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Simulation of energy production by bifacial modules with revision of ground reflection

Ufuk Alper Yusufoglu[a,*], Tae Hun Lee[a], Tobias Markus Pletzer[a], Andreas Halm[b], Lejo Joseph Koduvelikulathu[b], Corrado Comparotto[b], Radovan Kopecek[b], Heinrich Kurz[a]

[a]RWTH Aachen University, Institute of Semiconductor Electronics, Sommerfeldstraße 24, D-52074, Aachen, Germany
[b]International Solar Energy Research Center Konstanz e.V., Rudolf-Diesel-Str. 15, D-78467, Konstanz, Germany

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Abstract

Bifacial solar modules are becoming increasingly more attractive stimulated by the development of new solar cell structures enabling to capture solar insolation on both front and rear surfaces. The possibilities to be installed in the conventional south facing orientation or even vertically are further advantages. Although the potential of bifacial modules have been already shown in specific time intervals and for various ground albedos there is a lack in simulation studies up to now. In this study, we simulated the annual energy yield (AEY) of south facing bifacial modules using a rigorous calculation method of the ground reflected radiation reaching the rear module surface. The necessary tilt angle optimization is done incorporating the influence of module elevation and considering the inherent albedo coefficient. These simulations are able to reproduce measurement observations and show that at optimum tilt angles produced annual energy can be increased by 30% compared to a standard module simply by positioning modules two meters above ground instead of a close to ground installation. Furthermore, a linear relationship between albedo coefficient and AEY is demonstrated.

Keywords: Bifacial module; simulation; annual energy yield; albedo; view factor

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* Corresponding author. Tel.: +492418027892; fax: +492418022246.
E-mail address: yusufoglu@iht.rwth-aachen.de

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1. Introduction

Bifacial modules bear a huge potential in competing with or even in substituting the standard monofacial modules because of their ability to capture sunlight not only from front but also through the rear side. Current measurements and analysis studies [1-4] are limited to analyses done for specific locations and albedos, bounded time intervals and module mountings. Hence, unlike for standard (monofacial) modules there is a need for more comprehensive studies addressing the whole set of relevant parameters affecting the bifacial performance. Therefore, using our simulation tool we aim in this study to analyze the potential and performance of south-facing bifacial modules considering the combined influences of climate, ground reflection, module elevation and tilt angle.

2. Modelling steps for the annual energy yield

2.1. Modelling of irradiance at the plane of the module (POM) surfaces

The irradiance data needed were acquired from GeoModel Solar – SolarGIS incorporating global horizontal (GHI), diffuse horizontal (DHI) and direct beam irradiances within a 15 minute resolution. Utilizing the information about the sun's position the direct component of the irradiance was computed geometrically for both front and rear surfaces with respect to the individual angles of incidence. The diffuse irradiance component at tilted POM was calculated applying the Perez model [5] again for both surfaces. To account for the albedo contribution for the front surface the well-known equation is used [6]:

$$E_{POM,Albedo,front} = \alpha GHI \frac{1-\cos\beta}{2} \tag{1}$$

, where α denotes the albedo coefficient of the ground and β is the tilt angle of the module.

Although the albedo part is of minor importance for standard modules it is of vital significance for the bifacial modules and therefore needs to be modelled accurately. Using Eq. 1 for the rear surface would overestimate the albedo component since the attenuation of the radiation due the resultant shadow of the module on the ground is not incorporated.

Therefore, we demonstrate an approach accounting for this effect based on the principle of the view factor known form the heat transfer fundamentals [7]. View factor $F_{1\rightarrow2}$ (see Fig. 1) denotes the fraction of the radiation received by surface 2 emitted from surface 1. The product of this view factor and the module area (denoted as V_F) will provide the ratio of the irradiance reaching the solar module to the available irradiance on the ground. The factor (1-cosβ)/2 in Eq. 1 is also based on this principle. Assuming that the ground reflected radiation is totally diffuse and shadowing is caused only by the direct irradiance the principle of view factor can be applied for the calculation of ground reflected irradiance at the module rear side.

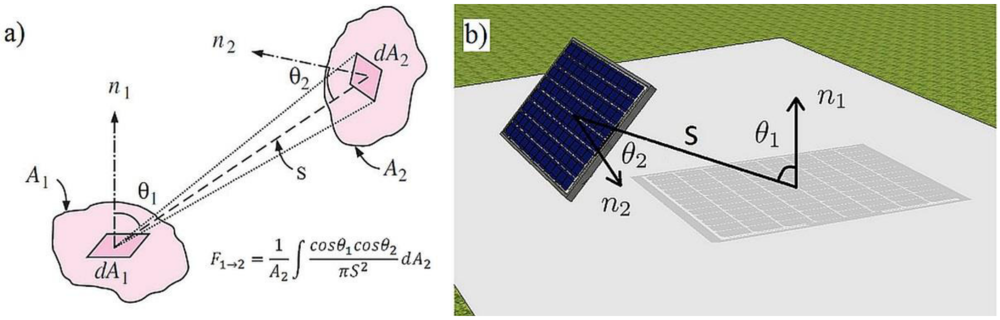

Fig. 1. (a) Definition of view factor and; (b) its implementation for the ground reflected radiation.

The GHI is decomposed into diffuse and direct part, whereby the former will remain unchanged except substituting β with 180°-β to account for the tilt angle regarding the rear surface. The direct portion of the ground reflected radiation (GHI-DHI) will be emitted only from the area outside the shadow whereas the diffuse part of the irradiance will be emitted from the whole underlying surface. Hence Eq.1 needs to be separated into two parts to attribute for this constraint:

$$E_{POM,Albedo,rear} = \alpha DHI \frac{1-\cos\left(180^\circ - \beta\right)}{2} + \alpha\left(GHI - DHI\right)\left(\frac{1-\cos\left(180^\circ - \beta\right)}{2} - F_V\right) \tag{2}$$

$$E_{POM,Albedo,rear} = \alpha DHI \frac{1+\cos\beta}{2} + \alpha\left(GHI - DHI\right)\left(\frac{1+\cos\beta}{2} - F_V\right) \tag{3}$$

, which will be used for the AEY simulations explained in the next section. The necessary geometric entities shown in Fig. 1 are calculated based on the sun's position. S denotes the distance between the centers of the module and the shadow, whereas θ_1 and θ_2 denote the angles between the normal of shadow (ground) and module, respectively.

Furthermore, the angle-of-incidence dependent transmission of the irradiance from both surfaces of the module to the cells' surface is incorporated as described in [8]. The direct irradiance reaching the cells is determined by scaling down the direct light at the plane of the module with this angle-of-incidence dependent transmission. For the attenuation of diffuse and ground reflected irradiance through glass and encapsulant the average value of the angle-of-incidence dependent transmission is used. Lastly, it must be noted that all the simulations in this study were done considering a single module and assuming a uniform albedo coefficient across the whole underlying ground surface.

2.2. Electrical and thermal modelling of the bifacial module

The AEY simulations are based on the measured *I-V* data of six-inch n-type crystalline bifacial cells fabricated at ISC Konstanz. Details about the fabrication process can be found in [9]. The *I-V* curves of the cells were separately measured for front and rear sides using a black chuck. The measured data are used to fit them to the two diode model. To account for the photo current of the rear side a parallel current source is added to the one belonging to the photo current of the front. Thus, the total photo current is the addition of both scaled with the corresponding irradiance reaching the front and rear. The shunt resistance was extracted from the dark *I-V* curves. The bifaciality of the used cells ($\eta_{\mathrm{rear}}/\eta_{\mathrm{front}}$) is on average about 80 %.

The temperature of the cells were calculated using the nominal operating cell temperature (NOCT) formula choosing a T_{NOCT} = 45°C for standard and two degrees more for bifacial modules [10].

3. Simulation approach and results

Using the mentioned modelling structure, AEY of a south-facing bifacial module containing 60 cells is simulated at two different locations, Oslo/Norway and Cairo/Egypt using a time step of 15 minutes. After finding the installation dependent optimum tilt angles, the influences of installation height, albedo coefficient and climate on the AEY of bifacial modules are analyzed. To emphasize the advantages of bifacial modules each simulation scenario was carried out for standard modules as well and both were compared based on the annual energy.

3.1. Determining the optimum tilt angles

There is a significant difference in determining the optimum tilt angles of standard and bifacial modules. For standard modules the tilt angle is optimized based on maximizing the utilization of direct and diffuse irradiance. The albedo part does not have a significant influence. For bifacial modules, however, the optimum tilt angle depends on a larger set of parameters requiring the albedo coefficient and installation height of the module to be taken into account. Fig. 2 depicts the optimum tilt angles of standard and bifacial modules in Oslo and Cairo under varying albedo coefficients. In this first analysis, the lower edge of the bifacial module was set at 2 meters above ground to minimize the attenuation effect of shadow on the ground and hence to attribute the influence of albedo coefficient to the optimum tilt angle.

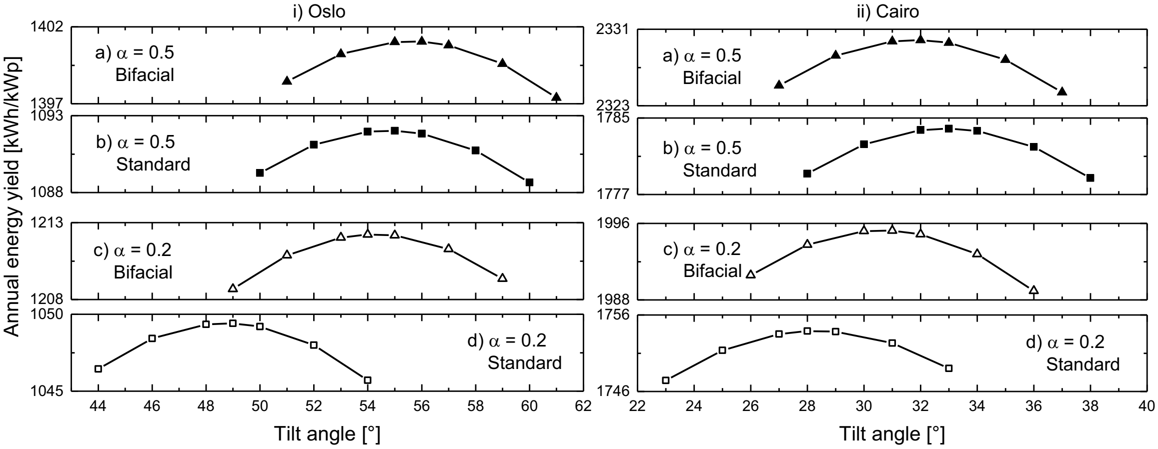

Fig. 2. (a) Optimum tilt angles of standard and bifacial modules in (i) Oslo and (ii) Cairo and their dependence on the albedo coefficient. Bifacial modules were simulated using an elevation height of 2 m.

It is observed that the optimum tilt angle of bifacial modules is slightly larger (3° in Cairo and 5° in Oslo) than those of standard modules provided an albedo coefficient of 0.2. The increase in AEY through the use of bifacial module can be seen as well which will be discussed in more detail in the next section. Here it is important to note that the annual energy yield was calculated using the yearly energy produced by the modules divided by the power at the standard testing conditions (STC) under front illumination only. As can be seen in Fig. 2 for standard modules tilted ± 5° away from their optimum the change in the annual energy yield is small. However, with increased tilt angles the distance between shadow and the module is increased. Thus, the ground reflected irradiance reaching the rear side of module is attenuated less. Since the absolute gain in irradiance at the rear side is larger than the decrease at the front larger tilt angles are favorable at this albedo coefficient. However, at a larger albedo coefficient of 0.5 the difference in optimum tilt angle for standard and bifacial modules vanishes. Additionally, the optimum tilt angle of standard module is increased as well. Since the ground reflection grows to a significantly larger extent standard modules can make increased use of this ground reflected irradiance through larger tilt angles. Thereby, the gain in utilizing the ground reflected irradiance is larger than the loss in utilizing the sky irradiance. Furthermore, due to the increased irradiance at this albedo coefficient reaching the front and hence reducing the relative contribution of the rear side to the overall energy production the optimized tilt angles are dominated by the front performance.

In the second analysis, the combined effect of installation height and albedo coefficient is analyzed. The optimum tilt angles of bifacial modules dependent on these factors are shown listed in Table 1.

Table 1. Optimum tilt angle of bifacial modules dependent on installation height and albedo coefficient.

Module	Cairo			Oslo		
elevation [m]	α = 0.2	α = 0.35	α = 0.5	α = 0.2	α = 0.35	α = 0.5
0	35	39	42	55	56	58
0.5	32	33	34	54	55	57
2	31	32	32	54	55	56

The optimum tilt angle increases with increasing albedo coefficient for all module elevations. In addition, optimum tilt angles also increase as modules are mounted closer to ground. At low module elevations the distance between shadows and the modules are shorter. This drawback can be reduced by increasing tilt angles thus forcing shadows fall at larger distances away from modules. Due to higher angles of incidences and abundance of direct irradiance the differences in optimum tilt angles at varying module elevations are larger in Cairo than in Oslo. If this module elevation dependent optimum tilt angle was not taken into account, a bifacial module in Cairo mounted on the ground (α=0.5) with a tilt angle of 32° instead of the optimum 42° would yield to 1.4% loss in annual energy. Oslo, however, suffers less from non-optimal installations owing to frequent diffuse light and oblique angles of incidences.

3.2. Influence analysis of albedo coefficient and installation height for bifacial modules in different climates

Measurement results reported in [1,2] show that bifacial modules in upper rack positions produced more power compared to bifacial modules in lower rack positions and additionally a near logarithmic dependence of power on the module elevation was demonstrated [1]. This experimental finding is reproduced through simulations carried out using the conditions shown in Table 1 (see Fig 3a).

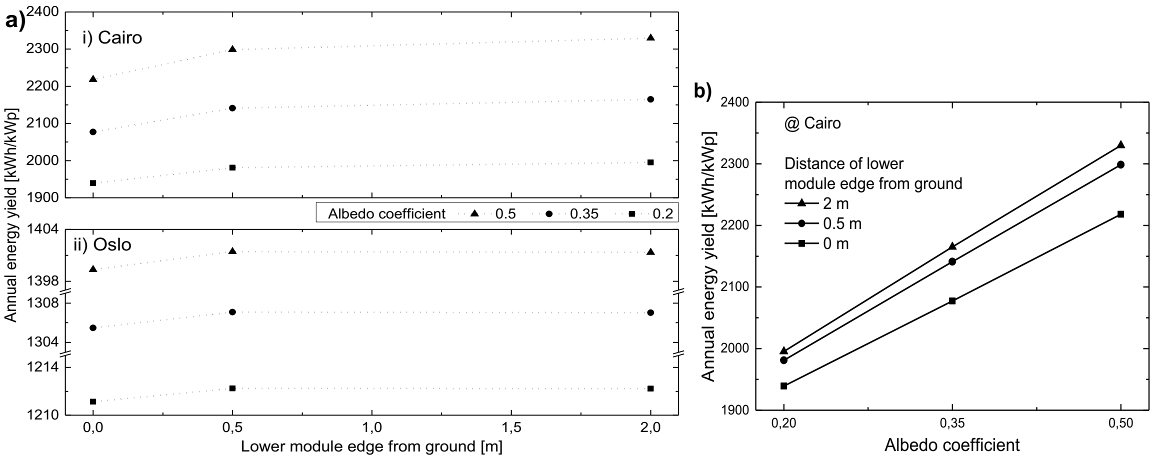

Fig. 3. (a) AEY of the bifacial module at optimum tilt angle in (i) Cairo and (ii) Oslo and its dependence on the albedo coefficient of the ground and module elevation; (b) Dependence of AEY on the albedo coefficient shown for the instance of Cairo.

Since sunlight strikes Oslo at more oblique angles and the diffuse radiation is more frequent than the direct one the effect of module elevation on AEY is relatively smaller and wears off more rapidly compared to Cairo, which is subject to the opposite conditions. The distance of the shadow to the module is in Cairo generally shorter compared to Oslo and hence attenuates the ground reflected radiation accordingly in a larger extent. Moreover, due to its lower latitude modules in Cairo have a smaller optimum tilt angle compared to those in Oslo. This is another fact causing a shorter distance between module rear side and the shadow and hence limits utilization of ground reflection. This reduction can be gradually overcome by increasing the module elevation, which can be observed in Fig. 3a.

Furthermore, plotting AEY versus the albedo coefficient (Fig. 3b) results in a linear relationship for all module elevation heights. For the sake of simplicity only the case for Cairo is shown but the trend is similar for Oslo. The largest slope is obtained for the highest module elevation. Since higher installations diminish the shadow area the benefit of a more reflective ground can be utilized in a larger extent.

The final investigation compares bifacial module with the standard one. For this purpose both module types are simulated at their corresponding optimum tilt angles. The annual energy produced by the standard module is taken as reference. The gain in annual energy is obtained using the ratio of the annual energy produced by the bifacial module to the standard one and is presented in Table 2.

It can be seen that provided a highly reflective ground bifacial modules can help to increase annual energy production up to 30%. Even at more common α of 0.2 the gains reach 15%. Due to the above mentioned reasons the influence of module elevation is more profound for Cairo. Thanks to frequent diffuse radiation Oslo benefits at low α more from bifacial design compared to Cairo since shadowing does not come up as a dominant loss factor. On the other hand, enhancing the utilization of ground reflection through higher elevations similar or even more gains can be achieved also in Cairo.

Table 2. Annual energy gain (%) using bifacial module and its dependence on site, module elevation and albedo. Annual energy produced by the standard module is taken as reference.

Module	Cairo		Oslo	
elevation [m]	$\alpha = 0.2$	$\alpha = 0.5$	$\alpha = 0.2$	$\alpha = 0.5$
0	10.6 %	24.3 %	15.4 %	28.1 %
0.5	12.9 %	28.8 %	15.5 %	28.3 %
2	13.8 %	30.6 %	15.5 %	28.3 %

4. Conclusion

The determination of the optimum tilt angles of bifacial modules requires a more complex treatment than those of standard modules since additional parameters such as mounting conditions and albedo have a direct influence. It is shown that in locations with more diffuse irradiances the performance of bifacial modules is less prone to installation variations. In Cairo, however, which is subject to frequent direct light, the difference in optimum tilt angle can be as much as 10 degrees for different installation heights. We showed an increasing trend in optimum tilt angle for lower installations and higher albedo coefficients. Secondly, it is demonstrated that higher installations from ground are favorable for all locations with improved advantages for locations with more direct light. Furthermore, there is a linear relation between the annual energy yield and the albedo coefficient. Provided a highly reflective ground (α=0.5) bifacial modules are able to generate up to 30% more energy than standard modules. Bifacial modules have also a great potential for locations dominated by low-light conditions being able to produce 15% more energy than standard modules even at a common surface albedo coefficient of 0.2.

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