A Comparison Study of the Performance of South/North-facing vs East/West-facing Bifacial Modules under Shading Conditions

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***Abstract* — Horizon obstructions can decrease the diffuse and direct light received by photovoltaic (PV) modules. In this paper, we compare the performances of the two bifacial PV system orientations: optimally tilted facing south/north ($Bi_{S/N}$), and vertically installed facing east/west ($Bi_{E/W}$) under no-shading and shading conditions. We considered multiple locations with different latitudes and weather types and observed that without any horizon obstructions, $Bi_{S/N}$ outperforms $Bi_{E/W}$ for most locations. However, certain types of obstructions cause $Bi_{E/W}$ to have higher energy yield than $Bi_{S/N}$. For sunnier and lower latitude locations such as Albuquerque, NM, a very large obstruction at south causes this result. On the other hand, for higher latitude locations (e.g. Anchorage, AK), much smaller obstructions at south is enough to have higher energy yield for $Bi_{E/W}$ than $Bi_{S/N}$. Under certain shading conditions $Bi_{E/W}$ produces up to 75 kWh/year more energy than $Bi_{S/N}$.**

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

I. INTRODUCTION

Because of a fast-growing commercialization of the bifacial photovoltaic (PV) technology, a precise study of different parameters involved in the installation of bifacial PV systems is crucial so that predictions about annual energy yield are accurately predicted. Effect of parameters such as albedo, tilt angle, height, and size on the performance of bifacial PV systems has been studied rigorously and the optimum parameters have been obtained for different conditions [1-3]. Furthermore, the performance of different installation configurations for bifacial PV systems such as vertical east/west-facing modules has been compared to the performance of traditional monofacial PV systems and has been shown that depending on the latitude, diffuse fraction and the albedo, vertical bifacial PV systems may have higher energy yield than south-facing monofacial PV systems [4].

In this paper we compare the performance of two popular installation configurations for bifacial modules:

1) Optimally tilted south/north-facing module ($Bi_{S/N}$)
2) Vertical east/west-facing module ($Bi_{E/W}$)

In [1], it has been shown that for a reasonable clearance from the ground (one meter), $Bi_{S/N}$ always performs better than the $Bi_{E/W}$. However, these results are based on an assumption that there is no direct and diffuse shading due to the surrounding objects. Presence of such objects may block the direct and diffuse light from getting absorbed by the modules and reduce their performance. In this paper, we study the effect of surrounding objects on annual energy yield of both $Bi_{S/N}$ and $Bi_{E/W}$ and compare their performance under different shading conditions. We seek to determine that under what shading conditions $Bi_{E/W}$ will outperform the $Bi_{S/N}$.

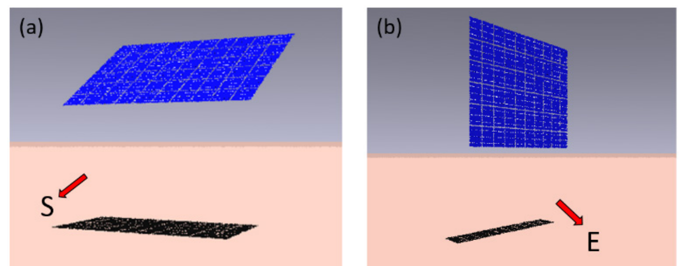

Fig. 1. Optimally tilted south/north-facing module (a), and vertical east/west-facing module (b) scenes rendered in RADIANCE.

II. SHADE-FREE SIMULATIONS

Before studying the impact of surrounding objects on the performance of bifacial PV modules, the performance of $Bi_{S/N}$ and $Bi_{E/W}$ without any objects in their surroundings are modeled for multiple locations listed in Table 1.

TABLE 1
CHARACTERISTICS OF THE SITES IN THE SIMULATIONS

Location	Latitude	Longitude
Singapore, Singapore	1.17º N	103.50º E
Hawaii, USA	19.73º N	156.05º W
Cairo, Egypt	30.04º N	31.24º E
Albuquerque, USA	35.09º N	106.61º W
Beijing, China	39.90º N	116.41º E
Paris, France	48.86º N	2.35º E
Anchorage, USA	61.22º N	149.90º W

For both cases of $Bi_{S/N}$ and $Bi_{E/W}$, we simulate a single bifacial module with a height of 1 m above the ground and albedo of 21% (light soil). RADIANCE [5] software is used to perform the simulations. To perform annual simulations, cumulative sky approach [6] is used within RADIANCE. In simulations, we used the dimensions and electrical characteristics of Prism Solar's Bi60-368BSTC bifacial module with front and backside efficiencies of 17.4% and 15.6%, respectively. The optimum tilt angle for south/north-facing modules depends on multiple parameters such as height, albedo of the ground, and size of the system. However, a good approximation of optimum tilt angle for a reasonable height from the ground (1 m) and albedo (21 %) is the latitude of the location. [3] Therefore, in the simulations, we set the tilt angle of $Bi_{S/N}$ to be equal to site's latitude.

Fig. 2 shows the results of RADIANCE simulations for locations listed in Table 1. We observe that for all locations, except Singapore, the $Bi_{S/N}$ performs better than $Bi_{E/W}$. Because of a very low latitude of Singapore (1.17º) and hence a very low tilt angle for $Bi_{S/N}$, performance of this system is affected adversely by self-shading and therefore the yield of $Bi_{S/N}$ is slightly lower than $Bi_{E/W}$ for Singapore. Also, that for high latitudes, the energy yield of $Bi_{S/N}$ and $Bi_{E/W}$ as well as their difference is lower, because global horizontal irradiance is usually lower for the high latitude locations compared to sunnier locations with lower latitude.

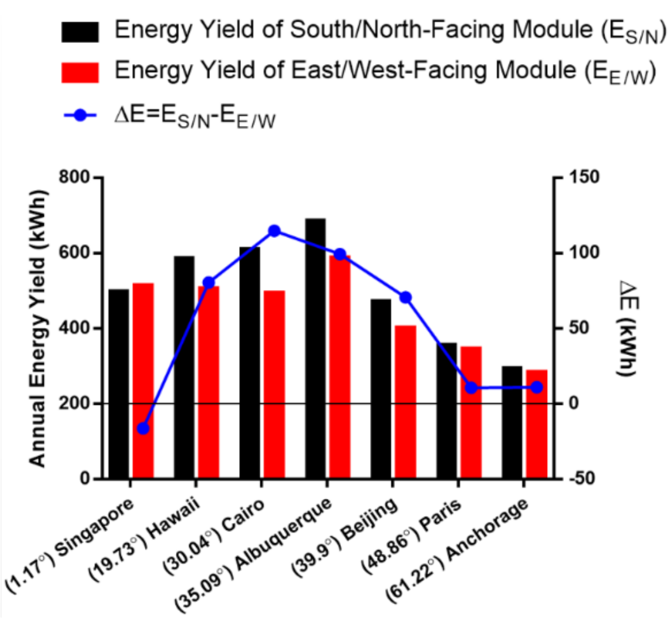

Fig. 2. Comparison of the performances of $Bi_{S/N}$ and $Bi_{E/W}$ PV systems indicates that for systems installed in Singapore yield of $Bi_{S/N}$ is slightly lower than $Bi_{E/W}$ while for all other locations the $Bi_{S/N}$ systems have higher yield than $Bi_{E/W}$.

III. Effect of Surrounding Obstructions

Presence of surrounding obstructions can decrease the field view of the PV module to the sky and hence decrease its annual energy yield. Also, the obstructions may occasionally block the direct light from the sun which has a significant impact on the PV system performance.

Using the RADIANCE simulation tool, we calculate the annual energy loss due to horizon obstructions. We assume to have cubic shape obstructions which can resemble surrounding buildings. We characterize obstructions with four parameters of height (h), width (w), azimuth angle (φ), and distance from the module (r) as shown in Fig. 3. The range of these parameters are shown on Fig. 3 as well. A parametric sweep study over these parameters is performed for both $Bi_{S/N}$ and $Bi_{E/W}$ and the energy loss due to each type of obstruction was calculated. Step size in the sweep for parameters h, w, φ, and r was 5 m, 10 m, 30°, and 10 m, respectively. We chose the material of the obstruction to be concrete which exhibits surface reflection of 28%.

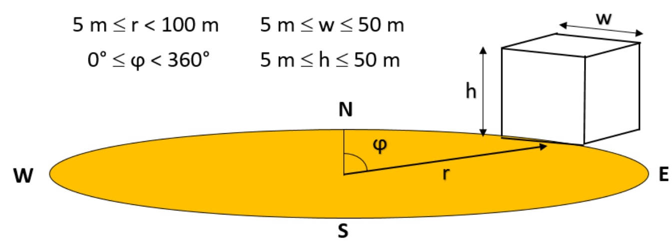

Fig. 3. Schematic of the horizon obstruction in the simulations and the range of the parameters in the sweep.

As discussed in section I, we seek to find the characteristics of the obstructions whose presence cause $Bi_{E/W}$ to perform better than $Bi_{S/N}$. We performed this analysis for two locations of Albuquerque, NM and Anchorage, AK. As shown in Fig. 2, these two locations represent two extremes in terms of the total energy yield and weather types.

To identify such obstructions, we used J48 classification algorithm [7] in Weka; a data mining software [8]. J48 is an algorithm which generates pruned/unpruned decision trees. Our features are the obstruction's four parameters (h, w, φ, and r) and the class labels are:

Y: The energy yield of $Bi_{E/W}$ is more than the $Bi_{S/N}$

N: The energy yield of $Bi_{E/W}$ is less than the $Bi_{S/N}$

We generated heavily pruned decision trees for both locations and identified the Y class labels in the leaves of the tree. The accuracy of the classifiers are 99.3% and 97.8% for Albuquerque, NM and Anchorage, AK, respectively. Fig. 4 (a) and (b) show the characteristics (feature range) of the obstruction with class label Y (higher energy yield for $Bi_{E/W}$ than for $Bi_{S/N}$) for Albuquerque, NM and Anchorage, AK, respectively.

From Fig. 4 (a) we observe that we can classify the obstructions which cause $Bi_{E/W}$ to perform better than $Bi_{S/N}$ in Albuquerque, NM into three categories. Investigating the characteristics of these obstructions reveals that all of them correspond to large obstructions in south (120° < φ < 210°) which are also very close to the module (r ≤15). Having such obstructions block the direct and diffuse light on the modules. However, $Bi_{S/N}$ module is impacted more by the shading. The main irradiance source of the $Bi_{S/N}$ module is from its front side and if that view of the module is blocked then its performance will be decreased significantly. $Bi_{E/W}$ performs better under these shading conditions because it doesn't receive much irradiance from south and blocking that view would have less impact on $Bi_{E/W}$ modules. To compare the size of the obstruction from the view of the module, elevation angle (El_{obs}) and azimuth span angle (Az_{obs}) of the obstruction with respect to the bottom of the module were calculated using (1) and (2). Schematic of the obstruction with defined parameters of El_{obs} and Az_{obs} are shown in Fig. 5. Note that the elevation angle is calculated from the bottom of the modules which is one meter above the ground and it is reflected in (1). These parameters are calculated for the middle cell at the bottom of the module. For other cells, the El_{obs} and Az_{obs} parameters will be slightly different.

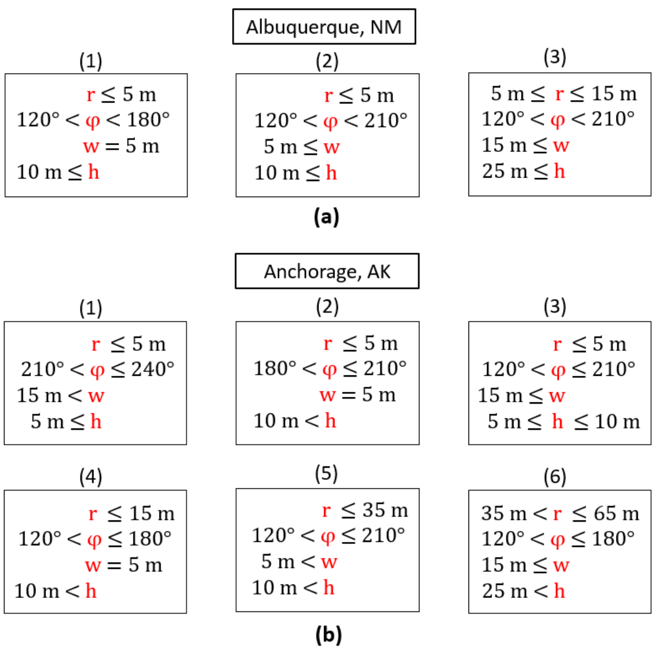

Fig. 4. Characteristics of the obstruction which cause $Bi_{E/W}$ system to have higher energy yield than $Bi_{S/N}$ for Albuquerque, NM (a) and Anchorage, AK (b).

$$El_{obs} = Arc\tan(\frac{h-1}{r}) \tag{1}$$

$$Az_{obs} = 2Arc\tan(\frac{W}{2r}) \tag{2}$$

Fig. 6 shows examples of the obstruction from the three categories shown in Fig. 4 (a). These examples of obstructions have the minimum elevation angle and azimuth span angle and the median azimuth angle from the ranges provided in Fig. 4 (a). These obstructions are plotted in the 2-D plane of the sky dome along with the sun paths on the summer solstice, and winter solstice for Albuquerque, NM. Any obstruction with higher elevation angle or azimuth span angle will cause $Bi_{E/W}$ to have higher energy yield than $Bi_{S/N}$. As discussed before, we can observe from Fig. 6 that these obstructions are very large and block the sun path around the late morning and noon for large time period of the year which means the modules experience heavy direct shading. However, as mentioned before $Bi_{S/N}$ would be impacted more by this shading since it is facing the obstruction directly and large portion of its front side irradiance is blocked by the obstruction. This finding may not be very valuable, since it is evident that the modules shouldn't be installed close to large obstructions. We are more interested in the shading conditions which may not seem evident.

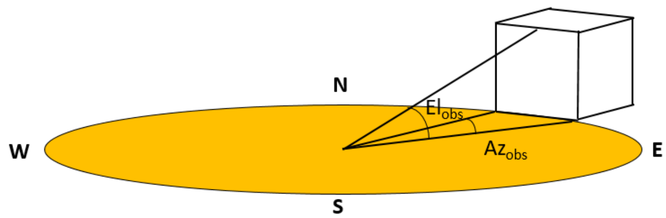

Fig. 5. Schematic of the obstruction with defined parameters of El_{obs} and Az_{obs}.

Following the same procedure, we show examples of the obstruction from the six categories in Fig. 4 (b) for Anchorage, AK in Fig. 7. These obstructions have the minimum elevation angle and azimuth span angle and the median azimuth angle from the ranges provided in Fig. 4 (b). Note that the categories shown in Fig. 4 (b) overlap with each other for certain range of the obstruction characteristics.

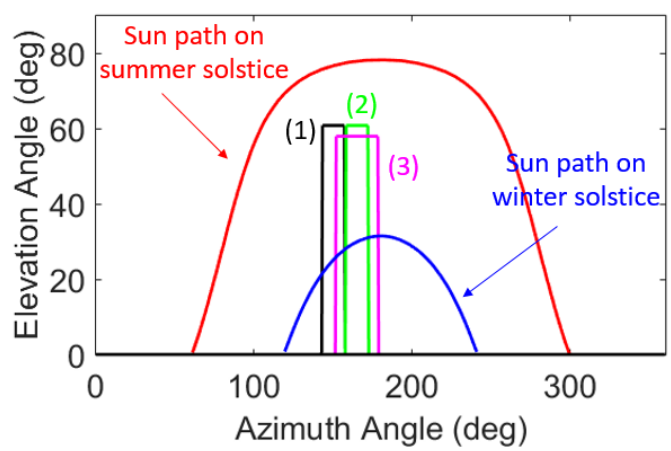

Fig. 6. Examples of obstructions from three categories in Fig. 4 (b) (Albuquerque). Any obstruction larger than shown obstructions will result in higher energy yield for $Bi_{E/W}$ than $Bi_{S/N}$.

Similar to Fig. 6, we observe that three examples of (1) - (3) in Fig. 7 are very large obstructions at south and evident that $Bi_{S/N}$ would perform poorly if installed facing them. However, comparing Fig. 7 with Fig. 6, we see that so much smaller horizon obstructions can also cause $Bi_{E/W}$ to have higher energy yield than $Bi_{S/N}$ (examples (4) - (6) in Fig. 7). This can be explained by two reasons. First, as we see from Fig. 2, energy yield difference between the $Bi_{E/W}$ and $Bi_{S/N}$ modules is smaller for higher latitudes locations such as Anchorage and having a much smaller obstruction at south would be enough to cause $Bi_{S/N}$ to have higher loss than $Bi_{E/W}$. The second reason is that as shown in Fig. 7, the elevation angle of the sun is lower for Anchorage than Albuquerque and having an even small obstruction can cause direct shading on $Bi_{S/N}$ module for long period throughout the year.

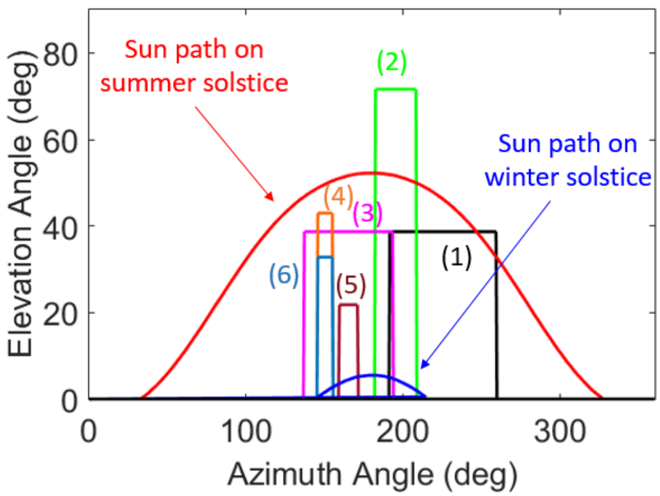

Fig. 7. Examples of obstructions from six categories in Fig. 4 (b) (Anchorage). Any obstruction larger than shown obstructions will result in higher energy yield for $Bi_{E/W}$ than $Bi_{S/N}$.

Analyzing the energy loss due to the obstructions shown in Fig. 4 (b) indicates that having such obstructions cause $Bi_{E/W}$ system to outperform $Bi_{S/N}$ by up to 75 kWh/year. This analysis suggests that in higher latitude locations, for certain obstruction types, $Bi_{E/W}$ becomes a better option in terms of high annual energy yield.

In this work, we use annual energy yield as a metric to compare bifacial PV systems. However, $Bi_{E/W}$ produces more energy earlier and later in the day which can be more valuable PV energy production in some locations where energy demand peaks in the morning and evenings. Also, there is a special interest in vertical modules in some locations due to their lower soiling and shading loss than tilted modules. [9-11]

IV. Conclusion

Using RADIANCE ray-tracing software, we modeled a bifacial PV module with two orientations: optimally tilted facing south/north ($Bi_{S/N}$) and vertically installed facing east/west ($Bi_{E/W}$). We compared the annual energy yield of the two systems under no-shading condition for different locations and observed that $Bi_{S/N}$ module had higher energy yield than $Bi_{E/W}$ for all locations except for Singapore (latitude of 1.17º) for which $Bi_{E/W}$ outperformed $Bi_{S/N}$. Due to very low tilt angle of the module, self-shading effect was very large for this location.

Next, we investigated the performance of two systems under shading conditions caused by horizon obstructions. We assume cubic shape obstruction to simulate buildings around the modules especially in urban areas. We considered two locations of Albuquerque, NM and Anchorage, AK for this purpose. We found out that for a sunnier and lower latitude location such as Albuquerque, only very large obstruction (with respect to the module's view) can cause $Bi_{E/W}$ to have higher energy yield than $Bi_{S/N}$. On the other hand, for a higher latitude location such as Anchorage, even with much smaller obstructions (elevation angle of ~20°) $Bi_{E/W}$ modules performs better than $Bi_{S/N}$ and this amount can be up to 75 kWh/year for certain shading cases. In this study we didn't consider different losses such as soiling and shading that PV system may experience. It has been shown that vertical modules have much less soiling and shading losses which means if under some conditions, $Bi_{E/W}$ and $Bi_{S/N}$ receive same amount of irradiance, $Bi_{E/W}$ would be better option because it will have lower soiling and shading losses.

As next steps, more realistic horizon obstructions such as real buildings will be modeled and the performance of PV system will be tested under those conditions. We will also use field measurement data to validate our findings.

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