positive, indicating spectral gains for direct irradiance. At air mass of 5.0 the gain is highest at 10.3%, while at air mass 1.1 the gain is 0.8%. The relationship between air mass and direct light spectral factor can be described with second order polynomial equation with three fitting coefficients s_{dir0} , s_{dir1} and s_{dir2} (Eq. 11).

$$S_{dir}(m) = s_{dir2} \cdot m^2 + s_{dir1} \cdot m + s_{dir0}; \quad 1 < m < 6 \quad (11)$$

Fig. 5. Direct light spectral factor of the reference c-Si solar cell versus the air mass.

With the diffuse and direct spectral factors obtained from selected spectra measurement set, the diffuse and direct irradiances can be corrected using Eq. 7, 8, 10 and 11 knowing only air mass and the share of diffuse irradiance in the plane of the array. Both parameters are easily accessible and the spectral correction can thus be integrated into PV performance model DDPR with only limited effort, without additional spectra measurements.

Fig. 6. RMSE of the DDPR and the spectrally upgraded S-DDPR models for mc-Si module outdoor measurements (Ljubljana, June 2014) together with final yield (Y_F) of the module

To evaluate the accuracy improvement of proposed spectral correction, we applied both DDPR and spectrally corrected S-DDPR model to one month (June 2014) outdoor measurements of mc-Si PV module in Ljubljana. The measurements were used to obtain performance model coefficients and also to calculate the accuracy of the tested models. The RMSE of the performance models in June 2014 are shown in Fig. 6 together with final yield of the evaluated PV module. The error is higher at lower irradiances for both models, while in the middle range the S-DDPR model renders lower RMSE. Overall in June 2014 the RMSE of the S-DDPR model is 2.3%, while for the DDPR model without spectral compensation the error is 2.7%. Additionally, based on yearly (2014) outdoor measurements of mc-Si PV module in Ljubljana we calculated monthly RMSE of both performance models on monthly basis, using model coefficients obtained in the month of June. Results are shown in Fig. 7, with relatively higher errors for winter months

due to snow. For eight snowless months (from March to November), the average RMSE for DDPR model was 3.7% and 3.3% for the S-DDPR model.

Fig. 7. RMSE of the DDPR and the spectrally corrected S-DDPR models for mc-Si module outdoor measurements (Ljubljana, 2014) together with final yield (Y_F) of the module

3.2. Discussion

The separate measurements of diffuse and direct light solar spectra revealed that in Slovenia the diffuse light has spectrally negative effect on c-Si modules compared to AM1.5 spectrum. The reason lies

in the dominant blue part of the solar spectra (Fig. 2) which corresponds to the color of the sky dome and can cause spectral losses up to 23.9%. In cloudy conditions when the sky is covered with clouds the spectral losses are lower, in average 3.5%. The proposed diffuse light spectral correction relies on the share of diffuse irradiance in the plane of the array (r_{dif}) as an input parameter (Fig. 3). Due to the manual work required (shading ring manipulation) relatively few measurements were obtained only for two specific cases – cloudy and sunny conditions. Thus, the obtained diffuse light spectral correction is well defined for clear sky conditions ($r_{dif} < 0.2$) as well as cloudy conditions ($r_{dif} = 1$). Between both cases, additional measurements are required for various intermediate weather conditions, for example partially cloudy sky covered with thin clouds or fog. In this aspect, additional input parameters like precipitable water as well as additional fitting coefficients may be required to compensate the diffuse irradiance spectral influence on PV module performance. For this research, use of two spectrophotometers simultaneously would be the perfect choice. Due to budget constraints we are currently busy designing the automatic shading device in order to increase the number of spectra measurements in all weather conditions.

In the case of direct irradiance the spectral influence is positive with up to 10.3% gain in performance at air mass of 5.0 (Fig. 5). The proposed direct light spectral model is a second order polynomial equation, however, the model is only defined for air mass values lower than 5.0. Additional measurements are required at higher air mass values in order to extend the range of the model and to verify if second order polynomial equation is still appropriate for the increased range. When compared to similar studies (King et al., 2004) one can easily notice that in this study the spectral gain at air mass 1.5 is not set to zero. That is due to the fact that in our case we compare the spectra of direct irradiance to the AM1.5 reference which includes direct as well as diffuse components. By applying the air mass correction only to direct irradiance we effectively avoid the errors that are caused by cloudy weather. During the cloudy weather for example the air mass has little to no effect on the solar spectrum, causing non-avoidable deviation in air mass spectral correction (Louwen et al., 2016). In our approach the air mass correction during cloudy weather has very limited influence on PV module performance calculations since the direct irradiance component is close to zero, minimizing the errors of spectral correction.

The validation of the proposed spectral correction revealed that the highest improvement in the accuracy of the S-DDPR model compared to the DDPR model is in the middle of irradiance range, between 300 W/m² and 800 W/m². We expected higher differences at irradiances below 300 W/m² due to diverse weather conditions from cloudy to clear sky with higher air mass values. We believe that the limited accuracy of the diffuse and direct irradiance measurements at such conditions is dominant reason for

lower performance of both models. Thus, the additional spectral correction has only limited impact on the accuracy at lower irradiances due to already distorted irradiance data. Another reason may include the fact that the mono c-Si reference solar cell was used for determining the spectral factor while both PV performance models were applied to mc-Si module. However, even with those setbacks the proposed spectral correction nevertheless lowered the RMSE of the DDPR model from 2.7% to 2.3% for the measurements of mc-Si PV module in the month of June 2014 in Ljubljana, Slovenia. In the case of eight snowless months in Ljubljana in 2014, the error lowered from 3.7% to 3.3%. By addressing the abovementioned issues there is additional potential to further improve the accuracy of spectrally corrected S-DDPR model.

4. Conclusion

The solar spectra measurements in the plane of the array for different weather conditions revealed that for c-Si PV modules the spectral influence of diffuse light is negative. We detected up to 23.9% spectral losses for clear sky conditions when the sky dome is blue, resulting in blue rich diffuse light spectrum. The spectral losses of diffuse light can be modeled by diffuse light spectral factor in a form of third order polynomial equation with the share of diffuse irradiance as an input parameter. Besides clear and overcast sky, additional research and measurements are required to evaluate the impact of diffuse light spectra at various weather conditions. For the direct light solar spectra, we detected a gain up to 10.3% for c-Si modules at air mass value of 5.0. The direct light spectral factor can be modeled by second order polynomial equation with air mass as an input parameter. In this case the air mass shows promising results as spectral correction input parameter since only the direct part of the solar irradiance is corrected. Contrary, when air mass correction is used for total irradiance error is induced in the case of cloudy weather, when air mass has little influence on the solar spectra. In the proposed method however direct light air mass spectral correction has limited impact at cloudy conditions due to direct irradiance component being close to zero.

Proposed direct and diffuse light spectral factors can be easily used to correct measured diffuse and direct irradiances for spectral influence on the conversion efficiency of PV modules. Corrected values are used as an input of advanced PV performance models, which separately address diffuse and direct irradiances. In this respect, we upgraded the DDPR model with spectral correction into S-DDPR model and

validated the accuracy based on outdoor measurements of mc-Si PV module at our PV module test site in Ljubljana, Slovenia. The initial results show good improvements of accuracy; the RMSE of evaluated models for one month measurements in June 2014 dropped from 2.7% to 2.3% in the case of spectral correction applied (in S-DDPR model). For eight snowless months in 2014 the RMSE of DDPR and S-DDPR model was 3.7% and 3.3%, respectively. Furthermore, the proposed spectral correction has maintained robustness and ease of implementation of the DDPR model. However, additional spectra measurements are required to further evaluate (especially diffuse light) solar spectra effect on performance of silicon PV modules as well as other PV module technologies.

Acknowledgements

Authors thank Kristijan Brecl, Marko Jankovec, Bostjan Glazar and Joze Stepan for helpful discussion and continuous support at the PV outdoor monitoring site. The authors acknowledge the financial support from the Slovenian Research Agency (Research Programme P2-0197 and Project J2-7105). B. Kirn personally acknowledges the Slovenian Research Agency for providing PhD funding.

References

- Almonacid, F., Rus, C., Hontoria, L., Fuentes, M., Nofuentes, G., 2009. Characterisation of Si-crystalline PV modules by artificial neural networks. *Renew. Energy* 34, 941–949. doi:10.1016/j.renene.2008.06.010
- Alonso-Abella, M., Chenlo, F., Nofuentes, G., Torres-Ramírez, M., 2014. Analysis of spectral effects on the energy yield of different PV (photovoltaic) technologies: The case of four specific sites. *Energy* 67, 435–443. doi:10.1016/j.energy.2014.01.024
- De Soto, W., Klein, S.A., Beckman, W.A., 2006. Improvement and validation of a model for photovoltaic array performance. *Sol. Energy* 80, 78–88. doi:10.1016/j.solener.2005.06.010
- Ding, K., Ye, Z., Reindl, T., 2012. Comparison of Parameterisation Models for the Estimation of the Maximum Power Output of PV Modules. *Energy Procedia* 25, 101–107.
- Dittmann, S., Friesen, G., Williams, S., Betts, T.R., Gottschalg, R., Beyer, H.G., Guerin de Montgareuil, A., Van der Borg, N., Burgers, A.R., Huld, T., Muller, B., Reise, C., Kurnik, J., Topic, M., Zdanowicz, T., Fabero, F., 2010. Results of the 3rd modeling round robin within the European project “PERFORMANCE” - comparison of module energy rating methods, in: *Proceedings of the 25th*

European Photovoltaics Solar Energy Conference. pp. 4333–4338.

Duck, B.C., Fell, C.J., 2015. Comparison of methods for estimating the impact of spectrum on PV output, in: 2015 IEEE 42nd Photovoltaic Specialist Conference. doi:10.1109/PVSC.2015.7356211

Galleano, R., Zaaiman, W., Virtuani, A., Pavanello, D., Morabito, P., Minuto, A., Spena, A., Bartocci, S., Fucci, R., Leanza, G., Fasanaro, D., Catena, M., 2013. Intercomparison campaign of spectroradiometers for a correct estimation of solar spectral irradiance : results and potential impact on photovoltaic devices calibration. Prog. Photovoltaics Res. Appl. 22, 1128–1137. doi:10.1002/pip

Gracia Amillo, A.M., Huld, T., Vourlioti, P., Müller, R., Norton, M., 2015. Application of satellite-based spectrally-resolved solar radiation data to PV performance studies. Energies 8, 3455–3488. doi:10.3390/en8053455

Huld, T., Gottschalg, R., Beyer, H.G., Topič, M., 2010. Mapping the performance of PV modules, effects of module type and data averaging. Sol. Energy 84, 324–338.

International Electrotechnical Commission, 2008. IEC 60904-7 Ed.3: Photovoltaic devices - Part7: Computation of the spectral mismatch correction for measurements of photovoltaic devices.

International Electrotechnical Commission, 2008. IEC 60904-3 Ed. 2: Photovoltaic devices - Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data.

Jardine, C.N., Betts, T.R., Gottschalg, R., Infield, D.G., Lane, K., 2002. Influence of Spectral Effects on the Performance of Multijunction Amorphous Silicon Cells, in: Proceedings of the 17th European Photovoltaic and Solar Energy Conference. Munich.

King, D.L., Boyson, W.E., Kratochvill, J.A., 2004. Photovoltaic Array Performance Model, Sandia Report. Sandia National Laboratories.

Kirn, B., Brecl, K., Topic, M., 2015. A new PV module performance model based on separation of diffuse and direct light. Sol. Energy 113, 212–220. doi:10.1016/j.solener.2014.12.029

Kirn, B., Topič, M., 2016. Combining Solar Irradiance Databases and PV Performance Model for PV System Performance Analysis, in: 32nd European Photovoltaic Solar Energy Conference and Exhibition. München, pp. 1660–1664. doi:10.4229/EUPVSEC20162016-5CO.16.1

Kurnik, J., Jankovec, M., Brecl, K., Topic, M., 2011. Outdoor testing of PV module temperature and performance under different mounting and operational conditions. Sol. Energy Mater. Sol. Cells 95, 373–376. doi:10.1016/j.solmat.2010.04.022

Kurnik, J., Jankovec, M., Brecl, K., Topič, M., 2008. Development of outdoor photovoltaic module monitoring system. Inf. MIDEM 38, 75–80.

Lee, M., Panchula, A., 2016. Spectral correction for photovoltaic module performance based on air mass and precipitable water, in: 43rd IEEE 43rd Photovoltaic Specialists Conference. IEEE, pp. 1351–1356. doi:10.1109/PVSC.2016.7749836

Louwen, A., Waal, A.C. De, Sark, W.G.J.H.M. Van, 2016. Evaluation of different indicators for representing

solar spectral variation, in: 43rd IEEE Photovoltaic Specialists Conference. pp. 133–137.

Marion, B., 2008. Comparison of predictive models for photovoltaic module performance, in: 33rd IEEE Photovoltaic Specialists Conference. IEEE. doi:10.1109/PVSC.2008.4922586

Marion, B., 2002. A method for modeling the current-voltage curve of a PV module for outdoor conditions. Prog. Photovoltaics Res. Appl. 10, 205–214. doi:10.1002/pip.403

Marion, B., Schaefer, R., Caine, H., Sanchez, G., 2013. Measured and modeled photovoltaic system energy losses from snow for Colorado and Wisconsin locations. Sol. Energy 97, 112–121. doi:10.1016/j.solener.2013.07.029

Martín, N., Ruiz, J.M., 1999. A new method for the spectral characterisation of PV modules. Prog. Photovoltaics Res. Appl. 7, 299–310. doi:10.1002/(SICI)1099-159X(199907/08)7:4<299::AID-PIP260>3.0.CO;2-0

Nofuentes, G., García-Domingo, B., Muñoz, J. V., Chenlo, F., 2014. Analysis of the dependence of the spectral factor of some PV technologies on the solar spectrum distribution. Appl. Energy 113, 302–309. doi:10.1016/j.apenergy.2013.07.044

PVsyst [WWW Document], 2016. URL <http://www.pvsyst.com/en/> (accessed 6.3.16).

Sutterlueti, J., Ransome, S., Kravets, R., Schreier, L., 2011. Characterising PV modules under outdoor conditions: what's most important for energy yield, in: 26th European Photovoltaic Solar Energy Conference and Exhibition. pp. 3608–3614.

Tsuno, Y., Hishikawa, Y., Kurokawa, K., 2009. Modeling of the I–V curves of the PV modules using linear interpolation/extrapolation. Sol. Energy Mater. Sol. Cells 93, 1070–1073. doi:10.1016/j.solmat.2008.11.055