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 number 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.

Keywords: Bifacial; PV Array; PV Module; PV System; Photovoltaic; Performance

1 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 yet be predicted with confidence using current PV performance modeling applications because these tools typically assume that PV modules are illuminated on only one side. However, recent updates to software such as PVsyst are including the capability to model bifacial PV systems in limited configurations.

Analytic and empirical studies have shown that use of bifacial modules can potentially increase system yield achieved by at least 10% over a fixed latitude tilt monofacial array, and increased yield can be much higher under certain conditions. The bifacial benefit appears to increases with tilt angle, module height above ground surface, reflectivity of the ground, 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 and more spatially vairable 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 (NREL) and the University of Iowa (UIowa) 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 current results obtained from the first objective. More results from this project are available [1-7].

2 BIFACIAL FIELD TESTING

Sandia has built a number of field testbeds using several types of bifacial PV modules to obtain performance data in a number of different configurations. In most of these set-ups we have included reference monofacial modules of the same size as comparisons. The following bifacial testbeds have been developed and are discussed here:

- Multiple modules, individually monitored on microinverters at five different orientations at three different climate sites (16 bifacial modules per site)
- Four vertical modules, individually monitored on microinverters in Turku Finland (60˚ N).
- String-level performance at four different fixed-tilt angles
- Bifacial string performance on single axis trackers
- Bifacial string performance on two dual-axis trackers

In this paper we are reporting on three different bifacial module technologies including:

- Prism Solar (co-diffused n-type mono silicon) 60-cell, glass-glass frameless
- SolarWorld (p-type mono-PERC) 72-cell, glass-clear backsheet, framed
- Sunpreme (HIT) 60 cell glass-glass, frameless

Each of these module types have different performance characteristics and production methods and costs. The n-type Si cells used by Prism Solar are more expensive to produce than p-type, but have low degradation rates, high bifacial ratios and experience little to no light induced degradation (LID). The p-type mono-PERC cells used by SolarWorld are currently less expensive to produce than n-type or HIT cells but have lower bifacial ratios and suffer from LID, which may recover over time in the field [8]. The HIT cells used by Sunpreme are much more expensive to produce but have high efficiency and bifacial ratios and a lower temperature coefficient. Differences between the modules are that both Prism Solar and Sunpreme use a glass-glass, frameless construction, while SolarWorld bifacial modules use a glass-clear backsheet with a frame, which is compatible with standard mounting systems.

2.1 Multiple modules, individually monitored on microinverters at five different orientations at three different climate sites.

Three nearly identical test systems are comprised of 16 bifacial and 16 monofacial modules divided into five different configurations that vary tilt and azimuth angles as well as ground albedo. Fig 1 shows the installed system in New Mexico (NM). Table I describes the five different configurations at this site. Nearly identical copies of this system are installed in Las Vegas, Nevada and Williston, Vermont. The differences are in the albedo between the ground surfaces at each site and tilted modules in Vermont are all at 30˚. These systems are part of a project at the Regional Test Centers being performed with Prism Solar.

An additional module-scale bifacial system is deployed at the University of Applied Sciences in Turku, Finland (60˚N) to test the performance of vertical, E-W facing bifacial modules from Prism Solar at high latitudes (Fig 2).

Figure 1: Prism Solar test array in New Mexico.

Table I: Orientation and ground surface of Prism Solar test system in New Mexico.

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

*30˚ tilt in Vermont

Figure 2: Vertical bifacial array in Turku, Finland.

2.2 String-level performance at different fixed tilt angles

This system is focused on discovering how bifacial modules behave in series strings at different tilts. Sandia built four rows of racking, each at a different tilt angle (45˚, 35˚, 25˚, 15˚). Each row has two strings of eight modules (one bifacial and one monofacial). Bifacial modules are from Sunpreme (15˚ and 35˚) and Prism Solar (25˚ and 45˚). Fig 3 shows that bifacial and monofacial modules are interleaved to avoid any east or west bias in the light behind the rows. However, in the rows with lower tilt angles, there is some partial shading of the bifacial modules from the thicker adjacent monofacial modules.

Figure 3: String-level bifacial and monofacial test array in New Mexico.

2.3 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. While this array is still under construction, front and back side irradiance data is available during tracker operation and is used estimate performance.

Figure 4: Single axis tracker with bifacial module strings in New Mexico.

2.4 Bifacial string performance on a two-axis tracker

As part of the Regional Test Center program, two dual-axis trackers from AllEarth Renewables have been installed in Williston, Vermont, each holding two strings (one of bifacial modules and one of monofacial modules) (Fig 5).

Figure 5: Two axis trackers in Vermont with bifacial and monofacial strings on each.

3 PERFORMANCE RESULTS

All of the test beds described above have been collecting data and some initial results are shared below.

Instantaneous bifacial gain at time t, $BG_i(t)$ is defined here as:

$$\mathrm{BG_i(t)} = 100\% \times \left(\frac{\mathrm{P_{bifacial}(t)}/P0_{\mathrm{bifacial}}}{\mathrm{P_{monofacial}(t)}/P0_{\mathrm{monofacial}}} - 1\right) \qquad (1)$$

where $P_{bifacial}$ and $P_{monofacial}$ are measured power values and $P0_{bifaical}$ and $P0_{monofacial}$ 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:

$$\mathrm{BG_E} = 100\% \times \left(\frac{\sum_{1\,month} \mathrm{P_{bifacial}}\ /\ \mathrm{P0_{bifacial}}}{\sum_{1\,month} \mathrm{P_{monofacial}}\ /\ P0_{\mathrm{monofacial}}} - 1\right) \quad (2)$$

When performance from monofacial reference modules is not available, we compute a potential bifacial gain (BG_P) from measured front and back side irradiance as:

$$\mathrm{BG_P} = 100\% \times \mathrm{R_b}\left(\frac{\mathrm{G_f + G_r}}{\mathrm{G_f}} - 1\right) \qquad (3)$$

where R_b is the bifacial ratio (quotient of backside to frontside flash rating) and G_f and G_r are the plane-of-array irradiance on the front and rear sides, respectively.

3.1 Single module monitoring on microinverters at five different orientations at three different climate sites.

As of September 2017, the Prism Solar RTC arrays have been operating for 19 months in New Mexico, 8 months in Nevada, and 4 months in Vermont. Initial results comparing total energy produced and bifacial gains in energy are shown in Figs 6, 9, and 10. Fig. 7 shows the avarage power and bifacial gains in New Mexico as a function of solar time and Fig 8. compares these quantities by month.

The main conclusions from these figures are that bifacial modules in these arrays significantly outperform the monofacial references. Bifacial gains vary between 15% and over 100%. The highest gains are associated with orientations that are not optimal for monofacial (e.g., W90). S15Wht and W15Wht arrays in New Mexico (albedo = 0.55) produced as much as or greater amount of energy than the monofacial at near latitude-tilt (S30Nat), which proves that low tilt bifacial over a high albedo surface can match or exceed latitude-tilt monofacial.

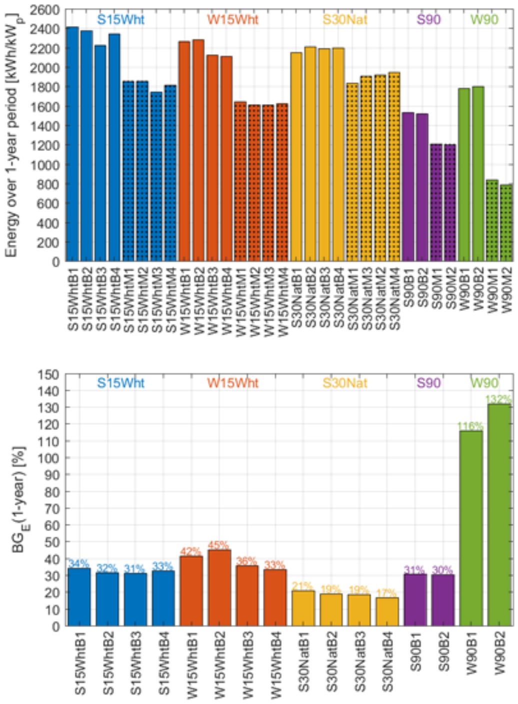

Figure 6: Chart showing total energy and bifacial gain from each module in the Prism Solar RTC array in New Mexico for the first 12 months of study.

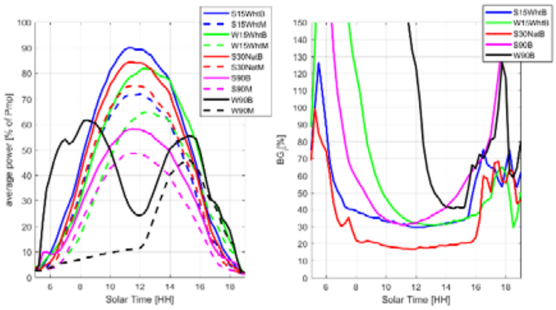

Figure 7: Average power (left) and bifacial gain (right) for Prism Solar RTC array in New Mexico for the first 12 months of study.

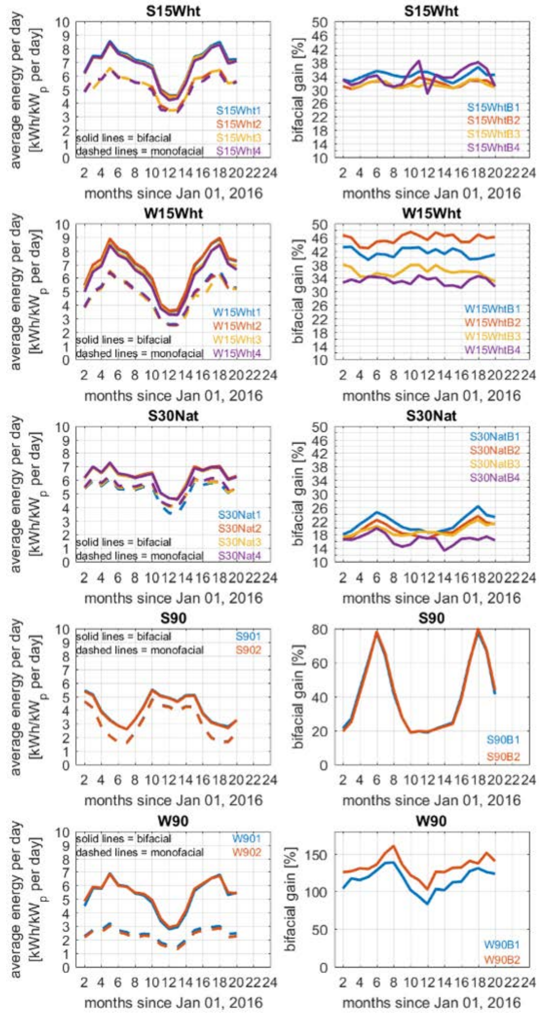

Figure 8: Monthly average power (left) and monthly bifacial gain (right) for Prism Solar RTC arrays in New Mexico.

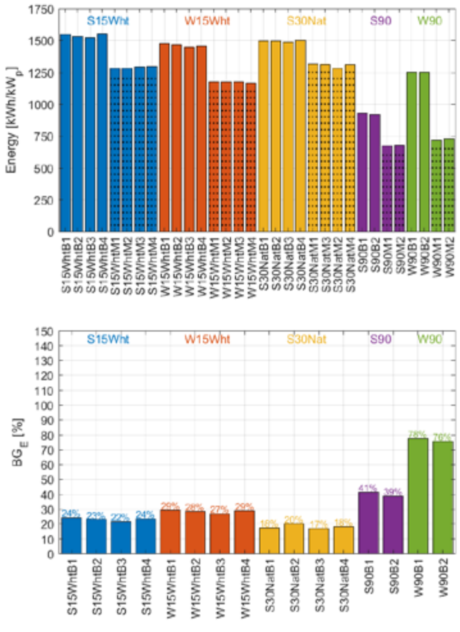

Figure 9: Chart showing total energy and bifacial gain from each module in the Prism Solar RTC array in Nevada for the first 8 months of study.

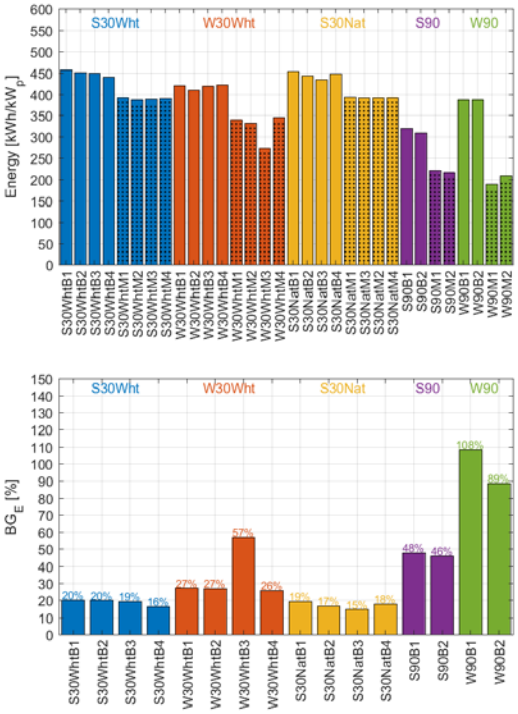

Figure 10: Chart showing total energy and bifacial gain from each module in the Prism Solar RTC array in Vermont for the first 4 months of study.

Initial results from the vertical bifacial system in Finland are compared with a monofacial reference system with an azimuth of 220˚ (~SW) and tilt of 43˚ in Fig 11. For the three days shown, the bifacial modules produced 37% more energy (normalized to front side rating). Power output from the vertical bifacial array occurs earlier and produces power for longer time periods than for the monofacial array.

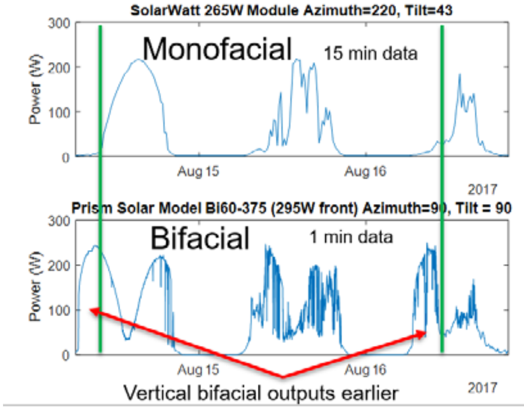

Figure 11: Three-day comparison of output from monofacial and vertical bifacial modules in Turku, Finland.

3.2 String-level performance at different fixed tilt angles

The performance difference between strings of bifacial and monofacial modules in New Mexico is compared in Figs. 12-13. Fig 12 compares the instantaneous bifacial gains plotted against sun azimuth. This plot shows how bifacial gains tend to be greater for S-facing bifacial arrays at the beginning and end of the day when the sun angles are higher. An exception occurs for the 15˚ and 25˚ tilted arrays due to partial shading caused by modules of differing thicknesses during these times. Fig 13 compares the energy produced from each string. It is notable that the energy produced appears to be inversely proportional to BG_E. An exception is that the BG_E for Sunpreme 15˚ and Prism 25˚ are nearly equal. This result may not be representative due to the partial shading in the lower titled arrays. Also worth noting is that the Sunpreme and Prism Solar modules use different cell technologies (HIT and n-type c-Si, respectively) and have different temperature coefficients and performance characteristics that cause some of the differences that are not related to the modules' bifaciality.

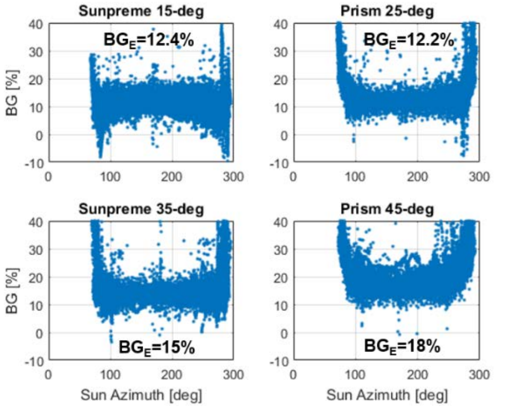

Figure 12: Plot of instantaneous bifacial gains vs. sun azimuth from strings of Prism Solar and Sunpreme modules from June 1 to Aug 31, 2017 in New Mexico (albedo = ~0.25).

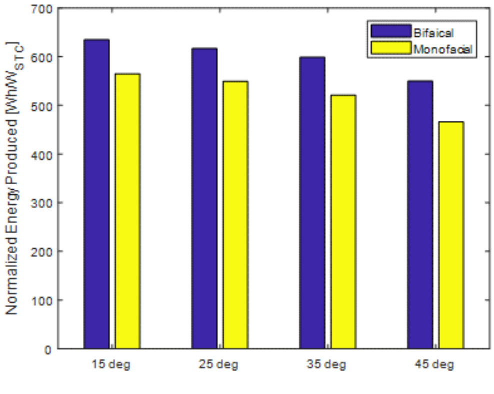

Figure 13: Normalized energy produced from bifacial and monofacial strings for each tilt angle in New Mexico.

3.3 String-level performance on single axis trackers

Because there are currently only two strings of bifacial modules installed on the single axis trackers in New Mexico, it is not possible to report bifacial gains for this array. Instead, we use the measured front and back side irradiance to estimate the potential bifacial gain (BG_P) (assuming the bifacial ratio =1) for each tracker. It should be noted that these trackers are controlled by light sensors which sometimes cause the trackers to face the wrong direction relative to the sum position. The data shown in Fig. 14 is calculated only when the tracker is within +/- 5˚ if its correct position. The estimated BG_P for these trackers is approximately 10%, but would be lower in the case of $R_b < 1$.

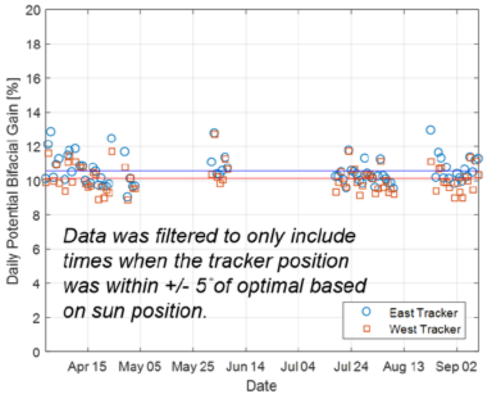

Figure 14: Daily potential bifacial gains for single axis trackers in New Mexico (albedo = ~0.25).

3.4 Bifacial string performance on two-axis trackers

Bifacial gains in energy were measured on two different two axis trackers each with a different bifacial module type. The first tracker used 60-cell Prism Solar bifacial modules with a R_b = ~0.93. The second used 72-cell SolarWorld framed bifacial modules with a lower R_b = ~0.62. Monofacial modules on both trackers are from SolarWorld. Both trackers have significant obstructions behind the bifacial modules that results in backside irradiance being partially blocked. Figs. 15 and 16 show the mean daily BG_E for the Prism Solar and SolarWorld strings, respectively. The Prism string BG_E is ~11% and greater than the SolarWorld (~6%) due to the difference in R_b. Using the measured irradiance and R_b for each module type, we calculated an average BG_P of 15.6% (Prism) and 9.5% (SolarWorld), which suggests that the obstructions cause approximately 4-5 percentage points of reduction in BG_E for each system. Both module types are perforing similarly when the differences in their bifacial ratos (R_b) are considered.

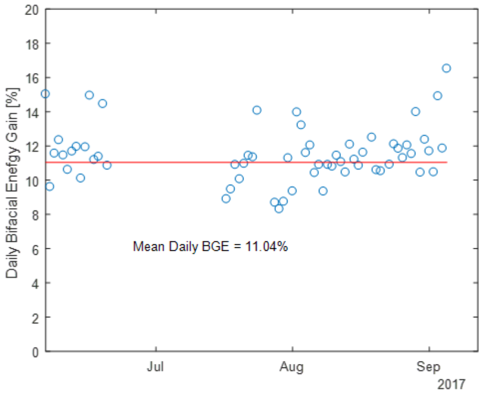

Figure 15: Daily bifacial gain in energy for a string of Prism Solar modules on a two axis tracker in Vermont (albedo = ~0.09).

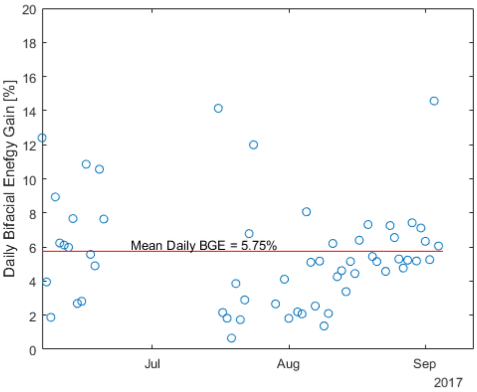

Figure 16: Daily bifacial gain in energy for a string of SolarWorld modules on a two axis tracker in Vermont (albedo = ~0.09).

4 CONCLUSIONS

Field data from a collection of bifacial PV systems in New Mexico, Nevada, Vermont, and Finland has been analyzed and compared with similar monofacial arrays and measured front and back irradiance. The following conclusions can be drawn from this analysis.

- Bifacial performance always exceeds 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, especially in cases with enhanced albedo.
- Bifacial gains for single bifacial modules and small systems are significantly higher than for 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 gains for large multi row systems are expected to be significantly lower.
- Bifacial module performance benefits from module-scale MPPT. Rear-side irradiance varies significantly in space throughout the array leading to current mismatch in series connected 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 very sensitive to enhanced albedo of the ground surface.
- 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.
- One must be careful when comparing different bifacial modules as they are not all alike. The bifacial ratio (flash rating of the back at STC divided by the front) can differ significantly between modules from different companies. Cell and module characteristics, module front side rating, bifacial ratio, temperature coefficient, and price all have to be considered when choosing the best bifacial module for a given project.

6 ACKNOWLEGEMENTS

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.

7 REFERENCES

[1] Deline, C., S. MacAlpine, B. Marion, F. Toor, A. Asgharzadeh and J. S. Stein (2017). "Assessment of Bifacial Photovoltaic Module Power Rating Methodologies – Inside and Out." Journal of Photovoltaics 7(2): 575-580.

[2] Hansen, C. W., R. Gooding, N. Guay, D. M. Riley, J. Kallickal, D. Ellibee, A. Asgharzadeh, B. Marion, F. Toor and J. S. Stein (2017). A Detailed Model of Rear-Side Irradiance for Bifacial PV Modules. 44th IEEE Photovoltaic Specialists Conference. Washington DC. SAND2017-6554 C.

[3] Marion, B., S. MacAlpine, C. Deline, A. Asgharzadeh, F. Toor, D. Riley, J. Stein and C. Hansen (2017). A Practical Irradiance Model for Bifacial PV Modules. 44th IEEE Photovoltaic Specialists Conference. Washington DC. SAND2017-7000C.

[4] Riley, D., C. Hansen, J. Stein, M. Lave, J. K. B. Marion and F. Toor (2017). A Performance Model for Bifacial PV Modules. 44th IEEE Photovoltaic Specialists Conference. Washington, DC. SAND2017-6586C.

[5] Shishavan, A. A., T. M. Lubenow, J. Sink, B. Marion, C. Deline, C. Hansen, J. Stein and F. Toor (2017). Analysis of the Impact of Installation Parameters and System Size on Bifacial Gain and Energy Yield of PV Systems. 44th IEEE Photovoltaic Specialists Conference. Washington, DC. SAND2017-7001C.

[6] Stein, J. S., L. Burnham and M. Lave (2017). One Year Performance Results for the Prism Solar Installation at the New Mexico Regional Test Center: Field Data from February 15, 2016 - February 14, 2017. Albuquerque, NM, Sandia National Laboratories. SAND2017-5872.

[7] Stein, J. S., D. Riley, M. Lave, C. Deline and F. Toor (2017). Outdoor Field Performance from Bifacial Photovoltaic Modules and Systems. 44th IEEE Photovoltaic Specialists Conference. Washington, DC. SAND2017-6464C.

[8] Nicolai, M., M. Zanuccoli, M. Galiazzo, M. Bertazzo, E. Sangiorgi and C. Fiegna (2016). "Simulation Study of Light-induced, Current-induced Degradation and

Recovery on PERC Solar Cells." Energy Procedia 92(Supplement C): 153-159.