Uncertainty Quantification of Bifacial Performance Modeling

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Uncertainty Quantification of Bifacial Performance Modeling

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Abstract**—**Analysis on uncertainty in the annual energy of PV systems that can be attributed to parameters of particular importance to bifacial PV modules is presented. Monte Carlo simulations are used to evaluate the effect of uncertain module bifaciality factors, module transmission fractions, albedo values, and ground clearance. The analyses cover a wide spectrum of potential PV array archetypes through variation of installation parameters. The results of the Monte Carlo analysis reveal that the uncertainty is largely dependent on albedo uncertainty, but more simulations are needed to identify trends across system archetypes. The simulations are aimed at attributing an annual energy uncertainty factor for bifacial considerations that can be applied in post-processing of project probability of exceedance analysis.

Keywords—photovoltaic, energy modeling, uncertainty.

I. Introduction

Uncertainty in project PV project performance is a key consideration in project financing that must be accounted for to avoid overestimation of annual energy and insufficient project payback. This uncertainty can come from any step in the performance modeling pipeline, such as uncertainty in solar resource measurement or uncertainty in performance models themselves. One area of potential modeling uncertainty that has not been fully investigated is uncertainty in the performance of bifacial PV modules, where irradiance is absorbed and converted to electricity on both the front and rear surfaces of the module. As bifacial modules continue to gain market share, the uncertainty in the rear-side contribution to the annual energy output must be quantified to give investors a better understanding of the expected project performance.

The uncertainty of annual energy is often expressed through the application of annual energy factors unique to the individual sources of uncertainty [1]. Factors for sources of uncertainty such as solar resource measurement uncertainty are regularly calculated as part of an independent engineer's uncertainty calculation for prospective PV projects. For bifacial systems, however, there is not much consensus on how to calculate said uncertainty factor for the bifacial energy added to the system output. This work presents a unique approach to quantifying the uncertainty of bifacial energy output through analysis of input parameter distributions of particular importance to bifacial module energy production. These values are the bifaciality factor, the fraction of light transmitted through the module glass, the clearance height of the module from the ground, and the measured ground albedo.

II. Background

Bifacial PV systems differ from monofacial PV systems in their ability to convert incident irradiance from both the front and back surfaces of the PV module into electricity. The additional rear-side output of the module is similar to the front-side output in that it is primarily dependent on the magnitude of incident irradiance, but there are different considerations for input variable sensitivity and uncertainty in these bifacial systems. Variables such as the ground albedo and module ground clearance height can have an outsized effect on rear-side insolation as compared to front-side insolation. Previous efforts at quantifying rear-side insolation model sensitivity have revealed that the insolation is mainly dependent on albedo when the albedo range is high, and on ground coverage ratio, or the ratio of panel length to row-to-row distance, when dealing with low albedo ranges [2].

Modeling bifacial PV modules involves the calculation of plane-of-array (POA) irradiance hitting the rear-side of the module at a given time step. The rear-side incident irradiance can vary depending on the location of the sun relative to the module, panel installation parameters such as tilt and azimuth, and the ground albedo. While many of these parameters are known before the system is installed, or easily measurable, others are unknown or difficult to measure and can thus lead to unaccounted for uncertainty in bifacial system performance. Such variables include the ground albedo, or ratio of light that is reflected from the ground. Often the seasonal changes in albedo are not considered in system performance despite the outsized effect these changes can have on bifacial system annual output due to increased ground reflection on the back surface. The ground clearance height of the module also determines the amount of direct and diffuse light received on the rear surface of the module due to changing angles between the module and the sun's ray along with changing shading conditions due to module position. The ground clearance height that a system is installed at can vary across a wide range of heights based on project-specific ground reflection and shading considerations. Higher ground clearance heights often increase bifacial energy output by allowing for increased ground reflected irradiance on the backside of the module. Other module-specific variables such as the transmission fraction and bifaciality factor are often not reported on module specification sheets. The transmission fraction describes the amount of light that passes through the top glass of the module's rear surface (primarily between gaps in PV cells) [3]. The bifaciality factor is the ratio of the bifacial module's rear surface output to the front surface output for the

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same STC conditions [3]. This bifaciality factor is usually determined through standardized indoor testing procedures but is often not included in module specification sheets. Bifaciality factors have been reported to be anywhere from 0.65 to 0.95 depending on the cell type and manufacturer [4]. Each of these variables can introduce uncertainty into the bifacial gain, or additional energy provided by the module's rear-side, and ultimately the annual energy that is of primary concern to the PV project investment. The uncertainty in these models stemming from these variables must be analyzed as these are variables that are often overlooked or not directly measurable when installing new systems.

III. Methodology

Annual energy simulations of bifacial PV systems were performed using the PySAM Python wrapper of the performance models provided by NREL's System Advisor Model (SAM) [5]. A system with a capacity of 50 MW and system specifications provided in Table I is simulated with assumed bifacial PV module behavior. The annual energy production in kWh is evaluated for a variety of PV system archetypes to gain an understanding of the bifacial uncertainty as it relates to systems of different module tilts, azimuth angles, ground coverage ratios, and other system installation parameters. The bifacial gain of the system is also evaluated for each system archetype by subtracting the monofacial system annual energy output from the bifacial system annual energy output for each simulation to isolate the energy produced from the rear surface of the module. These archetypes are defined based on the following system parameters and specified ranges shown in Table II. For each system archetype, a reference or "true" annual energy value is used to compare against a distribution of 100 annual energy and bifacial gain values derived using values for ground clearance height, albedo, bifaciality factor, and transmission factor that have been stochastically sampled from a normal distribution around the mean value given for the reference case. The distribution on each of these four variables is defined with one standard deviation being $\pm$ 10% from the reference value for each variable. While not every system archetype from the variable ranges in Table II was simulated, enough simulations were performed to investigate trends in annual energy and bifacial gain changes for both fixed-tilt and single-axis tracking systems. The distribution space of the four variables is canvased through Monte Carlo sampling in which random samples of each variable are taken from each probability range before re-calculating the annual energy to determine each variable's effect on the annual energy uncertainty in each system archetype. The relative difference between the annual energy reference value and Monte Carlo sampled annual energy results at each of the 100 samples taken was found using the following relation:

$$D_{r,E} = \frac{E_{MC}-E_R}{E_R} \quad (1)$$

$$D_{r,B} = \frac{B_{MC}-B_R}{B_R} \quad (2)$$

Where E_{MC} is the annual energy output from a given Monte Carlo simulation, B_R is the bifacial gain of the reference simulation, $D_{r,E}$ is the relative difference between reference and sampled annual energy, and is the $D_{r,B}$ is the relative difference in bifacial gain between reference and sample simulations. The $D_{r,E}$ and $D_{r,B}$ values from each sample were then averaged to find the mean bias error (MBE) of the simulation and the standard deviation of the samples from said the reference energy value was also evaluated.

TABLE I. Bifacial system specifications

System Spec	Value
Weather location	Phoenix, AZ
Module efficiency	19.02%
DC:AC Ratio	1.33
Inverter efficiency	96.8%
DC Losses	4.4%
AC Wiring Losses	1.0%
Annual Degradation	0.5%/year

Recognizable trends in the MBE and standard deviation across the archetype grid motivated the parameters used in subsequent archetype simulations in order to examine as many variable boundaries as possible.

TABLE II. Variable ranges for bifacial system archytypes

Variable	Units	Lower bound	Increment	Upper bound
Tilt angle	deg	0	10	40
Azimuth	deg	90	90	270
Ground clearance height	meters	1	1	4
Ground coverage ratio	none	0.3	0.1	0.6
Albedo	none	0.2	0.2	0.8
Bifaciality	none	0.65	0.1	0.95
Transmission fraction	none	0	0.013	0.026
Tracking type	0/1	0 (fixed tilt)	1	1 (single-axis)

IV. Results

Annual energy mean bias errors for the Monte Carlo simulations of the different fixed-tilt system archetypes are plotted against the annual energy standard deviations of said simulations in Figure 1. This Figure and all figures presented in this manuscript were generated using the Plotly Python package [6]. Both the mean bias error and standard deviation are presented as percentages of the reference annual energy for the system archetype. The color scale in the plot represents the different annual albedo values used in the simulation, while the symbols represent different ground clearance heights of the modules. Analysis of this Figure reveals that deviation from the reference annual energy values increase for increasing albedo. This can be attributed to changes in annual energy production from both the front and rear surfaces of the modules, as changing albedo impacts the ground reflected irradiance that reaches both modules. Further trends of the bifacial specific sensitivities can be seen in Figure 2, which shows the bifacial annual energy gain calculated from the difference between monofacial and bifacial systems for each system archetype. The results in this Figure, normalized to a percentage of the reference bifacial annual energy gain in a manner similar to that of Figure 1, effectively isolate the bifacial portion of the annual energy production and the sensitivities of the bifacial gain to the key variables being investigated in this work. Analysis of this Figure reveals that the standard deviation in bifacial gain increases for decreasing albedo, likely due to the decreased backside ground reflected irradiance. The standard deviation is also generally lower at 3-meter ground clearance height (squares) The bounds of bias error for the bifacial gain is within $\pm$ 0.04% for all archetypes.

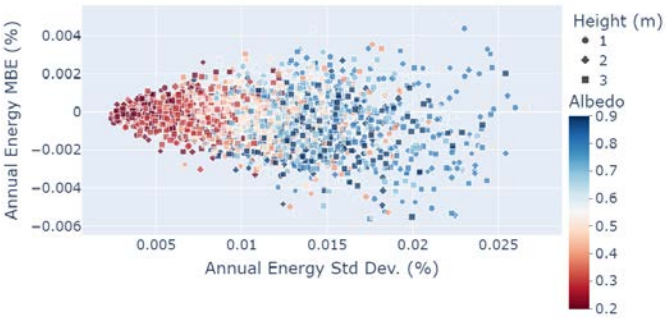

FIGURE 1. ANNUAL ENERGY MBE AND STANDARD DEVIATION FOR FIXED-TILT BIFACIAL SYSTEM SIMULATIONS

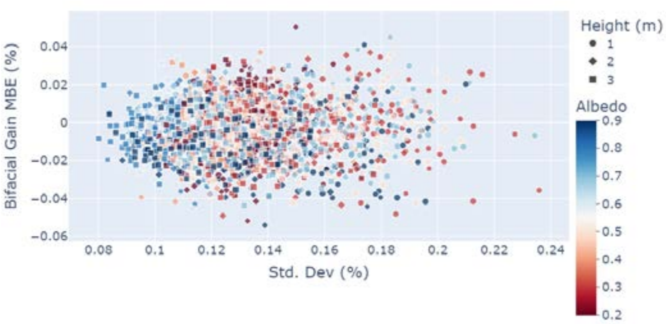

FIGURE 2. BIFACIAL GAIN MBE AND STANDARD DEVIATION FOR FIXED-TILT BIFACIAL SYSTEM SIMULATIONS

The results for non-tracking archetypes were further categorized by system archetype parameters such as tilt angle, azimuth angle, ground coverage ratio, and ground clearance height to further investigate trends in bifacial system behavior. These results are shown in Figures 3-6. Figure 3 shows increased standard deviation for systems with a fixed tilt angle of 0° that would have poor bifacial energy gain due to minimal view factors between the sun and the rear surface of the module that is parallel to the horizontal ground. Figure 4 shows the bifacial gain dependence based on azimuth angle, with higher standard deviation being seen for systems oriented facing East or West as compared to the typical South facing configuration. Figure 5 shows increased bifacial gain deviation from the reference value for higher GCR values such as 0.6 or 0.8 likely because of increased row-to-row shading. Figure 6 divides the bifacial gain values based on ground clearance height and reveals more variance in results for the lowest height of 1 meter due to lower view factors for irradiance to hit the rear surface of the module.

Bifacial system archetypes based on single-axis tracking systems were simulated as well, with the annual energy MBE and standard deviation results being shown in Figure 7. The trends in annual energy bias and standard deviations are similar to those for the bifacial systems due to the dependence of both front and rear module surface energy production on system parameters such as albedo, ground coverage ratio, and ground clearance height. When evaluating the bias error and standard deviation in bifacial gain for single-axis tracking systems as shown in Figure 8, no clear trends in parameter sensitivity can be identified. The bounds of the mean bias error for these single axis-tracking simulations fall within $\pm$ 0.03%.

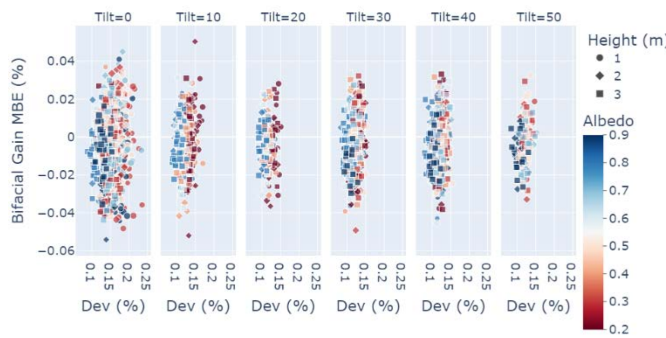

FIGURE 3. BIFACIAL GAIN MBE AND STANDARD DEVIATION FOR FIXED-TILT SYSTEMS SEPARATED BY TILT ANGLE

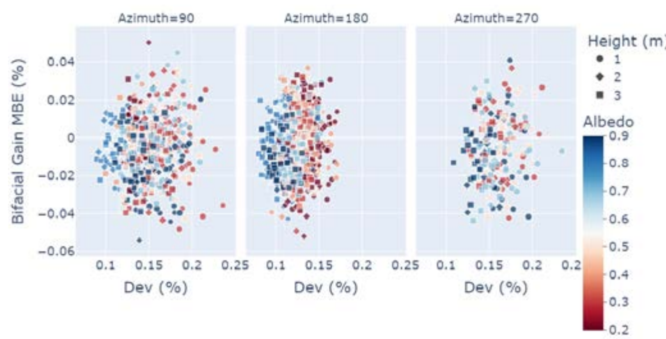

FIGURE 4. BIFACIAL GAIN MBE AND STANDARD DEVIATION FOR FIXED-TILT SYSTEMS SEPARATED BY AZIMUTH ANGLE

The single-axis tracking simulations were also evaluated based on the system archetype parameters of GCR and ground clearance height. Different tracker tilt angles and azimuth angles were not evaluated in the simulations as east to west tracking systems on horizontal trackers are the predominant system archetype of interest. In Figure 7, we see similar annual energy bias errors and deviations as for fixed tilt systems; however, in Figure 8, the increase in standard deviation of the bifacial gain with decreased albedo that was present for fixed tilt systems has disappeared. Future work should investigate whether this is a result of the weather file used (Phoenix, AZ), backtracking in the single-axis tracking system, a result of the bifacial model algorithm, or something else. The GCR dependence shown in

Figure 9 is similar to that of the fixed-tilt systems, with higher GCR values leading to more row shading and more deviation from the reference bifacial gain value. The ground clearance height dependence shown in Figure 10 does not reveal any clear trends in bifacial gain bias error or deviation from the reference value.

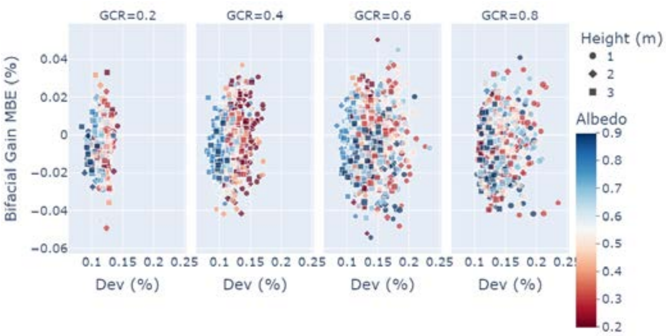

FIGURE 5. BIFACIAL GAIN MBE AND STANDARD DEVIATION FOR FIXED-TILT SYSTEMS SEPARATED BY GROUND COVERAGE RATIO (GCR)

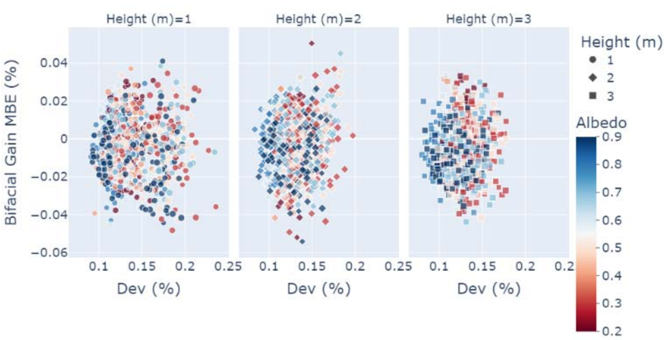

FIGURE 6. BIFACIAL GAIN MBE AND STANDARD DEVIATION FOR FIXED-TILT SYSTEMS SEPARATED BY GROUND CLEARANCE HEIGHT

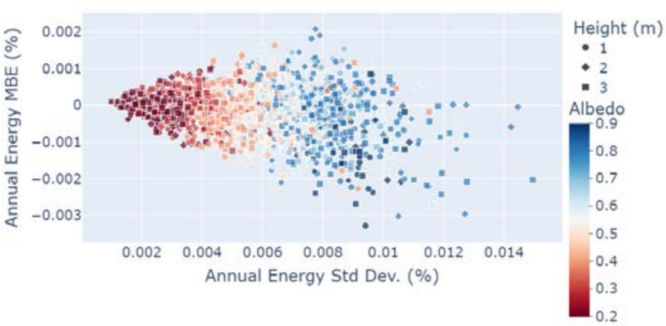

FIGURE 7. ANNUAL ENERGY MBE AND STANDARD DEVIATION FOR SINGLE-AXIS TRACKING BIFACIAL SYSTEM SIMULATIONS

V. SUMMARY AND CONCLUSIONS

This manuscript contains bifacial system simulations that quantify the sensitivity of bifacial performance gain to various PV system parameters that are of particular importance to bifacial systems. Monte Carlo simulations of numerous bifacial system archetypes in which normal distributions of albedo, ground clearance height, bifaciality, and transmission fraction are used to determine sets of MBE and standard deviation from a reference annual energy value. Results of these simulations show clear sensitivity in albedo for annual energy production and bifacial gain. The ranges of bias error for bifacial gain have been found to be $\pm 0.02\%$ for fixed-tilt systems and $\pm 0.03\%$ for single-axis tracking systems. These results can be used to inform uncertainty quantifications for bifacial models used in bifacial system performance estimates based on the approach described in [1]. Scripts for the PySAM implementation of this sensitivity analysis will be made publicly available in the near future. Future work in this area could include simulations of more bifacial system archetypes such as vertical fixed-tilt bifacial systems.

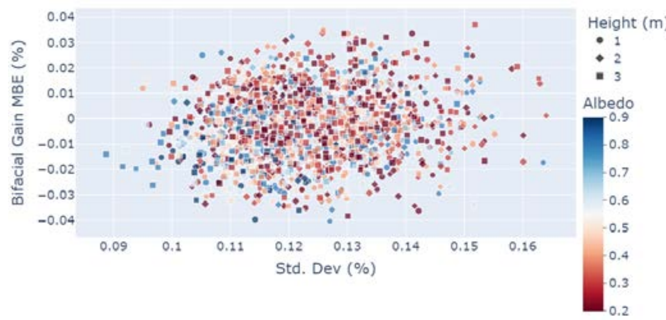

FIGURE 8. BIFACIAL GAIN MBE AND STANDARD DEVIATION FOR SINGLE-AXIS TRACKING BIFACIAL SYSTEM SIMULATIONS

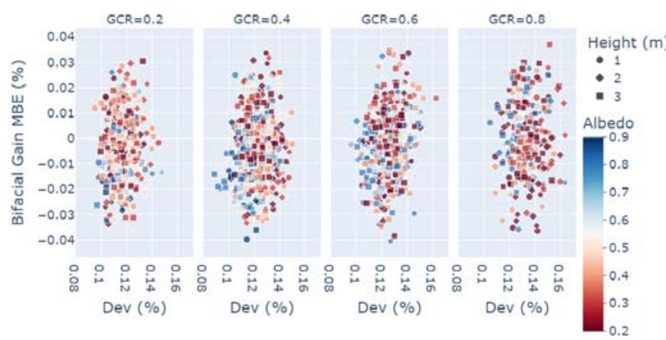

FIGURE 9. BIFACIAL GAIN MBE AND STANDARD DEVIATION FOR SINGLE-AXIS TRACKING SYSTEMS SEPARATED BY GROUND COVERAGE RATIO (GCR)

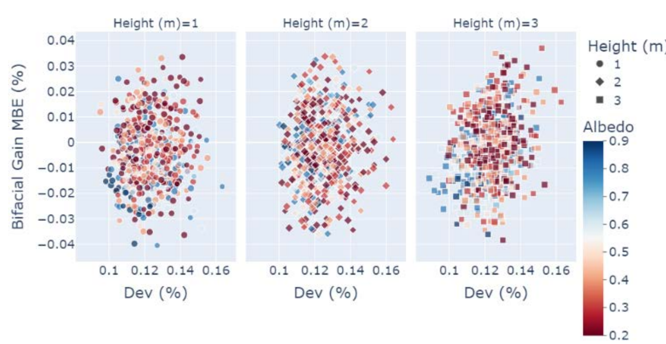

FIGURE 10. BIFACIAL GAIN MBE AND STANDARD DEVIATION FOR SINGLE-AXIS TRACKING SYSTEMS SEPARATED BY GROUND CLEARANCE HEIGHT

VI. Acknowledgment

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