PVPerformance MODELING COLLABORATIVE

SAND2017-10301C

Outdoor Field Performance of Bifacial PV Modules and Systems

33rd EU PVSEC
Amsterdam, Netherlands
September 25-29, 2017

Joshua S. Stein[1], Dan Riley[1], Matthew Lave[1], Chris Deline[2], Fatima Toor[3], and Clifford Hansen[1]

[1]*Sandia National Laboratories*
[2]*National Renewable Energy Laboratory*
[3]*University Of Iowa*

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..

Paper Number: 6CO.13.3

SAND2017-XXXX C

Team Acknowledgements

This work is part of a collaborative project between three institutions

- **Sandia National Laboratories**
  - Joshua Stein - PI
  - Clifford Hansen
  - Dan Riley
  - Matthew Lave
- **National Renewable Energy Laboratory**
  - Chris Deline – Co-PI
  - Bill Marion
  - Sarah MacAlpine
- **University of Iowa**
  - Prof. Fatima Toor
  - Amir Asgharzadeh (PhD Candidate)

EU PVSEC Poster (Tuesday)

- A Detailed Performance Model for Bifacial PV Modules. (***6BV.2.35***)

3-Yr Bifacial Research Project (FY16-18)

Collaborative project between Sandia, NREL and University of Iowa
(https://pvpmc.sandia.gov/pv-research/bifacial-pv-project/)

Task 1: Measure Outdoor Bifacial Performance

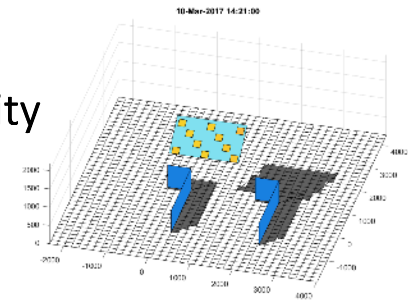
- Module scale
  - Adjustable rack IV curves (height, tilt, albedo, and backside shading effects)
  - Spatial variability in backside irradiance
  - Effects of backside obstructions and shading
  - Prism Solar RTC (tilt, orientation, and albedo effects)
  - Vertical bifacial modules at Turku University, Finland (latitude effects)
- String scale
  - Fixed tilt rack (tilt, system size, and mismatch effects)
  - Single axis tracker (investigate potential)
  - Two-axis tracker
- System scale
  - String level monitoring on commercial rooftop system (validation data)

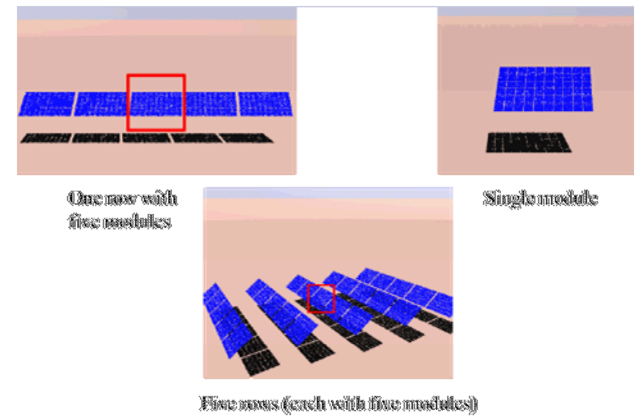
3-Yr Bifacial Research Project (FY16-18)

Collaborative project between Sandia, NREL and University of Iowa

Task 2: Develop Performance Models

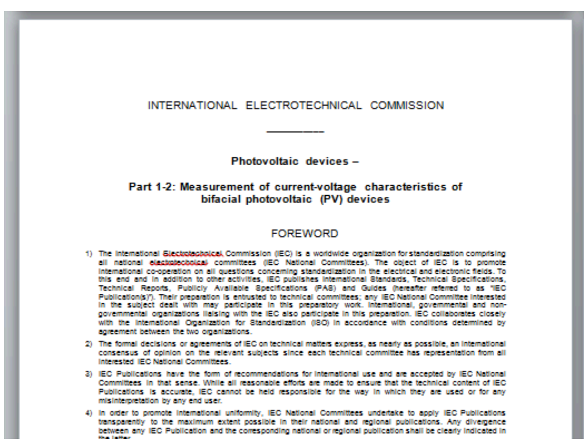
- Irradiance modeling
  - Ray tracing methods – Sensitivity studies
    - Univ of Iowa
  - View (Configuration) Factor methods
    - Sandia and NREL
- Module performance models
    - Sandia





Task 3: Support Rating Standards

- Support new bifacial rating standard (IEC 60904-1-2 - Draft)
  - NREL



INTERNATIONAL ELECTROTECHNICAL COMMISSION

Photovoltaic devices –

Part 1-2: Measurement of current-voltage characteristics of bifacial photovoltaic (PV) devices

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.

2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.

3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.

4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.

Measuring Bifacial System Performance

- We measure and compare bifacial PV performance to similar monofacial modules and systems.
- Bifacial performance is affected by:
  - Factors that affect irradiance on back (and front) of module
    - Sun position (latitude, season), module tilt and azimuth
    - Albedo
    - Height above ground
    - System size and configuration
    - Self shading effects and interactions
    - Obstructions and shadows, and system size (racking)
    - Snow and soiling factors
  - Factors that affect power and energy production
    - Bifacial ratio (back/front module rating)
      - » Varies with cell technology and module design (>90%, >80%, >60%, ~35%)
    - Mismatch effects
      - » Spatially variable backside irradiance increase mismatch losses
      - » Perhaps mitigated by dc-dc optimizers and microinverters

Bifacial Performance Metrics

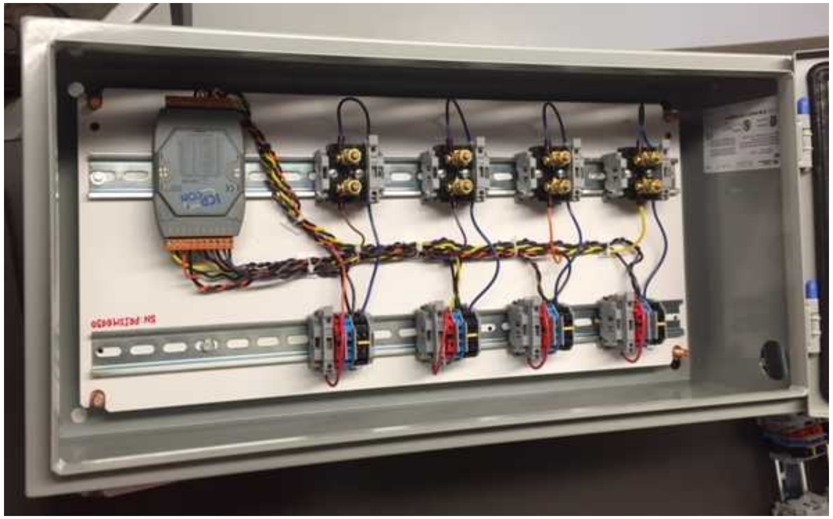
- $E_{bifacial} = (1 + BG_E)E_{monofacial}$ (also works for power)
  - Assumes bifacial and monofacial deployed at same orientation
- Bifacial Gains – quantifies difference between bifacial and monofacial performance
  - Difference can be from bifaciality and other differences (e.g., temperature coefficient, spectral, and AOI differences)
  - **Instantaneous Bifacial Gain in Power (BG_i)**
    - $\mathrm{BG_i(t)} = 100\% \times \left(\frac{\mathrm{P_{bifacial}(t)\ /\ P0_{bifacial}}}{\mathrm{P_{monofacial}(t)\ /\ P0_{monofacial}}} - 1\right)$
  - **Bifacial Gain in Energy (BG_E)**
    - $\mathrm{BG_E} = 100\% \times \left(\frac{\sum_{1\,month} \mathrm{P_{bifacial}\ /\ P0_{bifacial}}}{\sum_{1\,month} \mathrm{P_{monofacial}\ /\ P0_{monofacial}}} - 1\right)$
- "Potential" Bifacial Gain ($BG_{Potential}$)
  - $BG_{potential} = 100\% \times R_b\left(\frac{G_f + G_r}{G_f} - 1\right)$
    - R_b = bifacial ratio = Pmp_{back}/Pmp_{front} (at STC)
    - G_f = POA irradiance on front of bifacial module
    - G_r = POA irradiance on back of bifacial module
- The ultimate metric is LCOE

Prism Solar RTC Systems

- Systems in New Mexico, Nevada, and Vermont
  - NM: ~19 months of data
  - NV: ~8 months of data
  - VT: ~4 months of data
- Five orientations at each site
- Optimal racking (no backside shading)
- Module-scale DC monitoring (I and V)
- Data corrected to front flash ratings

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



Measured Albedo in NM
- Natural = 0.2 – 0.3
- White = 0.5 – 0.6

Prism Solar Systems in Nevada and Vermont

Vermont System in winter (before data collection)

Nevada Prism Solar System

Measured Albedo in VT
- Natural = 0.1 (Summer)
- White = 0.2 (Summer)

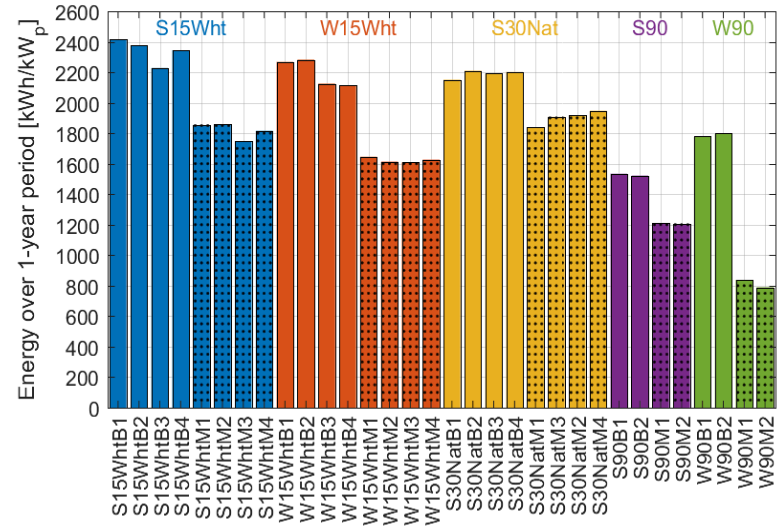
Measured Albedo in NV
- Natural = 0.2
- White = 0.3

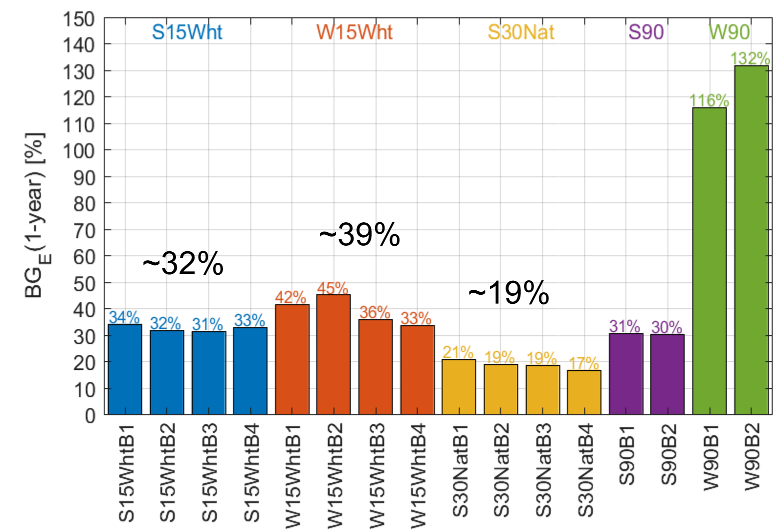
Vermont System in summer (trackers in background)

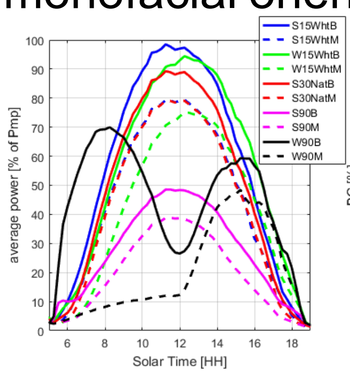
Prism Solar Results from New Mexico

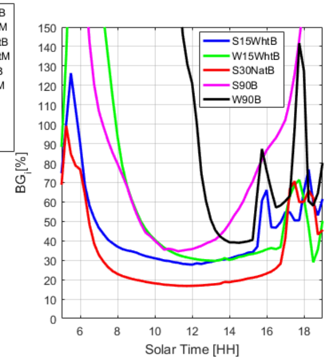
- Bifacial modules outperformed monofacial in all cases (energy).
- Bifacial energy gains ranged from 17%-132% in NM
- Enhanced albedo = ~0.55 vs. 0.25 for natural surface.
- W-facing vertical bifacial experienced bifacial energy gains over 100% due to cool morning and hotter afternoons.
- Bifacial gains vary significantly by time of day (sun position)
- Bifacial advantages increase with non-optimal monofacial orientations.

First Year Results



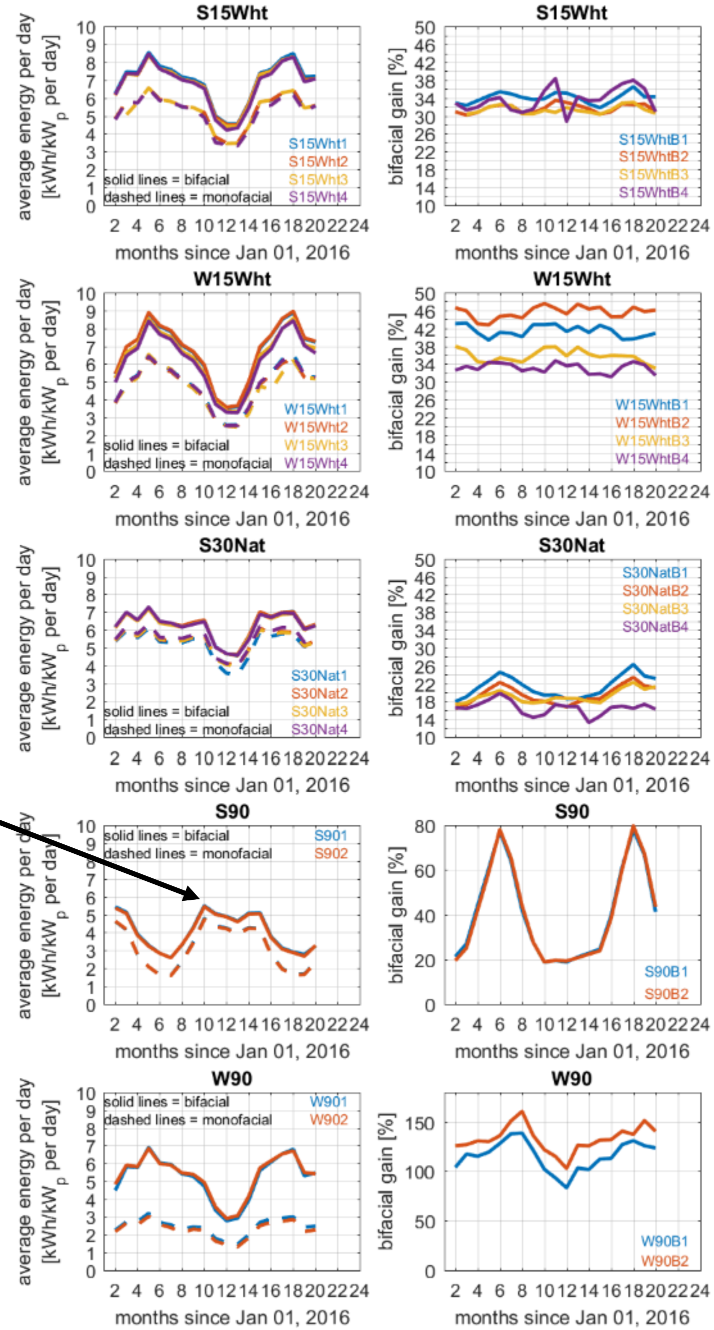






Prism NM Results

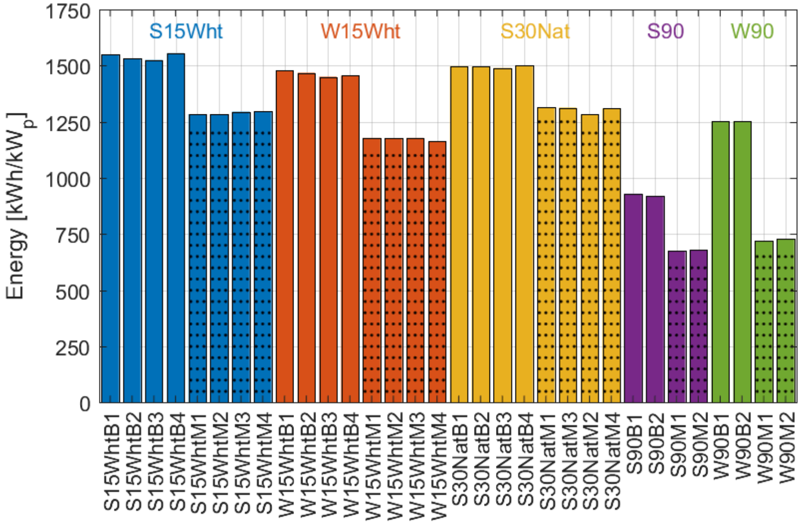
- **No significant degradation** is observed in the first 19 months of deployment in New Mexico.
- Most systems produce max energy in the summer.
    - Exception: S90 array peaks in winter

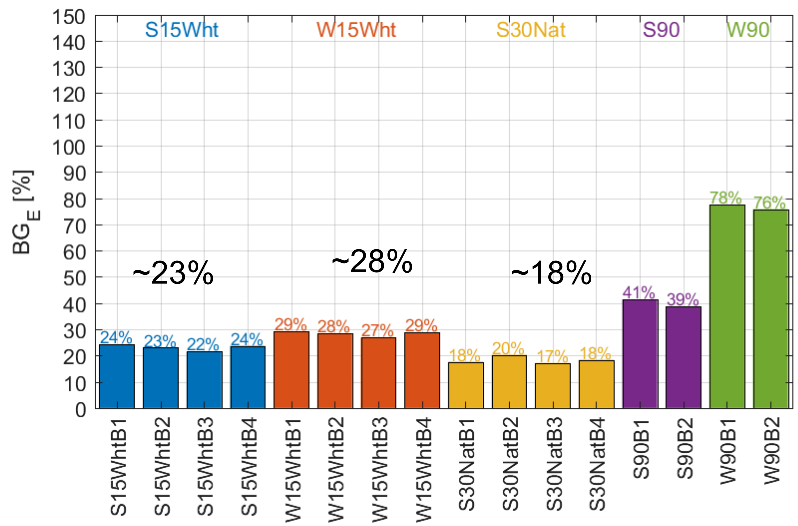


Prism Solar Results from Nevada

- Bifacial modules outperformed monofacial in all cases (energy).
- Bifacial energy gains ranged from 17%-78% in NV.
- Enhanced albedo = ~0.3 vs. 0.2 for natural surface.
    - Ground less reflective than in NM.

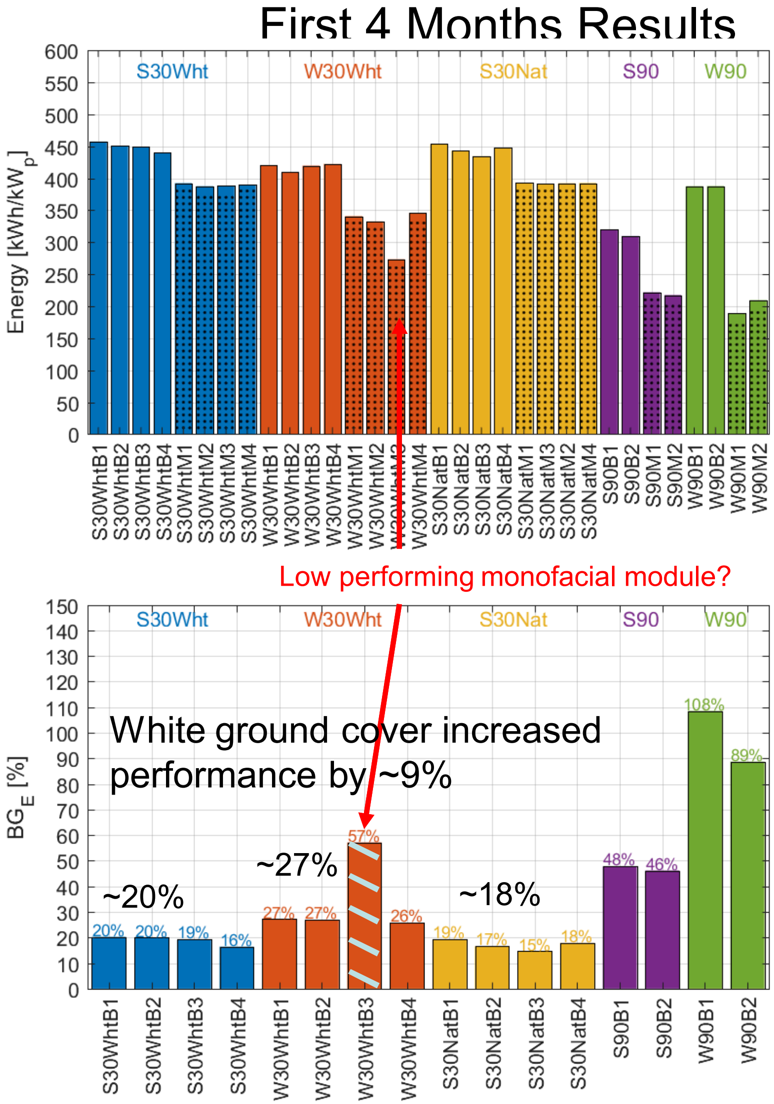
First 8 Months





Prism Solar Results from Vermont

- Bifacial modules outperformed monofacial in all cases (energy).
- Bifacial energy gains ranged from 15%-108% in VT
- Bifacial advantages increase with non-optimal monofacial orientations.
- Enhanced albedo = ~0.2 vs. 0.09 for natural surface (grass).
    - Much lower than for other sites.

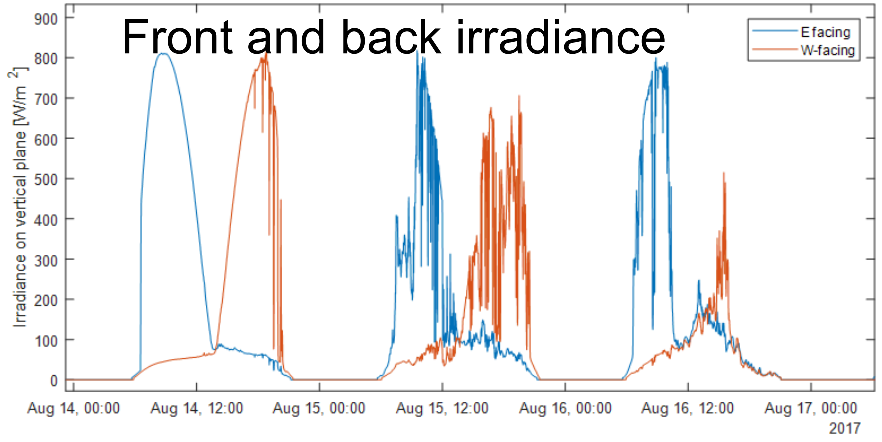


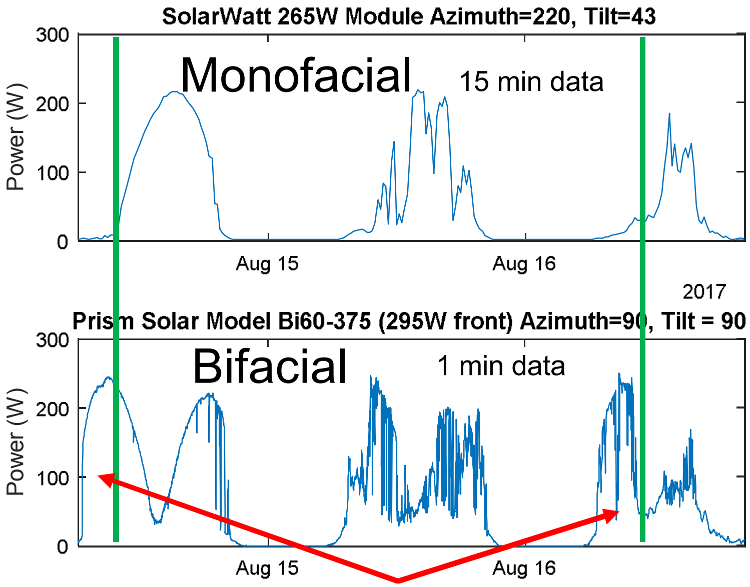
Vertical Bifacial System in Finland (~60˚N)

- 4 Prism Solar bifacial modules grid connected with microinverters
- Front and back POA irradiance
- Module temperature monitored
- DC current and voltage measured on each module.

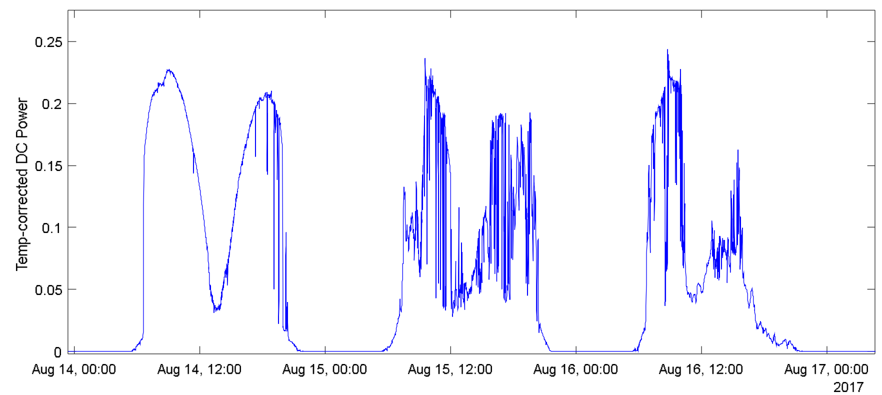
Initial Results:

- Normalized bifacial output 37% more energy over three day period compared with monofacial azimuth = 220, tilt=43





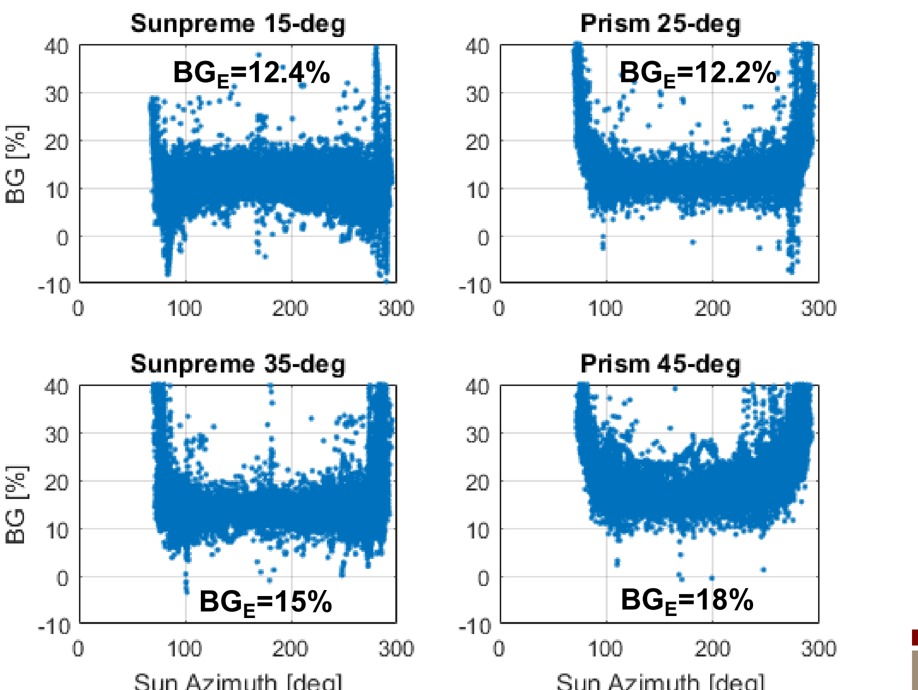
Vertical bifacial outputs earlier



Fixed Tilt String-Level Performance

- Four rows at 15˚, 25˚, 35˚,and 45˚ tilt.
- Each row has two strings of 8 modules (one monofacial and one bifacial)
- Modules are alternated to minimize backside spatial irradiance bias.
- Two types of bifacial modules are used:
  - Prism Solar (n-Type c-SI)
  - SunPreme (HJT/HIT)
  - Monofacial modules are from SolarWorld

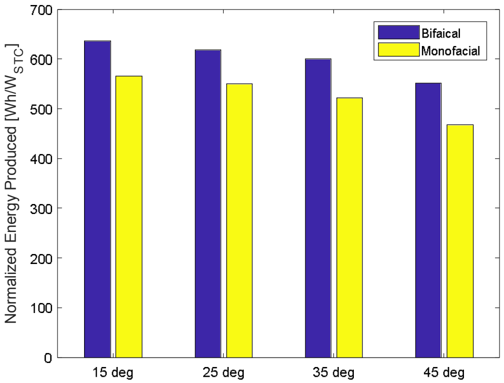
Data from June 1 – Aug 31, 2017



Fixed-tilt String-level Arrays

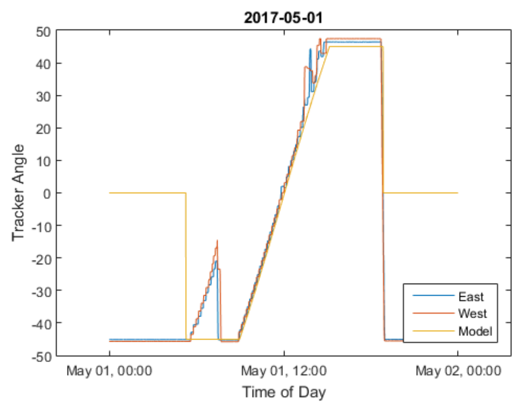
Preliminary Results (Summer)

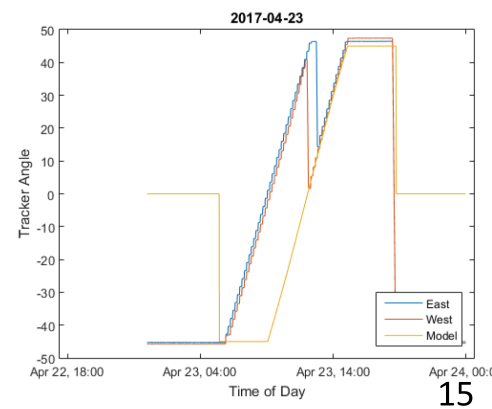
- Bifacial gain in energy (BG_E) appears to increases with tilt angle (15˚ and 25˚ are similar due to slight shading effects)
- Total energy generated (3 summer months) is inversely proportional to BG_i.



Bifacial Single Axis Tracker (NM)

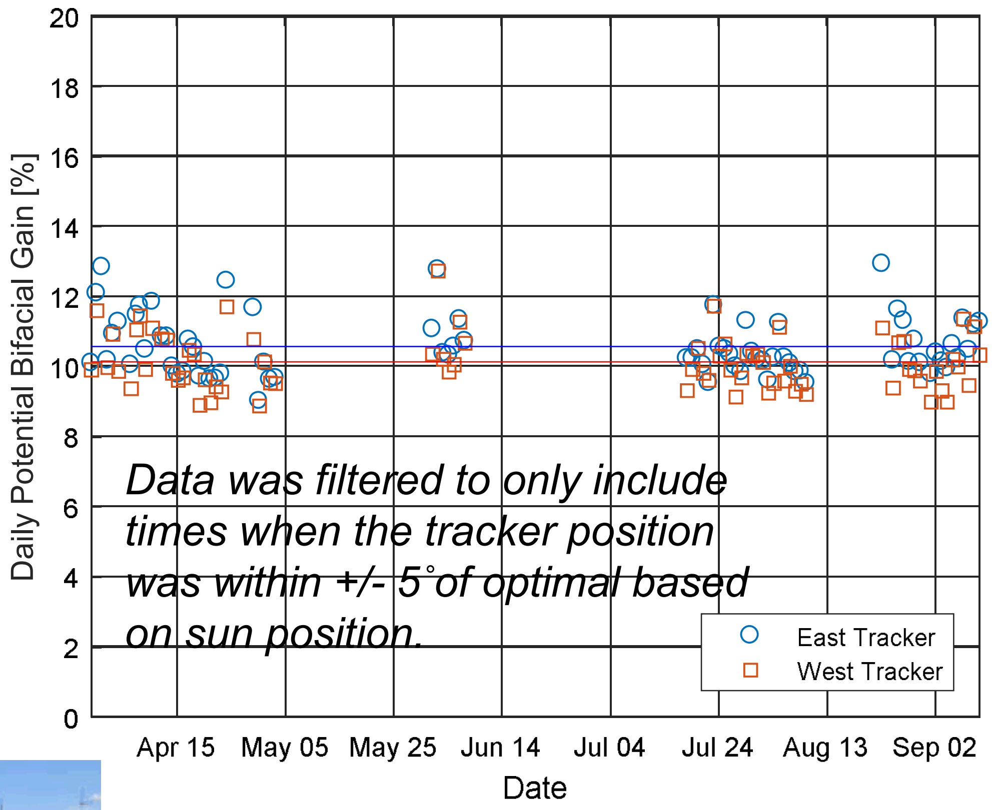
- Module and Inverters installed
  - Row 1: String 1: Sunpreme
  - Row 1: String 2: TBD
  - Row 2: String 1: Prism Solar
  - Row 2: String 2: TBD
- Inclinometers, front and back reference cells on each tracker
- Tracking issues
  - Three photodiodes with shade block control tracker movement
  - We are experiencing problems with the tracker starting to move too early ("off-track").



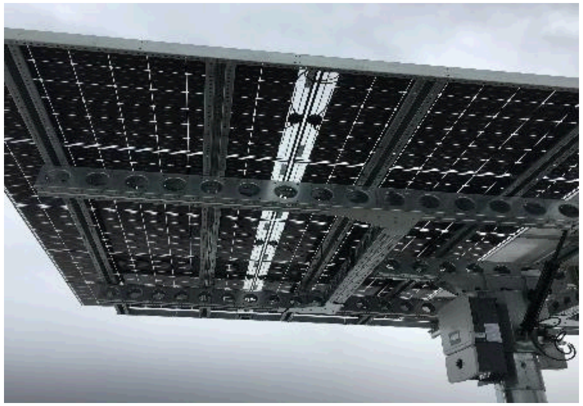


Bifacial Single Axis Tracker (NM)

- Daily Potential Bifacial Energy Gains were estimated from front and back irradiance data using reference cells.
- Potential gains increase when tracker is off-track, but yield decreases



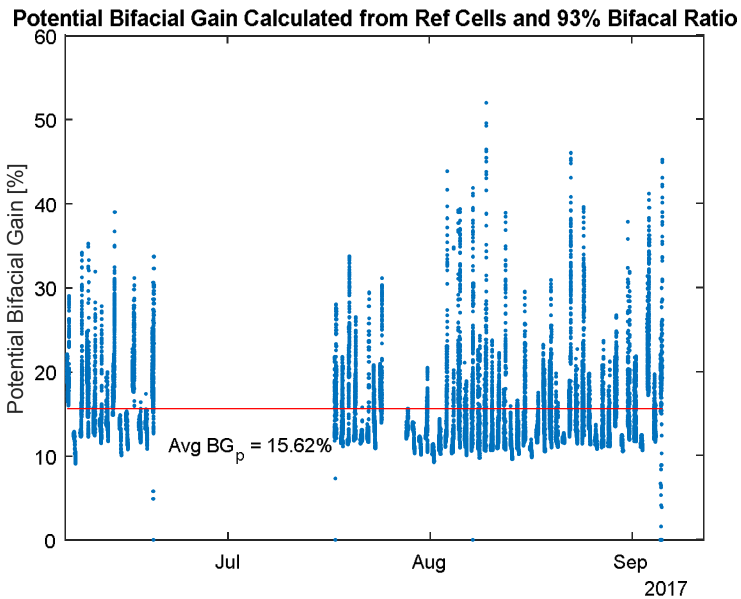
Bifacial Two Axis Trackers (VT)

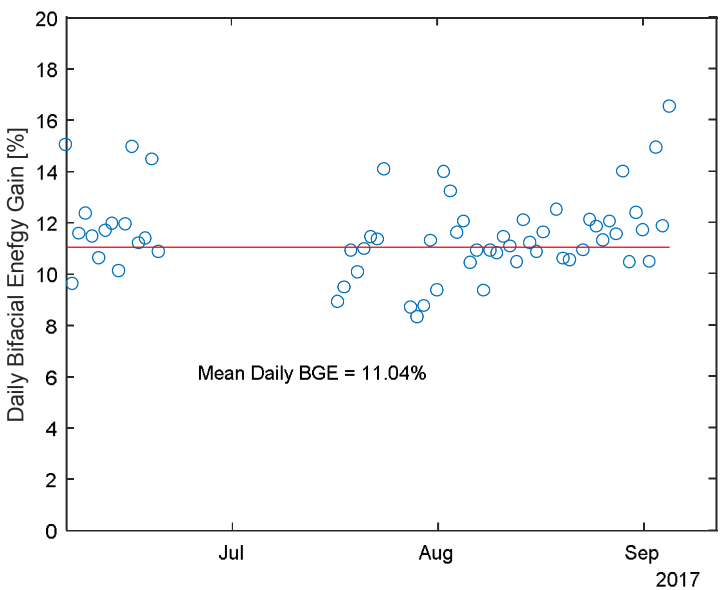


- Two 2-axis trackers each have two **strings** (one of monofacial and one of bifacial)
  - Bifacial system 1 (Prism Solar) = R_b=~93%
  - Bifacial system 2 (SolarWorld) = R_b=~62%
  - Significant obstructions behind bifacial modules mean that this is not an optimized design.
  - No winter data yet.

Two-Axis Tracker (VT) Results

- Mean potential bifacial gain = 15.6%, 9.5% SolarWorld gains in ()
- Mean instantaneous gain = 12.3% ,6.8%
- Mean of daily bifacial gain in energy = 11%, 5.8%
- Gains are expected to be even higher in winter when ground is covered in snow.
- Gains are lower than module-scale tests
  - Mismatch, racking and self shading effects.





Conclusions 1

- **Bifacial performance always exceeds monofacial performance** when module output is normalized for front side STC rating and the back 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.
- 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 back side irradiance is available.
- 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.

Conclusions 2

- 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 back 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. **Commercial white rooftops** have albedo >0.65.
- 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. Module front side rating, temperature coefficients, bifacial ratio and price all have to be considered when choosing the best bifacial module for a given project.

Questions?

Joshua S. Stein

jsstein@sandia.gov