SAND2017-6464C

Outdoor Field Performance from Bifacial Photovoltaic Modules and Systems

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Abstract — **Bifacial PV modules and systems deliver more energy than equivalent monofacial modules in the same orientation. However, bifacial performance models are not yet mature enough to predict bifacial gains for all system configurations. Field performance data is needed at a variety of different spatial scales in order to improve and validate these models. This paper reports on a number of bifacial field installations intended for this purpose.**

I. Introduction

Bifacial photovoltaic (PV) cells, modules, and systems offer a rapid pathway to significantly decreased levelized cost of energy compared with conventional monofacial PV modules. Unlike increasing cell efficiency, which takes many years to bring laboratory innovations to the production line, bifacial PV technology is available today but is underutilized. One major barrier to broader use of bifacial PV modules and systems is a lack of knowledge and experience with system designs that take advantage of the specific features of bifacial cells. Bifacial system performance cannot be predicted with confidence using current PV performance modeling applications because these tools assume that PV modules are illuminated on only one side.

Analytic and empirical studies have shown that use of bifacial modules can potentially increase system yield by at least 10% over a fixed latitude tilt monofacial array, and increased yield can be much higher under certain conditions [1-2]. The bifacial benefit varies with tilt angle, module height above array base, reflectivity (albedo) of the array base, and other factors that influence the total amount of light reaching both sides of the PV cells. However, the sensitivity to these parameters is complex and as system size and ground coverage ratio increases, bifacial gains suffer as the array increasingly covers the ground with shadows and less light is available to the back of the modules.

In order to better understand the factors that affect bifacial PV system performance Sandia National Laboratories (Sandia), the National Renewable Energy Laboratory and the University of Iowa have teamed on a three-year research project aimed at better understanding the actual performance potential of bifacial PV systems.

The project aims to achieve the following three objectives:

1. Obtain field performance data from bifacial modules, strings, and arrays in a variety of orientations and environments.
2. Develop and standardize bifacial module rating methodology
3. Develop and validate bifacial performance models that can be used to inform bifacial array designs.

This paper describes the results obtained from the first objective in the first half of the project period. Other papers that describe results related to the second and third objectives are presented in other sessions [3-6].

II. Bifacial Field Testing

Sandia has built a number of testbeds using bifacial PV modules to obtain performance data in different configurations. In most of these testbeds we have included monofacial modules of the same size as comparisons. The following bifacial testbeds have been developed:

- Single module IV tracing at different tilts and heights
- Single module DC monitoring on microinverters at five different orientations (three different climate sites).
- String-level DC performance at different tilt angles.
- Bifacial DC string performance on single axis trackers.
- Bifacial DC string performance on two-axis trackers.

A. Single module IV tracing at different tilts and heights

Sandia built a rack that fits four PV modules in landscape and can be easily adjusted in height above ground and tilt angle. IV curves on each of the four modules are measured using a multitracer. Irradiance is measured in two locations on the front side and three locations on the back side. IV curves are being measured at 5 minute intervals. Fig. 1 shows the setup.

Fig 1. Sandia's adjustable, single modules IV curve rack in Albuquerque, NM. Two bifacial modules are on the right and two monofacial modules are on the left.

B. Single module monitoring on microinverters at five different orientations.

A second test system is comprised of 16 bifacial and 16 monofacial modules divided into five different configurations that vary tilt and azimuth angles as well as ground reflectivity. Fig. 2 shows the installed system. Table 1 describes the five different configurations. Copies of this system are also installed in Nevada and Vermont. These systems are part of a project at the Regional Test Centers being performed with Prism Solar.

Fig. 2. Bifacial and monofacial modules at five different orientations. Two of the arrays are installed over white rock to enhance back side ground reflections.

Table 1: Orientation and ground surface of test modules.

Label	**Orientation**		**Ground Surface**
	Tilt	**Azimuth**	
S15Wht	15˚	180˚ (South)	White gravel
W15Wht	15˚	270˚ (West)	White gravel
S30Nat	30˚	180˚ (South)	Natural
S90	90˚	180˚ (South)	Natural
W90	90˚	270˚ (West)	Natural

C. String-level performance at different fixed tilt angles

This system is aimed at learning how bifacial modules behave in a series string. Sandia built four rows of racking, each at a different tilt angle (45˚, 35˚, 25˚, 15˚) (Fig 3). Each row has two strings of eight modules which are alternated. Two rows used Sunpreme bifacial modules and two used Prism Solar bifacial modules. Monofacial modules from SolarWorld were used.

Fig. 3. Fixed-tilt, string level bifacial testbed at Sandia.

D. String-level performance on single axis trackers

Sandia has also installed two rows of single axis trackers designed to hold four strings of bifacial modules (Fig. 4). Currently, two strings of bifacial modules have been installed. The tracker movement is controlled by light sensors, time of day, and control parameters set by the operator rather than sun position.

Fig. 4. Single axis tracker for bifacial modules being constructed at Sandia.

E. Bifacial string performance on two-axis trackers

As part of the Regional Test Center program, two 2-axis trackers from All Earth Renewables have been installed in Vermont, each holding two strings (one of bifacial modules and one of monofacial modules) (Fig. 5). DC voltage and current is measured on each string.

Fig. 5. Two-axis trackers with bifacial modules at the Vermont Regional Test Center.

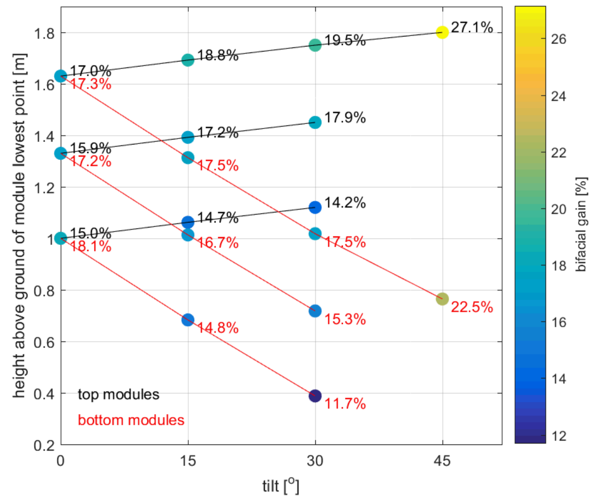

Fig. 6. Single module bifacial gains measured as a function of tilt angle and height of module bottom edge off ground.

III. Preliminary Results

All of the test beds described above have been collecting data and some preliminary results are shared below. Instantaneous bifacial gain at time t, $BG_i(t)$ is defined here as:

$$BG_i(t) = 100\% \times \left(\frac{P_{bifacial}(t) \,/\, Pmp_{bifacial}}{P_{monofacial}(t) \,/\, Pmp_{monofacial}} - 1\right)$$

where $P_{bifacial}$ and $P_{monofacial}$ are measured power values and $Pmp_{bifaical}$ and $Pmp_{monofacial}$ are front side power ratings measured on a flash tester at STC with the back of the bifacial module covered with an opaque material. An integrated bifacial gain in energy, BG_E (for example, one month) can be calculated as:

$$BG_E = 100\% \times \left(\frac{\sum_{1\,month} P_{bifacial} \,/\, Pmp_{bifacial}}{\sum_{1\,month} P_{monofacial} \,/\, Pmp_{monofacial}} - 1\right)$$

A. Single module IV tracing at different tilts and heights

The adjustable rack with four modules was set up to measure IV curves at specific tilt angles and orientations. It was moved every 1-2 weeks over several months. Figure 6 shows bifacial gains measured as a function of tilt angle and height above ground. When tilted, bifacial gains increase with module height. Bifacial gain seems to have a weak sensitivity to tilt angle, except when transitioning between 30˚ and 45˚ tilt. The high bifacial gains seen for 45˚ are enhanced due these measurements being made in the summer when the sun rises and sets well north of east and west, respectively. This results in direct sunlight on back of modules. In addition, higher sun elevation in the summer results in smaller shadows on the ground at midday, increasing bifacial gains.

B. Single module monitoring on microinverters at five different orientations.

Fig. 7 shows example results from the single module monitoring on microinverters at five different orientations [7]. This work was done in partnership with Prism Solar and used their bifacial modules. In every case, bifacial output is greater than the monofacial in the same orientation (Fig. 8). The west-facing vertical bifacial modules produced more energy than the latitude-tilt monofacial modules. During the day bifacial gains are greatest when the angle of incidence on the array is large. This indicates that bifacial module advantages are greatest for non-optimal, monofacial array orientations. However, total energy is typically lower.

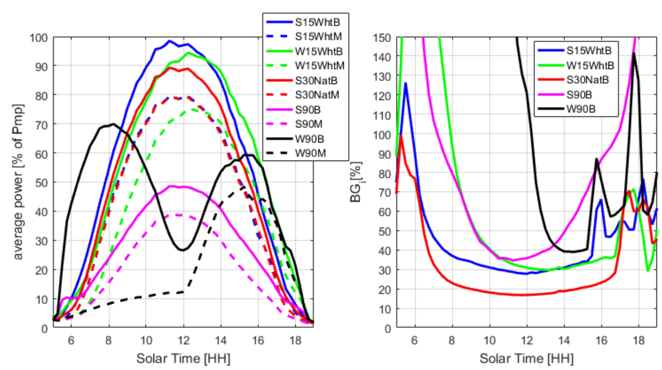

Fig. 7. Left: Average power output, Right: bifacial gains over six months from the bifacial and monofacial modules on microinverters.

Fig 8. shows that annual bifacial gains for the W-facing vertical modules can exceed 100%. This is because it is always cooler in the mornings in NM when the W-facing bifacial module is illuminated on the backside. The cooler temps result in increases in the efficiency that exceed the reductions from the bifacial ratio. Energy production would likely be higher for E-facing bifacial modules but bifacial gains would be lower.

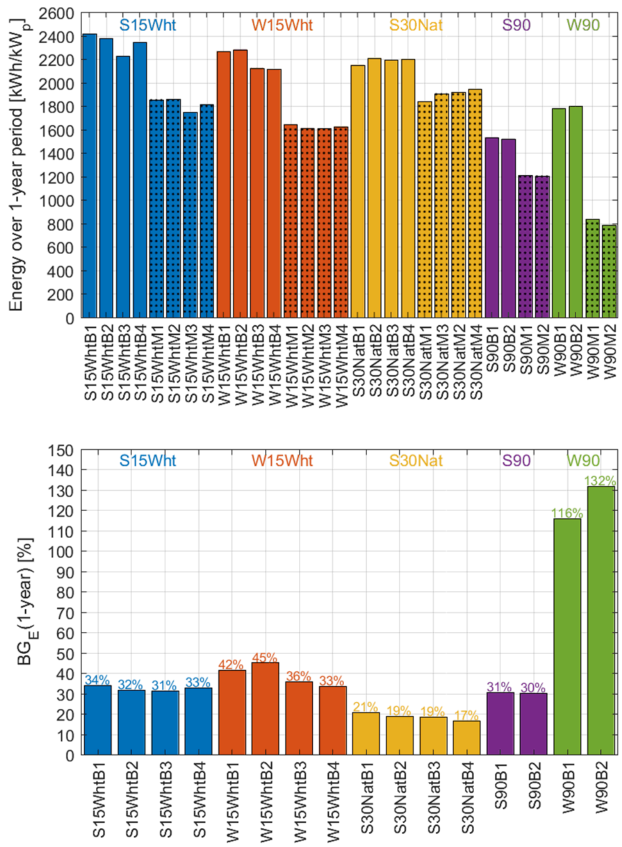

Fig. 8. One-year energy yield for bifacial and monofacial modules (top) and annual bifacial gain in energy for Prism Solar bifacial modules (bottom) deployed in New Mexico.

C. String-level performance at different tilt angles

Sting-level DC current and voltage was measured on bifacial and monofacial strings at 15˚, 25˚, 35˚, and 45˚ in Albuquerque, NM from May 10 to June 11, 2017. Bifacial and monofacial modules were alternated to reduce spatial bias in back side irradiance. However, since the bifacial modules were frameless and the monofacial modules had frames there was initially a problem with partial shading of the bifacial modules in the morning and afternoon due to the monofacial module frames that rose above the bifacial modules on the rack. This was eventually fixed by changing the bifacial module clips to raise the modules to a similar level as the monofacial modules. Fig. 9 shows instantaneous bifacial gains before and after the fix was made. The main effect of the partial shading was to significantly reduce the output of the bifacial modules at the start and end of the day. After the fix (red points) the bifacial gains at these times increased significantly. Bifacial gain in energy for each array was calculated after the fix was made. In order of increasing tilt angles, these gains are 11.8%, 12.3%, 15.4% and 19%, respectively.

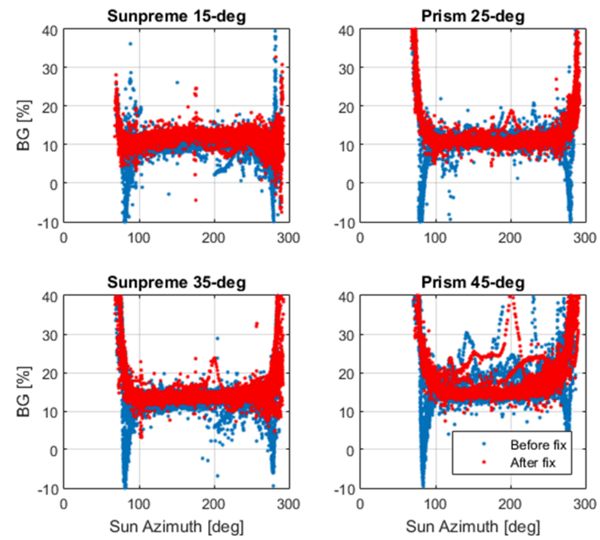

Fig. 9. Instantaneous bifacial gains for strings at four different tilt angles. Blue points are before partial shading issue was fixed. Red point are after.

Fig 10 compares energy produced between arrays. The 15˚ array produced the most energy during this late spring period, which is consistent with the solar elevation at this time of year. It is important to note that while the bifacial gains are greatest for the 45˚ system, the most energy is produced by the 15˚ system at this time of year. Once a full year of data is available it is expected that the 35˚ row will produce the maximum energy, since the Sandia site is at 35˚ N. latitude.

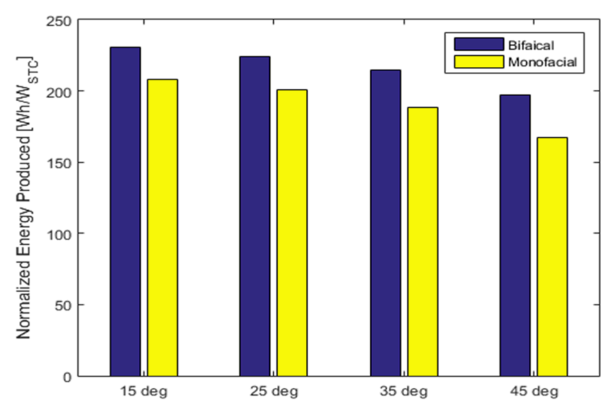

Fig 10. Comparison of the energy produced by each array (normalized by front side STC rating).

D. Bifacial string performance on single axis trackers

Two strings of bifacial modules were installed each on its own tracker. While we are monitoring DC current and voltage from these strings, we have yet to install a reference monofacial string for calculating bifacial gains. We can, however, estimate potential bifacial gain using the front and rear facing reference cells that are part of the monitoring system. This potential bifacial gain can be estimated as:

$$BG_{potential} = \left[G_f + G_r\right]/G_f$$

where G_f and G_r are measured plane-of-array irradiance on the front and rear, respectively. Actual bifacial gains would likely be somewhat lower due to module bifacial ratios being <1.

In addition, there is one more problem with this system. The trackers are controlled by an algorithm that uses light sensors to optimize tracker position. Unfortunately, the algorithm occasionally does not converge and points the trackers in the wrong direction relative to the sun. To account for this problem, we calculated the daily potential bifacial gain only using times when the optimal tracker angle (calculated using PVLIB function, *pvl_singleaxis*) was within +/- 5˚ of the measured angle. Daily potential bifacial gains are show in Fig 11 and are mostly between 8%-14%. When the tracker is off-track, potential bifacial gains are larger.

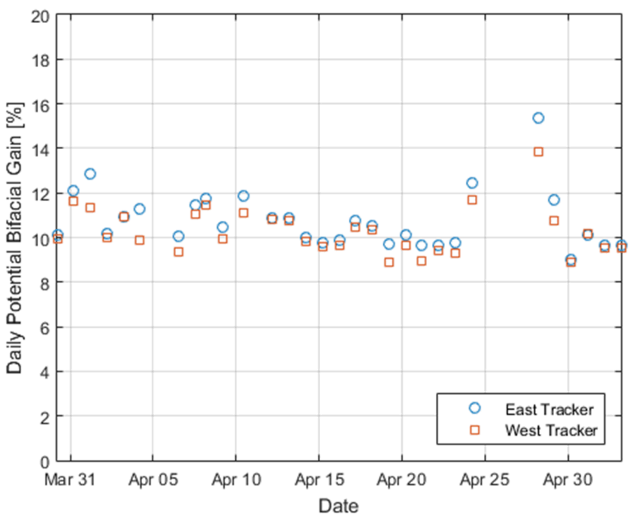

Fig. 11. Daily potential bifacial gain on single axis trackers in Albuquerque, NM.

E. Bifacial string performance on two-axis trackers

Preliminary data from the two 2-axis trackers in VT for the first six days of operation was analyzed and is shown in Fig 12.

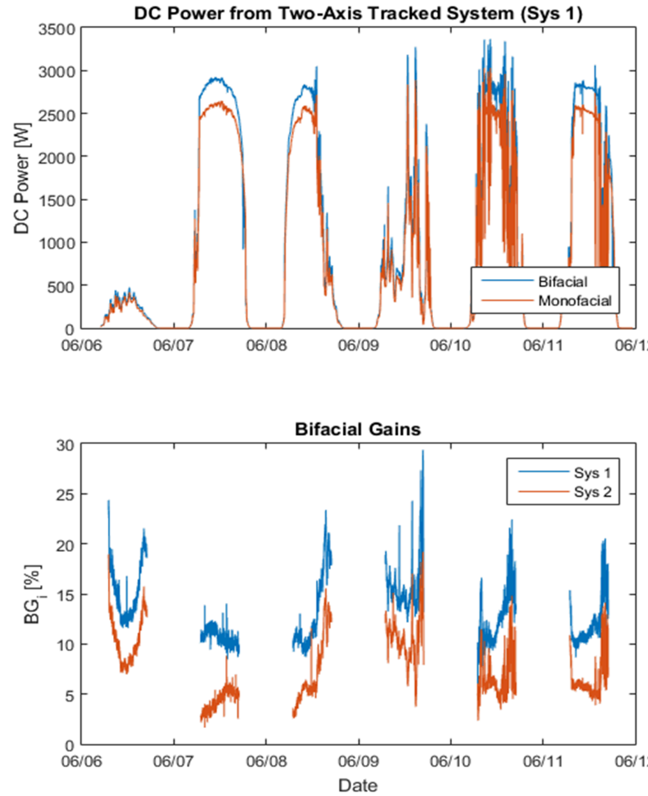

Fig. 12. Power output from system 1 (top) and instantanenous bifacial gains for systems 1 & 2 (bottom).

The reason that bifacial system 2 has lower gains than system 1 is that the bifacial ratio (back to front Pmp) is over 90% for system 1 and only about 60% for system 2. In addition, the trackers were not specifically optimized for bifacial arrays. The support structure for the modules includes several wide beams that obstruct light reaching the modules from the back side (Fig. 13). Thus bifacial gains would be higher if these obstructions could be eliminated or minimized. Also, gains are expected to be significantly higher in the winter when the ground is covered in snow.

Fig. 13. View of the rear side of the tracker for System 1 showing that support structure blocks the back side of the bifacial modules.

IV. Discussion and Conclusions

Bifacial photovoltaic cells, modules, and systems can offer significant boosts in energy produced when compared with similar monofacial PV systems. However, the energy gains depend a lot on the technology chosen and how the system is deployed. We have demonstrated the potential of bifacial PV in a number of different deployment scenarios including single modules, small arrays with microinverters, multi-row, fixed tilt arrays of module strings, single axis tracking and dual axis tracking. From an examination of this field data we can make a number of important conclusions.

- Bifacial performance will always exceed monofacial performance when module output is normalized for front side STC rating and the rear side receives some amount of light.
- Bifacial gains increase as the orientation of the front side of the array (tilt and azimuth) deviates from the optimal orientation for monofacial. However, total energy production of tilted bifacial systems appears to be maximized at the same orientation as for monofacial modules. One exception is E-W bifacial vertical modules, which can outperform optimally oriented monofacial modules, especially with enhanced albedo. Other exceptions may exist.
- Experiments with single bifacial modules and small systems with few surrounding structures result in significantly higher bifacial gains than would be achieved in larger systems. This is because a larger fraction of modules is at the edges of smaller systems and therefore more rear side irradiance is available.
- Bifacial modules with module-scale MPPT (microinverters or optimizers) perform significantly better than series connected modules and string-level MPPT. We believe this is because rear-side irradiance varies significantly in space throughout the array and this can lead to current mismatch in series connected modules. This means that the module with the lowest current (i.e. lowest rear side irradiance) in the string limits the performance of the other modules.
- Bifacial gain of isolated modules and small arrays improves as the array height increases. This is because the module's view of the ground increases and light from more distant (unshaded) surfaces is available to the rear side. This is especially true for lower sun angles when shadows from modules high off the ground appear further away from the array. This is likely one of the reasons that the bifacial performance on the 2-axis trackers in VT was so high despite significant back side obstructions from the tracker supports.
- Bifacial performance is quite sensitive to enhanced albedo of the ground surface. In the Prism Solar RTC array, arrays with enhanced albedo produced more energy than those over lower albedo ground.
- Vertical E-W bifacial modules produce energy earlier and later in the day than S-facing arrays. Such an output power profile may better match demand for electricity and could be a beneficial design under time of use rates.

In conclusion, bifacial modules significantly outperform monofacial modules in conventional designed systems. Additional performance benefits from bifacial modules are possible with optimized system designs that enhance albedo, avoid backside obstructions and minimize ground shading beneath the array.

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's National Nuclear Security Administration under contract DE-NA0003525.

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