Analysis of the Impact of Installation Parameters and System Size on Bifacial Gain and Energy Yield of PV Systems

Amir Asgharzadeh[1], Tomas Lubenow[1], Joseph Sink[1], Bill Marion[2], Chris Deline[2], Clifford Hansen[3], Joshua Stein[3], Fatima Toor[1]

[1]Electrical and Computer Engineering Department, The University of Iowa, Iowa City, IA, 52242, USA
[2]National Renewable Energy Laboratory, Golden, CO, 80401, USA
[3]Sandia National Laboratories, Albuquerque, NM, 87185, USA

***Abstract* — In this work, we present the combined effect of installation parameters (tilt angle, height above ground, and albedo) on the bifacial gain and energy yield of three photovoltaic (PV) system configurations: a single module, a row of five modules, and five rows of five modules utilizing RADIANCE based ray tracing model. We show that optimum tilt angle is dependent on parameters such as height, albedo, size of the system, and time of the year. For a single bifacial module installed in Albuquerque, NM, the optimum tilt angle is lowest (~5º) for summer solstice and highest (~65º) for winter solstice. For larger systems, optimum tilt angle can be up to 20º more than that for a single module system. We also show that modules in large scale systems, generate lower energy due to large shadowing areas cast by the modules on the ground. For albedo of 21 %, middle module in a large array generates up to 7% less energy than a single bifacial module. To validate our model, we utilize measured data from Sandia's fixed tilt bifacial PV testbed and compare it with our simulations. We find that due to higher non-uniformity, lower tilt angles demonstrate high normalized root mean square deviation (NRMSD) between measured and simulated values than high tilt angles.**

I. Introduction

In recent years, there has been growing interest in bifacial photovoltaic (PV) technology because it enables higher performance and lower price per watt ($/W) compared to conventional monofacial PV technology. However partly due to lack of accurate bifacial PV system modeling methods to predict system performance, utilization of this technology has remained limited. Understanding the effect of different installation parameters, such as height, tilt angle, albedo of the ground and array size on the bifacial PV system performance can help determine the optimum installation parameters for the system and allow for an accurate prediction of the energy yield of the system.

Other research groups have studied the impact of installation parameters, such as, tilt angle, height above ground and albedo, on the energy yield of small bifacial PV arrays based on measured data without considering the effect of system size [1]. Yusufoglu *et al.* [2] conducted a comprehensive performance analysis of a single bifacial module. However more realistic scenarios include a larger number of modules and rows. For these systems, the large shadowing areas cast by the modules on the ground can significantly negatively impact their performance. In this work, we show the combined effect of tilt angle, height, albedo and size of the system on the energy yield and bifacial gain of the PV system.

II. Irradiance Modeling

We modeled the PV systems using RADIANCE [3], which is a simulation software to compute the radiance profile of physical systems by ray-tracing methods. The sky irradiance model used in this study approximates the Perez direct and diffuse model [4]. In our model, we utilized the dimensions and electrical characteristics of Prism Solar's Bi60-368BSTC bifacial module (front and backside efficiencies of 17.4% and 15.6%, respectively, which is equivalent to a bifaciality of ~90%). NREL's National Solar Radiation Data Base (NSRDB) [5] was used to derive typical meteorological year version 3 (TMY3) weather (hourly) data for Albuquerque, NM for global horizontal irradiance (GHI), diffuse horizontal irradiance (DHI) and direct normal irradiance (DNI). Azimuth and zenith angles (also hourly data) were calculated using Sandia National Laboratories' PV_LIB Toolbox [6].

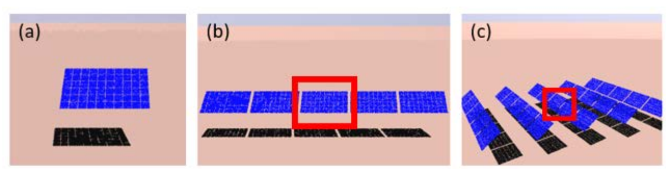

Fig. 1. Three south-facing PV systems consisting of (a) a single module (b) a row of five modules and (c) five rows of five modules each, were simulated to study the impact of the size on the system performance.

We considered three south-facing PV system configurations: (i) single module, (ii) a row consisting of five modules, and (iii) five rows, each with five modules, to investigate the impact of the system size on its bifacial gain and energy yield. Since the modeling of the multiple module configurations requires significant computation resources, we made our analysis feasible by considering the performance of only the middle module in the array. The row spacing for the five-row case was defined using a value obtained for the shadow length of the row of modules on Dec 21st (winter solstice) when the sun is the lowest in the sky and casts the longest shadow on the ground; using this length ensures that the modules will be shadow free for the entire year [7]. Fig. 1 shows the three simulated systems with the representative modules in the multi-module systems enclosed with red outlines.

Parametric sweeps over the three parameters affecting PV system performance were conducted to study their individual and combined effects. Tilt angle was varied from 5º to 90º (with steps of 5º). Module height above the ground, which is defined as the height of the lower edge of the module above the ground, was varied from 0.2 m to 3 m (with steps of 0.2 m). Typical height for ground mounted systems is 1 m while for car-port systems it is around 3 m, which is why we modeled heights of up to 3 m. We used three ground materials with different albedos: lite soil (21%), beige roofing material (43%) and a white ethylene propylene diene monomer (EPDM) roofing material (81%), which can also represent snow-covered ground. The albedo values for each of the materials were measured at NREL.

We ran hourly simulations sweeping parameters mentioned above around three representative dates of the year: summer solstice, winter solstice and fall equinox. Sun position for any day of the year is between the sun position on summer solstice and winter solstice, and for the fall equinox the length of the day and night are equal, so the analysis of these three days helps determine the seasonal and annual trends. For each case, we also considered one clear day and one cloudy day to study the effect of cloudy weather condition on the system performance.

To calculate the daily energy yield and bifacial gain in energy (BGE), we used the irradiance data for each of the 60-cells in the module at each time step and averaged it. The average value was multiplied by the effective area of the module and power conversion efficiency value to calculate the power generated by the module. Multiplying the power with the time step (1 hour) gives the energy of that particular time period in Watt-hours (W.h). For modeling bifacial modules, we added the front and backside energy to obtain total energy generated by the module. We summed over energy in each time step to obtain the daily energy. BGE was calculated using Eq. (1):

$$BGE \equiv \frac{E_b}{E_m} - 1 \qquad (1)$$

where E_b and E_m are the energy yield of the bifacial and monofacial module, respectively. It is important to note that by averaging cell irradiance data, we are neglecting backside non-uniformity. Currently we are working to improve our model by defining by-pass diodes in the model to account for the backside non-uniformity.

III. Effect of Installation Parameters

In this section, we present the effect of installation parameters on energy yield and bifacial gain of a single bifacial module for three clear days around summer solstice, fall equinox, and winter solstice. TMY3 weather data was used as an input for simulations. By comparing the GHI values in TMY3 weather data with the GHI data obtained from Ineichen clear sky model [8, 9], we can determine the clearness of sky for specific days. A parameter called clear sky index (K_c) which is the ratio of measured GHI over clear sky GHI, indicates how much clear a day was. Fig. 2 shows this comparison for three days where K_c is close to unity indicating that the sky on these days was clear with a good approximation.

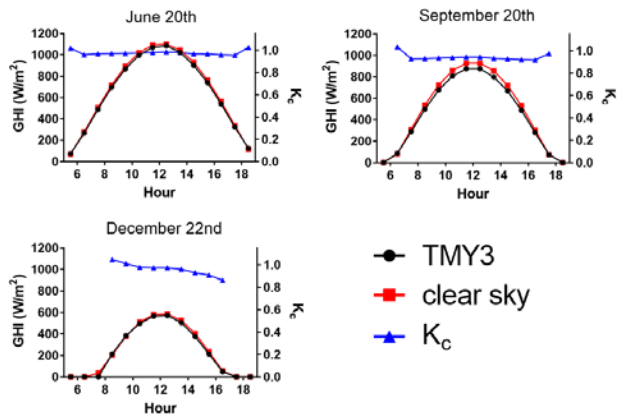

Fig. 2. Comparison of GHI values from TMY3 weather data and Ineichen clear sky model. K_c value of close to unity, indicates the sky was clear on these days.

A. Effect of tilt angle

For bifacial modules, optimum tilt angle can be different from monofacial modules and it depends heavily on parameters such as height, albedo, size of the system, and time of the year. Fig. 3 shows the energy yield and BGE as functions of tilt angle for two different heights (minimum height of 0.2 m and maximum height of 3.0 m in simulations) and three different albedo values (21%, 43%, and 81%). Comparing the energy yield figures from Fig. 3 (a), (c) and (e), we observe that optimum tilt angle for modules installed at 3.0 m is around 5º for summer solstice, 35º (site's latitude) for fall equinox and 65º for winter solstice. However, for modules installed closer to the ground (0.2 m), optimum tilt angle is usually higher. We will see in the section IV that optimum tilt angle is dependent on other parameters, such as height, albedo, size of the system, and time of the year and we need to study it more carefully. We also observe from BGE plots in Fig. 3 (b), (d) and (f) that by increasing tilt angle bifacial gain increases in summer. This can be explained by two reasons. First is that because of sun's position in summer, backside of the module receives more direct light when the module is installed at a high tilt angle and causes BGE to increase. Second reason is that for south-facing bifacial modules, most of the irradiance comes from the frontside and backside contribution is smaller than the frontside. We also know that optimum tilt angle for frontside irradiance is low (in summer solstice), so by increasing the tilt angle, frontside irradiance gets smaller and cause BGE to increase (backside irradiance can increase or decrease and it depends on the albedo of the ground. For higher albedos, backside irradiance is more when back of the module faces ground, while it is opposite for lower albedos). However, for fall equinox and winter solstice, we can see from Fig. 3 (d) and (f) that the trend is opposite, because the optimum tilt angle is higher. For fall equinox optimum tilt angle for frontside irradiance is approximately equal to site's latitude of 35º and for winter solstice it is higher, around 65º. By increasing the tilt angle from 5º up to the optimum tilt angle, frontside irradiance increases and cause BGE to decrease. That is why the slope of BGE decreases as we move from summer to winter.

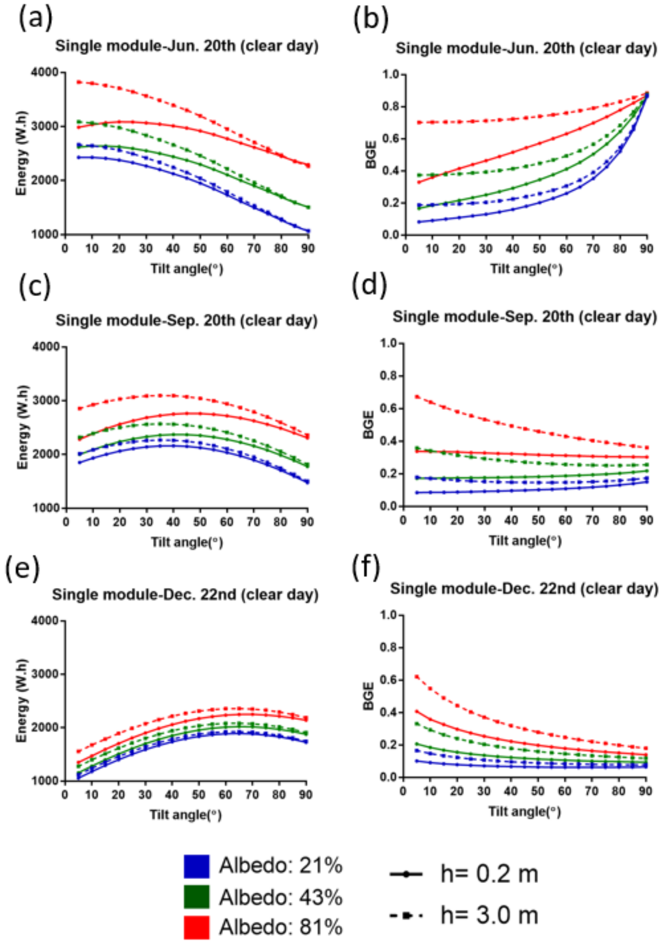

Fig. 3. (a) Energy yield and (b) bifacial gain of single module system as a function of tilt angle on a clear day around summer solstice (June 20th). (c) Energy yield and (d) bifacial gain of the system on a clear day around fall equinox (September 20th). (e) Energy yield and (f) bifacial gain of the system on a clear day around winter solstice (December 22nd).

B. Effect of height

Height of the bifacial module from the ground also impacts the energy yield. When the bifacial module is installed close to the ground, backside irradiance is affected profoundly by self-shadowing and by increasing the clearance from the ground, backside of the module gets more light from both the sky and the ground. Fig. 4 shows the impact of height on energy yield and bifacial gain. We plotted the data for tilt angles of 5º, 35º and 65º and albedos of 21%, 43%, and 81% to show the trends for different albedos and tilt angles. We observe that both energy yield and bifacial gain start to increase by increasing the height. However, we can see a saturating effect where as the height of the module increases the performance is not affected. This saturating effect is observed at 2.0 m for summer solstice, 1.0 m for fall equinox and 0.6 m for winter solstice. At these module heights the effect of self-shadowing on backside irradiance is diminished and increasing the height doesn't increase the performance.

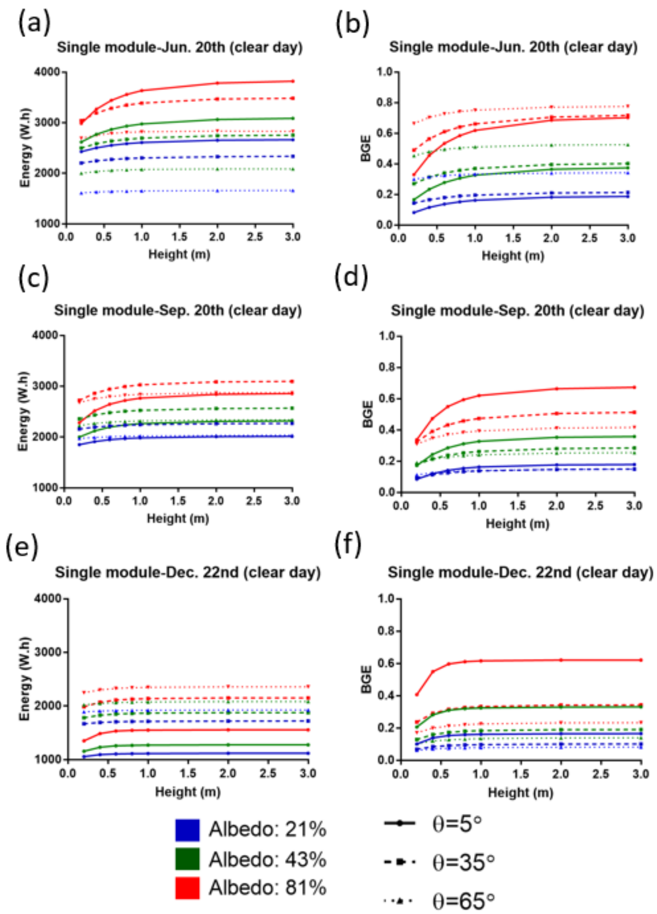

Fig. 4. (a) Energy yield and (b) bifacial gain of single module system as a function of height on a clear day around summer solstice (June 20th). (c) Energy yield and (d) bifacial gain of the system on a clear day around fall equinox (September 20th). (e) Energy yield and (f) bifacial gain of the system on a clear day around winter solstice (December 22nd).

C. Effect of albedo

Increasing the reflectivity (albedo) of the ground, increases intensity of the reflected rays which hit front and back sides of the module and increases the system's performance. Fig. 5 shows the effect of albedo on energy yield and bifacial gain for different tilt angles and heights. We see that the relationship is linear for both energy yield and BGE. However, because of high insolation in the summer, slope of energy yield plot is higher for summer solstice than for fall equinox or winter solstice. We also observe that the slope of the energy yield data is lower when the module is close to the ground and the tilt angle is low (~9.3, 7.2, and 4.9 W.h/albedo (%) in summer solstice, fall equinox and winter solstice respectively). However, for modules installed at higher heights and tilt angles, slope is higher (~19.3, 13.9, and 7.2 W.h/albedo (%) in summer solstice, fall equinox and winter solstice respectively).

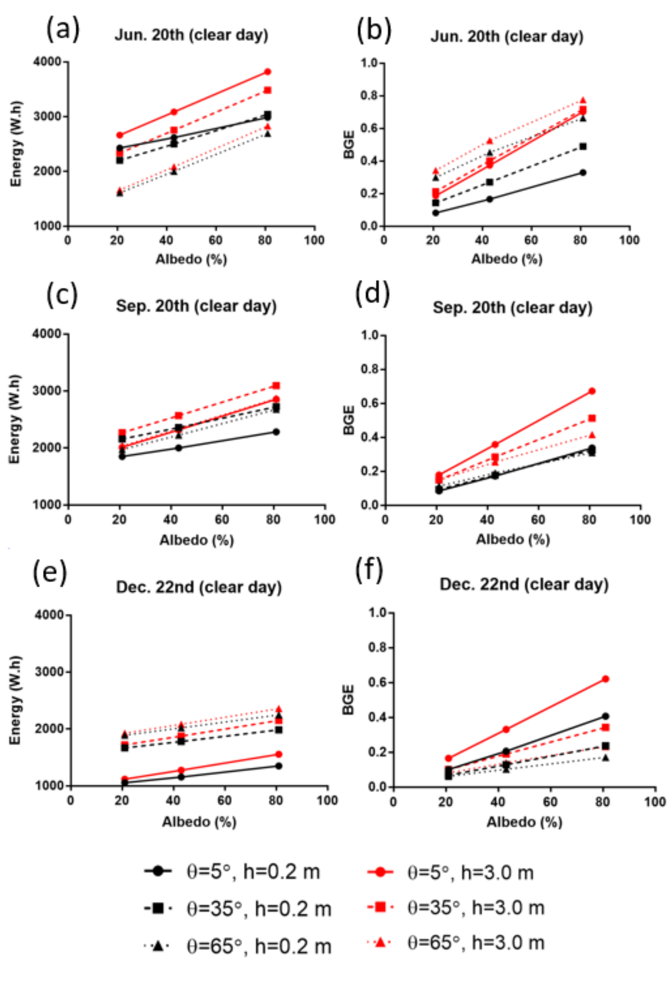

Fig. 5. (a) Energy yield and (b) bifacial gain of single module system as a function of albedo on a clear day around summer solstice (June 20th). (c) Energy yield and (d) bifacial gain of the system on a clear day around fall equinox (September 20th). (e) Energy yield and (f) bifacial gain of the system on a clear day around winter solstice (December 22nd).

IV. OPTIMUM INSTALLATION PARAMETERS AND EFFECT OF SYSTEM SIZE AND CLOUDY WEATHER CONDITION

So far, we analyzed the effect of installation parameters on a single bifacial module and saw that to achieve the highest performance, module needs to be installed at the highest possible albedo and its height from the ground should be high enough to minimize the self-shadowing effect. However, the optimum tilt angle varies under different conditions. We interpolated the simulation data to get resolution of one degree for tilt angle and determined the optimum tilt angle for different conditions. Fig. 6 shows the optimum tilt angle for three different sized systems (single module, one-row, and multi-row systems) for different heights and albedos and for both cloudy and clear days around summer solstice, fall equinox, and winter solstice. Fig. 7 shows that clear sky index is less than unity for shown three days, which indicates the sky was not clear during these days.

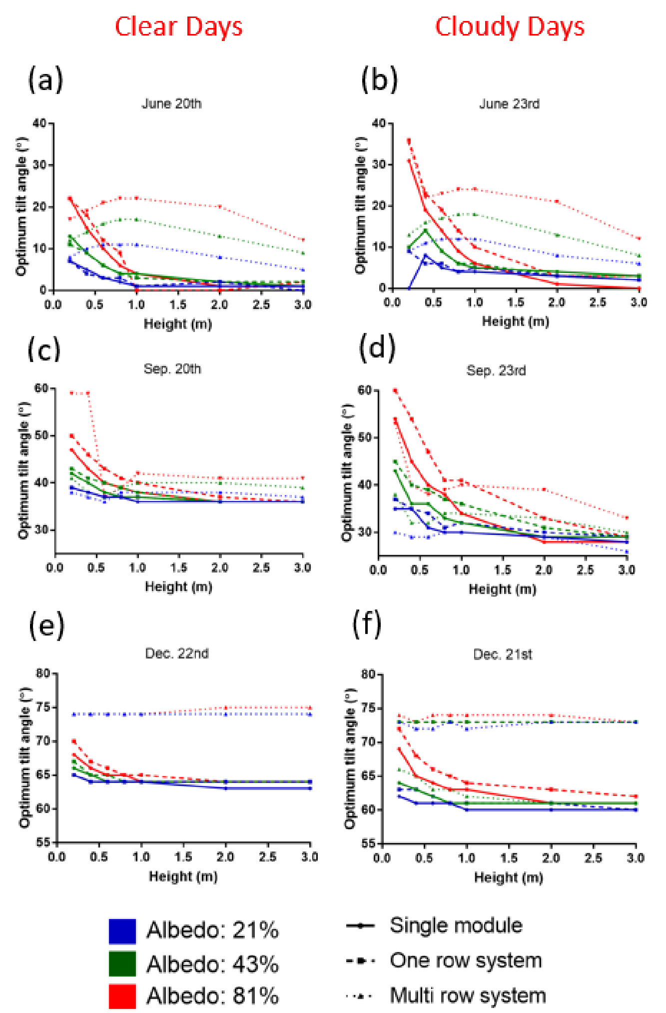

Fig. 6. Optimum tilt angle as function of height and albedo for clear days in summer solstice, fall equinox and winter solstice (Figures (a), (c) , and (e) respectively) and for cloudy days around the three dates (Figures (b, (d) , and (f)). Results are depicted for single module, one-row and multi-row systems.

Fig. 6 (a), (b) and (c) show that for lower module heights when the system size is not large (single module or one-row system), optimum tilt angle is higher. The modules installed close to the ground face large portion of their own shadow and by increasing the tilt angle, backside of the module receives more light from the ground and sky and sees less of the dark shadowing area. For cloudy days, optimum tilt angle tends to be higher for modules installed close to the ground relative to clear days. This is because cloudy weather conditions mean reduced direct sunlight and hence reduced reflection from the ground onto the back of the module. Therefore to achieve higher irradiance, back of the module tends to be toward the sky more than the ground requiring higher tilt angles for higher energy yield. Another observation is that, for large scale systems (multi-row system), optimum tilt angle can be up to 20º more than small scale systems. By increasing the number of modules, shadowing area gets larger and to receive more irradiance, tilt angle needs to be higher to diminish the shadowing effect.

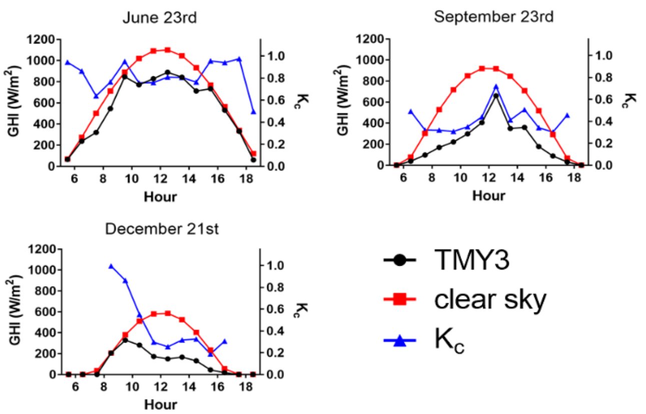

Fig. 7. Comparison of GHI values from TMY3 weather data and Ineichen clear sky model. K_c value of less than one, indicates three chosen days are not clear days.

V. EFFECT OF SYSTEM SIZE ON THE PERFORMANCE

Using the optimum tilt angle for module height of 1 m and albedo of 21%, we compared the performance of the three PV systems. The data is shown in Fig. 8. Monofacial data for the same height and albedo (for single module system) is also shown in the figure. By comparing the data in Fig. 8, we observe that by increasing the number of modules, energy yield decreases significantly due to larger shadowing area on the ground. Middle module in the multi-row system has about 7% lower energy production than the single module system on summer solstice. This value for fall equinox and winter solstice is about 4% and 3%, respectively. Note that in all cases, as expected, the bifacial modules produce more energy than the monofacial modules. We found from our simulation data (not shown here) that for the albedo of 81%, modules in large arrays can have up to 14% lower performance compared to single module systems. Fig. 8 also shows that highest bifacial gain is for single module system and drops as system size gets larger.

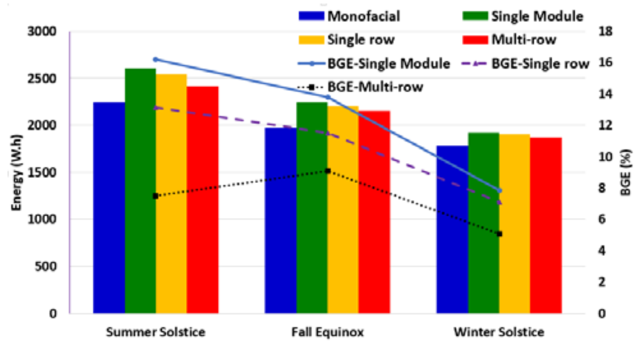

Fig. 8. Energy yield and BGE of single module, single row and multi-row PV systems for optimum tilt angle at the module height of 1 m and albedo of 21% for clear days on summer solstice, fall equinox and winter solstice.

VI. MODEL VALIDATION

To validate our RADIANCE model we used it to simulate Sandia's fixed-tilt string-level arrays. Fig. 9 shows the system. It consists of 4 rows with different tilt angles (15º, 25º, 35º, and 45º). Each row has two strings of 8 modules (one monofacial and one bifacial). Each row has also 3 reference cells near the middle of the row: one for front and two for back side. Backside reference cells are installed on top and bottom of the middle module in the row (Fig. 10). Our simulations also included the concrete blocks used for the array footings.

Fig. 9. Sandia's fixed-tilt string-level arrays, Albuquerque, NM.

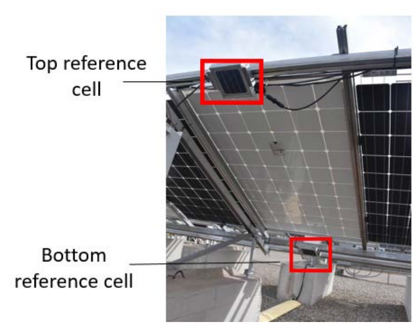

Fig. 10. Each row has two backside reference cells (top and bottom)

Simulated irradiance was compared to field measurements for a clear day on March 1st, 2017. The comparison shows a good match between the measured and simulated data. Fig. 11 and 12 compare measured and simulated data for frontside and backside irradiance respectively.

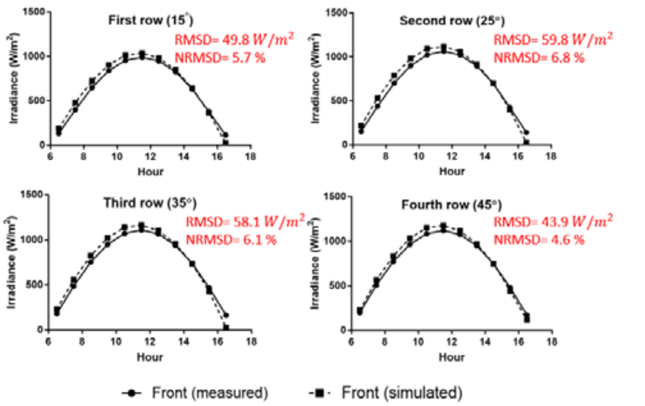

Fig. 11. Simulated vs measured frontside irradiance for Sandia's Fixed-Tilt String-Level Arrays.

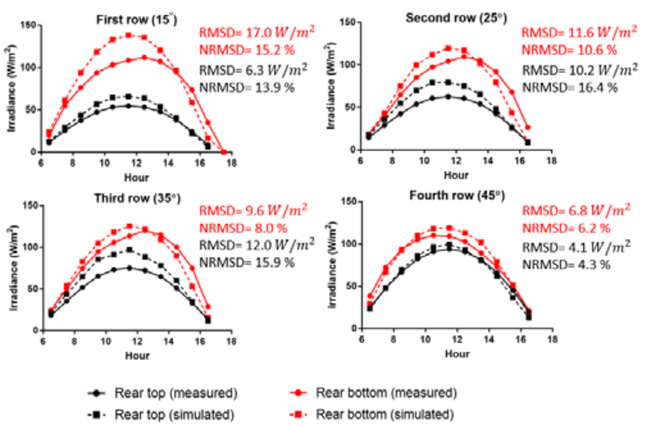

Fig. 12. Simulated vs measured backside irradiance for Sandia's Fixed-Tilt String-Level Arrays.

For each case, RMSD (root mean square deviation) and NRMSD (normalized RMSD) was calculated to compare the simulated data to measured data. Considering the backside irradiance data, we observe that top and bottom reference cells can receive different irradiance. This non-uniformity in the backside irradiance decreases the performance of the system. By increasing the tilt angle, non-uniformity decreases, because modules receive more uniform irradiance from the sky than the ground.

VII. CONCLUSION

We performed a set of RADIANCE simulations to study the effect of tilt angle, module height above ground, albedo and size of the system. We showed the effect of installation parameters on energy yield and bifacial gain of a single module on clear days around summer solstice, fall equinox and winter solstice. We found that modules installed at the highest possible albedo with high enough height, have higher production. However, optimum tilt angle is more complicated and is dependent on other parameters such as height, albedo, size of the system, and time of the year and is usually higher for modules installed closer to the ground.

We showed that the system size is an important factor that impacts the performance of bifacial PV arrays. Three different-sized systems were modeled and their performance was compared. We found that for large scale bifacial systems, optimum tilt angle is usually higher and can be up to 20° more than that for smaller systems. We also observed that energy yield of the modules in a large array can decrease up to 7% (relative to single module system) with ground albedo of 21%.

We also modeled the Sandia's fixed-tilt string-level arrays and compared the simulated irradiance data to measured data to validate our model. Results show a good match between measurements and the simulation.

VIII. ACKNOWLEDGEMENTS

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