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Bifacial photovoltaic systems energy yield modelling

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Abstract

A bifacial photovoltaic model was developed not only to calculate the power and energy yield for bifacial modules for various setup and installation conditions but also to identify suitable bifacial module applications and markets. The bifacial model shows that the energy yield for bifacial modules is very much location dependent and hugely influenced by how they are setup and installed. There is a need to have the modules mounted at a certain elevation above the ground to gain maximum energy yield. It is also important to ensure there is no blockage for the direct sun to shine on the area directly beneath the module. For locations at low latitude, a higher elevation is required. For locations at high latitude, the probability of the direct sunlight reaching the ground directly under the module is higher. Therefore, less module mounting elevation is required. However, there is a saturation point for energy yield improvement with increased module mounting height. In addition to the mounting height, a sufficient length of clearance path in front of the module array should be considered. The model also shows that the ground reflectance is one of the key parameters for bifacial module performance. The model indicates that >10% of energy yield gain with 20% background reflectance from REC bifacial multi-crystalline silicon solar module array with a bifaciality of 0.6 is achievable in Konstanz, Germany. This correlates well with the measured field energy yield data of the bifacial prototype modules.

Peer review by the scientific conference committee of SiliconPV 2015 under responsibility of PSE AG

Keywords: Energy yield; Bifacial solar modules

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1. Introduction

In recent years, the bifacial solar module has gained much attention [1]. However, there is currently no commercially available software to model the performance of a bifacial photovoltaic system such as PVSYST photovoltaic software [2]. Modelling the field performance of bifacial modules presents a number of difficulties that are not present for monofacial modules. The bifacial system modelling is significantly more complex than the monofacial system modelling due to the need to estimate the rear illumination of the module, which depends on the percentage of diffused radiation, the sun elevation, the background reflectance, the height of the module above the ground and the module tilt angle. In addition, the field performance of bifacial modules is highly dependent on the location and system design. In this paper the development of an empirical model for the field performance of a bifacial photovoltaic module is discussed. The model attempts to overcome a number of challenges in modelling the rear side illumination for different module heights, module tilts, ground albedos, diffuse radiation components (primarily due to atmospheric effects) and solar positions.

2. Simulation process flow

The simulation process flow for developing a bifacial photovoltaic model in this work is shown in Figure 1. The inputs to the simulation flow chart are module performance details, system installation details and the global horizontal irradiance (GHI) data.

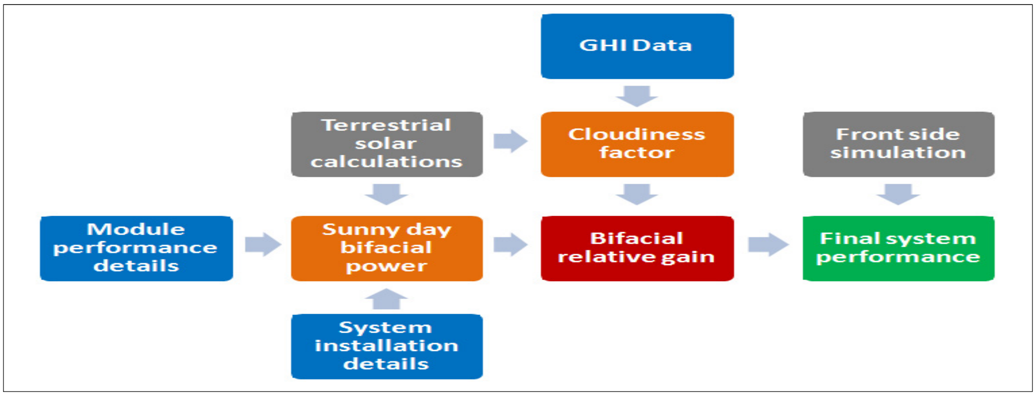

Fig. 1. The bifacial modelling process flow. The GHI data, the module performance details and the system installation details are the inputs. The terrestrial solar calculation and the front side power simulation are used in the primary calculation. The sunny day bifacial power and the cloudiness factor are used in the secondary calculation. The bifacial relative gain is calculated in the tertiary calculation and the final system performance can be simulated.

The sunny day bifacial power is calculated using solar geometry to determine the front and rear power output using terrestrial solar radiation based on the sun position and system location [3]. The model of diffused radiation and ground reflected radiation is based on the work published by G. M. Masters [4]. For the sunny day calculation, the cloudiness factor is not considered. The cloudiness factor is the GHI data at a given time as a percentage of the ideal GHI available on a clear day at the relevant point in time, which is calculated in the terrestrial solar calculations. For this work, the additional power from the rear side of the bifacial module is added to the power produced from the front side to provide the total module power. By assuming this, the series resistance effects and other potential effects cannot be considered.

There are three major parameters that are used in calculating the rear side illumination: (1) the diffused radiation incident at the rear of the module, (2) the diffuse and direct beam component incident on a horizontal plane, and (3) the length of the shadow cast behind the module, considering only the distance directly behind the module. In addition, the rear side illumination has a complex dependence on the height of the module above the ground, the tilt of the module, and the position of the sun. The model considers three cases to account for these factors: (1) when the module is elevated infinitely high (far enough so that shading from the module on the ground is not a factor), (2) when the module is on the ground, and (3) when the module is at intermediate heights. Figure 2 shows a module mounted at different heights (h_1 and h_2) in order to harvest more gain for the rear side, where β is the module tilting angle, α_1 and α_2 are the elevation angles of the sun. Distances o_1, o_2, g_1 and d_1 are used in the bifacial relative gain calculation. The location determines system performance due to illumination, the percentage of diffuse radiation and the elevation of the sun. The system design changes performance through module height, module tilt, albedo and local shading as these affect the amount of radiation incident on the rear of the module.

The actual bifacial percentage gain is the increased power output expected from a bifacial module compared to a monofacial module with the same system characteristics. This depends on both the cloudiness factor and the theoretical bifacial percentage gain on a clear day. From the cloudiness factor a performance scaling factor, k_{cloud}, is determined to scale the theoretical bifacial percentage gain to obtain the actual bifacial percentage gain based on statistical observations from measured data as lower irradiance days have a higher percentage of diffused radiation.

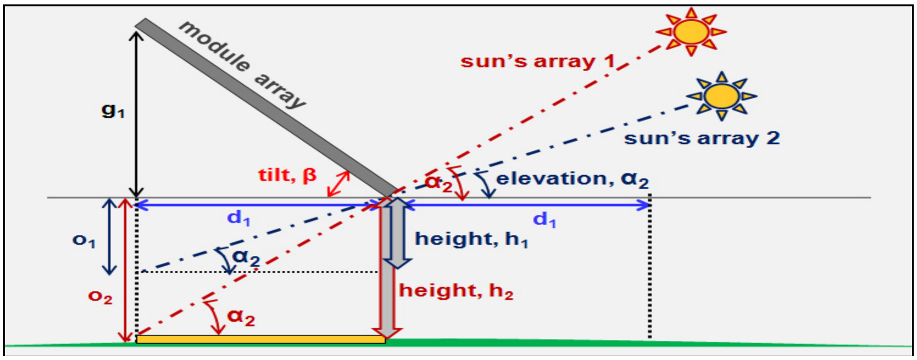

Fig. 2. The bifacial modelling schematic diagram shows a module with different mounting heights (h_1 and h_2). The amount of module mounting height is important for harvesting maximum power gain from the rear side. Sun's array 1 and sun's array 2 are from two different sun elevation angles. Symbol β is the module tilting angle, α_1 and α_2 are the elevation angles of the sun. Distances o_1, o_2, g_1 and d_1 are used in the bifacial relative gain calculation.

3. Simulation results

The potential applications of the bifacial simulation model are shown in Figure 3, Figure 4 and Figure 5. Germany and Singapore are chosen as the two different geographic locations representing countries with high and low latitude. The REC multicrystalline solar bifacial module used in the simulation work has 250W of power from the front side and 150W from the rear side. The bifaciality is 0.6, the module length is 1.67m and the width is 0.99m. In this work, air mass 1.5 spectrum (AM1.5) and an intensity of 100mW/cm2 (one sun illumination) were used.

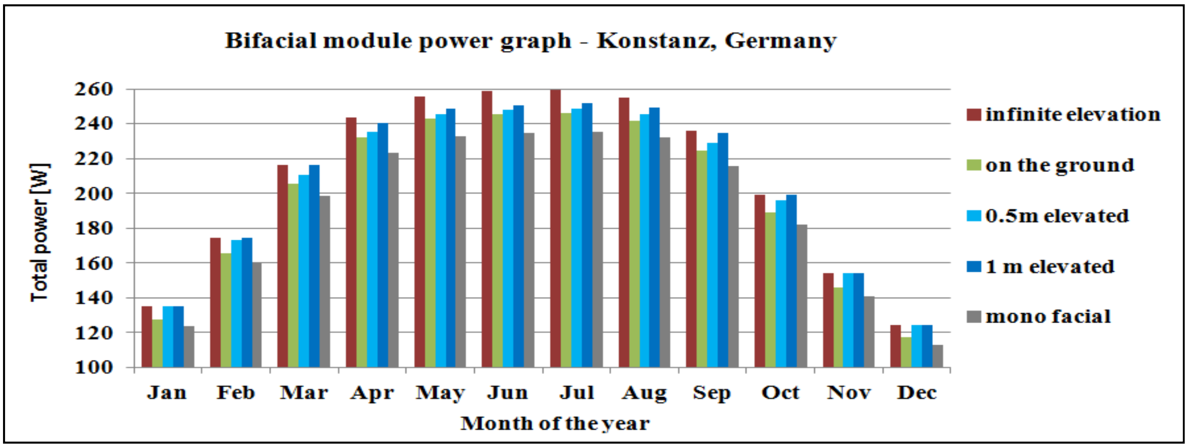

Fig.3. Module power comparison throughout a year at solar noon time in Konstanz, Germany. This is an example to illustrate the capability of the simulation. Different elevation heights were simulated and a 20% reflection coefficient was used for this simulation. The front module power is 250W and the rear module power is 150W. The module tilting angle is at 40 degrees.

The model compares the module power delivered throughout a year in Konstanz, Germany in Figure 3. The latitude of Konstanz is 47.7 degrees north. The module tilting angle used was 40 degrees. By using the simulation model, the tilting angle can be optimized to give the maximum mono-facial power. Assuming the front module power is always higher than the rear side for standard bifacial modules, the tilting angle should be set in a favourable position to the front side. Early in the morning and later in the afternoon, the simulation model calculated low front side module power due to the low sun elevation angle. With 20% background reflectance with infinite elevation of the bifacial module, the energy yield gain from the rear of the module was calculated to be 10.4%; with a 1 meter of elevation, the gain is 9.1%. This indicated that with a 1 meter elevation, 90% of the potential energy yield can be potentially achieved. When there is no elevation at all, the upper limit for energy yield is still 4.6%. This further indicates that an adequate amount of elevation is required to harvest maximum. In addition, the model compares the module power delivered throughout a day in the month of July in Konstanz, Germany. Early in the morning and later in the afternoon, the simulation model calculated low module power due to low sun elevation angle. With infinite elevation, the energy yield gain from the rear of the module was calculated to be 10.4%, with 1m of elevation, the energy yield is 9.1%. This indicated that with 1m of elevation, ~90% of the potential energy yield can be achieved. When there is no elevation at all, the upper limit for energy yield is still 4.6%.

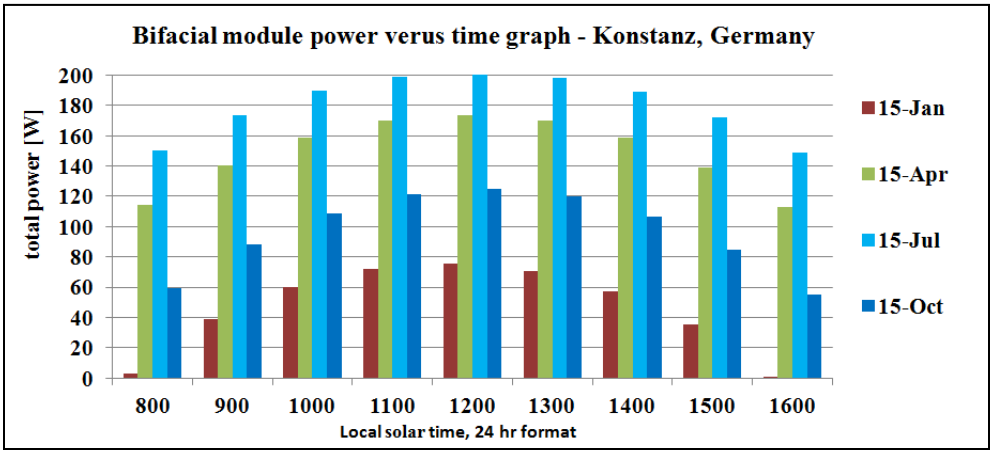

Fig.4. Module power comparison throughout a day in July in Konstanz, Germany. A 20% reflection coefficient for the ground under the module is used and the tilting angle is at 40 degrees.

In the next stage, the bifacial module performance at a country with low latitude is compared, and Singapore is used as an example as its latitude is 1.3 degree north. The model compares the module power delivered throughout a day on equinox. The module tilting angle used in the simulation is 10 degrees. From the simulation results, a similar trend is found: early in the morning and late in the afternoon there is low module power due to the low sun elevation angle. When the module is sitting directly on the ground, the energy yield gain from the rear side of the bifacial module is only 1.3%. With the case of infinite elevation, the energy yield is 10.4%. This value is in the same range as the studies done at the REC bifacial energy yield test site, where the data is collected for a duration of 2 months. The tall elevation height is crucial for countries with low latitude.

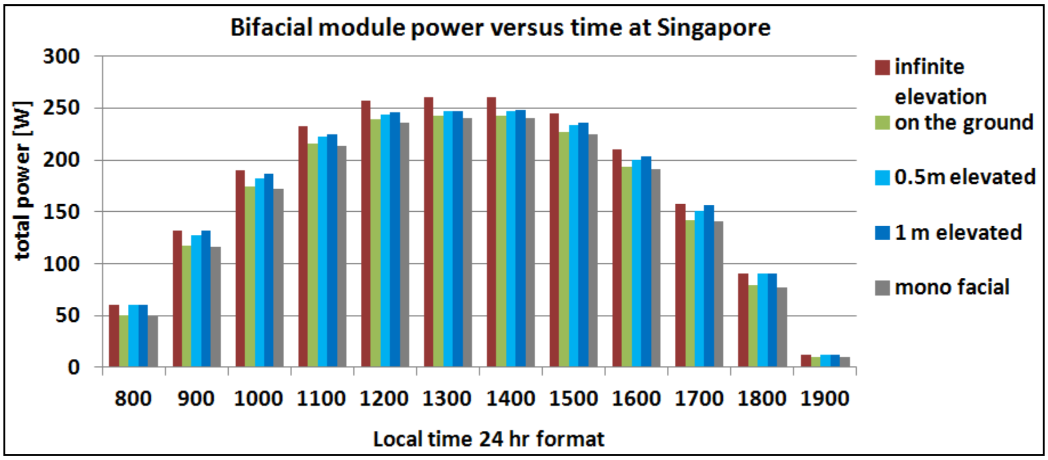

Fig.5. Module power comparison throughout a day at equinox in Singapore. Different elevation heights were simulated and a 20% reflection coefficient was used for this simulation. The module tilting angle is at 10 degrees.

From the Konstanz and Singapore simulation studies, we are able to conclude that the amount of module elevation depends on the location around the globe. For locations with high latitude, a lower amount of module elevation height would be sufficient compared to locations with low latitude. The altitude of the sun for Konstanz is lower than that of Singapore at any specific time throughout a day.

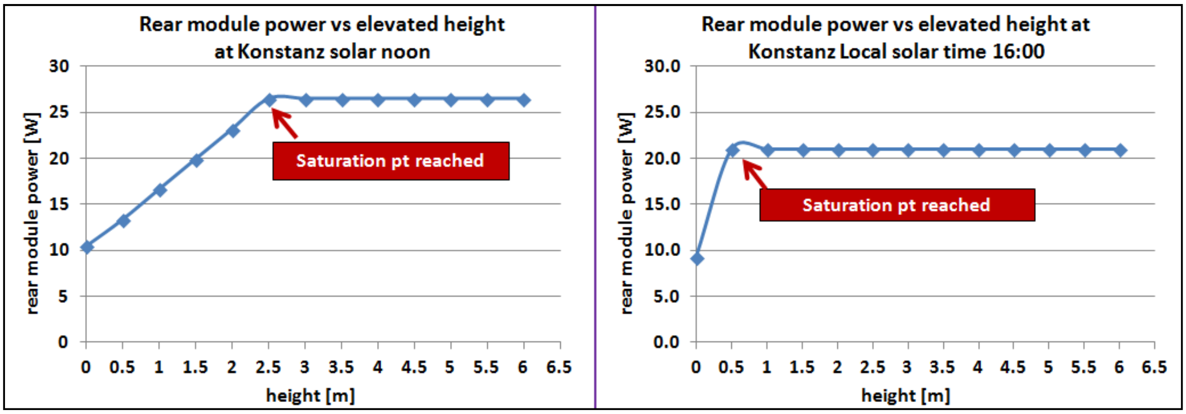

Fig.6. Module power comparison with varied module elevation height at Konstanz, Germany.

For a bifacial module with varying elevation, it is important to understand that once the saturation point/height is reached, there is no further electrical performance benefit exceeding that saturation point. The saturation point is reached when the shadow created by the module array is not covering any part of the ground area directly below the module. This also means that there is no shadowing effect directly below the module. Once the saturation point is reached, the scenario is similar to the case of infinite elevation height. From the model calculation, a 2.5 meters module elevation height is required in Konstanz at solar noon time to reach the power saturation point, but only 0.5 meter is sufficient at local solar time 4pm in the afternoon to reach the power saturation point.

The rear side module power increases proportionally with increased background reflectivity. Background reflectivity is an important parameter for bifacial module setup & installation. Figure 7 shows energy yield increases with increased albedo from a fixed elevation height of 1 meter. The module tilting angle is 40 degrees and with 1 meter of elevation. The module power increased proportionally with increased background reflectivity. This shows background reflectivity is an important parameter for bifacial module setup & installation.

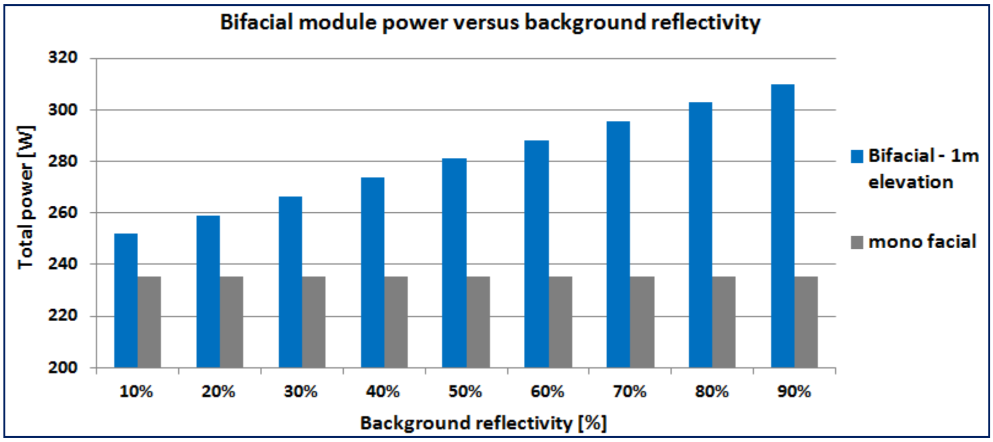

Fig.7. Module power comparison with different background reflectivity coefficient at Konstanz Germany.

4. Conclusion

Energy yield for bifacial modules is very much location dependent and hugely influenced by how they are setup and installed. In general, the bifacial modules work best in countries and regions at a higher latitude as the bifacial module performs better when the sun elevation angle is low. Besides, a ground surface with high reflectivity is desirable as it is one of the key parameters for bifacial module electrical performance. A background surface with a high reflection coefficient gives higher energy yield as this impacts the amount of reflected light. In addition, sufficient clearance distance in front of the module array should be considered. To obtain a higher energy yield, ensure there is no blockage for the direct sun array shining on the area beneath the module. Simulation shoes >10% in energy yield is achievable with REC multicrystalline silicon solar modules with a bifaciality of 0.6. This is by using realistic example of 20% background reflectance in Konstanz, Germany.

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