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Performance of Bifacial Photovoltaic Modules and Systems

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PHOTOVOLTAICS

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.

Main Tasks

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.

Bifacial Field Testbeds

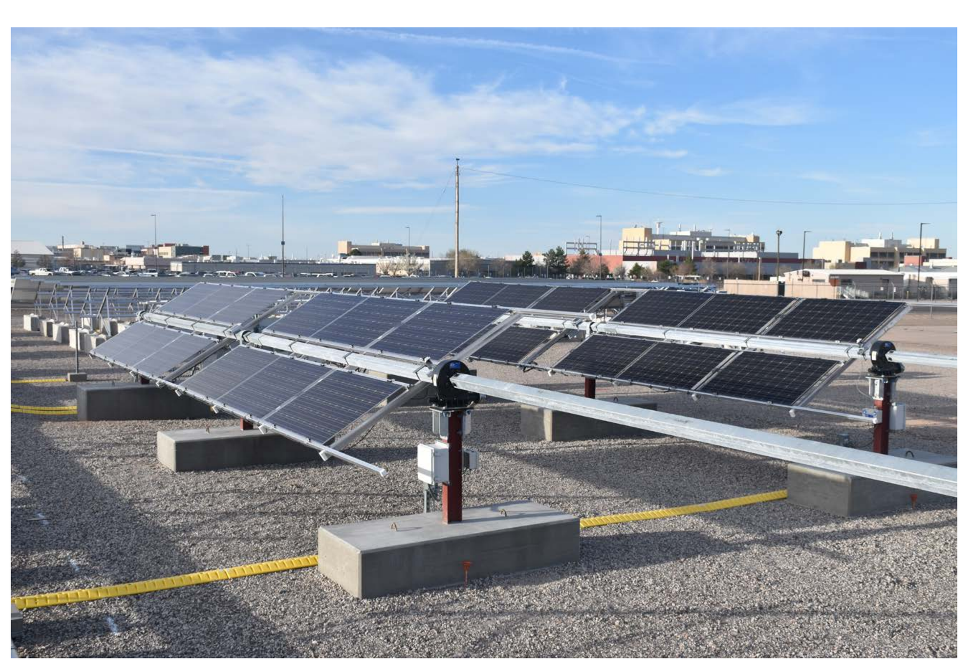
Sandia has built a number of field testbeds using bifacial PV modules to obtain performance data in a number of different configurations. In most of these set-ups we have included reference monofacial modules of the same size as comparisons. The following bifacial testbeds have been or will be developed:

- Single module IV tracing at different tilts and heights
- Single module monitoring on microinverters at five different orientations.
- String-level performance at different tilt angles
- Bifacial string performance on a single axis trackers
- Bifacial string performance on a two-axis trackers

Single module IV tracing at different tilts and heights.

Single module monitoring on microinverters at five different orientations.

String-level performance at different tilt angles



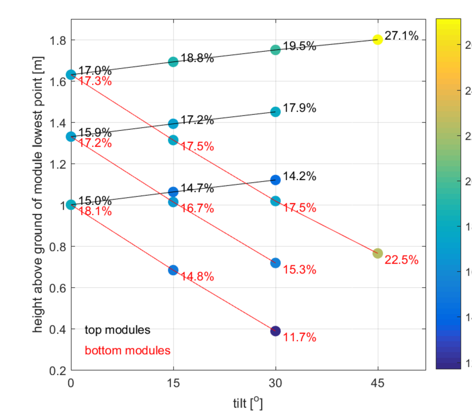
Bifacial string performance on a single axis trackers

Bifacial string performance on 2-axis trackers

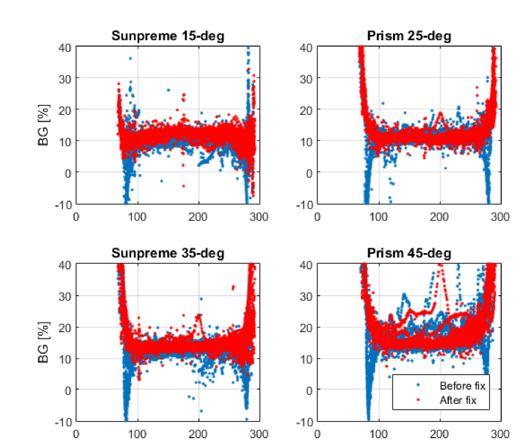
Bifacial Performance Metrics

Bifacial PV modules are typically rated according to their front side STC flash rating ($Pmp_{STC\text{-}Front}$). Rear side performance varies. Bifacial gain (*BG*) describes performance gain (%) over monofacial modules in same orientation.

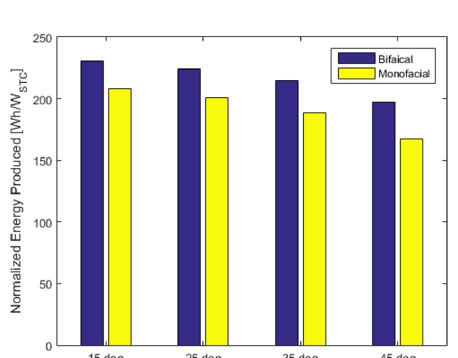
- $Bifacial\ Ratio = \frac{Pmp_{STC-Rear}}{Pmp_{STC-Front}}$
- $BG_{potential} = 100\% \times [G_f + G_r]/G_f$
- $\mathrm{BG_i(t)} = 100\% \times \left(\frac{\mathrm{P_{bifacial}(t)\ /\ Pmp_{bifacial}}}{\mathrm{P_{monofacial}(t)\ /\ Pmp_{monofacial}}} - 1\right)$
- $\mathrm{BG_E} = 100\% \times \left(\frac{\sum_{1\,month} \mathrm{P_{bifacial}\ /\ Pmp_{bifacial}}}{\sum_{1\,month} \mathrm{P_{monofacial}\ /\ Pmp_{monofacial}}} - 1\right)$



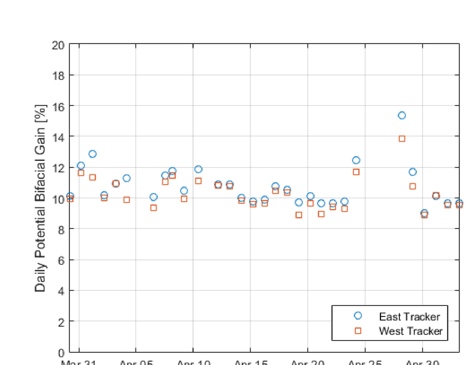
Single module bifacial gains measured as a function of tilt angle and height of module bottom edge off ground.



Instantaneous bifacial gains for strings at four different tilt angles.



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



Daily $BG_{potential}$ on single axis trackers in Albuquerque, NM.

Project Publications

- 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 PVSC. Washington DC.
- 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 PVSC. Washington, DC.
- 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 PVSC. Washington, DC.
- 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 PVSC. Washington DC.
- 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.
- 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.
- Deline, C., S. MacAlpine, B. Marion, F. Toor, A. Asgharzadeh and J. S. Stein (2016). Evaluation and Field Assessment of Bifacial Photovoltaic Module Power Rating Methodologies. 43rd IEEE Photovoltaic Specialist Conference. Portland.

Bifacial Performance Results

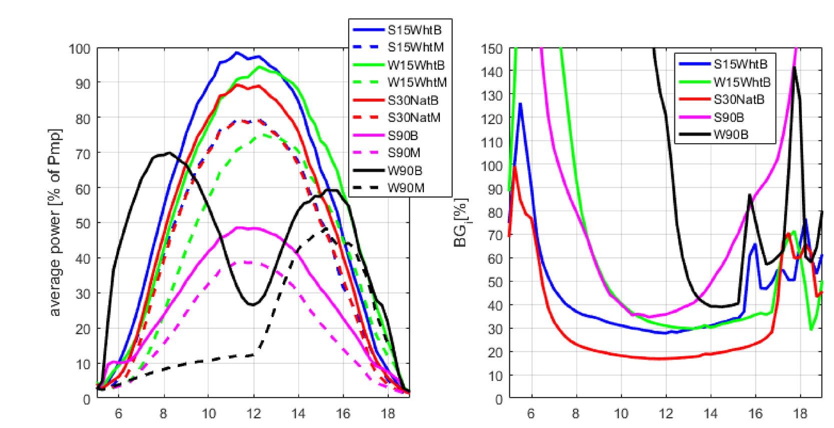
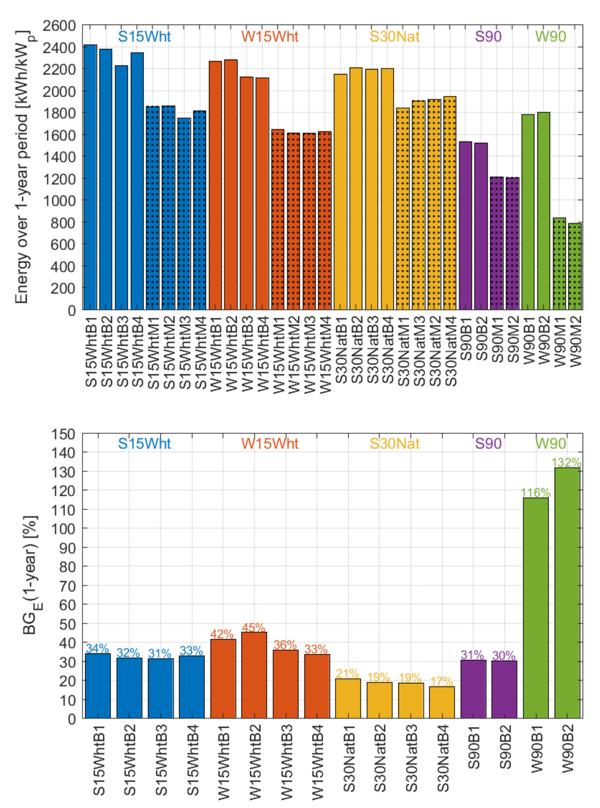
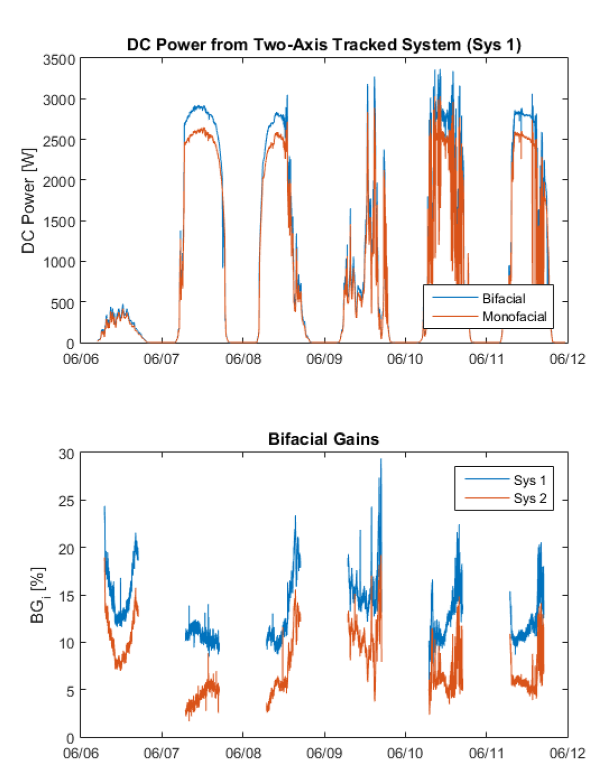


Fig. 7. Left: Average power output, Right: bifacial gains over six months from the bifacial and monofacial modules on microinverters.



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.



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

Summary and 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.

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