Project Title:	Performance Models and Standards for Bifacial PV Module Technologies
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Submission Date:	30 September 2018
Recipient:	Sandia
Address:	P.O. Box 5800 Albuquerque, NM 87185-1033
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Awarding Agency:	DOE EERE SETO PV subprogram
Working Partners:	National Renewable Energy Laboratory; University of Iowa
Principal Investigator:	Joshua S. Stein Distinguished Member of Technical Staff Phone: 505-845-0936 Email: jsstein@sandia.gov

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Executive Summary: This project has three main objectives: (1) to field and collect performance data from bifacial PV systems and share this information with the stakeholder community; (2) to develop and validate bifacial performance models and deployment guides that will allow users to accurately predict and assess the use of bifacial PV as compared with monofacial technologies and (3) to help develop international power rating standards for bifacial PV modules.

We have been overwhelmingly successful in all of these objectives over the past three years.

1. We have deployed outdoor comparisons of bifacial and monofacial PV systems at numerous sites and orientations including New Mexico, Colorado, Vermont, Nevada, Finland, and Alaska. We have received monitoring data from partner systems in Oregon. Results from these field studies have been published and presented at national and international conferences and workshops and these papers and presentations are available on our project website (https://pvpmc.sandia.gov/pv-research/bifacial-pv-project/), where we track downloads. As of mid-September we had tracked a total of over 8,000 separate downloads of our publications from the site.
2. Our team developed four different open-source modeling approaches to simulate and predict the irradiance reaching the backside of a bifacial PV array. These software packages are available for download and are being used by many researchers and industry stakeholders in the PV community. These tools are being used to verify and validate commercial models (e.g., PVsyst).
3. Our team contributed technical data and methods to the IEC TS60904 Part 1-2: Measurement of current-voltage characteristics of bifacial photovoltaic (PV) devices. This technical specification has been approved and will be available to the public in January 2019.

We finished off our project term by organizing and hosting the 2018 BifiPV Workshop in Denver, CO on September 10-11, 2018. With about 180 participants from 15 countries this workshop covered international progress in bifacial PV performance, reliability, characterization, and bankability and it highlighted the results from our three-year project.

Background: The technical landscape has changed dramatically since FY16 when we started this project. Bifacial PV has gone from a niche technology to being mainstream and is now projected to make up to 40% of the PV market share by 2028 [1]. However, there still remain many questions and problems to solve. At a recent Bifacial PV workshop [2], hosted by our project team, researchers and business people from across the industry discussed current needs for bifacial to continue to grow. The main messages from the workshop include the following points:

- Even with fairly modest bifacial gains, new bifacial projects can result in significant increases in the net present value over standard monofacial plants. This allows the opportunity to make new investments in technical innovations to increase bifacial performance (e.g., optimized racking, enhanced albedo, module power electronics, etc.)

- Current practice of reporting results from field studies of bifacial performance lacks a unified model for presenting bifacial advantages. Few researchers report enough details about their tests to allow comparison across labs. Many studies are still on single modules and thus significantly over estimate expected bifacial gains from larger plants.
- Bifacial cells are here to stay. Most new PV cells are easily made bifacial. Innovations in white template glass backsheets are increasing performance. More innovations in novel bifacial module designs are coming (e.g., transparent backsheets, shingled bifacial cells, integrated module level power electronics).
- Bifaical performance models are beginning to agree with each other. More accuracy in the inputs (e.g., albedo) is still needed.
- New bifacial module characterization standard (IEC 60904-1-2 is finished and will be available in January 2019. UL is introducing new standards aimed at bifacial modules.

Seeing where the industry is today, I believe our project was very well timed and has helped the bifacial PV industry grow in the US.

Introduction: This project had three main tasks defined:

1. Design, deploy, and monitor bifacial and similar monofacial PV systems to collect data and improve understanding of potential bifacial energy gains.

   Milestone: Year 1: Bifacial testbed is built at Sandia

2. Build and validate predictive models of bifacial PV performance.

   Milestone: Year 2: Bifacial performance model(s) developed and validated against field data. Peer-reviewed paper.

3. Provide technical support to international standards efforts for bifacial module characterization.

   Milestone: Year 3: IEC 60904 draft completed along with documentation of round robin results. Standard submitted to IEC process. Published design and site preparation white paper on bifacial PV systems.

Project Results and Discussion:

Field Measurements of Bifacial Performance

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 (Figure 1)
- Single module DC monitoring on microinverters at five different orientations (three different climate sites). (Figure 2)
- String-level DC performance at different tilt angles. (Figure 3)

- Bifacial DC string performance on single axis trackers. (Figure 4)
- Bifacial DC string performance on two-axis trackers. (Figure 5)

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.

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.

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

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

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

All of the test beds described above have been collecting data and some 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:

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

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.

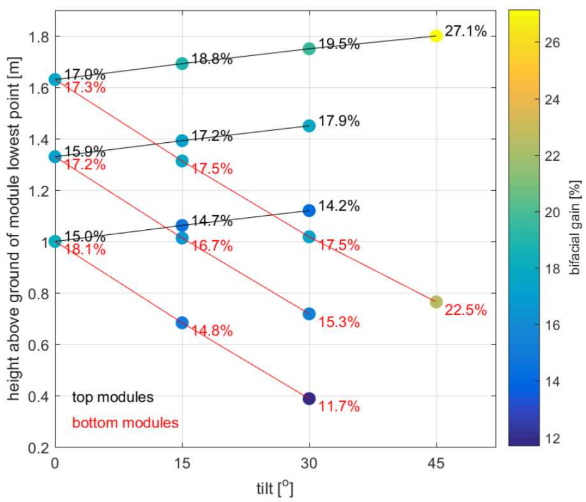


Fig. 6. Single module bifacial gains measured as a function of tilt angle and height of module bottom edge off ground.

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.

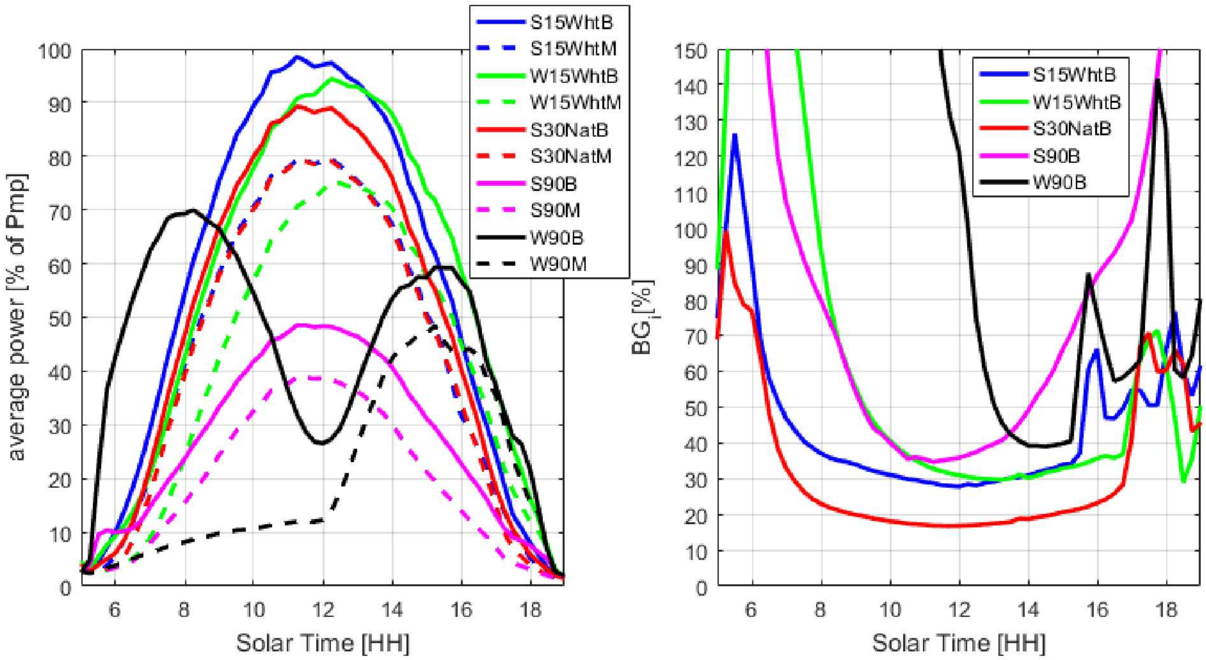
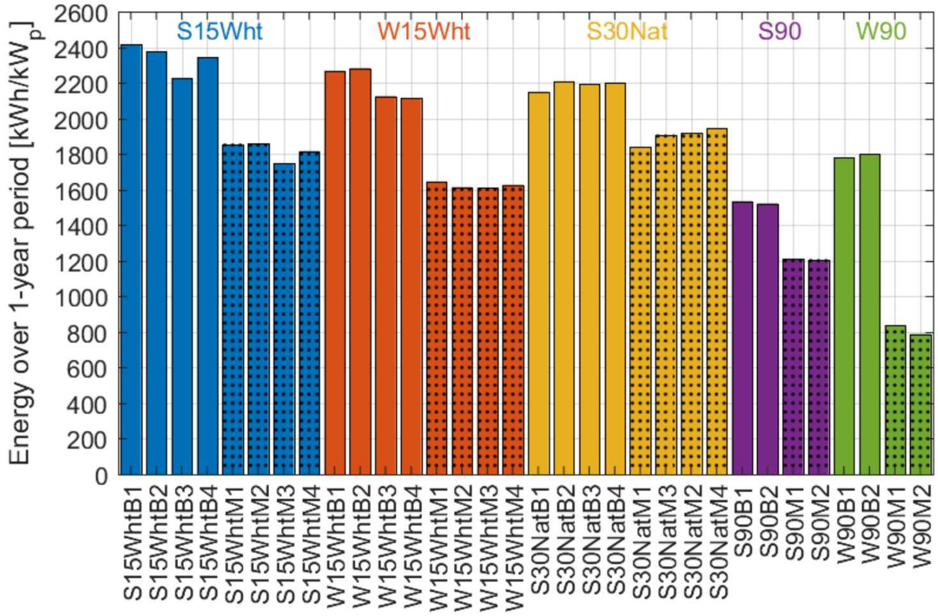


Fig. 7. Left: Average power output, Right: bifacial gains over six months from the bifacial and monofacial modules on microinverters.

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.



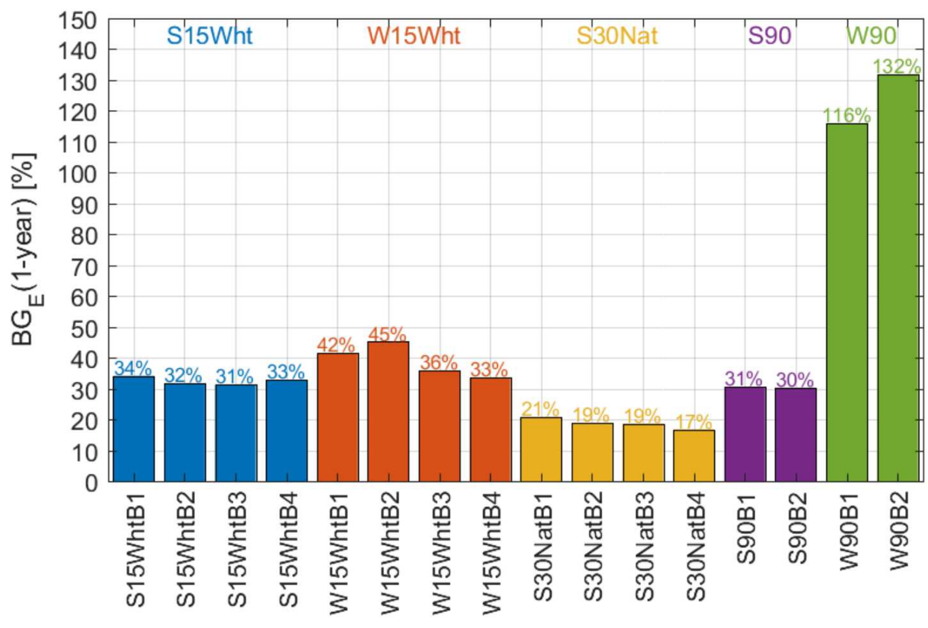


Fig. 8. One-year energy yield for bifacial and monofacial modules (top) and annual bifacial gain in energy for Prism Solar bifacial modules (bottom) deployed in New Mexico.

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.

We also tested module-scale optimizers on four of the strings (2 monofacial and 2 bifaical) on two of the rows. Results of this test are published in Riley et al. (2018).

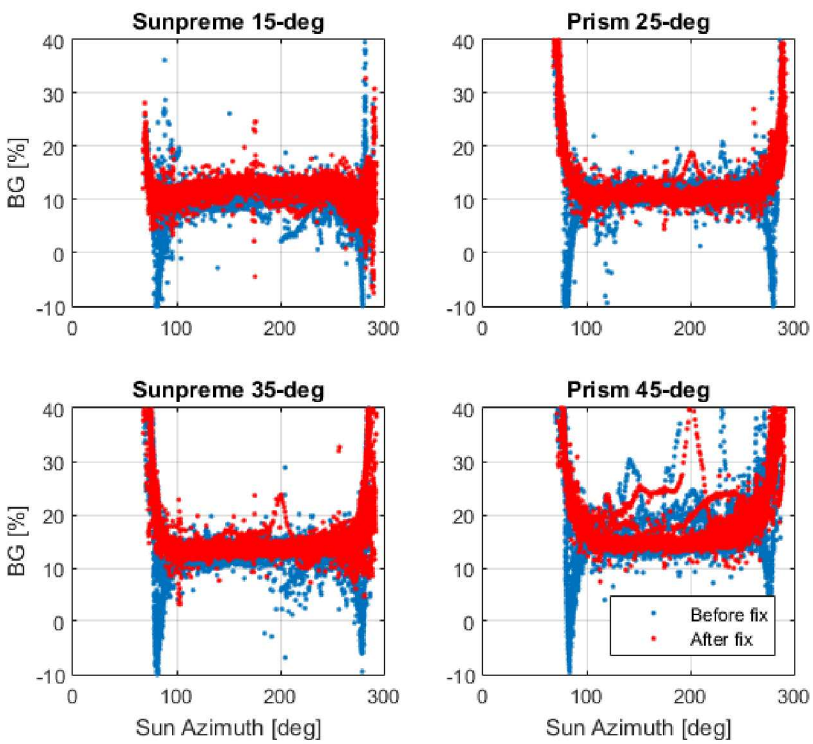


Fig. 9. Instantaneous bifacial gains for strings at four different tilt angles. Blue points are before partial shading issue was fixed. Red point are after.

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.

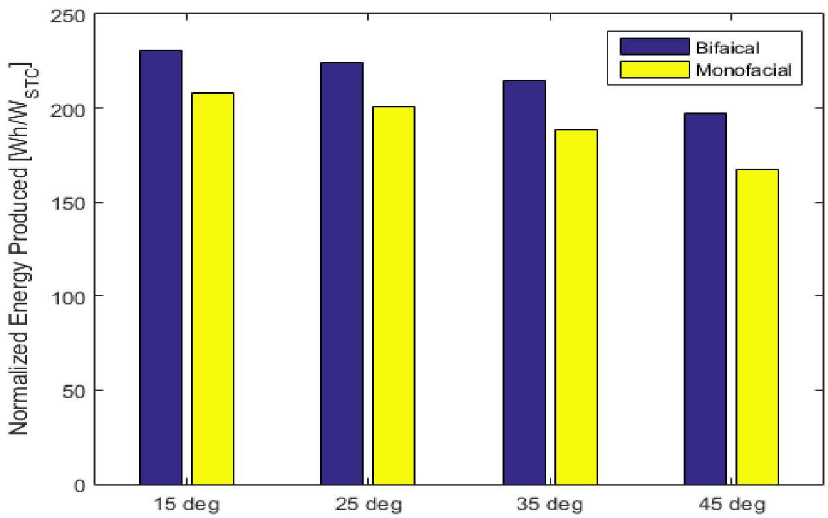


Fig 10. Comparison of the energy produced by each array (normalized by front side STC rating).

Bifacial string performance on single axis trackers

Initially, two strings of bifacial modules were installed on our single axis trackers. We monitored DC current and voltage from these strings, however we never installed a reference monofacial string for calculating bifacial gains. Instead, we worked out a deal with Array Technologies to install an updated version of their trackers and replace the residential-style system we had first installed. This replacement was completed late in FY18 and not enough data is available at the time of this report.

Bifacial string performance on two-axis trackers

Results from both of the two 2-axis trackers in VT was analyzed and results are summarized in Fig 11. It is very interesting to note that the bifacial arrays on both trackers outperform the monofacial arrays for all months. In the winter, the bifacial performance is especially high due to two factors. First, when snow covers the front of both arrays, the bifacial array continues to generate energy from the backside irradiance. Second, the bifacial modules were observed to shed snow faster than the monofacial modules, on average. During non-winter months, the Prism bifacial modules outperform the SolarWorld bifacials due to their higher bifaciality (90% vs. ~60%).

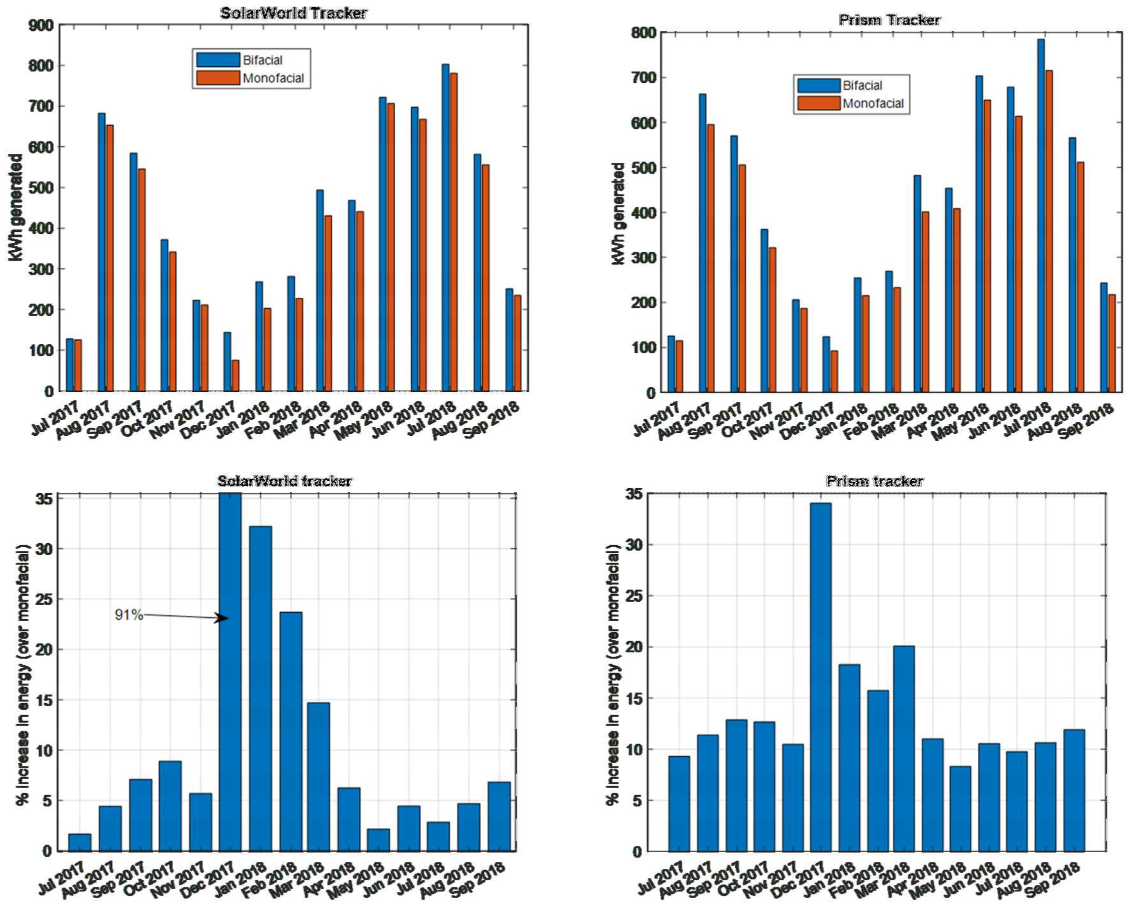


Fig. 11. Power output (top) and monthly bifacial energy gain (bottom) from SolarWorld (left) and Prism (right).

Modeling Results

Field performance data has been effective in establishing a baseline for bifacial performance. To ensure bankable energy predictions for future bifacial system installations, validated performance models are crucial. Through the past 3 years, several optical and energy predictive models for bifacial systems have been developed.

NREL has focused on ray tracing and 2D view factor modeling. We have developed a 2D view factor model (Marion et al., 2017) that has a very fast run time and low system memory requirements, for use with arrays with regular row spacing. We have also developed a RADIANCE-based[1] ray-tracing approach, with preprocessing of the sky dome[2] to significantly decrease the standard ray tracing run time. Both models have been ported to Python and deployed in open-source form on GitHub to enable

[1] Ward, G.J., *The RADIANCE lighting simulation and rendering system*, in *Proceedings of the 21st annual conference on Computer graphics and interactive techniques*. 1994, ACM. p. 459-472.

[2] Robinson, D. and Stone, A., 2004, September. Irradiation modelling made simple: the cumulative sky approach and its applications. In *PLEA conference* (pp. 19-22).

collaboration and public access. The view factor model has also been incorporated into System Advisor Model (SAM) for accurate bifacial performance modeling. Models have individually been validated using data collected onsite at NREL, as well as data from Sandia and other industry partners. In particular, an adjustable multi-row mock array was developed for model validation of the view factor and Radiance ray-tracing model (Fig. 12 and Fig. 13).

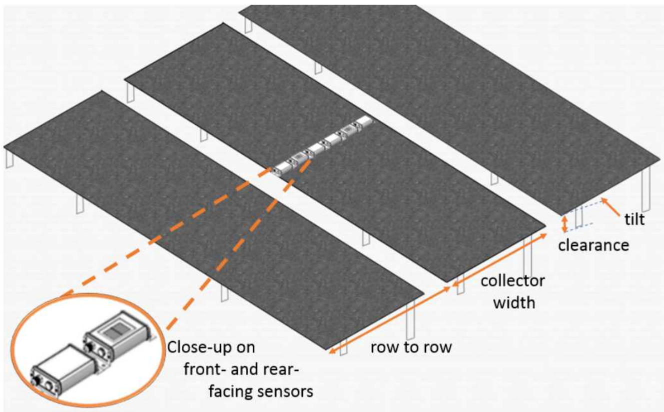


Fig. 12. Diagram (left) of the field test-bed built in Golden, CO, with two front-facing and four back-facing irradiance sensors. The array can be modified for row-to-row spacing, tilt angle, and clearance height. Photograph (right) shows array under construction, ballasts, and the white roof coating. (Ayala et al, JPV 2018)

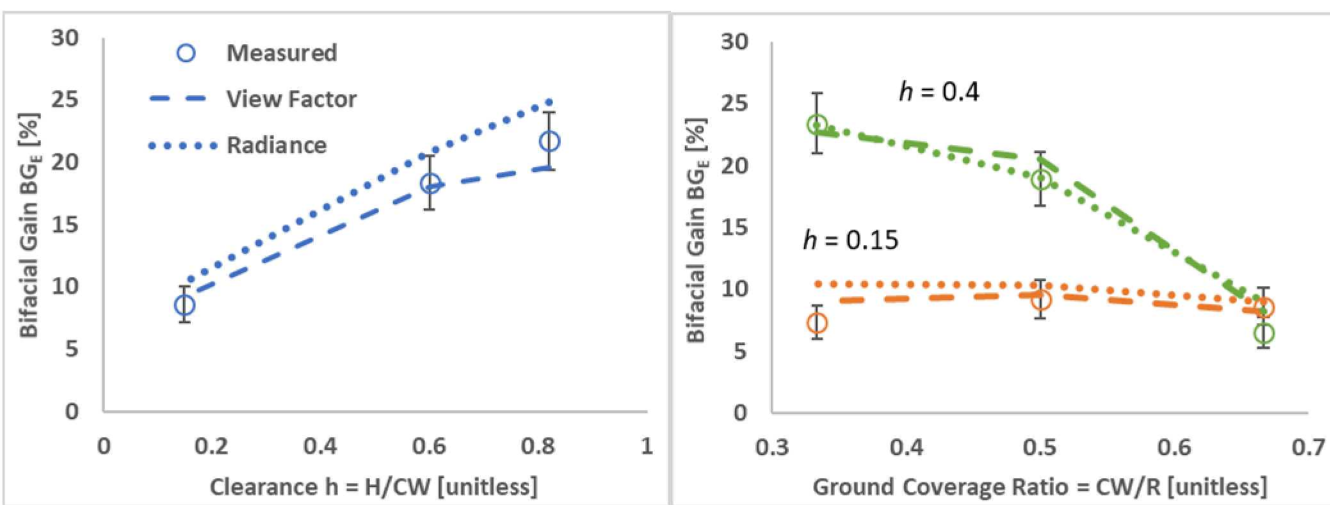


Fig 13. Measured and modeled results for the NREL test-bed. Clearance height *h* and row spacing *r* are normalized by the mock array collector width of *CW* = 0.61 m. Measurement uncertainty is driven by soiling of the roof surface and reference cell uncertainty at low irradiance. (Ayala et al, JPV 2018)

In addition to fixed-tilt installations, horizontal single-axis tracking (HSAT) performance models and field validation have been conducted. Two NREL performance models have been compared against field data (Fig. 14) and other commercial modeling tools (Fig. 15), and found to have good agreement.

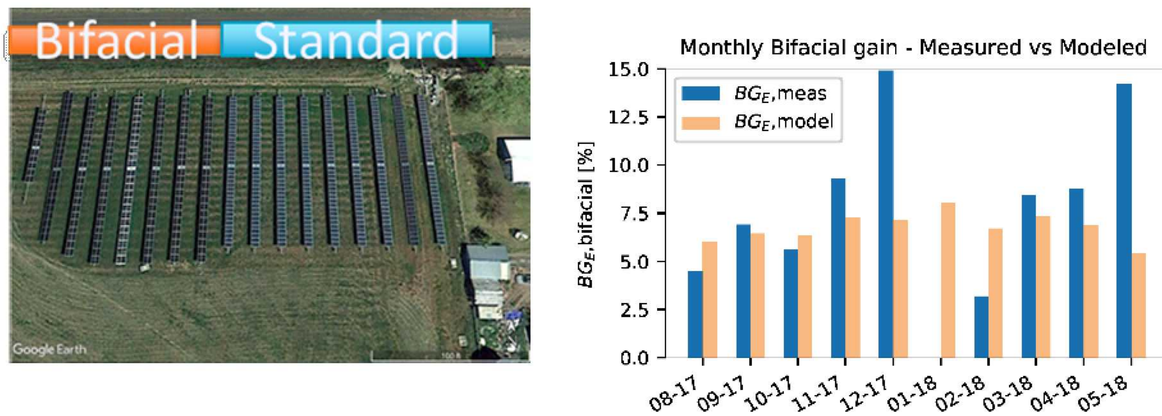


Fig. 14. Side-by-side bifacial site (left). Bifacial gain $BG_{E,bifacial}$ measured from AC production data, compared with VF model estimate. (Ayala et al, WCPEC 2018)

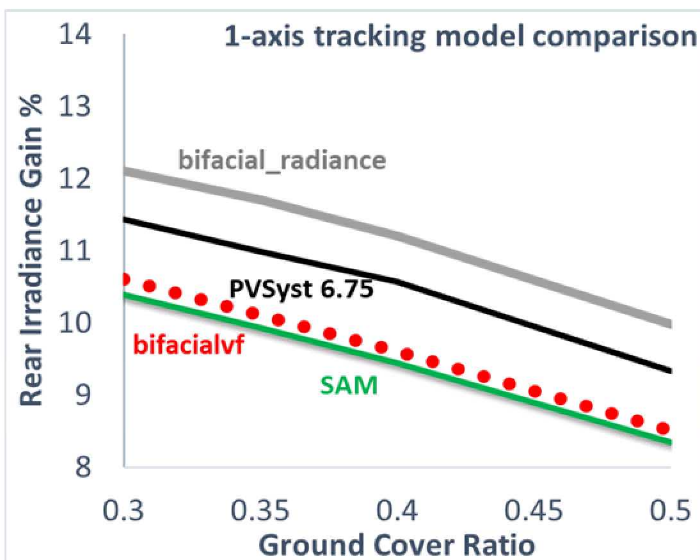


Fig. 15: Bifacial model intercomparison for 1-axis tracking system at different GCR values. Base parameters: 2-up portrait, 0.3 albedo, 2.5m hub height. (DiOrio, 2018)

Additional detailed simulations were conducted to estimate irradiance loss due to rear-side shading obstructions such as HSAT torque tubes. The more detailed bifacial_radiance performance model had to be used, which has the downside of being much more computationally intensive. Shading losses of up to 20% (5% when averaged over the entire module width) are predicted, particularly for close placement of shading objects (Fig. 16).

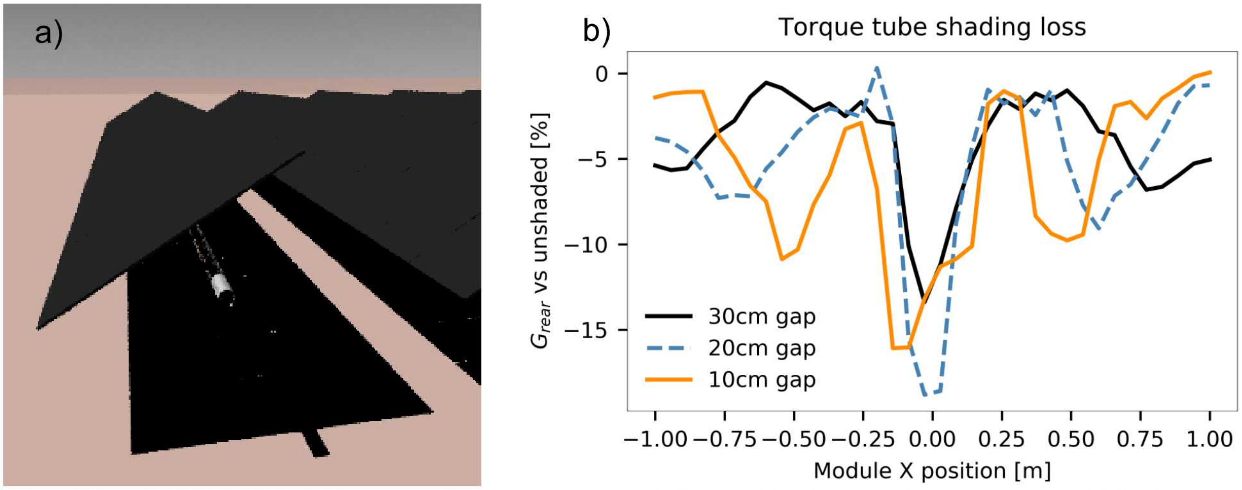


Fig. 16. a) RADIANCE image showing torque tube behind a modules row and b) G_{rear} across the module averaged over a sunny day. (Ayala et al., WCPEC 2018)

Bifacial Standards

Work completed in this project helped to establish a new bifacial module characterization standard (IEC 60904-1-2). This standard is finished and was unanimously approved by the national committees through the IEC. The final standard will be publicly available in January 2019, and incorporates several years of technical measurements, group discussions and wordsmithing. Field measurements and modeling work described in Deline et al, 2017 was instrumental in providing the technical basis for this standard. In preparation for a larger international round-robin testing the method, a US-based test of this standard was completed at the end of FY18 between NREL, Sandia, and CFV Solar Laboratory. Several other commercial labs have requested that we extend the round robin so that they can participate. We have agreed and this study continues. We will not share the results until all the parties have completed the measurements, however uncertainties were not found to be substantially higher for bifacial test article measurement than conventional monofacial module measurements.

In support of an international round-robin activity, NREL and CFV Solar provided measurements for 8-16 monofacial and bifacial test articles, with an additional 22 international measurement labs soon to participate. The international measurement activity was headed by the Solar Energy Research Lab of Singapore (SERIS) (Fig. 17).

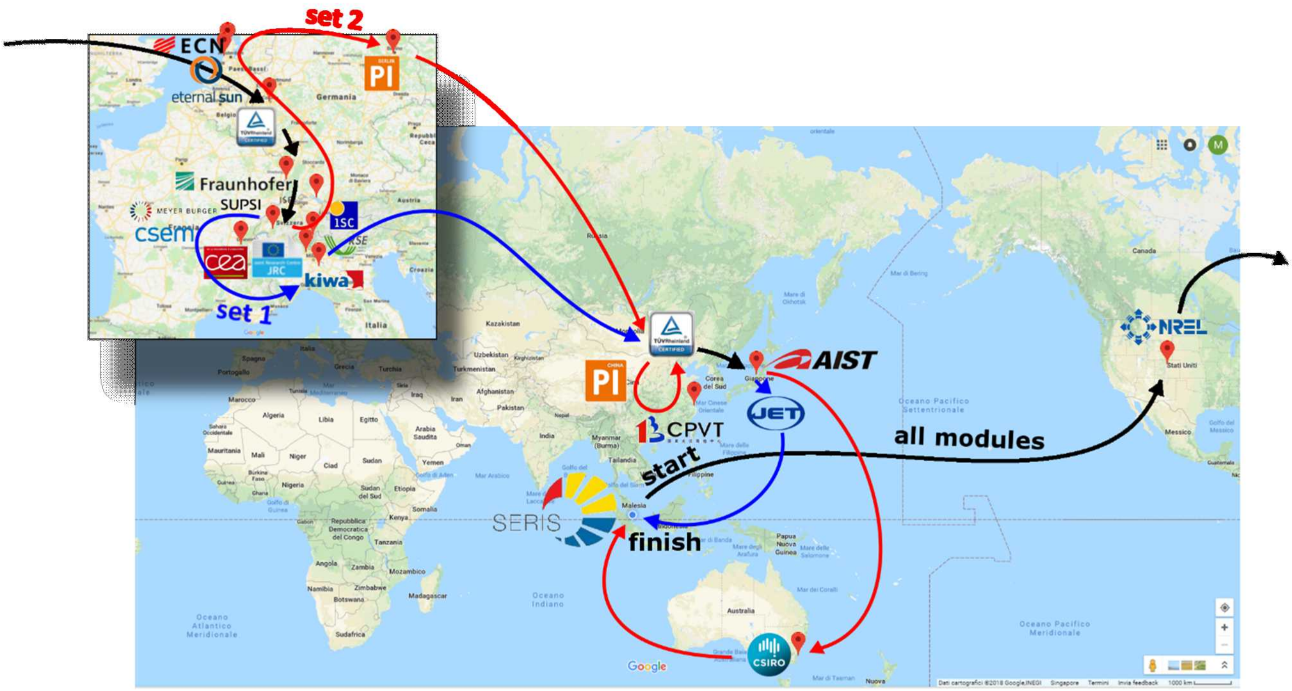


Figure 17: The circulation of testing items for the international bifacial round-robin activity led by SERIS. (Pravettoni et al., 2018)

Conclusions: We have completed all of our milestones and have generated a body of papers and presentations that are available to the public and are actively being read and downloaded. The aims of this project will continue with “Optimized Bifacial PV Systems” through FY21.

Budget and Schedule: The table below provides a summary of the project spend plan and actual expenses by quarter. We have ~$86k of carryover that is committed in contracts to supporting our two graduate students until the end of the fall term (Jan 2019). Their PhD theses will continue to support the aims of this project.

II. Project Spend Plan				**A. Federal Share Initial Plan**	**B. Federal Share Updated Actuals & Plan**
Year	**Quarter**	**From**	**To**		
2015	Q4	10/1/2015	12/31/2015	$280,000	$70,248
2016	Q1	1/1/2016	3/31/2016	$280,000	$287,070
2016	Q2	4/1/2016	6/30/2016	$280,000	$281,448
2016	Q3	7/1/2016	9/30/2016	$280,000	$285,417
2016	Q4	10/1/2016	12/31/2016	$250,000	$135,128
2017	Q1	1/1/2017	3/31/2017	$250,000	$305,305
2017	Q2	4/1/2017	6/30/2017	$250,000	$344,788
2017	Q3	7/1/2017	9/30/2017	$250,000	$273,552
2017	Q4	10/1/2017	12/31/2017	$220,000	$142,379
2018	Q1	1/1/2018	3/31/2018	$220,000	$301,486
2018	Q2	4/1/2018	6/30/2018	$220,000	$221,328
2018	Q3	7/1/2018	9/30/2018	$220,000	$266,960
Totals				**$3,000,000**	**$2,915,109**

Path Forward: The aims and objectives of this project will continue as DOE has decided to fund a new project entitled: "Optimized Bifacial PV Systems." This project, which is in partnership with NREL will focus on improving bifacial performance modeling capabilities. We will develop an approach to estimating the electrical mismatch caused by nonuniform irradiance hitting the backside of bifacial arrays. We will also bring the bifacial models developed during FY16-18 onto a super computer environment so that we can run true optimization calculations for various deployment scenarios.

Publications Resulting from This Work:

- Gerristen, E, Janssen, G., and Deline, C. 2018 "A "global" view of bifacial gain: dependence on geographic locations and environmental conditions," Chapter 8 in Bifacial Photovoltaics: Technology, applications, and economics, eds, Kopecek and Libal, IET Press, ISBN: 978-1-78561-274-9.

- Stein J.S and Deline, C. 2018 Bifacial Design Guidelines – The Effect of System Size on Bifacial Yields and Gains, in review and approval.

- DiOrio, N. and Deline, C. 2018 Bifacial Simulation in SAM, 5th Bifacial PV Workshop, Denver, CO

- Pravettoni, M, Deline, C. et al. 2018 The First Bifacial Round-Robin on Bi-Facial Modules, 5th Bifacial PV Workshop, Denver, CO

- Ayala Pelaez, S. et al., 2018 Single-Axis Tracked Bifacial System Results, 5th Bifacial PV Workshop, Denver, CO

- Marion B., 2018 Ground Albedo Measurements and Modeling, 5th Bifacial PV Workshop, Denver, CO
- Stein, J.S. and Jordan, D.C. 2018 Glass-Glass Photovoltaic Modules – Overview of Issues , DuraMAT Fall Workshop, Stanford, CA
- Riley, D. et al. 2018 Performance of Bifacial PV Modules with MLPE vs. String Inverters , WCPEC-7, Waikoloa, HI.
- Ayala Pelaez, S. et al.,. 2018. Model and Validation of Single-Axis Tracking with Bifacial PV , WCPEC-7, Waikoloa, HI. (Paper submitted to JPV)
- Ayala Pelaez, S. et al. 2018. Comparison of Bifacial Solar Irradiance Models with Field Validation . IEEE Journal of Photovoltaics, accepted
- Asgharzadeh, A. 2018. A Comparison Study of the Performance of South/North-facing vs East/West-facing Bifacial Modules under Shading Conditions , WCPEC-7, Waikoloa, HI.
- Ayala Pelaez, S. et al. 2018. Comparison of Bifacial Solar Irradiance Models with Field Validation . 10th PV Performance Modeling Collaborative Workshop, Albuquerque, NM
- Asgharzadeh, A. et al. 2018. Bifacial PV System Performance: Investigation of Shading Conditions . 10th PV Performance Modeling Collaborative Workshop, Albuquerque, NM
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- Stein, J.S., 2018. “ Solar PV Performance and New Technologies in Northern Latitude Regions “. Alaska Rural Energy Conference, Fairbanks, AK.
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- Stein, J.S. et al., 2017. Comparison of modeling methods and tools for bifacial PV performance . 9th PV Performance Modeling and Monitoring Workshop, Weihai, China.
- Deline, C., et al., 2017. Bifacial PV Performance Models: Comparison and Field Results . BiFiPV 2017 Workshop, Konstanz, Germany
- Hansen, C., et al., 2017. A Detailed Performance Model for Bifacial PV Modules . 33rd European PV Solar Energy Conference and Exhibition. Amsterdam, Netherlands.

- Stein, J. S., et al., 2017. Outdoor Field Performance of Bifacial PV Modules and Systems . 33rd European PV Solar Energy Conference and Exhibition. Amsterdam, Netherlands.
- Asgharzadeh, A. et al.., 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.
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- Marion, B., et al., 2017. A Practical Irradiance Model for Bifacial PV Modules . 44th IEEE PVSC. Washington DC.
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- Hansen, C. W., J. S. Stein, C. Deline, S. MacAlpine, B. Marion, A. Asgharzadeh and F. Toor (2016). Analysis of Irradiance Models for Bifacial PV Modules. 43rd IEEE Photovoltaic Specialist Conference. Portland, Oregon. SAND2016-0803 C.

Open Source Software Resulting from This Work:

- **bifacial_radiance:** Contains a series of Python wrapper functions from NREL to make working with RADIANCE easier, particularly for the PV researcher interested in bifacial PV performance.
- **bifacialvf:** A self-contained view factor (or configuration factor) model from NREL which replicates a 5-row PV system of infinite extent perpendicular to the module rows. Single-axis tracking is supported, and hourly output files based on TMY inputs are saved. Spatial nonuniformity is reported, with multiple rear-facing irradiances collected on the back of each module row.
- **3Dbifacial_VF**: Matlab functions and example scripts to model rearside irradiance using a 3D view factor approach. Able to simulate variations across individual modules in an array.
- **System Advisor Model (SAM):** a version of the bifacialvf function was added to SAM and is currently in beta testing. Planned release is in October 2018.

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[1] IRTPV, "International Technology Roadmap for Photovoltaics (ITRPV) – Results 2017, ITRPV, March, pp1-37, 2018.

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