A Sensitivity Study of the Impact of Installation Parameters and System Configuration on the Performance of Bifacial PV Arrays

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***Abstract* — In this work, we present the effect of installation parameters (tilt angle, height above ground, and albedo) on the bifacial gain and energy yield of three, south-facing 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 height and albedo have a direct impact on the performance of bifacial systems. However, the impact of the tilt angle is more complicated. Seasonal optimum tilt angles are dependent on parameters such as height, albedo, size of the system, weather conditions, and time of the year. For a single bifacial module installed in Albuquerque, NM (35˚ N) with a reasonable clearance (~1 m) from the ground, the seasonal optimum tilt angle is lowest (~5º) for the summer solstice and highest (~65º) for the winter solstice. For larger systems, seasonal optimum tilt angles are usually higher and can be up to 20º greater than that for a single module system. Annual simulations also indicate that for larger fixed-tilt systems installed on a highly reflective ground (such as snow or a white roofing material with an albedo of ~81%), the optimum tilt angle is higher than the optimum angle of the smaller size systems. We also show that modules in larger scale systems, generate lower energy due to horizon blocking and large shadowing area cast by the modules on the ground. For albedo of 21%, the center 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 National Laboratories' fixed-tilt bifacial PV testbed and compare it with our simulations.**

***Index Terms*—Bifacial PV, optimization, photovoltaic systems, ray tracing, solar power generation.**

I. Introduction

In recent years, there has been a growing interest in bifacial photovoltaic (PV) technology [1] because it promises higher performance yield and lower levelized cost of energy (LCOE) compared to conventional monofacial PV technology. However partly due to lack of accurate bifacial PV system modeling tools, utilization of this technology has remained limited. Understanding the effect of different installation parameters, such as height, tilt angle, the 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.

Castillo-Aguilella *et al.* 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 and data without considering the effect of system size [2]. Yusufoglu *et al.* conducted a comprehensive performance analysis of a single bifacial module [3]. However, more realistic scenarios include a larger number of modules and multiple rows. For these systems, the large shadowing areas cast by the modules on the ground can negatively impact their performance. Kreinin *et al.* studied the design factors such as the height, albedo, and the row spacing in bifacial PV systems and suggested that gains of above 40% are achievable utilizing optimal design parameters [4].

In this work, we show the effect of tilt angle, height, albedo, and size of the system on the energy yield and bifacial gain of the PV systems. In previous work [5], we presented the effect of installation parameters, such as tilt angle, height, and albedo on energy yield and bifacial gain of a single stand-alone bifacial module for three clear days around the summer solstice, fall equinox, and winter solstice. We also investigated the impact of system size on seasonal optimum tilt angles and total energy yield. This paper expands on our prior work and examines the impact of system configuration and size on the sensitivity of the performance to each installation parameter. Moreover, in this paper, we study the annual optimum tilt angle for fixed-tilted systems and its dependence on other parameters by performing annual simulations using a cumulative sky approach for two different sites. Furthermore, it was shown in our previous work [5] that by increasing the size of the bifacial system, the performance decreases. This paper investigates and quantifies the reasons for the performance loss in larger bifacial PV systems to provide a deeper understanding of the mechanisms involved.

II. irradiance Modeling

We modeled the bifacial PV systems using RADIANCE [6], which is a simulation software that computes the radiance profile of physical systems using a backward ray-tracing method. The sky irradiance model used in this study approximates the Perez direct and diffuse model [7]. This model has been used to simulate the bifacial PV systems previously by other researchers and its accuracy has been tested [8, 9]. 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 bifacial ratio of ~90%). NREL's National Solar Radiation Data Base (NSRDB) [10] was used to derive typical meteorological year version 3 (TMY3) weather (hourly) data for Albuquerque, NM (35º N) for global horizontal irradiance (GHI), diffuse horizontal irradiance (DHI) and direct normal irradiance

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(DNI). Solar azimuth and zenith angles (also hourly data) were calculated using Sandia National Laboratories' PV_LIB Toolbox [11].

We considered three south-facing PV system configurations: (i) single module, (ii) a row consisting of five modules (one-row), and (iii) five rows, each with five modules (multi-row), to investigate the impact of the system size and configuration on bifacial gain and energy yield. Since the modeling of the multiple module configurations requires significant computational resources, we made our analysis feasible by considering the performance of only the middle module in each 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 during the solar window from 9 AM to 5 PM for the entire year [12]. Fig. 1 shows the three simulated systems with the representative modules in the multi-module systems indicated by red rectangles.

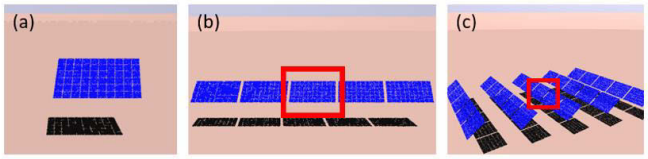

Fig. 1. Three south-facing PV systems consisting of (a) a single module (b) a row of five modules and (c) five rows of five modules each, were simulated to study the impact of the size on the system performance.

Parametric sweeps over three parameters affecting PV system performance were made 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 car-port systems have heights around 3 m. We included three ground materials with different albedos: light 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: the summer solstice, winter solstice, and fall equinox. Sun position for any day of the year is between the sun position on the 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 impact of cloudy weather condition on the system performance. By comparing the GHI values in TMY3 weather data with the GHI data obtained from Ineichen clear sky model [13, 14], we can determine the clearness of sky for specific days. A parameter called clear sky index (K_c) which is measured GHI divided by clear sky GHI indicates the extent to which the sky was clear on a particular day. Fig. 2 shows the comparison of GHI data (TMY3 versus clear sky model) for the clear (a, c, e) and cloudy (b, d, f) days around the summer solstice, fall equinox and winter solstice, respectively. K_c values of close to unity in Fig. 2 (a, c, e) show that the sky on June 20th, September 20th, and December 22nd was clear with a good approximation. However, from Fig. 2 (b, d, f), we see that the sky on June 23rd was partially cloudy, and on September 23rd and December 21st, it was overcast.

To calculate the daily energy yield and bifacial gain in energy (BGE), we used the irradiance data for each of the 60-cells (front and back) 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 (one hour) gives the energy of that particular time period in Watt-hours (Wh). 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. This value shows the energy gain in using bifacial PV system over the equivalent monofacial system (with the same installation parameters). It is important to note that by averaging cell irradiance data, we are neglecting backside non-uniformity [15, 16]. Currently, we are working to improve our model by defining by-pass diodes in the model to account for potential mismatch from the backside irradiance non-uniformity.

III. Impact of Installation Parameters

In this section, we present and compare the impact of installation parameters on energy yield and bifacial gain of the three PV systems discussed in section II for three clear days shown in Fig. 2. The effect of cloudy sky condition (on the optimum tilt angle) will be discussed in section IV.

A. Tilt angle

Due to the ability of absorbing the light from the backside, the seasonal optimum tilt angles for bifacial modules can be different from monofacial modules. In our recent work [5], it was shown that seasonal optimum tilt angles for bifacial systems depend on the time of year and installation parameters. It was shown that for a single bifacial module

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installed in Albuquerque, NM (35° N) with a reasonable clearance (~1 m) from the ground, the seasonal optimum tilt angle is lowest (~5º) for the summer solstice and highest (~65º) for the winter solstice. We also observed that for modules installed closer to the ground, the seasonal optimum tilt angles are usually higher. We will discuss the seasonal and annual fixed optimum tilt angles in section IV in more detail.

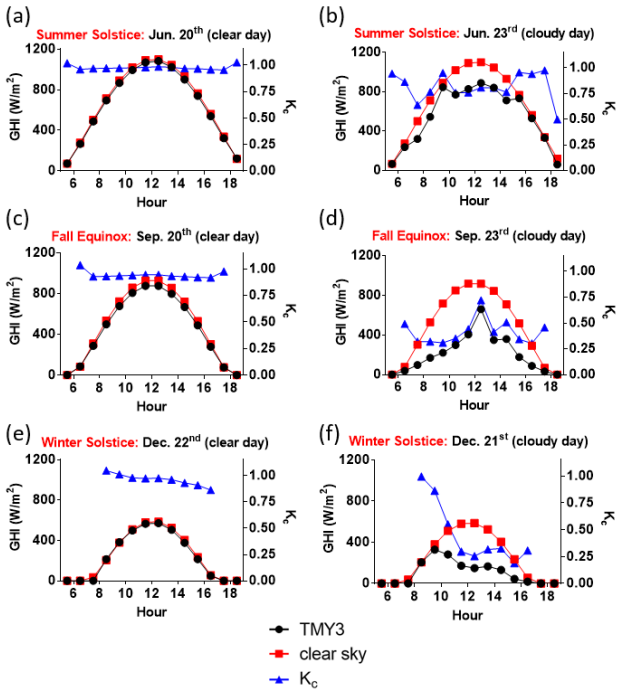

Fig. 2. Comparison of GHI values of TMY3 weather data and Ineichen clear sky model [15, 16] for the six days in the study.

In this section, we investigate the impact of the system size and configuration on the dependence of the performance on the tilt angle. Fig. 3 presents the energy yield as a function of tilt angle for the single module (dotted line), the one-row system (dashed line), and the multi-row (solid line) systems with the albedo of 21% (light soil) and the height of 1.0 m. These plots illustrate that increasing the size of the system, decreases the performance. Fig. 3 (a,b,c) shows that the one-row system produces less energy than the single module and more energy than the multi-row system. We will analyze the different reasons for this decrease in section V.

Another important observation from the Fig. 3 is the anomalous increase (outlined by circles in Fig. 3) in the energy yield and BGE of the multi-row system which occurs at tilt angles of 50º, 65º, and 75º for the summer solstice (Fig. 3 a), fall equinox (Fig. 3 b), and winter solstice (Fig. 3 c), respectively. The increase in the BGE indicates that the backside irradiance at these tilt angles is higher for the multi-row system (compared to other configurations). The only reason which can justify this effect is the reflection of the light from the modules in the back rows which boosts the backside irradiance.

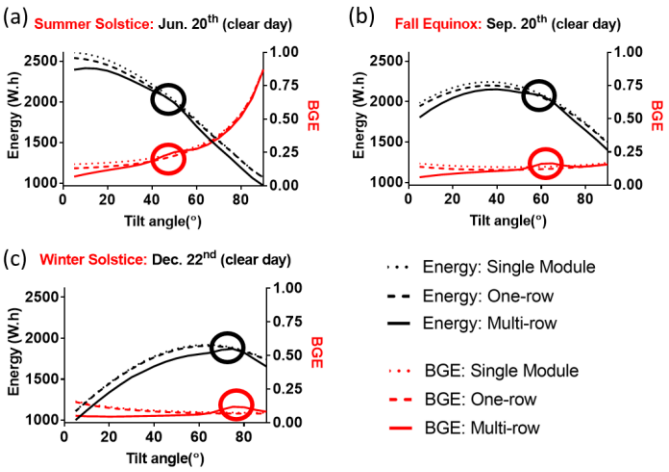

Fig. 3. Energy yield and BGE for the single module, one-row system, and multi-row systems as a function of the tilt angle for the albedo of 21% and height of 1 m for clear days around (a) the summer solstice, (b) fall equinox, (c) winter solstice. The circles are added to the data curves to highlight the anomalous increase in the energy yield.

To investigate and quantify the contribution of the reflection from the back rows, we plotted the backside irradiance of multiple cases for the multi-row system on the winter solstice (Fig. 4). First, we changed the color of all parts of the module (cells, silver contact) to black in our simulations. After simulating the scene, we observed that the backside irradiance decreases but the local maximum at 75° tilt angle still remained (purple diamond curve in Fig. 4); this was because while we turned the color of the module black, we only effectively eliminated the impact of diffuse reflection. However, the specular reflection from the modules which causes glare [17] and increases the backside irradiance was not eliminated. By changing the texture and material properties of the PV modules, we are able to eliminate the specular reflection too. Simulating the new scene confirms that the increase of the backside irradiance in a certain tilt angle was due to the specular reflection from the back rows (black cross curve in Fig. 4) because now we did not observe an irradiance maximum at 75° tilt angle. Fig. 3 shows that the anomalous increase occurs at different tilt angles for different times of the year. For our particular test case, these angles are 50º, 65º, and 75º for the summer solstice, fall equinox, and winter solstice, respectively. However, these angles will also depend on the row spacing and length.

B. Height

The 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 greatly reduced by self-shadowing; by increasing the clearance from the ground, the backside of the module gets more light from both the sky and the ground. We showed in [5] that the energy

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yield and BGE increase as the module installation height increases. However, a saturating effect occurs after certain heights, where the energy yield and BGE do not increase as the installation height increases.

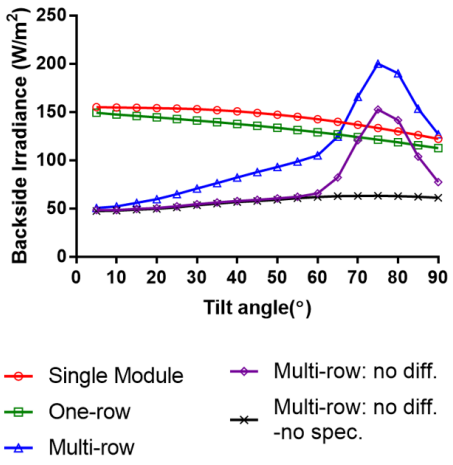

Fig. 4. Backside irradiance for the single module (red circle), one-row (green square), multi-row (blue triangle), multi-row without diffused reflection (purple diamond), and multi-row without diffused and specular reflection (black cross) for albedo of 21% and height of 1 m in winter solstice.

In this section, we study the effect of the system size and how it impacts the system energy yield and BGE for different installation heights. Fig. 5 shows the height dependence data for an albedo of 21% and tilt angles of 5º, 35º, and 65º for the summer solstice, fall equinox, and winter solstice, respectively. These tilt angles are chosen because they are close to the seasonal optimum tilt angles for modules with a reasonable clearance (~1 m) from the ground (As discussed in Section IV, the dependence on the height decreases after a certain height; for clear days, this height value is around 1 m). The data indicate that the rate at which energy yield changes with height for the multi-row system for large installation height values (greater than 1.0 m) is higher compared to the single module and one-row systems, which indicates that the saturation height for this system is greater than the other systems. In this case, increased height is required to reduce the effect of larger shadowing area and to have a larger field view of the unshaded ground. However, due to the limited extent of the multi-row system, results have been impacted by the edge effect at large heights. To mitigate the impact of this effect, a larger number of rows and modules should be used.

C. Albedo

Increasing the reflectivity (albedo) of the ground increases the intensity of the reflected rays reaching the front and back sides of the module and increases the system's performance. However, the contribution of the reflected rays from the ground is larger for the backside. As we showed in [5] for single modules, there is a linear increase in energy yield and BGE as a function of ground albedo. We observed that the slope of the energy yield versus albedo (%) is lower when the module is close to the ground than for modules installed at higher heights. This is due to increased self-shading which reduces ground reflected irradiance's contribution at low ground clearance.

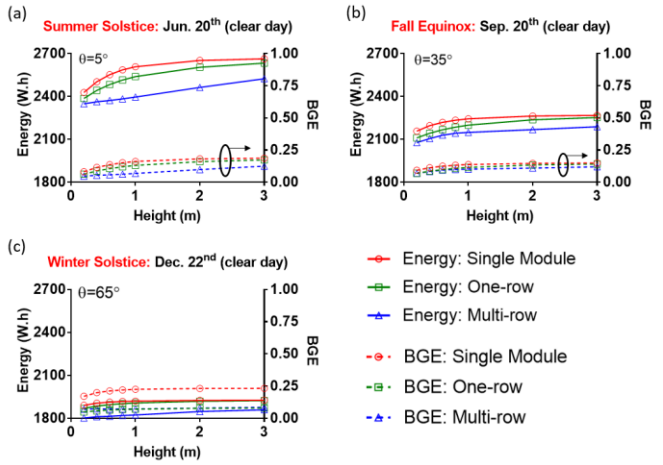

Fig. 5. Energy yield and BGE for the single module, one-row system, and multi-row systems as a function of the height for the albedo of 21% and tilt angles of 5°, 35°, and 65° for clear days around (a) the summer solstice, (b) fall equinox, (c) winter solstice, respectively.

We also investigated how the change in the system size affects the rate at which energy yield changes with albedo. Fig. 6 shows the data for the three configurations for the height of 1.0 m and the tilt angles of 5°, 35°, and 65° for clear days around the (a) summer solstice, (b) fall equinox and (c) winter solstice, respectively. Larger shadowing area due to the multiple numbers of modules reduces the effective albedo in the modules' field of view. Lower slope of the multi-row system in Fig. 6, compared to the one-row and single module systems confirms this fact.

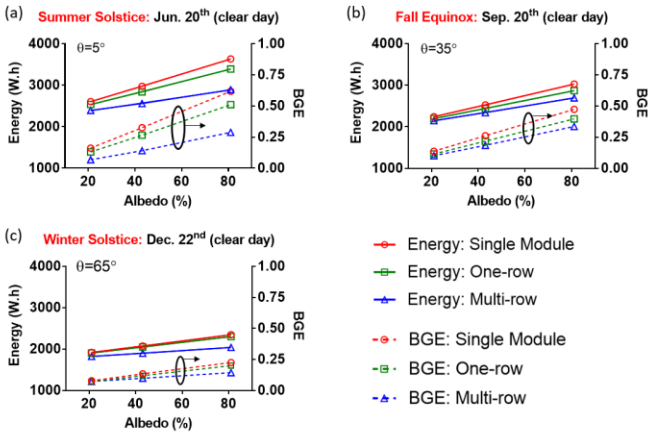

Fig. 6. Energy yield and BGE for the single module, one-row system, and multi-row systems as a function of the albedo for the height of 1 m and tilt angles of 5°, 35°, and 65° for clear days around (a) the summer solstice, (b) fall equinox, (c) winter solstice, respectively.

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IV. OPTIMUM PARAMETERS AND ANNUAL SIMULATIONS

The data analysis presented so far indicates that to achieve the highest energy yield, modules need to be installed over the highest possible albedo and the height should be high enough to minimize the self-shadowing effect. However, the seasonal optimum tilt angles vary as a function of time and the specific conditions at the site. We interpolated the simulation data to get a resolution of one degree for tilt angle and determined the seasonal optimum tilt angle on each day of the simulations for different conditions. Fig. 7 shows the seasonal optimum tilt angle for three different sized bifacial systems (single module, one-row, and multi-row systems) for different heights and albedos and for both clear (Fig. 7 a, c, e) and cloudy (Fig. 7 b, d, f) days around the summer solstice, fall equinox, and winter solstice, respectively. Seasonal optimum tilt angles for monofacial counterparts of bifacial systems were also calculated theoretically [18] and showed on the plots in Fig. 7.

The global tilted irradiance includes direct beam, diffuse sky, and diffuse ground-reflected radiation. Their contributions vary depending on PV orientation, location and weather. Comparing the daily optimum angles for clear days (Fig. 7 a, c, e) with cloudy days (Fig. 7 b, d, f) shows that the optimum tilt angle (for modules not too close to the ground) is lower on cloudy sky conditions for both monofacial and bifacial modules (except for the summer solstice in which the optimum tilt angle is slightly higher (3°-5°) on the cloudy day). For south-facing systems, beam irradiance is so much higher than the other components on clear days and the optimal tilt angle is close to the value that maximizes this irradiance component. However, on cloudy days, the most significant light component received by the modules is the sky diffuse irradiance. By lowering the tilt angle, frontside of the modules see a larger portion of the sky and therefore receive higher sky diffuse irradiance. However, the ability of the bifacial modules to absorb light from the backside as well as frontside, causes them to have higher optimum tilt angle than their monofacial counterparts on cloudy days.

Fig. 7 also shows that for lower module heights when the system size is not large (single module or one-row system), the seasonal optimum tilt angle for bifacial modules is higher. The modules installed close to the ground face large portion of their own shadow and by increasing the tilt angle, the backside of the module receives more light from the ground and the sky and sees less of the dark shadowing area. However, the optimum tilt angle of the monofacial modules is not dependent on the height.

Increasing the albedo of the ground increases the ground reflected irradiance that the modules receive. However, for south-facing tilted modules, the amount of this irradiance component is higher on the backside than the frontside. Plots in Fig. 7 indicate that the higher albedo leads to higher optimum tilt angle for monofacial and bifacial modules (especially in lower height values). Because at higher tilt angles modules receive higher ground reflected irradiance on both frontside and backside.

Another important observation is that, for multi-row bifacial systems, optimum tilt angle can be up to 20º greater than for small-scale bifacial 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. Unlike bifacial modules, the optimum tilt angle of the monofacial modules is not dependent on the size of the system. The data also indicates that the dependence of the optimum tilt angle (slope) on the height decreases as the height increases and after a certain height the optimum tilt angle is approximately constant. For clear days, this height value is around 1.0 m. For cloudy days, it is usually higher (2.0-3.0 m).

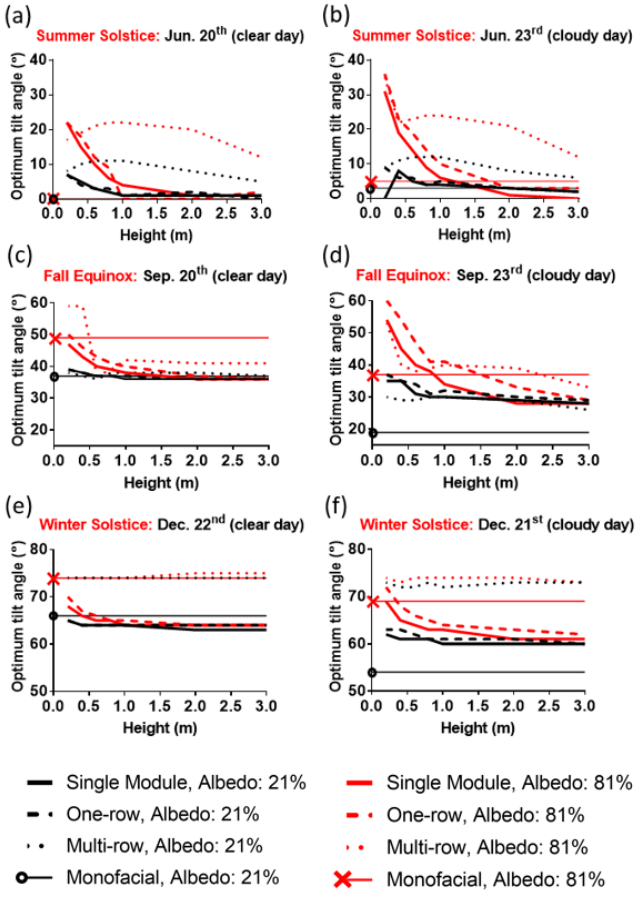

Fig. 7. Seasonal optimum tilt angle as function of height and albedo for clear (a, c, e) and cloudy (b, d, f) days around the summer solstice, fall equinox and winter solstice. Results are depicted for bifacial single module, one-row and multi-row systems and their monofacial counterparts.

Finding the seasonal optimum tilt angle would be beneficial for the systems with a control on adjusting the tilt angle, such as one-axis tracking bifacial systems. A controller can be designed to adjust the tilt angle with respect to the weather condition and the position of the sun. However, for the fixed-

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tilt systems, it is more relevant to perform annual simulations in order to find the annual fixed optimum tilt angle for the system. Using cumulative sky approach [19] within RADIANCE, we conducted annual simulations to find the energy yield of the systems. To study the dependence of the systems' performance on the latitude and climate type, two different locations were chosen (Table 1). Climate types are according to the Köppen climate classification. [20]

TABLE 1
CHARACTERISTICS OF THE SITES IN THE SIMULATIONS

Location	Latitude	Climate Type
Albuquerque, NM	35.1º	BSk: cold semi-arid climate
Anchorage, AK	61.2º	Dfc: Subarctic climate

Fig. 8 (a) and Fig. 8 (b) show the annual optimum tilt angle for the single module and multi-row systems in Albuquerque, NM, and Anchorage, AK, respectively. A clear difference is observable between the optimum tilt angles of two different sized systems. For both locations, the dependence of the optimum tilt angle on the height is negligible for heights larger than one meter. In Albuquerque, the optimum tilt angle for single module system is ~35º (for heights higher than one meter) which is the latitude of the site. This analysis shows that the optimum tilt angle of a bifacial single module would be similar to the monofacial equivalent system in Albuquerque. However, the multi-row system which consists of 25 modules have higher optimum tilt angle and is dependent on the albedo. For albedos of 21%, and 81%, the optimum tilt angle is ~36º and 40º, respectively. For grounds with high albedo, the tilt angle needs to higher because of the reasons explained earlier in this section. For Anchorage, the trend is opposite. Multi-row systems have lower optimum tilt angles than the single modules. The reason is that the row spacing for these systems are chosen to be equal to the row spacing of the systems in Albuquerque. This means that the modules are not shadow-free for the entire year and they experience partial shadowing on the frontside, especially in the winter (in order to have a shadow-free system for the entire the year in Anchorage, the row spacing should be very high (~12 m) which is not practical and economical). Lower tilted modules cast a shorter shadow on the ground and reduce the frontside shading which is why the optimum tilt angle for larger systems is lower than the single module systems.

V. ANALYZING THE REASONS OF REDUCTION IN THE PERFORMANCE OF LARGE SCALE SYSTEMS

Using the optimum tilt angle for the module height of 1.0 m and albedo of 21%, we compared the performance of the three PV systems for Albuquerque, NM. The data is shown in Fig. 9. Monofacial data for the same height and albedo (for single module system) is also shown in the figure. The data indicates that by increasing the number of modules, energy yield decreases significantly. The middle module in the multi-row system has about 7% lower energy yield than the single module system on the summer solstice. This value for fall equinox and winter solstice is about 4% and 3%, respectively. Note that in all the 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 PV arrays can have up to 14% lower performance compared to single module systems. Fig. 9 also shows that highest bifacial gain is for the single module system and drops as the system size gets larger.

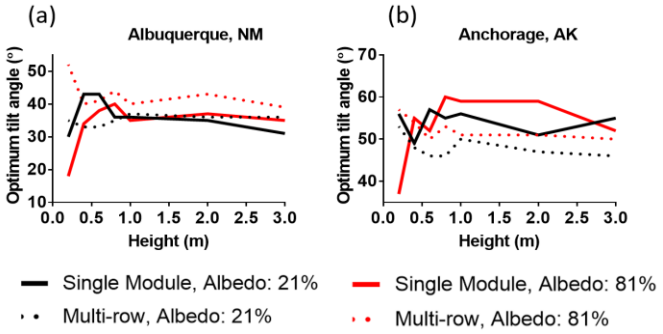

Fig. 8. Annual optimum tilt angle for systems in (a) Albuquerque, NM and (b) Anchorage, AK.

The decrease in the performance of the larger system can be because of various reasons. First, larger systems cast larger shadows on the ground and it reduces the backside irradiance and hence, the total performance of the system. The second reason is the blocking of the direct and diffuse irradiance by front and back rows of the module. As mentioned in section II, the spacing between the rows is large enough and ensures that the modules are shadow free during the solar window from 9 AM to 5 PM the entire year. This guarantees that the there is no direct blocking of the sunlight onto the modules, and the modules can only block diffuse and reflected rays from the ground. Quantifying the losses due to these reasons requires decoupling the shadowing and blocking effects. To do so, we conducted a few more simulations for Sep. 20th. First, we mapped the shadow pattern of the multi-row system onto the ground while simulating the scene for only a single module (Fig. 10). This eliminates the blocking effect of the front and back rows while keeping the shadowing effect unchanged. Subtracting the results of the multi-row system from the results of this simulation gives us the loss due to the horizon blocking. However, as we saw before in section III (A), reflection from the surrounding modules (especially the back row) would increase the irradiance to some extent. To account for this effect, we simulated another multi-row scene with non-reflective (black and textured) modules. Table 2 shows the results of the simulations for the different scenes on Sep. 20th (with the same installation parameters of the height of 1.0 m, albedo of 21%, and the tilt angle of 35°).

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The difference in the performances of the scenes 1 and 2 (95 Wh) is the total loss in the energy yield of the middle module in the multi-row system, compared to a single module. The difference between the daily energy yield of the scenes 2 and 3 (34Wh) represents the energy gain of the multi-row system due to the reflection from the back-row modules. The difference between the performance of the scenes 3 and 4 shows the horizon blocking effect of the surrounding modules (45 Wh). This analysis shows that while the multi-row system produces 34 Wh more energy than the single module due to the reflection from the modules in the back row, it generates 45 Wh, and 85 Wh less energy due to the horizon blocking and shadowing effects, respectively (which results in a total of 95 Wh lower energy yield than the single module system).

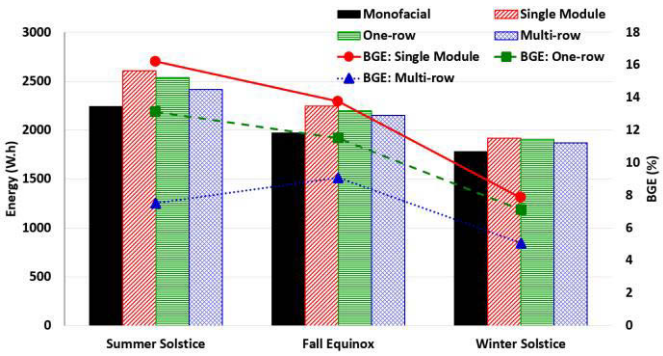

Fig. 9. Energy yield and BGE of the single module, one-row and multi-row PV systems for optimum tilt angle at the module height of 1 m and albedo of 21% for clear days on the summer solstice, fall equinox and winter solstice.

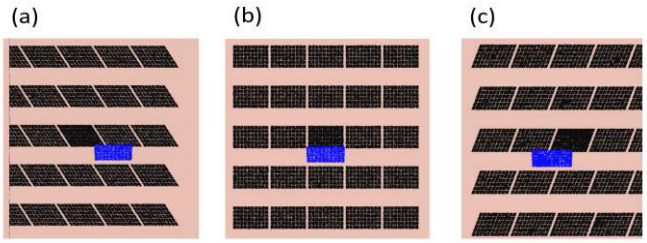

Fig. 10. Single module with mapped shadow pattern of the multi-row system on the ground at (a) 10 am, (b) 12 pm, and (c) 2 pm.

TABLE 2
ENERGY YIELD OF THE FOUR SIMULATED SCENES

Scene	Daily Energy Yield (Wh)
1. single module system	2244
2. multi-row system	2149
3. multi-row system- no reflection	2115
4. single module- with mapped shadow	2160

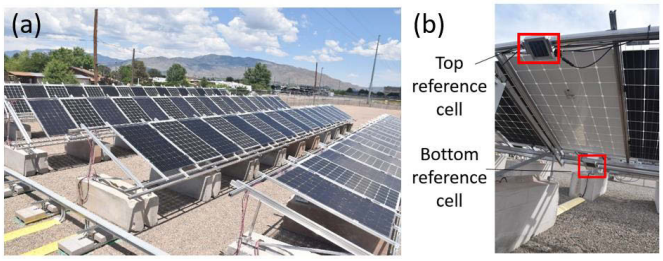

Fig. 11. (a) Sandia's fixed-tilt string-level arrays. (b) Each row has two backside reference cells (top and bottom).

VI. MODEL VALIDATION

To validate our RADIANCE model, we used it to simulate fixed-tilt string-level bifacial arrays at Sandia National Laboratories (Sandia). Fig. 11 (a) 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 also has three reference cells near the middle of the row: one for front and two for the back side. Backside reference cells are installed on top and bottom of the middle module in the row (Fig. 11 b). Our simulations also included the concrete blocks used for the array footings.

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. 12 and Fig. 13 compare measured and simulated data for frontside and backside irradiance respectively. 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 (Fig. 13), 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 (Fig. 13 a to Fig. 13 d), because modules receive more uniform irradiance from the sky than the ground. The mismatch between the measured and simulated data may be due to the optical properties of the materials set in the simulations.

VII. CONCLUSION

We performed a set of RADIANCE simulations to study the effect of tilt angle, module height above the ground, albedo, and size of the system on the performance of south-facing bifacial PV systems. We showed the effect of installation parameters on energy yield and bifacial gain for representative days around the summer solstice, fall equinox and winter solstice. We found that modules installed at the highest possible albedo with high enough height, have higher production. The dependence of the system's energy yield on the albedo is linear with a good approximation. However, we observe a saturating increase in the dependence of the energy yield on the height. Unlike albedo and the height, the

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dependence of the system's performance on the tilt angle is more complicated. Seasonal optimum tilt angles are dependent on other parameters such as height, albedo, the size of the system, and time of the year and are usually higher for modules installed closer to the ground.

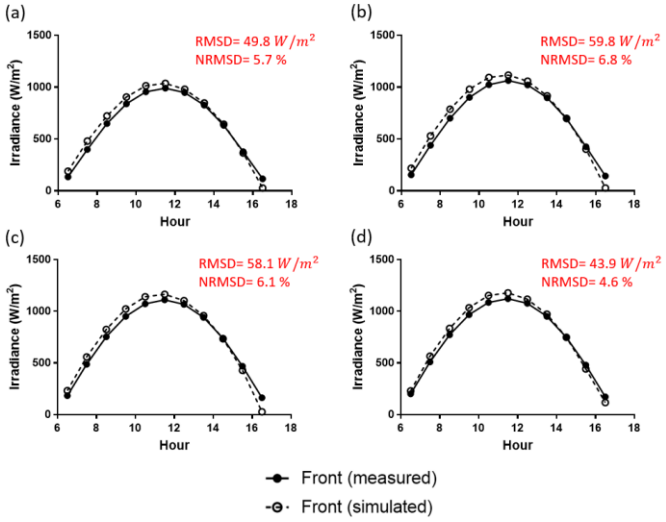

Fig. 12. Simulated versus measured frontside irradiance for (a) first row (15°), (b) second row (25°), (c) third row (35°), and (d) fourth row (45°) of Sandia's fixed-tilt string-level arrays.

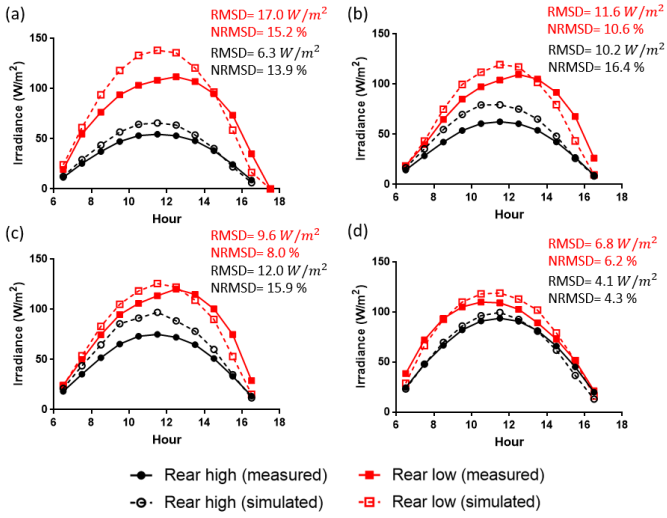

Fig. 13. Simulated versus measured backside irradiance for (a) first row (15°), (b) second row (25°), (c) third row (35°), and (d) fourth row (45°) of Sandia's fixed-tilt string-level arrays.

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, south-facing bifacial systems, the 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 center module in a large array can decrease up to 7% (relative to single module system) with a ground albedo of 21%. We investigated and quantified the different reasons for this loss and found that the larger shadowing area on the ground (due to the larger number of modules) plays the most important role in the decrease in the performance of larger systems. Blocking of the diffuse sunlight by the surrounding modules is another reason that the large systems perform worse.

We also modeled 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.

Future work will examine the additional installation parameter of system azimuth. As azimuth deviates from south-facing, BGE increases significantly while energy yields tend to decrease. One exception may be for vertical bifacial arrays. Nevertheless, when site parameters (e.g., building orientation) prevents true south facing designs, bifacial PV may provide additional yield benefits over monofacial PV modules.

VIII. ACKNOWLEDGEMENTS

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy under contract DE-NA0003525. The project is funded by the U.S. Department of Energy SunShot National Laboratory Multiyear Partnership (SuNLaMP) – Photovoltaic Subprogram grant #: 1625350.

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