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Modelling of bifacial gain for stand-alone and in-field installed bifacial PV modules

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Abstract

Bifacial solar cells enable the absorption of light also by the cell's rear side, hence increasing the energy yield of a bifacial module, Y_b, compared to the energy yield of a monofacial module installed under the same conditions, Y_m, by $BG = (Y_b - Y_m) / Y_m$, the bifacial gain. This contribution presents a simulation model for the prediction of the BG of bifacial PV modules (stand-alone and integrated in a PV field). The model has been implemented as a software tool and the results obtained by applying the tool to various relevant system configurations (ground albedo, geographical locations, module height and tilt, diffuse irradiation fraction) are shown. These results allow to determine the optimum installation parameters for highest BG for a given installation site. Finally, the tool is validated by comparing the simulated results with the actual BG monitored on bifacial modules during several months on an outdoor testing site.

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Keywords: photovoltaic modules; bifacial; energy yield; simulation; photovoltaic systems

1. Introduction

With their ability to additionally absorb light by their rear side, therefore increasing the energy yield, compared to standard modules, bifacial modules promise to further reduce the levelized cost of energy (LCOE) of photovoltaic modules. In order to determine the LCOE of bifacial modules and therewith their profitability, it is necessary to

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predict the exact gain in energy production. However, most existing simulations [1,2,3,4] are limited to stand-alone south-facing bifacial modules. Consequently, a simulation tool capable of modelling the annual energy yield *Y* of both stand-alone bifacial module installations, including vertical and tracked systems, and of in-field installed bifacial modules, has been developed. Its purpose lies in analyzing the potential of bifacial modules in more numerous and more realistic configurations.

Nomenclature

BG	bifacial gain	A_s	area of surface beneath the module
LCOE	levelized cost of energy	A_{sh}	area of shadow covered region
Y	annual energy yield	A_{nsh}	area outside the shadow
α	ground albedo	L	lengths of reflective surface beneath module
GHI	global horizontal irradiance	$I_{sc,f/r}$	short circuit current of module front/rear side
f_D	fraction of diffuse irradiance	$V_{oc,f/r}$	open circuit voltage of module front/rear side
d_R	module row distance	MPP	maximum power point
h_M	module elevation of the lower edge	P_{mpp}	module power
$I_{tot,f/r}$	total irradiance on module front/rear side	α_{mpp}	module temperature coefficient
$I_{dir,f/r}$	direct irradiance on module front/rear side	FF	fill factor
$I_{diff,f/r}$	diffuse irradiance on module front/rear side	ϑ_M	module temperature
$I_{refl,f/r}$	reflected irradiance on module front/rear side	ϑ_{amb}	ambient temperature
$F_{A1\rightarrow A2}$	view factor from surface A_1 to surface A_2	NOCT	nominal operating cell temperature
A_M	module area	VMBM	vertically mounted bifacial module

2. Modelling steps of the bifacial PV module

In order to correctly determine the rear side contribution to the energy yield of a bifacial module, it is necessary to calculate the amount of solar irradiation that reaches the rear side of such modules as a function of a set of input parameters, which include the sun's position (calculated from time, date and location), module installation configuration, ground albedo α, global irradiance GHI and fraction of diffuse irradiance f_D. When considering bifacial modules installed within a PV field with neighbouring modules and adjacent module rows, additional parameters, such as the row distance d_R, come into play (see Fig. 1).

2.1. Optical model

The total irradiance reaching the front side of the module $I_{tot,f}$ is the sum of the direct, diffuse and reflected components $I_{dir,f}$, $I_{diff,f}$ and $I_{refl,f}$. Whereas $I_{dir,f}$ is calculated using the position of the Sun and the beam normal irradiance BNI, $I_{diff,f}$ is determined using the Perez model [5]. Lastly, $I_{refl,f}$ is calculated using an isotropic model, as suggested by Ineichen et al. [6]. The direct and diffuse irradiances reaching the rear side of the module $I_{dir,r}$ and $I_{diff,r}$ are calculated using the same methods as the front side. However, the isotropic model delivers inaccurate results for the rear side ground reflected irradiance $I_{refl,r}$ and according to Yusufoglu et al. [1], a more complicated calculation is required, suggesting to use the concept of the view factor known from heat transfer fundamentals.

The view factor $F_{A1\rightarrow A2}$ is a purely geometric quantity describing the fraction of the radiation leaving a random surface A_1 that strikes the surface A_2 directly [2] and depends on the orientation of the surfaces relative to each other and the distance between them, where in this case A_1 is the ground and A_2 is the module rear surface. The view factor is based on the assumption that the surfaces are ideal diffuse reflectors, and is independent of other surface properties and temperature. $F_{A1\rightarrow A2}$ can be computed as the integral of the portions of radiation leaving the differential areas dA_1 that reach the differential areas dA_2 and is given by

$$F_{A1\rightarrow A2} = \frac{1}{A_1}\int_{A_1}\int_{A_2}\frac{\cos\theta_1\ \cos\theta_2}{\pi r^2}\ dA_1 dA_2, \tag{1}$$

where r is the distance between the differential areas dA_1 and dA_2. The angles between the normal vectors of the surfaces and the line that connects dA_1 and dA_2 are θ_1 and θ_2 respectively. The ground beneath the module A_s is then divided into two parts, the area inside and the area outside the shadow, A_{sh} and A_{nsh} (see Fig. 2).

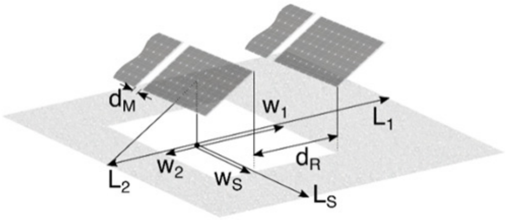

Fig. 1. In-field module set-up and definition of the field installation parameters and other input parameters of the simulation

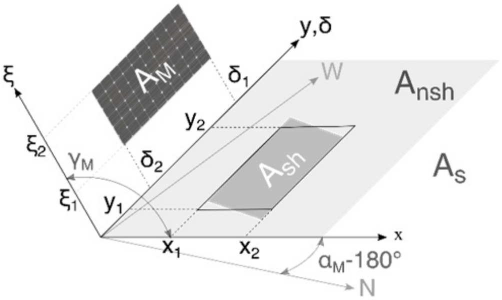

Fig. 2. Geometry for determining the view factor between shadow region A_{sh} and the module rear surface $A_{M,r}$ inclined at the angle γ_M.

Because the direct (beam) horizontal irradiance BHI is blocked by the module, casting the shadow on the ground, only the diffuse horizontal irradiance DHI is reflected from the shadow region. However, from the region outside the shadow, both BHI and DHI are reflected. $I_{refl,r}$, which is the sum of the reflected irradiances from the two regions A_{nsh} and A_{sh}, is therefore reduced due to the shadow region on the ground and is given as

$$I_{refl,r} = \ \alpha\ GHI\ F_{A_{nsh}\rightarrow A_M} + \alpha\ DHI\ F_{A_{sh}\rightarrow A_M}. \tag{2}$$

However, since r, θ_1 and θ_2 are variables dependent on the differential areas, solving equation (1) for the given configuration is highly complex. Gross et al. [7] solved the equation for two rectangular areas of arbitrary position, albeit with parallel boundaries. The method described can hence be used to determine the view factor $F_{A_S\rightarrow A_M}$ from the entire ground surface A_s to A_M. By fitting the parallelogram area of the module shadow to a rectangle, as shown in Fig. 2, the developed method can also be used to determine $F_{A_{sh}\rightarrow A_M}$. Using the superposition rule [8], $F_{A_{nsh}\rightarrow A_M}$ can be determined from the other two view factors. Furthermore, because the view factor, and therefore the reflected irradiance, is dependent on the distance between the two considered surfaces, the view factor is determined separately for each cell of the module, additionally repeating the calculation for every time step of 15 minutes, since the module shadow on the ground is constantly moving.

In case the considered bifacial module is installed in a field, the amount of $I_{refl,r}$ is further reduced due to increased shadowing on the ground, and additionally due to blocking of the ground reflected irradiance by the modules in the row behind it. The length $L_1 = 7.5m$ [1] of the area originally available for reflection is thereby reduced depending on the module elevation of the lower edge h_M, the distance between the module rows d_R, and the cell row, where cells at the top edge of the module are more strongly blocked off than the cell rows at the bottom (see Fig. 3).

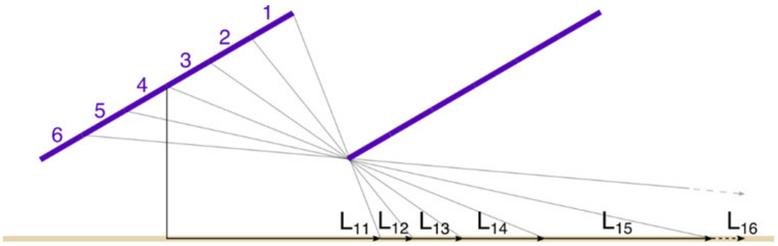

Fig. 3. Reduction of the length of the reflective surface due to blocking of the ground-reflected irradiance by the rear module row. Cells in top row more strongly blocked off than cells in bottom row.

2.2. Electrical and thermal model

With the combination of the simulated total front and rear side irradiances and the I/V parameters measured indoor at STC for separate front and rear side illumination, the short circuit currents and open circuit voltages for the front and rear side of the bifacial module, $I_{sc,f}$, $I_{sc,r}$, $V_{oc,f}$ and $V_{oc,r}$, can be determined separately for the given operating conditions. Whereas the dependency of I_{sc} on the incident irradiation is linear, that of V_{oc} is logarithmic. The front and rear side contributions are combined to a total $I_{sc,b}$ and $V_{oc,b}$ using a simplified version of the model suggested by Singh et al. [9]. The short circuit current of the bifacial module $I_{sc,b}$ and its open circuit voltage $V_{oc,b}$ are thus given by

$$I_{sc,b} = I_{sc,f} + I_{sc,r} \ , \tag{3}$$

$$V_{oc,b} = V_{oc,f} + \left(V_{oc,r} - V_{oc,f} \ \ln\left(\left(I_{sc,r} + I_{sc,f}\right) / \, I_{sc,f}\right)\right) / \ln\left(I_{sc,r}/I_{sc,f}\right) . \tag{4}$$

The output power of either a monofacial or bifacial module can then be calculated as

$$P_{mpp} = \ FF \, V_{oc} \, I_{sc} \, \left(1 + \alpha_{mpp} \, (\vartheta_M - 25°\mathrm{C})\right) , \tag{5}$$

where α_{mpp} is the temperature coefficient of the module's P_{mpp} , ϑ_M the module temperature. ϑ_M is calculated using the nominal cell temperature (NOCT) approach [10] and using the ambient temperature ϑ_{amb} measured at the installation site, following the assumptions made by Ufuk et al. [1]: $T_{NOCT,m}$ = 45°C for monofacial modules and $T_{NOCT,b}$ = 47°C for bifacial modules. As a simplification, the fill factor FF has been fixed to the value measured at STC, leading to an underestimation of P_{mpp} for low irradiance levels and to an overestimation for high irradiance levels. The annual energy yield Y is defined as the ratio of the annual energy production of a given module to its front peak power $P_{f,0}$ and is given by

$$Y = \sum_i \frac{P_{mpp,i}}{P_{f,0}} \, \Delta t \, . \tag{6}$$

To quantify the advantage of bifacial modules, each simulation is carried out for a standard module as well, comparing the resulting energy yields Y using the bifacial gain BG, which is the relative increase of the energy yield of a bifacial module compared to a monofacial module, and is defined as

$$BG = \frac{Y_b - Y_m}{Y_m} . \tag{7}$$

3. Results of the simulation

The developed model is used to determine the bifacial gain of various installation configurations, including stand-alone and in-field installations for different geographical locations. The performance of bifacial modules in special installations, such as vertical and tracked systems, are also examined. For all the following simulations, the meteorological data from the complete year 2005 acquired at the installation sites in El Gouna, Egypt, and Constance, Germany, are retrieved from the SoDa database [11].

3.1. South-facing stand-alone bifacial module

The resulting BG of stand-alone south-facing bifacial modules installed at an elevation of h_M = 1.5 m and an elevation angle of 25° in El Gouna and 37° in Constance are presented in Tab. 1 for albedo coefficients of α = 0.2 and α = 0.5. It can be clearly seen, that bifaciality offers a significant advantage, especially at higher albedos. The higher BG in Constance is due to the overall higher amount of diffuse irradiation.

Table 1. Simulated bifacial gain of modules installed at various locations for albedo coefficients of 0.2 and 0.5. BG increases for larger albedo and is higher in Constance, due to higher amount of diffuse irradiance.

	El Gouna		Constance	
	α = 0.2	α = 0.5	α = 0.2	α = 0.5
Bifacial gain BG	13.46 %	33.85 %	15.98 %	35.73 %

The effect of the ratio of diffuse to global irradiance, given by the diffuse irradiance factor f_D on the BG, is shown in Fig. 4, where increasing f_D reduces the shadow's influence on the reflected irradiance by increasing the second component of equation (2). This consequently increases $I_{tot,r}$ and BG, explaining the higher BG in Constance.

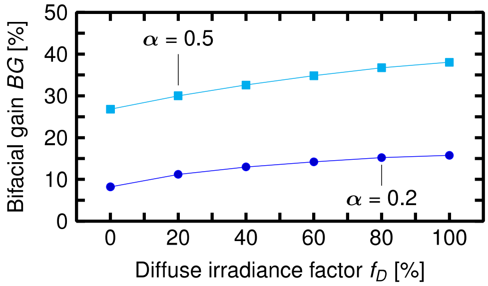

Fig. 4. The incident BHI is blocked by the module, reducing the solar irradiation available for reflection in the shadow region. Consequently, increasing f_D causes reduction of shadow's influence and increases $I_{tot,r}$ and BG.

3.2. East-west-facing stand-alone vertical bifacial module

Vertically mounted PV modules are particularly interesting in combination with bifaciality. With one side of the vertically mounted bifacial module (VMBM) facing East, and the other West, a VMBM has a higher energy production in the morning and evening, than a south-facing module, with a drop in production at noon. The reflected irradiance of both the east and west-facing sides of the module were calculated using the view factor, since the isotropic model would deliver inaccurate results.

Table 2. Vertically mounted bifacial module with a bifaciality factor of 91.4% at h_M = 0.5 m has a lower yield than a south-facing monofacial module, except in Constance with α = 0.5.

		El Gouna		Constance	
		α = 0.2	α = 0.5	α = 0.2	α = 0.5
BG	Monofacial south-facing → Bifacial vertical	–14.88 %	–5.99 %	–4.52 %	+15.77 %

Tab. 2 shows, that a VMBM in El Gouna, has a lower Y, regardless of the albedo, with a loss of −14.88 % and −5.99 % for α = 0.2 and α = 0.5 respectively. Whereas the loss in the annual energy yield in Constance for an albedo of 0.2 is −4.52 %, a VMBM located there would have a 15.77 % higher Y for $\alpha = 0.5$. Even in case of a negative

BG, a VMBM offers the advantage of shifting the peak energy production to the morning and evening. A combination of the two configurations (south facing and VMBM) in one PV system would provide a homogenous energy production curve over the whole day.

3.3. Stand-alone bifacial module with sun-belt tracking

Certain tracking systems, in particular those based one axis tracking, can contribute to a further reduction of the LCOE of solar energy. In this work, the influence of a simple, cost effective, sun-belt tracking system on the annual energy yield of a PV module is examined. With a rotation axis parallel to the ground, the module is tilted eastwards in the morning and westwards in the afternoon. Since this kind of tracking is best suited for regions near the Equator, the simulation is carried out for Kasese, Uganda, quantitatively comparing the benefits of bifaciality and tracking in Tab. 3.

Table 3. Adding tracking to a monofacial module increases Y by up to 18 %, while bifaciality increases it by up to 44 %. Bifaciality results in a 1.53 % and 21.9 % higher yield than simple tracking, for $\alpha = 0.2$ and $\alpha = 0.5$ respectively.

	Nr.	A	→	B	Kasese, Uganda	
					$\alpha = 0.2$	$\alpha = 0.5$
$BG_{A \to B}$	1	Monofacial fixed	→	Monofacial tracked	14.71 %	17.93 %
	2	Monofacial fixed	→	Bifacial fixed	16.47 %	43.77 %
	3	Monofacial tracked	→	Bifacial fixed	1.53 %	21.91 %
	4	Monofacial fixed	→	Bifacial tracked	40.10 %	62.20 %

Table 3 shows, that while simple tracking increases the *BG* significantly by 14.71 % and 17.93 % for $\alpha = 0.2$ and $\alpha = 0.5$ respectively, the increase of *BG* is higher when using fixed bifacial modules, with gains of 16.47 % and 43.77 %. Hence, a fixed bifacial module has a 1.53 % and 21.91 % higher yield than a tracked monofacial module. Bifaciality is therefore more advantageous than simple tracking systems in sun-belt regions, with the benefits of bifaciality more prominent for higher ground albedo coefficients. Bifacial modules can also be mounted on simple tracking systems, further increasing the energy yield gain compared to fixed monofacial modules to 40.10 % and 62.20 % for $\alpha = 0.2$ and $\alpha = 0.5$ respectively.

3.4. Bifacial module field

Since PV modules are rarely installed as stand-alone systems, but rather in a field with several neighbouring modules and module rows, this chapter is dedicated to the simulation of the performance of bifacial module fields. In addition to mutual shadowing of the front side, the influence of additional shadowing on the ground and the blocking of reflected irradiance has to be taken into account, making bifacial modules more sensitive to field installations than monofacial modules. Since both a bifacial and monofacial module’s front sides are affected equally by front side shadowing, the effect on *BG* is cancelled out and will therefore not be taken into account, due to the complexity of the calculation on field level.

Fig. 5 shows the *BG* of the centre module of a field with three rows, each consisting of eleven modules, at different row distances d_R, for $\alpha = 0.2$ and $\alpha = 0.5$ respectively. Since the bifacial gain of a module is only affected by rows directly in front of it and behind it, only three rows are simulated.

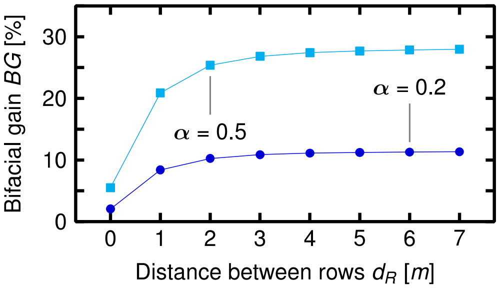

Fig. 5. Bifacial gain BG in El Gouna increases with increasing distance between rows d_R, which each have 11 modules. Additional module rows have a negligible influence on BG for d_R > 3 m.

As expected, the smaller the distance between the module rows, the stronger *BG* of the centre module row is reduced, whereby the effect becomes almost negligible for d_R > 3 m. At this row distance, mutual shading by neighbouring rows would already be significant for monofacial modules. To make solar park projects more profitable, it is favorable to increase the land coverage, albeit without tangibly decreasing the energy yield of each module, making a row distance of d_R > 2.5 m a reasonable choice in this case. In this case, the use of bifacial modules would not increase the land usage compared to monofacial modules.

Since there are discrepancies between the performances of the modules at the edge and at the centre of the field, the bifacial gains of all modules of a field with five rows, each with eleven modules, and a row distance of 2.5 m, are determined and shown in Fig. 6.

As expected, the modules mounted at the edge of the field have a higher *BG*, since there are less modules in their surrounding casting shadows and blocking the reflected irradiance. However, this only affects the two outer most modules of each row. Fig. 6 also shows an increased performance in the first and last module rows, compared to the inner rows. The best and worst performing modules in a field have bifacial gains of 31.41 % and 27.72 % compared to 33.85 % of a stand-alone bifacial module, resulting in a *BG* of the complete system that makes bifacial modules an attractive option for increasing the energy yield.

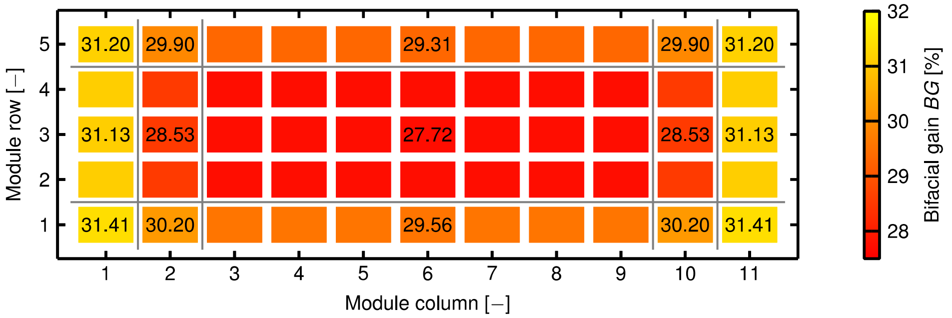

Fig. 6. Calculated BGs for modules within a PV field with a ground albedo of 0.5. The field is located at 27° latitude and the modules are mounted at a height of 1.5 m (distance between lower edge of the module and the ground) with a fixed tilt of 25°. The distance between the module rows is 2.5 m.

4. Validation of the results

To verify the accuracy of the developed model, simulations are carried out using the exact configuration of a test site mounted in the TUB (Technische Universität Berlin) campus in El Gouna. The results of the simulation are consequently compared to the measurement data obtained in 2014. The setup consisted of two neighbouring modules, bifacial and monofacial, mounted at a tilt of 20° and a height of 1.2 m. Whereas the 295.4 W monofacial module is fabricated at Bosch Solar Energy AG, the 255.8 W (front) bifacial module with a bifaciality factor of 91.4 % is manufactured by GSS using ISC Konstanz’s n-type bifacial cells, called BiSoN [12]. Using two upward- and downward-facing pyranometers, the average albedo of the ground beneath the modules, which consisted of a cement foundation surrounded by sand, is measured, delivering a result of 0.3.

In addition to monitoring the module output power, *GHI*, the ambient temperature, the wind speed and direction, are also continuously measured. However, neither *DHI* or *BHI*, which the simulation tool needs, are measured separately. However, as shown by Shoukry in [13], the monthly average of the diffuse irradiance factor f_D is relatively constant over the years. This therefore allows for the application of the f_D data, available from SoDa only for 2005, to the *GHI* data, measured in El Gouna in 2014. This provides the *DHI* data for the measurement period in 2014 needed for the validation.

Fig. 7 depicts the measured and simulated bifacial gain of the described setup for the months January to May, showing a small deviation between the results, except in February, where the deviation of 1.5 % absolute is comparably large. An actual f_D in February 2014, different than the respective 2005 data, could be the cause of the deviation. The otherwise good agreement shows the reliability of the developed model in simulating *BG*. However, the simulation tool still requires several improvements, to also accurately determine the annual energy yield Y_b. These improvements include, among others, a more accurate electrical model , the consideration of mutual front side shadowing as well as taking into account the daily and seasonal variation of the ground albedo a soiling model for desert applications and the reduction of the calculation time.

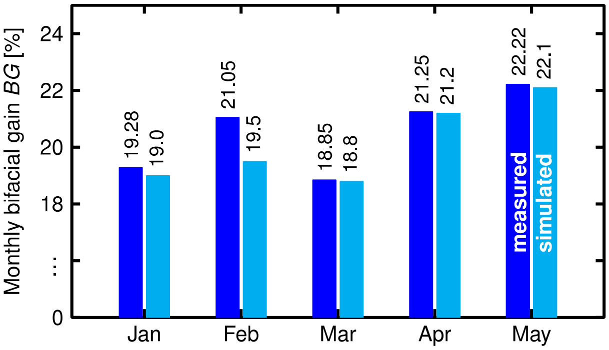

Fig. 7. Small deviation between measured and simulated monthly bifacial gain of modules installed at 27° latitude in 2014. The two neighbouring modules are mounted at a height of 1.2 m and a tilt of 20°. The ground albedo is 0.3.

5. Conclusions

The high values (simulated and measured) for *BG* obtainable under realistic installation conditions show how bifacial PV technology can significantly contribute to the reduction of the LCOE of PV generated electricity. However, before this technology will see a large distribution on the market, several hurdles still have to be overcome; an important one being bankability. One of the prerequisites to make bifacial PV technology bankable is the capability to predict the energy yield of bifacial PV systems with the same accuracy as it is already possible today for monofacial systems using commercially available software tools. Consequently, a model for the prediction of the *BG*s of bifacial modules (stand-alone and in-field) has been developed and applied to various system configurations.

One of the simulation results shows that, while a stand-alone module with an optimum configuration yields a 33.9 % *BG*, the bifacial gain of the same module is decreased to 31.4 % in a field installation for the best and 27.7 % for the worst performing modules (ground albedo of 0.5 for all cases). The decrease is caused by the module shadows on the ground and the blocking of the reflected irradiance by other module rows. Furthermore, simulations show, that vertically mounted bifacial modules can achieve a higher annual energy yield than south-facing monofacial modules in locations at higher latitudes. Examining sun-belt tracking systems located near the Equator demonstrated, that while adding tracking to a monofacial module would increase its yield by up to 18 %, a fixed bifacial module would increase the yield by up to 44 %. Bifaciality is therefore more advantageous than simple tracking in locations near the Equator, assuming the ground albedo is high enough.

The reliability of the developed model was shown using a five month long measurement conducted at the ISC Konstanz test site at the TUB campus in El Gouna, resulting in good correlation between the measured and simulated BG.

References

[1] Yusufoglu, Ufuk, et al. "Analysis of the Annual Performance of Bifacial Modules and Optimization Methods." *Photovoltaics, IEEE Journal of* 5.1 (2015): 320-328.

[2] Yusufoglu, Ufuk, et al. "Simulation of energy production by bifacial modules with revision of ground reflection." Energy Procedia 55 (2014): 389-395.

[3] Rosas, Daniel, "Application of photovoltaic bifacial modules in a digital solar power plant simulation." May 2015. Master Thesis, Technical University of Berlin.

[4] Matthieu Chiodetti. Bifacial pv plants: performance model development and optimization of their configuration. 2015. Master Thesis, KTH Royal Institute of Technology.

[5] Perez, Richard, et al. "Modeling daylight availability and irradiance components from direct and global irradiance." *Solar energy* 44.5 (1990): 271-289.

[6] Ineichen, Pierre, Olivier Guisan, and Richard Perez. "Ground-reflected radiation and albedo." *Solar Energy* 44.4 (1990): 207-214.

[7] Gross, U., K. Spindler, and E. Hahne. "Shapefactor-equations for radiation heat transfer between plane rectangular surfaces of arbitrary position and size with parallel boundaries." *Letters in heat and mass transfer* 8.3 (1981): 219-227.

[8] Cengel, Yunus A., Afshin Jahanshahi Ghajar, and Hsiaokang Ma. *Heat and Mass Transfer: Fundamentals & Applications, 4e*. McGraw-Hill, 2011.

[9] Singh, Jai Prakash, Armin G. Aberle, and Timothy M. Walsh. "Electrical characterization method for bifacial photovoltaic modules." *Solar Energy Materials and Solar Cells* 127 (2014): 136-142.

[10] Ross Jr, R. G. "Flat-plate photovoltaic array design optimization." *14th Photovoltaic Specialists Conference*. Vol. 1. 1980.

[11] Soda, solar energy services for professionals. URL http://www.soda-is.com/eng/index.html. Accessed: 15.04.2015-16.10.2015.

[12] Libal, J., V. D. Mihailetchi, and R. Kopecek. "Low-cost, high-efficiency solar cells for the future: ISC Konstanz's technology zoo." *Photovoltaic International* 5 (2014).

[13] Shoukry, Ismail. "Bifacial Modules - Simulation and Experiment." November 2015. Master Thesis, University of Stuttgart.