Performance Estimation of Bifacial PV Systems using the View Factor Matrix

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ABSTRACT

A bifacial Photovoltaic (PV) simulation model is created by combining the optical *View Factor* matrix with electrical output simulation in *python* to analyse the energy density of bifacial systems. A discretization of the rear side of the bifacial modules allows a further investigation of mismatching and losses due to inhomogeneous radiation distribution. The model is validated, showing a deviation of -1.25 % to previous simulation models and giving hourly resolved output data with a higher accuracy than existing software for bifacial PV systems.

KEYWORDS

Bifacial PV, photovoltaic, view factor simulation, bifacial radiance model, performance simulation, energy density

INTRODUCTION

The record power conversion of a monofacial silicon solar cell is currently 26.7 % [1] and reaches its physical limit at 29.4 % [2]. Compared to other evolutions in Photovoltaic (PV) technologies, a small change in the module structure to bifacial, can lead to improvements of 5 % to 10 % in system output – therefore installations and publications regarding bifacial PV technologies are increasing in a scientific context.

Bifacial projects are gaining attention in the international energy industry. At the end of January 2020, a bifacial solar project in Qatar was assigned to a project partner with the lowest price per kWh in the history of solar projects (US$ 0.01569/kWh) [3]. The number of globally installed bifacial performance doubled from 2018 to 2019 to 5,520 MW and is forecasted to reach around 21,000 MW in 2024. Therefore, bifacial PV is considered a topic of interest.

In this paper, for the first time, a highly resolved performance estimation model for the energy density of bifacial PV systems is created, using the View Factor matrix.

Bifacial modules collect light from the front and rear side, which allows the usage of diffuse and reflected albedo light. Therefore, bifacial modules are more affected by their surroundings than monofacial modules. The common PV module set-up needs to be adapted to the new requirements of bifacial PV and other surrounding parameters, like the ground albedo and the module height, which have to be considered. For bifacial PV systems, its energy yield is not as simple to model as for monofacial systems, especially the rear-side irradiance needs to be modelled accurately.

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Since no existing simulation and radiance model fulfils all the necessary requirements with a high output resolution for further data processing, a new simulation tool for bifacial systems is created. The existing bifacial radiance model *View Factors* is complemented to get the energy density on the rear and front side as a simulation result. And with it, an adaptable flexible tool is created to simulate bifacial PV systems, taking into account miscellaneous simulation parameters.
Following the bifacial radiance model and the necessary input parameters are described.

BIFACIAL RADIANCE MODEL

To model the rear irradiance on bifacial modules, the diffuse ground reflection has to be taken into account, as well as the direct beam reflection. Depending on the number of rows and the spacing between them, the self-shading has to be considered, as well. Additionally, the impact of shadows on the ground in the relevant area is evaluated.
By combining the mathematical *Perez model* [4] for reflections and the *View Factor* model [5], the performance of a bifacial PV system can be estimated.
The ground area is separated into two categories *shaded* and *unshaded*. The shaded area only reflects diffuse irradiance and the unshaded area reflects beam and diffuse irradiance. The ratio between the reflected irradiance and the irradiance at the back of the cell is calculated using the *View Factor* model [5].
The calculation is performed under the assumption, that a PV row is only influenced by the shadows of the two rows surrounding it. Therefore, the first row is reached by the highest amount of irradiance.
The power generated on the back side is calculated using the corresponding view factor for each shaded or unshaded area respectively. The view factor between two areas describes the fraction of the space surrounding and seen from the first area and occupied by the second area [6].
In this work the isotropic sky diffuse model is used, which applies that the diffuse irradiance is uniform for the sky dome [7].
Output-parameters in this model are the total incident irradiance on the front- and on the backside of the PV array, considering reflection losses, for every hour of the year in [W/m^2]. Additionally, the irradiance on the rear side can be accessed as the irradiance on the discretized segments. Assuming linear current response of the bifacial module for the inhomogeneous illumination on the backside, the electrical performance can be calculated using an one-diode equivalent model [8].
Following, the calculation of the bifacial system performance is exemplified.

Calculation of the bifacial system performance

In the following, the requirements, input parameter and the different simulation steps in the bifacial radiance model are described. First, the PV rows are discretized. Secondly, for every timestamp all necessary sun related parameters are calculated and the *View Factor* matrix is applied to get the radiation for the front and rear surface, taking into account the angle of incidence reflection losses.
The installation requirements for the python script are listed below.
The library *Pandas* is used to read the weather input data presented in tables and to perform calculations using matrixes. Furthermore, the library *Matplot* is applied to display integrated figures as diagrams with two axes and *Seaborn* to make those editable. *Numpy* and *Math,* libraries in *python,* as well*,* are imported to perform calculations using operators. In addition, the library *Os* is used to import directories and *Warnings* to access programmed warnings regarding false input. The *Pvlib* and *Pvfactors* libraries are both imported to utilize the preprogramed functions for electrical output, irradiance and geometry. To make the simulation locally independent *Datetime*-library is used to get current date and time for the sun parameter simulation.

To model bifacial radiation and performance, system-related and location-related parameters are needed as input. The fixed input-parameters for radiance are shown in Table 1. In the program they are listed in a dictionary.

Table 1. System simulation Input-parameters

n_pvrows	Number of PV rows
number_of_segments	Number of segments for each PV row
pvrow_height	Height of the PV rows, measured at their center [m]
pvrow_width	Width of the PV rows, considered 2D plane [m]
surface_azimuth	Azimuth of the PV surface [deg]
surface_tilt	Tilt of the PV surface [deg]
albedo	Measured albedo average value
rho_front_pvrow	Front surface reflectivity of PV rows
rho_back_pvrow	Back surface reflectivity of PV rows
horizon_band_angle	Elevation angle of the sky dome's diffuse horizon band [deg]
L_Position	Longitude of measurement position [deg]
L_Area	Longitude of timezone area [deg]
Latitude_Position	Latitude of measurement position [deg]
axis_azimuth	Axis azimuth angle [deg]
gcr	Ground coverage ratio (module area / land use)

Additionally, the *global horizontal irradiance* [W/m^2] and the *direct normal irradiance* [W/m^2] are imported using the global reference data from NASA for Ghana [9]. Since the solar zenith and solar azimuth angle are not given in the reference data, they are calculated using the isotropic sky diffuse model.
To model the bifacial performance, the following parameters regarding the PV module (cf. *Table 2*) are required as input. In the program, those parameters are listed in the dictionary.

Table 2: Performance Simulation Input-parameters

I_{sc_f}	Short-circuit current measured for front side illumination of the module at STC [A]
I_{sc_r}	Short-circuit current measured for rear side illumination of the module at STC [A]
V_{oc_f}	Open-circuit voltage measured for front side illumination of module at STC [V]
V_{oc_r}	Open-circuit voltage measured for rear side illumination of module at STC [V]
V_{mpp_f}	Front maximum power point voltage [V]
V_{mpp_r}	Rear maximum power point voltage [V]
I_{mpp_f}	Front maximum power point current [A]
I_{mpp_r}	Rear maximum power point current [A]
P_{mpp}	Power at maximum power point [W]
T_{koeff}	Temperature coefficient [1/°C]
T_{amb}	Ambient temperature for measuring the temperature coefficient [°C]

Following, the discretion of the rear side of the PV array is described.

Discretizing of the PV array

The PV array is discretized into different segments. Due to the homogeneity of the radiation on the front side, only the rear side is discretized. If modules with a tilt angle higher than 45° are simulated, due to inter-row shading effects, direct shading on the front side has to be considered, as well. In order to perform calculations and analyse every segment separately, the segments need an individual index. The discretization is performed using a loop for every row, which updates the dictionary, containing the simulation parameters.

By applying the discretization, the radiance is calculated for every segment separately and can be summed up for the total irradiance per row. Using this method, the differentiating irradiance distribution is taken into account. All values are area-dependent and are displayed in values per square meter.
The AOI (angle of incidence) reflection losses have to be taken into account. In this work, a model with fixed-angle is used, hence the isotropic irradiance model can be used. In the described model, the losses for direct, circumsolar and horizon irradiance components as well as the reflection losses for isotropic reflection are considered.
The model differentiates between the total incident irradiance on a surface (qinc) and the total absorbed irradiance by a surface (qabs), which accounts for the AOI reflection losses. To calculate the AOI reflection losses, the *Perez* model [4] is used. The model depends on the fixed reflectivity values for the front (*rho_front_pvrow)* and backside (*rho_back_pvrow)* of the module, which are contained in the simulation parameter. The calculation is given for every row and every surface segment.
By combining the mathematical *Perez* model [4] for reflections and the 2D *View Factor* model [5], the view factor between every segment and one another can be calculated in order to get a reliable result for the outgoing radiation of every segment and every PV row.
The view factor from surface A_1 to surface A_2 "represents the fraction of the space surrounding and seen by" [5] surface A_1 and occupied by surface A_2. Usually view factors are used in thermal radiation heat transfer theory [10], but, in this case they are translated into general radiation simulation.
The irradiance calculations are performed by accounting for the equilibrium of reflections between all segments of the PV array surfaces in the model. Additionally, every segment is divided using x and y coordinates for every timestamp. In the simulation, systematical-analytical solutions are used instead of numerical integration of double integral solutions to speed up the calculation process. By that, an annual simulation of a bifacial PV system with three rows is performed in under 1.5 minutes with accessible hourly resolved output data.
For each segment *i,* the following outgoing radiative flux ($q_{0,i}$) from a segment is calculated with the sum of the emitted radiative flux from a segment i ($q_{emitted,\ i}$) and the reflected flux from segment i ($q_{reflected,\ i}$) with the help of equation (1).

$$q_{0,i} = q_{emitted,i} + q_{reflected,i} \left[\frac{W}{m^2}\right] \tag{1}$$

In the following, assuming the outgoing radiative flux ($q_{0,i}$) is negligible, because a PV array cannot be considered as a real black body. And moreover, the operation temperatures are under 330 K and therefore can be associated with the emission of lower energy photons than the photons in the visible spectrum reflected by the surfaces. This is the reason why a simpler linear system can be written concluding the outgoing radiative flux (q_0), the reflected radiation in form of the spectral radiosity matrix (R) [10], the view factor (F) [4] and the sky irradiance term (Sky) as shown in equation (2).

$$\begin{gathered} q_0 = R.(F.q_0 + Sky) \\ (R^{-1} - F).q_0 = Sky \end{gathered} \tag{2}$$

The concluding *View Factor* matrix for an annual simulation has the shape [*number_of_segments +1, number_of_segments +1, 8760*]. The first two dimensions need to have one segment more than the number of segments of the PV module, because the sky is considered as an additional segment. The last dimension can be explained by the length and the data resolution of the simulation. In this case one year equals 8760 hours.
Using the calculated irradiance data, an electrical model is applied to receive the energy density.

Electrical performance calculation

The electrical output can be calculated using the *One-Diode* model [11]. The direct and diffuse light on the rear side is differently allocated compared to the front side, by which the direct light is more reflected onto the bottom of the bifacial PV module.

Throughout the year, the solar spectrum changes and therefore the module response differs from the front to the rear side – this effect is called mismatch.

Following a recent 12 month study by *PV lighthouse* [12] the annual mismatch losses in bifacial modules are around 0.23 % and therefore can be discounted in this simulation. The interrow shading losses are taken into account following *Quaschning* and *Hanitsch* [13].

To calculate the performance electrical output of the module per m^2, the performance of the front and rear side under Standard Test Conditions (STC) has to be known. They can be measured using a standard I-V measurement under single-sided illumination condition. In this study the module *LG NeON 2 BiFacial LG340N1T-V5* [14] and the *MS340M-DBHS MySolar Bifacial Frameless* [15] are investigated.

The electrical performance of a bifacial module is nonlinear to the irradiance, as a solution with higher accuracy. Accordingly, a one-diode equivalent model can be applied to calculate the electrical parameters.

In order to apply the one-diode model, a term assigned to the irradiance ratio (x) is defined by division of the irradiance on the rear side of the module ($qabs_r$) through the irradiance on the front side of the module ($qabs_f$), as displayed in equation (3). The hourly value of the irradiance qabs is calculated using the view factor model.

$$x = \frac{qabs_r}{qabs_f} \tag{3}$$

Using the *irradiance ratio,* x, the bifacial model is considered as a standard monofacial module, which operates at the sum of the current generated from the rear and the front side [16].

The power of the bifacial module (P_{bi}) can be defined with the short-circuit current of bifacial module for bifacial illumination (I_{SC-bi}), the open-circuit voltage of bifacial module for bifacial illumination (V_{OC-bi}) and the fill factor of bifacial module for bifacial illumination (FF_{bi}) with the help of equation (4).

$$P_{bi} = I_{SC-bi} \cdot V_{OC-bi} \cdot FF_{bi} \tag{4}$$

The relative current gain (R_{ISC}) is calculated in order to determine I_{SC-bi} and V_{OC-bi}, using the short-circuit current measured for front side illumination at STC (I_{sc-f}) and for the rear side (I_{sc-r}), as shown in equation (5).

$$R_{ISC} = 1 + x \cdot \frac{I_{SC-r}}{I_{SC-f}} \tag{5}$$

Consequently, the two parameters I_{SC-bi} (6), V_{OC-bi} (7) have to be calculated with the help of equation (6) and (7):

$$I_{SC-bi} = R_{ISC} \cdot I_{SC-f} \tag{6}$$

$$V_{oc-bi} = V_{oc-f} + \frac{(V_{oc-r} - V_{oc-f}) \cdot \ln(R_{ISC})}{\ln(\frac{I_{SC-r}}{I_{SC-f}})} \tag{7}$$

The Pseudo fill factor (pFF) (8) describes the fill factor of the module considering no series resistance effect and is calculated with the fill factor measured for front side illumination (FF_f) and the rear side (FF_r). With the help of the pFF in equation (8), the bifacial fill factor (FF_{bi}) is calculated in equation (9).

$$pFF = \frac{\left(\frac{I_{SC-r}}{I_{SC-f}}\right)\cdot FF_f - FF_r \cdot \left(\frac{V_{oc-r}}{V_{oc-f}}\right)}{\left(\frac{I_{SC-r}}{I_{SC-f}}\right) - \left(\frac{V_{oc-r}}{V_{oc-f}}\right)} \tag{8}$$

$$FF_{bi} = pFF - R_{ISC} \cdot \left(\frac{V_{oc-f}}{V_{oc-bi}}\right) \cdot (pFF - FF_f) \tag{9}$$

The output power and all described parameters are calculated for every row and every timestamp during the year, considering the AOI losses. Afterwards, the energy is summed up to get the overall energy density.
The calculated electricity yield of the bifacial solar modules is compared to a similar simulation for monofacial modules (P_{mono}) to define the bifacial gain (BG) with the help of equation (10).

$$BG = \frac{P_{bi} - P_{mono}}{P_{mono}} \tag{10}$$

Validation with PV*SOL

To validate the above model, a software by *Valentin Software GmbH* called *PV**SOL is used. The optical gain in PV*SOL is predicted with radiance models for the diffuse irradiation and the irradiation onto the inclined plane. Contrary to *View Factors*, the software cannot predict optical gains with numerical methods. Referring to previous literature, it is assumed, that the additional rear side yield, due to the albedo of the ground, is not modelled precisely without applying a numerical model [17].
For the following comparison, the *Perez* [4] model is applied to calculate the irradiation onto the inclined plane and the *Perez & Ineichen* [18] model is used to calculate the diffuse irradiation. The PV*SOL simulation concludes in a yearly energy density of 1749.6 kWh/m^2, not differentiating between different rows and interrow-shading.
As an additional comparison, the results of the application of other irradiance models is displayed, as well.

RESULTS AND DISCUSSION

The presented model is validated with the application on bifacial system simulation in northern Ghana under consideration of hourly radiance data concluding in a yearly energy density of 1771.77 kWh/m^2.
Additionally, the model is verified by applying a model in *PV*SOL* with the same radiation parameters and the same radiation models. The results are displayed in Table 3. The y-axis shows the radiation models for the calculation of the irradiance on the inclined plane and the x-axis shows the diffuse irradiance models.

Table 3: Comparison of radiance models in PV*SOL

Irradiance on inclined surface [kWh/m²]	Reindl [19]	Orgill & Hollands [20]	Erbs, Klein & Duffie [21]	Perez & Ineichen [18]	Hofmann [22]	Skartveit [23]
Liu & Jordan [24]	1701.1	1697.4	1696.7	1755.8	1660.6	1702.2
Hay & Davies [25]	1695.5	1691.7	1691	1746.3	1655.1	1696.8
Klucher [26]	1762.5	1757.3	1753.8	1702.5	1726.6	1762.5
Perez [4]	1718.2	1715.8	1714.9	**1749.6**	1692.4	1716.6
Reindl [19]	1702.6	1698.5	1697.5	1752.8	1662.8	1704

Following the *Perez and Ineichen* [18] model to calculate the diffuse irradiance and the *Perez* [4] model to calculate the irradiance on the inclined surface, the provided python *View Factor* model shows a deviation of -1.25 % to 1749.6 kWh/m^2. It can be assumed, that the presented model is more accurate than the comparison model in terms of modelling the module rear side. The accuracy is justified with the more accurate modelling of the total absorbed irradiance on the rear side with differentiation between the different rows. A closer consideration of the total absorbed irradiance by a surface during a day (cf. Figure 1) shows, that the second row (*Row 1*) receives a small amount less irradiance on the front side than the third row (*Row 2*). While the first row (*Row 0*) receives the highest irradiance on the rear side due to missing shading effects by bifacial rows in front. The second and the third row show similar values on the rear side, since both are affected by the rows before.

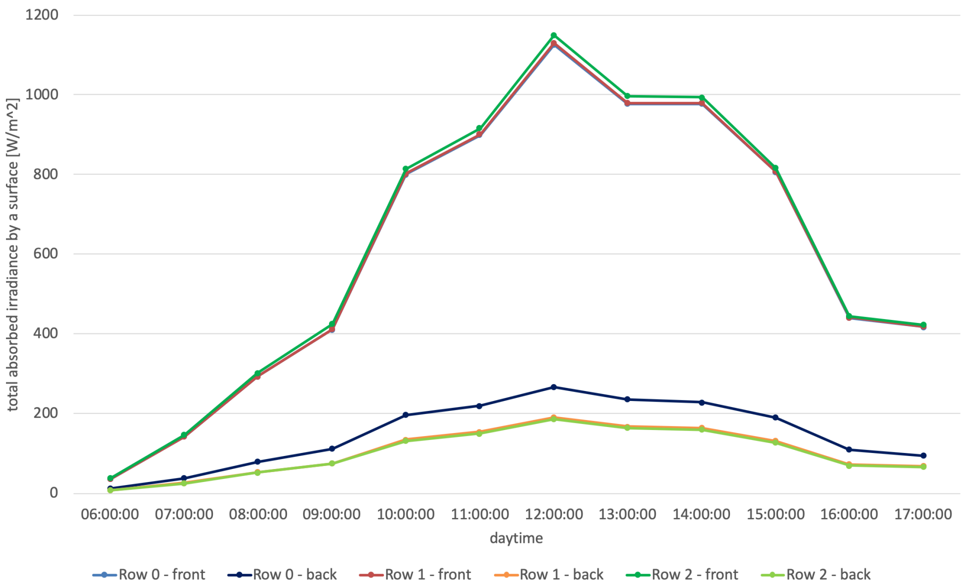

Figure 1. Irradiance distribution per row on the 13th of August

Due to the large deviations between different rows in the simulation, the presented simulation model is assumed more accurate than the comparison model in *PV*SOL*.

The mismatch is considered less than 1 % and is assumed as a relative value, due to its low impact on the irradiance on the rear side.

Further, the One-Diode-Model was applied, which neglects the effect of recombination current loss in the depletion region. The accuracy could be impacted by the temperature and experiences have shown, that the single-diode-model, compared to the two-diode model generates less precise results at low irradiance [27]. Otherwise, the One-Diode-Model is proven to predict the performance of bifacial PV modules under illumination within 1 % variation [8].

It is assumed that during an electrical characteristic measurement, the modules would show different outcomes over time due to different radiation sensitivities. Other Input-parameters, like thermal losses, have to be investigated and quantified for bifacial PV arrays, so they can be applied with accuracy.

CONCLUSION

The energy prediction model created is validated, being an accurate fast comparing- and decision-making tool. The bifacial energy density and the bifacial gain of PV systems can be estimated over a yearly period with variable input parameters. The precision is reflected in the discretization of the rear side into different segments and the differentiation between the simulated rows.

It can be refined including the temperature coefficients for the electrical model as well as applying the two-diode-model instead of the single-diode-model. Furthermore, future models should contain wavelength considerations to consider the influence of the spectral albedo on bifacial solar System. In the present simulation model, a stagnant bifacial PV system is considered. In terms of efficacy and energy density, a bifacial PV system combined with a solar tracking system results in higher outcomes.

Concluding, the presented bifacial PV performance simulation tool is validated and provides precise hourly resolved irradiance and electrical performance data for bifacial system simulation.

REFERENCES

[1] K. Yoshikawa et al.: "*Silicon heterojunction solar cell with interdigitated back contacts for a photoconversion efficiency over 26%,*" in: *Nat. Energy*, vol. 2, no. 5, p. 17032, 2017. Available: https://doi.org/10.1038/nenergy.2017.32.

[2] A. Richter: M. Hermle: and S. W. Glunz: "*Reassessment of the limiting efficiency for crystalline silicon solar cells,*" in: *IEEE J. Photovoltaics*, vol. 3, no. 4, pp. 1184–1191, 2013.

[3] C. Keating: "*Qatar utility hails ultra-low tariff in tender for 800MW bifacial PV park,*" 2020. Available: https://www.pv-tech.org/news/qatar-utility-reveals-world-record-tariff-in-tender-for-800mw-park. Accessed am 08. Feb. 2020.

[4] R. Perez et al.: "*A new simplified version of the perez diffuse irradiance model for tilted surfaces,*" in: *Sol. Energy*, vol. 39, no. 3, pp. 221–231, 1987.

[5] M. A. Anoma et al.: "*View Factor Model and Validation for Bifacial PV and Diffuse Shade on Single-Axis Trackers,*" pp. 1549–1554, 2018.

[6] J. Meseguer: I. Pérez-Grande: and A. Sanz-Andrés: "*Thermal radiation heat transfer.*" 2012.

[7] U. Gross: K. Spindler: and E. Hahne: "*Shapefactor-equations for radiation heat transfer between plane rectangular surfaces of arbitrary position and size with parallel boundaries,*" in: *Lett. Heat Mass Transf.*, vol. 8, no. 3, pp. 219–227, 1981.

[8] J. P. Singh: A. G. Aberle: and T. M. Walsh: "*Electrical characterization method for bifacial photovoltaic modules,*" in: *Sol. Energy Mater. Sol. Cells*, vol. 127, pp. 136–142, 2014. Available: http://dx.doi.org/10.1016/j.solmat.2014.04.017.

[9] NASA's Earth Observing System Data and Information System (EOSDIS): "*Ghana,*" 2018. Available: https://earthdata.nasa.gov. Accessed am 10. Dec. 2019.

[10] G. Smestad: "*Thermal radiation heat transfer,*" *Solar Energy Materials and Solar Cells*, vol. 33, no. 3. p. 392, 1994.

[11] K. Mertens: "*Photovoltaics: Fundamentals, Technology, and Practice.*" Wiley, 2018.

[12] K. Mcintosh et al.: "*The effect of non-uniform illumination on bifacial tracking modules : a simulation study,*" 2019.

[13] V. Quaschning and R. Hanitsch: "*Numerical simulation of current-voltage characteristics of photovoltaic systems with shaded solar cells,*" in: *Sol. Energy*, vol. 56, no. 6, pp. 513–520, 1996. Available: http://www.sciencedirect.com/science/article/pii/0038092X96000060.

[14] LG Electronics Inc.: "*Datasheet LG340N1T - V5,*" Seoul, Korea, 2019.

[15] Mysolar: "*Datasheet M120B325-345.*" Shanghai, 2019.

[16] H. Ohtsuka et al.: "*Characteristics of bifacial solar cells under bifacial illumination with various intensity levels,*" in: *Prog. Photovoltaics Res. Appl.*, vol. 9, no. 1, pp. 1–13, 2001. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/pip.336.

[17] D. Chudinzow et al.: "*Simulating the energy yield of a bifacial photovoltaic power plant,*" in: *Sol. Energy*, vol. 183, no. June 2018, pp. 812–822, 2019. Available: https://doi.org/10.1016/j.solener.2019.03.071.

[18] R. Perez et al.: "*Modeling daylight availability and irradiance components from direct and glo bal irradiance,*" in: *Sol. Energy, Vol. 44(5)*, 1990.

[19] D. T. Reindl and W. A. Beckman: "*Evaluation of Hourly Tilted Surface Radiation Models,*" in: *Sol. Energy 45(1) 9-17*, 1990.

[20] J. Orgill and K. Hollands: "*Correlation equation for hourly diffuse radiation on a horizontal surface,*" in: *Sol. Energy, Vol. 19(4)*, 1977.

[21] D. Erbs: S. Klein: and J. Duffie: "*Estimation of the diffuse radiation fraction for hourly, daily and monthly-average global radiation,*" in: *Sol. Energy, Vol. 28*, 1982.

[22] M. Hofmann and G. Seckmeyer: "*A new model for estimating the diffuse fraction of solar irradiance for photovoltaic system simulations,*" in: *Energies*, vol. 10, no. 2, 2017.

[23] A. Skartveit and J. Olseth: "*A model for the diffuse fraction of hourly global radiation,*" in: *Sol. Energy, Vol 38(4)*, 1987.
[24] B. Y. H. Liu and R. C. Jordan: "*The interrelationship and characteristic distribution of direct, diffuse and total solar radiation,*" in: *Sol. Energy*, vol. 4, no. 3, pp. 1–19, 1960. Available: http://www.sciencedirect.com/science/article/pii/0038092X60900621.
[25] J. E. Hay and J. A. Davies: "*Calculations of the solar radiation incident on an inclined surface,*" in: *Proc. First Can. Sol. Radiat. Data Work.*, 1980.
[26] T. M. Klucher: "*Evaluation of models to predict insolation on tilted surfaces,*" in: *Sol. Energy*, vol. 23, no. 2, pp. 111–114, 1979. Available: http://www.sciencedirect.com/science/article/pii/0038092X79901105.
[27] V. J. Chin: Z. Salam: and K. Ishaque: "*Cell modelling and model parameters estimation techniques for photovoltaic simulator application: A review,*" in: *Appl. Energy*, vol. 154, no. September, pp. 500–519, 2015. Available: http://dx.doi.org/10.1016/j.apenergy.2015.05.035.