YIELD SIMULATIONS FOR HORIZONTAL AXIS TRACKERS WITH BIFACIAL PV MODULES IN PVSYST

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ABSTRACT: The simulation of the energy yield of Bifacial PV modules is not straightforward, since most of the light reaching the back side of the PV modules is scattered back from the ground. For tracking systems this is particularly challenging since the geometry is changing as the sun moves through the sky. In PVsyst, a simplified 2D model was introduced to describe bifacial horizontal single axis trackers with regular spacing. The approach uses view factors to model the fraction of light that is scattered back to the back side of the PV modules. The bifacial calculation includes direct and sky diffuse contributions on the back side, as well as ground scattering to the front and back side of the modules.
Keywords: Bifacial, Tracking, PV System, Modelling, Simulation

1 INTRODUCTION

Bifacial PV modules are being used more and more commonly in PV installations. They increase the energy yield by collecting additional light that reaches the back side of the PV modules. Over the past years, many publications have calculated and measured the bifacial gain of PV modules for particular conditions, giving a wide range of results [1, 2, 3]. The expected increase in energy yield depends strongly on many parameters, like ground reflection properties, module orientation, mounting height, number and distance of surrounding modules, geographical location, climate, etc. Therefore, it cannot be predicted in a general way with simple estimations. A full simulation is required, to get a realistic value for the bifacial gain. The simulation of the energy yield of bifacial PV modules is not straightforward, since most of the light reaching the back side of the PV modules is scattered back from the ground. This is not part of a typical PV simulation, and additional steps have to be introduced to model this behavior. For tracking systems this is particularly challenging, since the orientation of the PV modules and the ground illumination are permanently changing as the sun moves through the sky.

2 BIFACIAL SIMULATION

In PVsyst, a model describing bifacial modules for fixed tilt installations with regular rows was introduced in early 2017, in the Version 6.6.0 [4]. The approach first calculates the irradiance reaching the ground, and then uses view factors to model the fraction of light that is scattered back to the rear side of the PV modules. Similar models have also been described elsewhere [3, 5, 6, 7]. The bifacial calculation of PVsyst includes ground scattering to the front and back side of the modules, as well as direct and sky diffuse contributions on the back side. The current simplified model assumes that the rows of PV modules have all the same orientation and are spaced equally. In this way, the model can be fully described in a two-dimensional cross section of the rows, as shown in figure 1. This approximation is well suited for long regular rows as they occur in large scale ground mounted PV installations, or on flat rooftop commercial installations. It cannot be applied directly to small experimental bifacial PV systems.

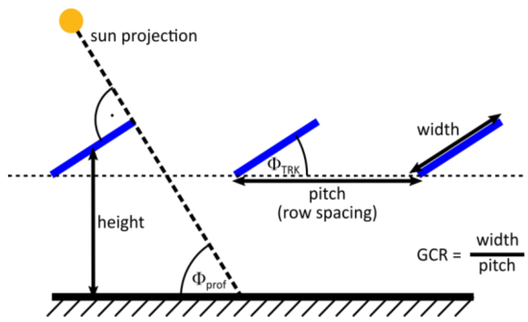

Figure 1: Two-dimensional model used for calculating the irradiance that is scattered back from the ground.

2.1 View Factor Model

The modeling of the bifacial PV modules proceeds in several steps, that are shown in figure 2. The front side irradiance is calculated like in a normal monofacial simulation. The rear side irradiance is composed of the part arriving directly from the sky (direct and diffuse), and the part that is scattered back from the ground. The direct sky contribution, which is only present in fixed tilt rows and does not occur with trackers, follows from straightforward geometrical considerations. The diffuse sky contribution on the back side is calculated as average over three points of the rear side, considering the different opening angles towards the sky. For the part that is scattered back from the ground, it is necessary to first determine the irradiance distribution on the ground. The part coming from the direct sunlight can be easily computed from geometrical considerations. The result are homogeneous stripes of irradiance that run parallel to the rows. The diffuse contribution at each point on the ground is an integral over the visible part of the sky, weighted with the cosine of the incidence angle. The sum of these two contributions gives the total irradiance distribution as function of the ground position. The scattering off the ground surface is assumed to follow the Lambertian law, meaning that the surface has the same apparent brightness from all viewing angles. The fraction of the irradiance that is scattered back is described by the ground albedo factor, which ranges typically between 0.2 and 0.6. For each point at the ground there is a view factor, describing how much of the scattered irradiance reaches the rear side of a row. This view factor is calculated as the integral over all scattering angles for which the rear side is visible, weighted with incidence angle modifier function (IAM). To get the contribution of the entire ground, the integral over all ground points along one row spacing is performed. When the result is normalized to the row width, we get the irradiance in W/m^2 for the additional irradiance reaching the rear side of the PV modules. This is an average value, since the integration was performed over the entire row width, which has a non-uniform irradiance distribution. The rear side irradiance contains inter-row shadings for direct and diffuse contributions, but it does not include shadings coming from obstruction very close to the rear side, like mounting structures or junction boxes. This shading is accounted for in the 'rear shading' factor, which has to be estimated by the user.

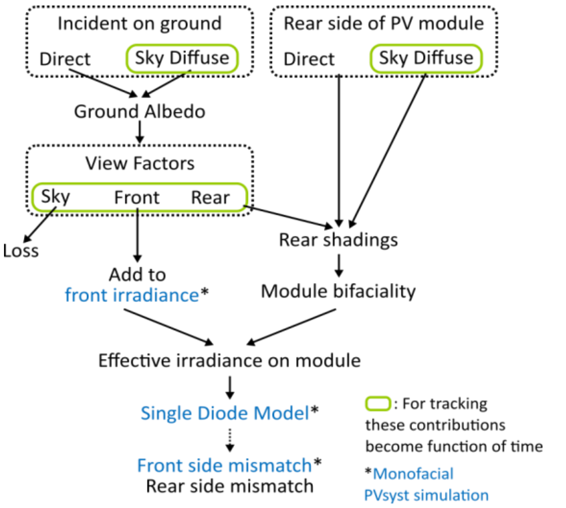

Figure 2: Simulation steps for the bifacial model. The blue steps are the interface to a normal non-bifacial simulation. The green steps are the contributions that are constant with fixed orientations and become functions of time with tracking installations.

Once the rear side irradiance has been calculated, the bifaciality factor of the PV module is applied to it. This factor ranges typically between 60% and 96%, and it describes the reduced efficiency of the module rear side. The reduced rear side irradiance is then added to the front side irradiance and used as input for the single diode model that describes the PV conversion in PVsyst. This approach results in an average value for the PV power, which neglects the mismatch arising from the non-uniform irradiance distribution. Since this non-uniformity is much more pronounced on the rear side of the modules, an additional parameter called 'rear side mismatch' is multiplied to the PV module power contribution from the rear side.

2.2 Generalization for Trackers

The model used in PVsyst to simulate bifacial PV modules has been generalized, so that it can also be applied to single axis trackers [8]. Like for the rows before, it is also assumed that the trackers have a regular orientation, width and spacing. Therefore, the two-dimensional model described in the previous paragraph, has to be changed to allow for a changing tilt. This means, that certain variables that were constant for fixed sheds, become functions of the sun position and thus of date and time. This is shown as green colored contributions in figure 2. It starts with the irradiance reaching the ground, where now both direct and diffuse contributions will depend on the tracker angle Φ_{Trk}. The view factors also need to become a function of Φ_{Trk}, as well as the diffuse contribution on the back side. The tracking algorithm in the simulations is always minimizing the angle of incidence for direct sunlight on the front side of the PV module. It does not aim to maximize irradiance for cloudy sky conditions, where smaller tracking angles might be more favorable. There is also a backtracking mode, that avoids mutual row shadings by tilting back to smaller angles when the sun is low in the sky.

2.3 Simulation Results

When performing a bifacial simulation, there are additional result variables. These include the irradiance on ground, the scattering losses, the view factor losses, direct and diffuse sky irradiance on the rear side, rear side shadings and bifacial mismatch.

After performing the bifacial simulation, PVsyst stores all the losses and intermediate results as hourly values. A summary of these values can be read off the final report that is generated after a simulation run. An example of a loss diagram for a bifacial tracking simulation is shown in figure 3. There is an additional branch on the right side of the diagram, describing all the contributions that lead to the additional irradiance on the rear side. It is important to note, that the irradiance on ground and scattering losses are normalized to the ground surface, while the view factor and subsequent losses are normalized to the PV module surface.

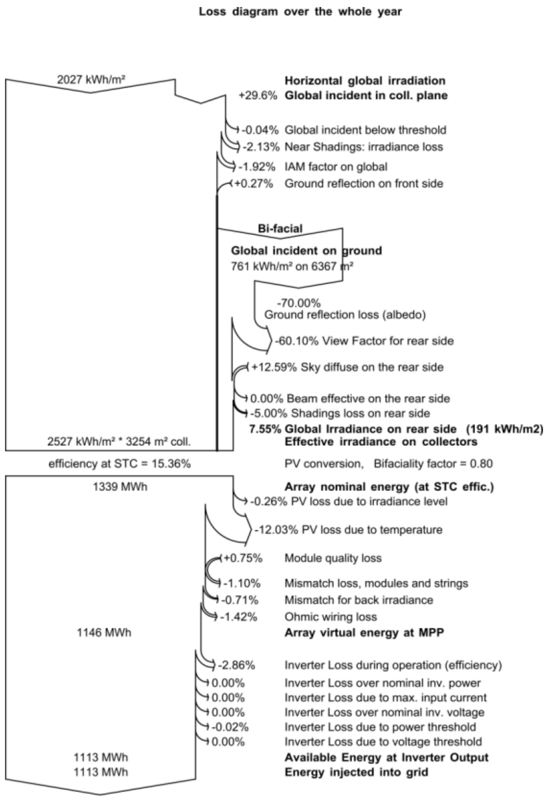

Figure 3: Loss diagram for a simulation with bifacial single axis trackers.

3 PARAMETRIC STUDIES

The PVsyst software is not only designed to simulate single cases of PV installations, but allows also to perform more general studies to understand the behavior of PV installations. It is possible to store hourly values of the simulations in text files, allowing a detailed custom analysis of the results. Furthermore, there are tools to perform parametric studies by running many simulations in an automated way, while changing sets of simulation input parameters. In the following we will present some results obtained with this kind of parametric scans. The parameters that were varied are the row spacing (pitch), the mounting height, the latitude and the climate. The parametric studies will give some insight on the general behavior of tracking and bifacial PV systems. This can be useful to understand under which conditions significant benefit can arise from these two technologies.

3.1 Gain factors

To study the potential gain of bifacial PV modules for tracking systems, it is useful to compare it to the gain obtained by passing from a fixed orientation to a tracking system. In this paper, we focus on the gain in irradiance in the collector plane. This includes row-to row shadings and reflections on the PV module surface. It does not consider any losses in the PV conversion step and all subsequent stages of power generation. This means that also the bifaciality factor of the PV modules and potential mismatch due to non-uniform illumination, is not treated here. This choice was made to get the results independent of any specific bifacial PV technology and electrical design details.

PV systems with bifacial trackers will boost the energy production by both increasing the front side irradiance by tracking the sun, and by collecting an additional irradiance contribution on the rear side of the modules. To make it clearer, how the total irradiance gain is related to tracking or bifacial modules, we consider four different scenarios as shown in figure 4. The basic reference is a fixed tilt non-tracking PV installation, which can be enhanced either by adding trackers, or by moving to bifacial PV modules. This is shown by the light green and orange arrows. The resulting two scenarios can both be converted into bifacial tracking installations, by switching to bifacial PV modules or adding trackers respectively. This gives raise to four different gain factors as depicted in the figure, named BG for bifacial gain and TG for tracker gain. The four quantities to be considered are then:

$BG_{irr}FT$: Bifacial gain for fixed tilt system
$BG_{irr}TR$: Bifacial gain for a tracking system
$TG_{irr}MF$: Tracker gain for a monofacial PV installation
$TG_{irr}BF$: Tracker gain for a bifacial PV installation
From these definitions it follows, that
$BG_{irr}FT \times TG_{irr}BF = TG_{irr}MF \times BG_{irr}TR$,
assuming that all other properties, like ground covering ratio or height, stay the same.

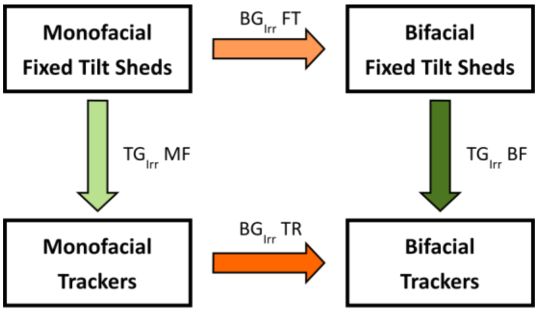

Figure 4: Gain factors for irradiance. Green arrows denote transitions from fixed orientation to tracking. Orange arrows denote transitions from monofacial to bifacial PV modules.

3.2 Geometric parameters

In a first analysis, we look at the different gain factors, when changing the row spacing (pitch) and mounting height. The system for this study is located in Albuquerque, USA, the weather data was generated by the Meteonorm 7.1 software, that is built into PVsyst. It yields hourly values that describe a typical year, and is based on satellite and ground data. The row width and pitch were chosen as 3m and 6.6m respectively, giving a ground covering ratio of 45%. The mounting height of 3m was chosen rather large, to maximize the bifacial contribution. For the ground scattering, an albedo value of 30% was chosen, which corresponds to a reasonably well reflecting surface. Higher albedo values can be reached when specially preparing the ground surface by painting or spreading bright white gravel.

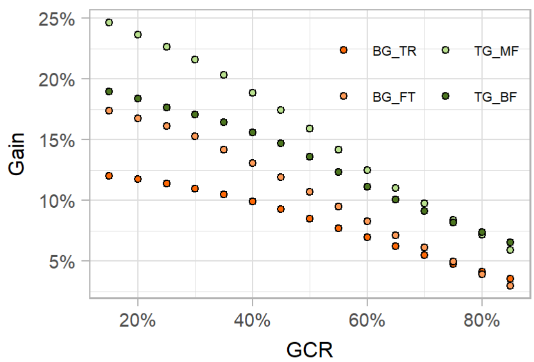

Figure 5: bifacial gain as function of ground covering ratio GCR for the different gain factors.

Ground covering ratio

To express the pitch in a general unit-free way, we use the ground covering ratio GCR, which is defined as the ratio between PV module surface and the total land surface of the installation. For regular row spacing and constant row width, this can be approximated by the ratio of row width over pitch: GCR = row width / pitch. Typical values for GCR are in the order of 40-60%. In the following study the GCR was varied from 10-90% by changing the pitch and keeping the width constant. For the fixed tilt scenarios, the best tilt was determined for each pitch value. The results of the GCR variation are shown in figure 5. As expected, a denser packing in the PV system leads to a decrease of bifacial and tracker gain. It can also be seen, that for this location, configuration and albedo value, the tracking gain always exceeds the bifacial gain. The largest increase in yield is achieved, when switching from a fixed orientation with monofacial PV modules to a tracking system. The bifacial gain in a tracking system is lower than in a fixed tilt system, because the tracker strongly boosts the front side irradiance, thus reducing the impact of the rear side contribution. A more detailed picture of the bifacial gain for different conditions of diffuse and direct irradiance will be presented in section 3.5.

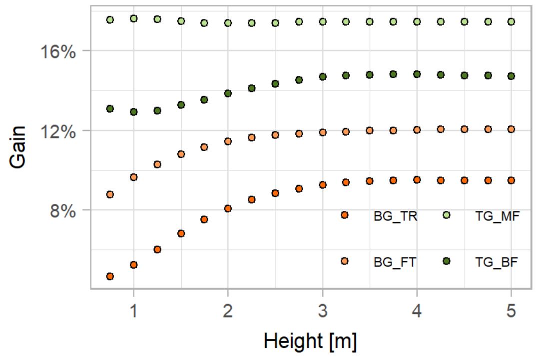

Figure 6: Bifacial gain as function of mounting height for the different gain factors.

Height over ground

The mounting height is a crucial parameter for bifacial PV systems. If the PV modules are mounted very low, the ground close to the back side of the PV modules will be shaded. At the same time, this is the region that has the most favorable view angle towards the rear side. Similarly, the ground region close to the front side of the modules will get most of the irradiance, but it has a very narrow view angle towards the module's rear side. This imbalance leads to a significant scattering loss towards the sky, and it will get attenuated as the mounting height increases. Although the pattern from the direct irradiance on ground will not change, the diffuse sky irradiance passing between the rows will be spread out more evenly, leading to a more uniform ground illumination. At the same time, the view angles towards the back side of the modules, will tend to become the same for different ground regions. Together this leads to an increase in bifacial gain, as shown in figure 6. As expected, the tracking gain for monofacial systems does not depend at all on the mounting height. Again, the benefits coming from having a tracking system, exceed the bifacial gain.

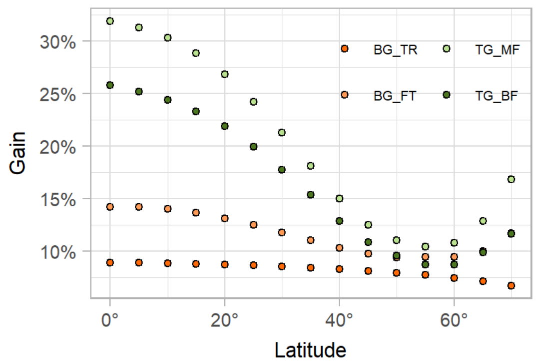

Figure 7: Bifacial gain as function of latitude, for clear sky conditions. For each latitude, the orientation of the fixed tilt scenarios was optimized.

3.3 Latitude

Next, we study how the tracker and bifacial gain is impacted by the latitude. To remove any impact coming from altitude, artificial locations were generated, all placed at sea level and latitudes ranging from 0° at the equator up to 70° northern latitude. The weather data used for this study is based on a clear sky model. This does not describe a realistic climate, but it makes the different latitude results comparable. The results are shown in figure 7. The highest gain factors can be expected at the equator and low latitudes. Since for these latitudes the horizontal tracking system is particularly well suited, the tracker gains highly exceed the expected bifacial gains. One can also see, that equipping a tracking installation with bifacial modules leads to a rather small gain. This is largely due to the fact that only clear sky conditions have been used, which have a smaller bifacial gain than conditions with a strong diffuse contribution. This will become clearer in the following section.

Site	Sharorah	Atacama	Stockholm	Kuala Lumpur
Latitude	17.5°N	23.42°S	59.35°N	3.12°N
Diff/Glob Irr.	26.1%	28.6%	49.5%	58.8%
PoA Irr	2999	2889	1225	1753
Ground Irr.	1059	1008	435	804
Rear Irr.	286	276	137	236
BG_{Irr}TR	**9.5%**	**9.5%**	**11.2%**	**13.5%**

Table I: Results for different geographical locations with distinct climates. Irradiances are giwen in W/m^2.

3.5 Climate

The benefit from a bifacial PV module is different for direct and diffuse light. Therefore, the ratio between cloudy and clear sky conditions for a given climate will impact the total bifacial gain that can be expected over one year. The ground illumination conditions are different for direct and diffuse light. The direct light creates sharp-edged shadows on the ground, giving rise to regular stripes alternating between full irradiance and complete shadow. On the other hand, the diffuse irradiance from the sky will create a blurry pattern of illuminated ground. For fixed tilt systems, this pattern is constant, while for tracking systems, the tilt changes with the sun position, and the pattern becomes a function of time. The different ground illumination patterns, cause also the amount of light that is scattered back to the rear side of the module, to be different for direct and diffuse light. The impact of this difference for different climate conditions is summarized in table I. Four different locations were compared:

Stockholm: Cold climate at high latitude with average diffuse content.

Sharorah: Dry and hot desert climate with small diffuse content

Atacama Desert: Dry and cool climate with small diffuse content

Kuala Lumpur: Tropical climate with a high diffuse content

The table shows the bifacial gain for tracking installations BG_{Irr}TR. The diffuse contents for the entire year ranges from 26% for Sharorah in Saudi Arabia up to almost 60% for Kuala Lumpur. The locations with higher diffuse content have a larger bifacial tracker gain. The reason for this behavior can be seen in figure 9.

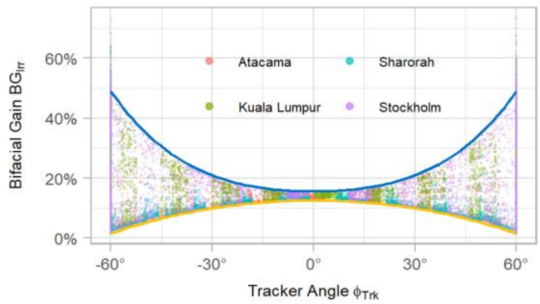

Figure 9: Distribution of bifacial gain factor for tracking systems. The blue and yellow curves are approximate, and represent the bifacial gain factor for the diffuse and direct component only.

In this figure, the hourly bifacial tracker gain is plotted against the tracker angle Φ_{Trk}. A tracker angle of 0° means that the sun is in the zenith, and the PV modules are horizontal. The different colors of the points code the four different locations. As can be seen, the points are all distributed between the blue and the yellow curve, which represent the bifacial gain for purely diffuse and purely direct light respectively. Any given tracker angle means, that the sun position in the projection perpendicular to the tracker axis is fixed. Therefore, the ground illumination pattern for direct light is always the same for a given tracker angle. The same is true for the diffuse illumination pattern. Both patterns are modulated by the absolute value of the direct normal and the diffuse horizontal irradiance respectively. We see, that the bifacial gain for direct light is highest for a tracker angle of 0°, which can also be deduced from figure 10. This plot shows the fraction of direct light reaching the ground in between the rows, and the view factors towards the rear and front side of the PV modules. When the trackers are horizontal, the stripes of light on the ground are widest, and therefore a larger fraction of direct light is reaching the ground. At the same time, the average view angle is also highest for this tracker position, since the back side of the PV modules are facing straight down. As the trackers move to higher angles, the stripes of illuminated ground will become narrower. On top of that, the front side of the PV modules will still point to the sun (in the 2D projection), meaning that the angle of incidence on the front side will be smaller than the one on the ground. This will increase the ratio between the irradiance reaching the front side of the PV modules and the irradiance reaching the ground. Furthermore, the view angle of the module rear side towards the ground will decrease as the modules tilt away from the horizontal position. These combined effects lead to the decrease of the bifacial gain for direct light as the tracker angle increases. The value will reach zero at the limit angle, where the inter-row shadings set on, and no more direct light reaches the ground. The drop of the bifacial gain for larger tracker angles is accentuated by the small contribution of light scattered back from the ground to the front surface of the PV modules, as shown in figure 10.

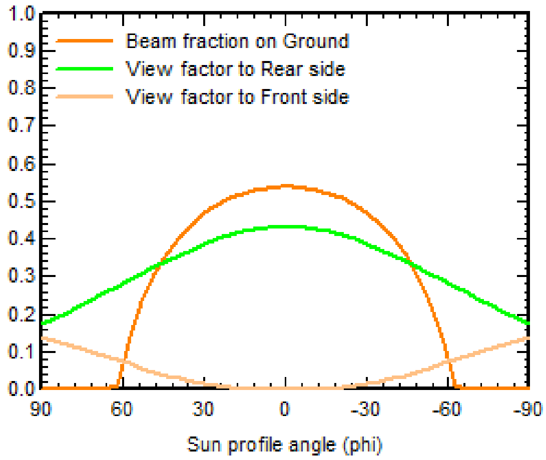

Figure 10: Bifacial model for the beam component.

The diffuse component, on the other hand, displays exactly the opposite behavior. The situation here is more complex than for the direct light. First of all, the fraction of diffuse sky light that reaches the front side of the PV modules, decreases as the tracker tilt increases, while the back side gets more and more diffuse irradiance from the sky. The fraction of diffuse light reaching the ground will also increase with the tracker angle, but the view factor of the module back side towards the ground will decrease, leading to less irradiance scattered back to the module's rear side. Overall, the decrease of irradiance on the front side and the increase of sky diffuse irradiance on the rear side, dominate the trend, and lead to an increased bifacial gain as the tracker angle increases.

For the case Φ_{Trk}=0° the bifacial gain for the direct component is maximal, and the one for the diffuse component is minimal. At this tracker position, the gain for the diffuse is always the larger of the two values, and thus the yellow and blue line in figure 9 never intersect. This can be explained by the fact that the ratio of irradiations reaching the front and rear side of the modules, is the same. Also, the light pattern on the ground is roughly similar for the two components, there are bright stripes between the tracker rows and more shaded stripes underneath the PV modules. For the diffuse component however, some of the light leaks right underneath the PV modules, where the view factor is much more favorable for the rear side. Therefore, the bifacial gain at this tracker position is slightly higher for the diffuse component.

From the above we see, that the bifacial gain is always higher for the diffuse light contribution than for the direct light contribution. This statement is only valid for horizontal axis tracking systems. For rows with fixed orientation, the picture becomes much more complex for direct light, and no general rule can be given.

4 SUMMARY

In this paper we described the bifacial model used in the PVsyst software, that is applied to horizontal axis tracker systems. The model is based on a simplified view factor approach, that can be reduced to a two-dimensional calculation. This is a suitable approximation for large fields of trackers with regular row spacing and width. The model captures the main bifacial contributions, namely the direct and diffuse light scattered back from

the ground, and the direct and diffuse light reaching directly the rear side of the PV modules.
The model was used to study the benefit arising by passing from fixed orientation to tracking systems (tracker gain) and by switching from monofacial to bifacial modules (bifacial gain). The gain values are a function of the geometrical layout, namely the row spacing expressed here in GCR, and the mounting height. Furthermore, the gain depends on the latitude at which the system is placed, and on the climate. The dependency on the climate comes from the fact that the bifacial gain for the diffuse part of the irradiance is different from the bifacial gain of the direct contribution. As a general result we found that the expected tracker gain is always higher than the bifacial gain. Both, bifacial gain and tracker gain are very sensitive to the GCR, whereas only the bifacial gain changes significantly with the mounting height. We found also that the tracking gain is very sensitive to the latitude, locations close to the equator benefitting much more from trackers than those at higher latitude. The bifacial gain is also slightly higher at low latitude. Finally, the trackers in climates with a large diffuse irradiance component tend to have a higher bifacial gain.

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