Field Performance of Bifacial PV Modules and Systems

PVPerformance MODELING COLLABORATIVE

Exceptional service in the national interest

Sandia National Laboratories

8th PVPMC Performance Modeling and Monitoring Workshop
Santa Anna Pueblo, New Mexico
May 9-10, 2017

Joshua S. Stein PhD.
Sandia National Laboratories,
Albuquerque, NM USA

U.S. DEPARTMENT OF ENERGY NNSA

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..

SAND2017-4868 C

Team Acknowledgements

This work is a collaborative project between three institutions

- Sandia National Laboratories
  - Joshua Stein - PI
  - Cliff 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 (graduate student)

Factors Influencing Bifacial PV Performance

- Bifacial PV makes lots of promises. What is the reality?
  - Bifacial performance is affected by many more factors than monofacial PV performance. Our project aims to quantify these effects and generate validated models to predict them.
- Factors that affect irradiance on back (and front) of module
    - Sun position (latitude, season), Tilt and Azimuth
    - Height above ground
    - System size and configuration
    - Albedo and self shading effects
    - 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 and module design (>90%, >80%, >60%, ~35%)
    - Mismatch effects (may be enhanced by variable rearside irradiance)

3-Yr Bifacial Research Project (FY16-18)

Sandia National Laboratories

Collaborative project between Sandia, NREL and University of Iowa

Task 1: Measure Outdoor Bifacial Performance

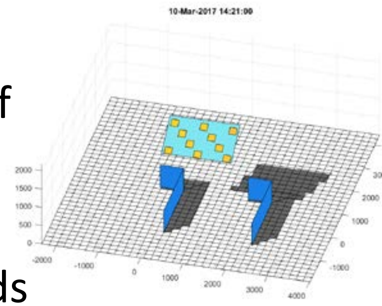
- Module scale
  - Adjustable rack IV curves (height, tilt, albedo, and backside shading effects)
  - Spatial variability in backside irradiance
  - Effects of backside obstructions and shading
  - Prism Solar RTC (tilt, orientation, and albedo effects)
  - Vertical bifacial modules at Turku University,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

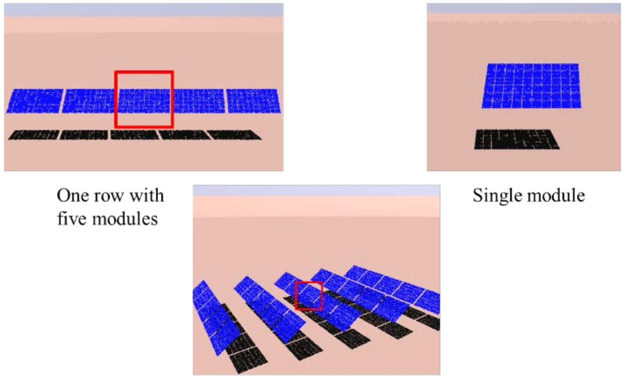
3-Yr Bifacial Research Project (FY16-18)

Collaborative project between Sandia, NREL and University of Iowa

Task 2: Develop Performance Models

- Ray tracing methods – Sensitivity studies – Amir Asgharzadeh (Univ of Iowa, PhD Candidate with Prof. Fatima Toor)
- View (Configuration) Factor methods – Cliff Hansen and Dan Riley (Sandia)
- – Sara MacAlpine and Bill Marion (NREL)





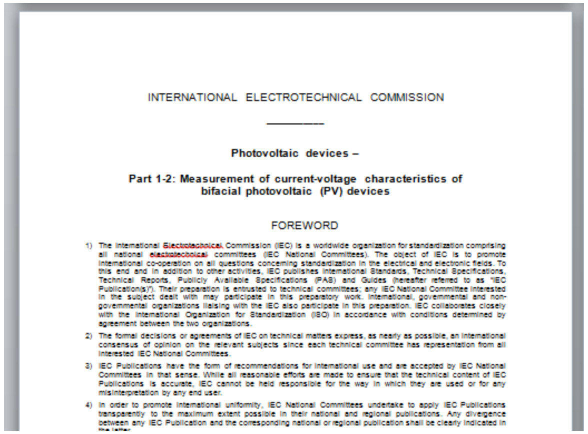
One row with five modules

Single module

Five rows (each with five modules)

Task 3: Support Rating Standards

- Support new bifacial rating standard (IEC 60904-1-2)– Chris Deline (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.

Module-Scale Adjustable Rack

Holds four modules
- -2 bifacial
- -2 monofacial

Reference Cells
- -2 front facing
- -3 back facing

Multitracer
- -measures IV curves and module temps

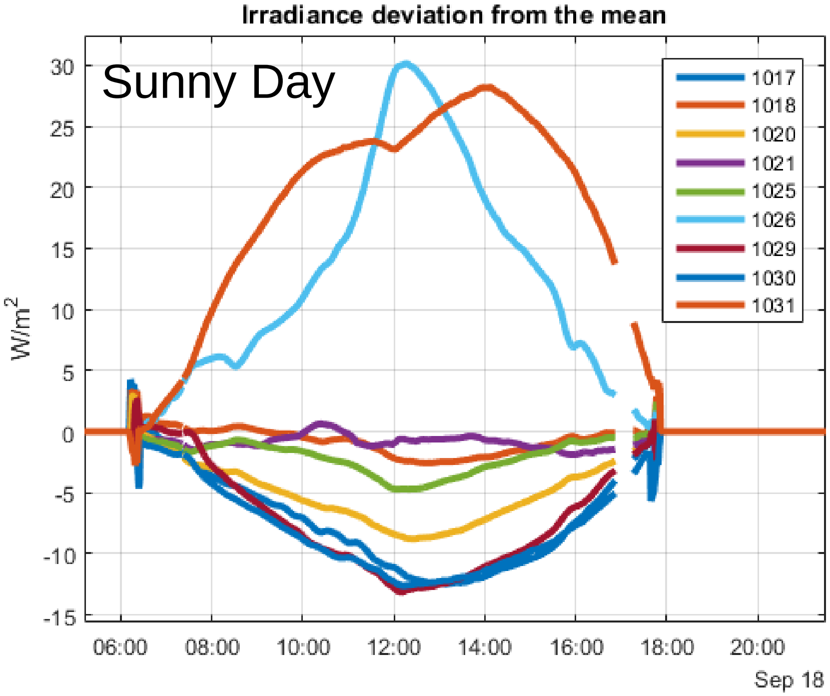
Variables
- -Height
- -Tilt
- -Albedo

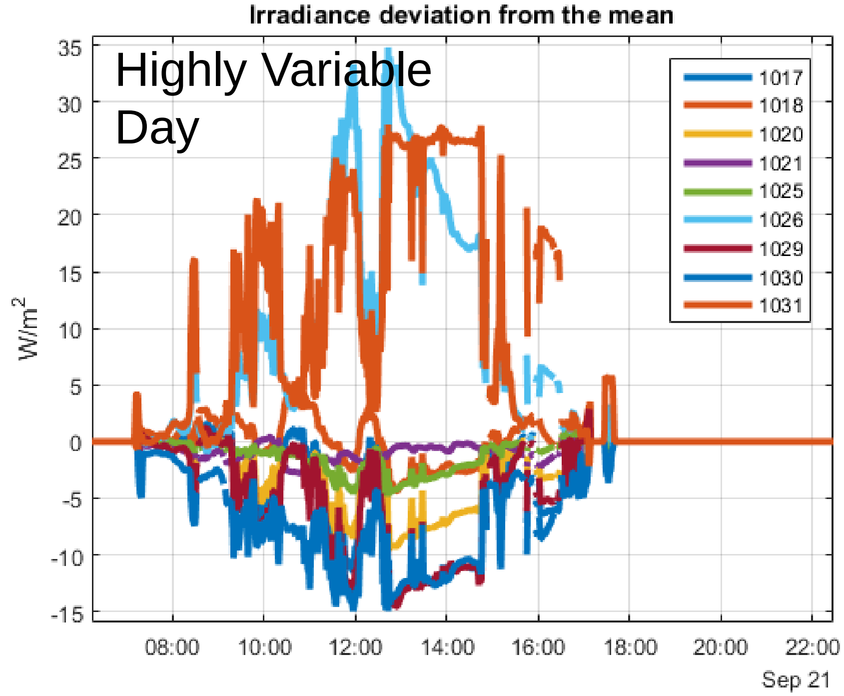
Backside Irradiance Mapping

- Measures 10 irradiances on the back side of a “module”
- “Module” can be moved and mounted anywhere to test different conditions
- Measurement cells calibrated to agree within 0.5%
- Data from the top mounting configuration shown on next slide

Backside Irradiance Mapping

Bottom cells exhibit higher irradiance values in this configuration





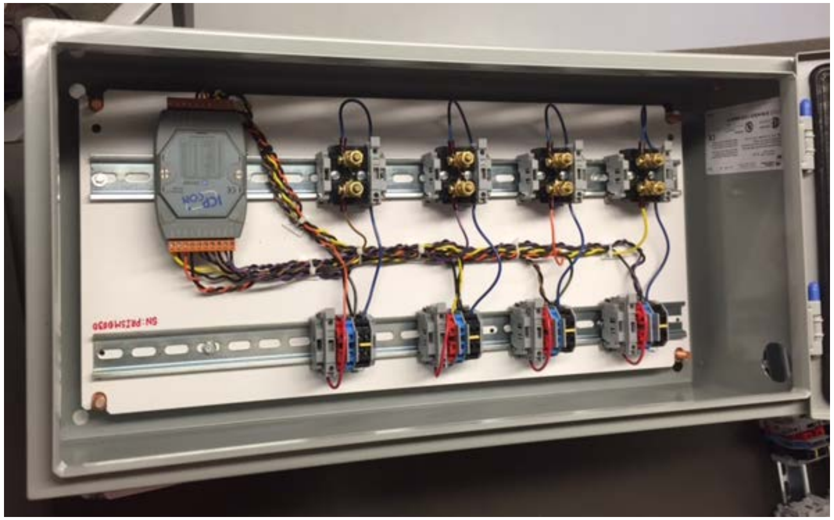
In this test configuration, irradiance on the backside differed by up to 42 W/m^2 on a sunny day

Prism Solar RTC Systems

- Systems in New Mexico, Nevada, and Vermont
  - NM: >1 year of data
  - NV: ~4 months of data
  - VT: 37 days 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

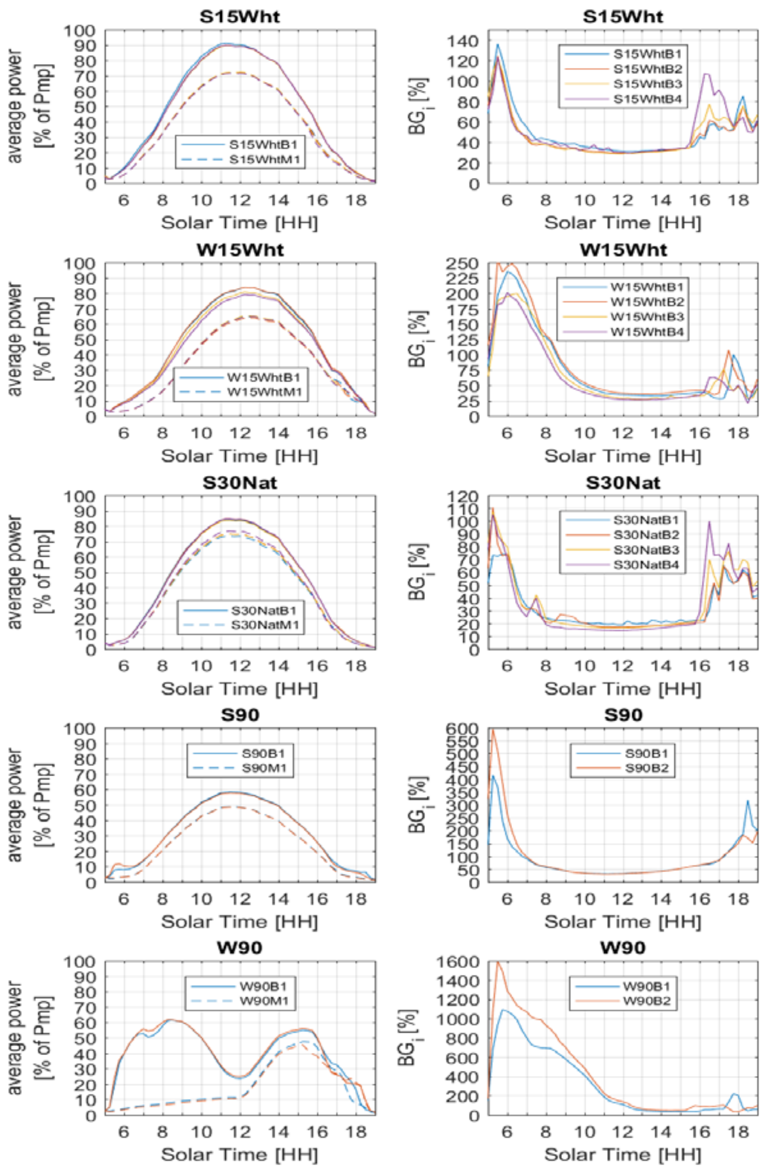
Label	Orientation		Ground Surface
	Tilt	Azimuth	
S15Wht	15˚	180˚ (South)	White gravel
W15Wht *	15˚	270˚ (West)	White gravel
S30Nat	30˚	180˚ (South)	Natural
S90	90˚	180˚ (South)	Natural
W90	90˚	270˚ (West)	Natural

*W30Wht in VT

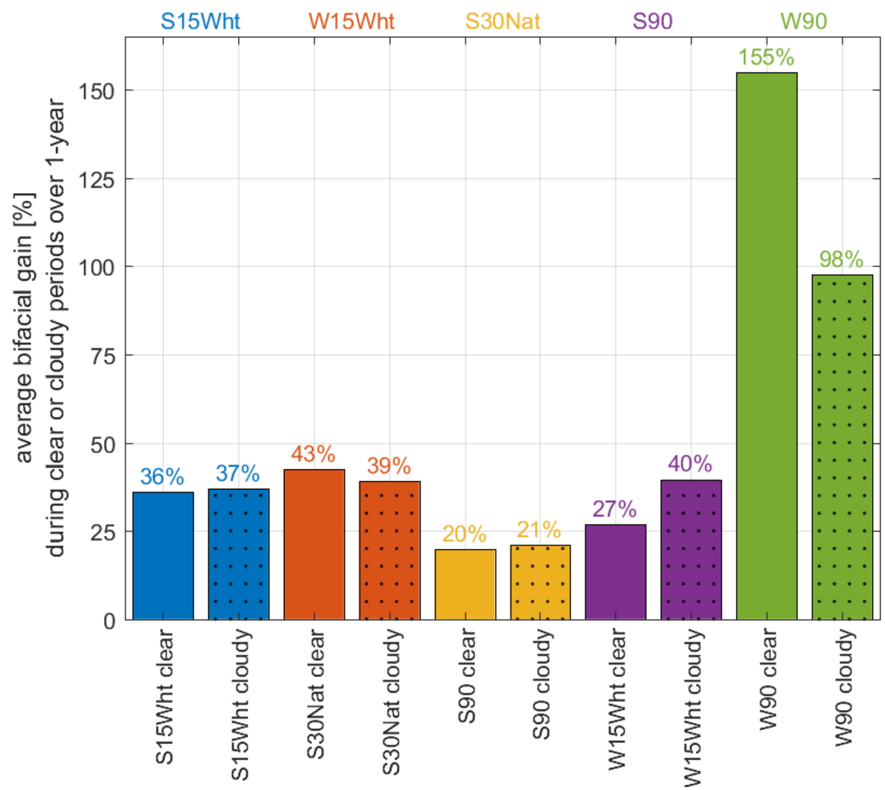


Measured Albedo in NM
- Natural = 0.2 – 0.3
- White = 0.5 – 0.6

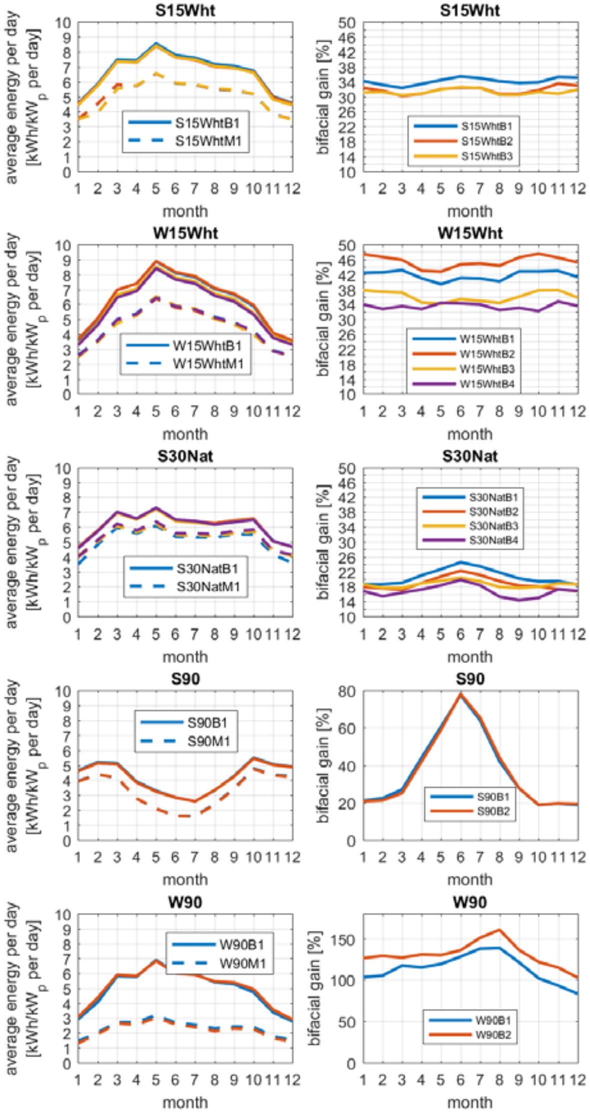
Prism Solar Results from New Mexico



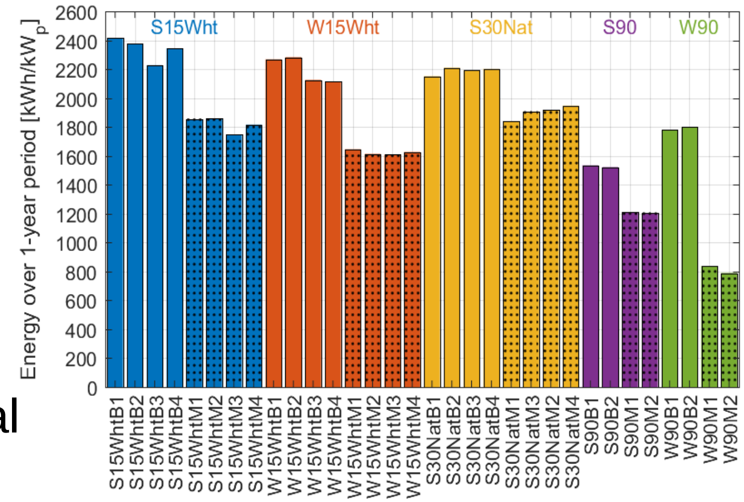
- Bifacial power gains vary throughout the day.
- Bifacial advantages increase with non-optimal monofacial orientations.
- Bifacial advantages are slightly sensitive to clear vs. cloudy sky conditions

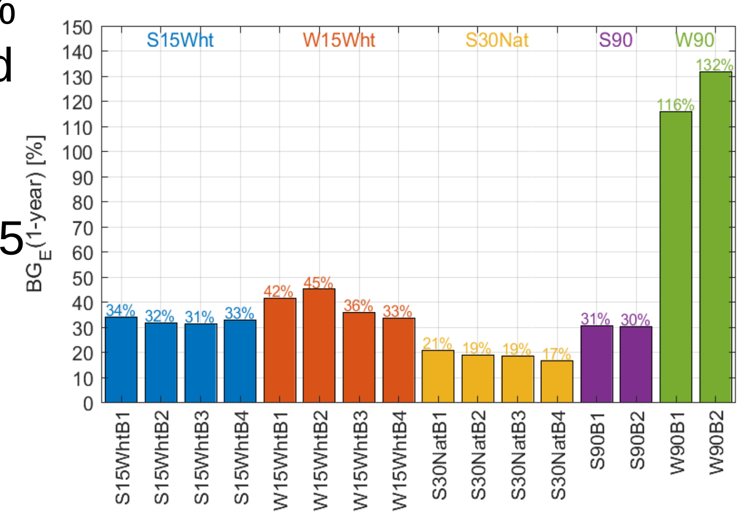


Prism Solar Results from New Mexico

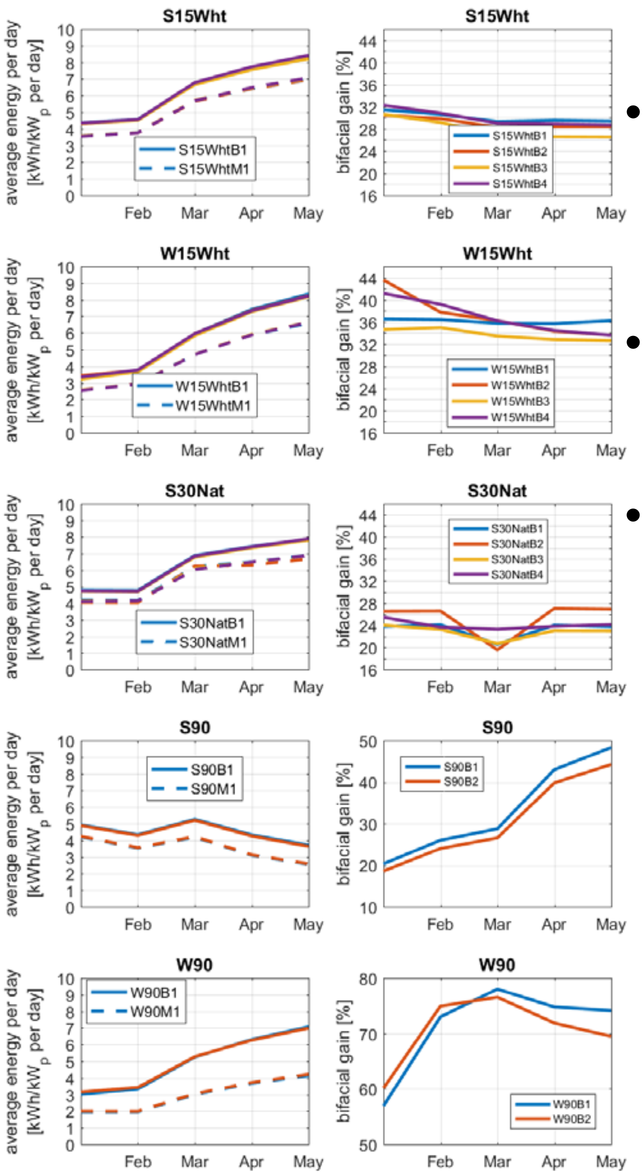


- Bifacial modules outperformed monofacial in all cases (energy).
- Bifacial energy gains ranged from 17%-132% in NM
- W-facing vertical bifacial experienced bifacial energy gains over 100% due to cool morning and hotter afternoons.
- Bifacial gains greater in summer (except for W15 and S15, which were flat)
- S90 produced more energy in winter due to low sun elevations

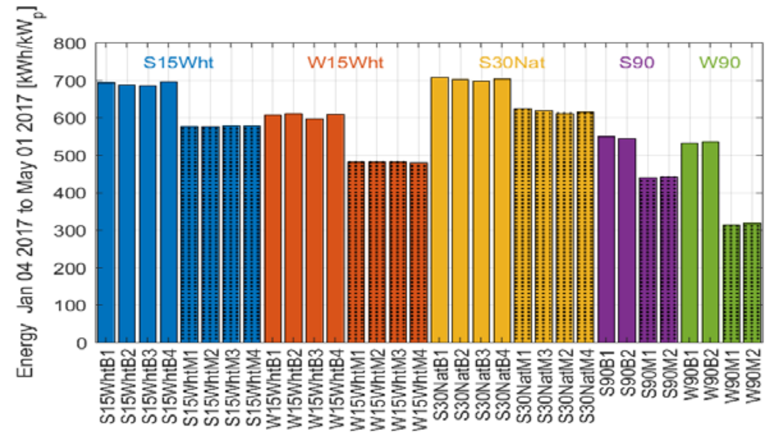


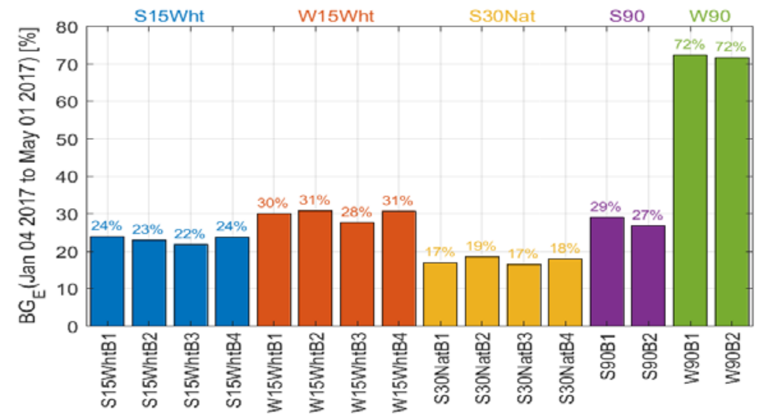


Prism Solar Results from Nevada

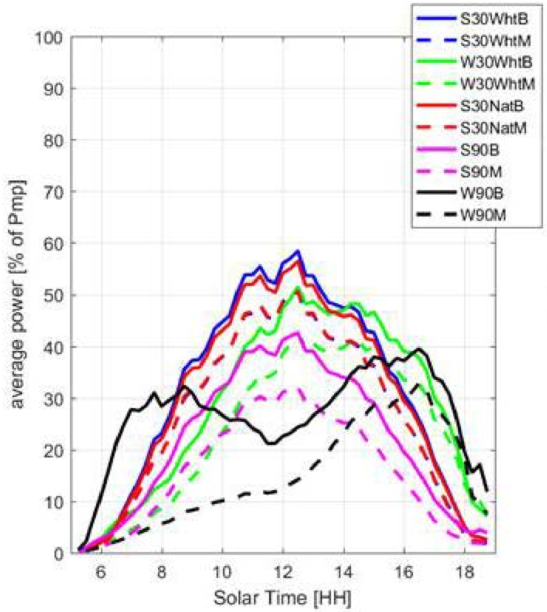


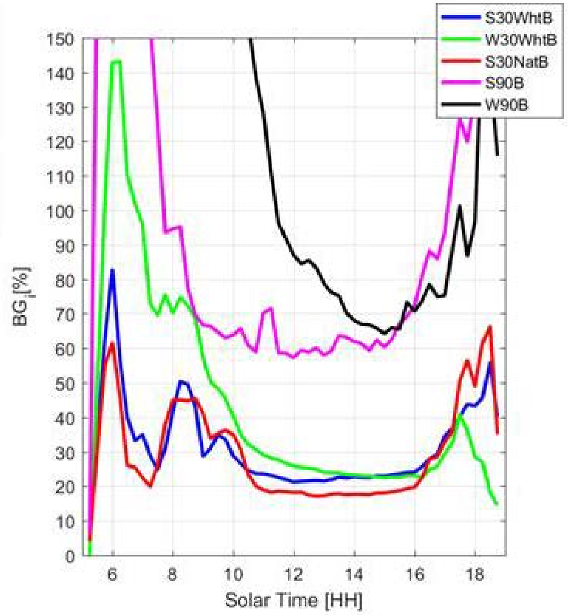
- Bifacial modules outperformed monofacial in all cases (energy).
- Bifacial energy gains ranged from 17%-72% in NV
- Results are largely similar to what is seen in NM
  - Exception is W90 gain is lower than in NM.
  - Likely due to lack of data from summer

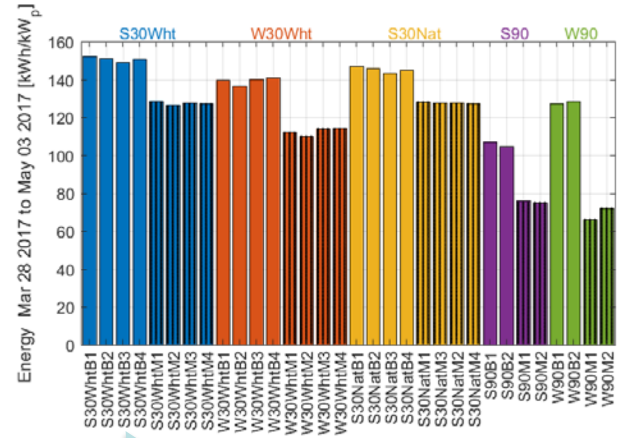


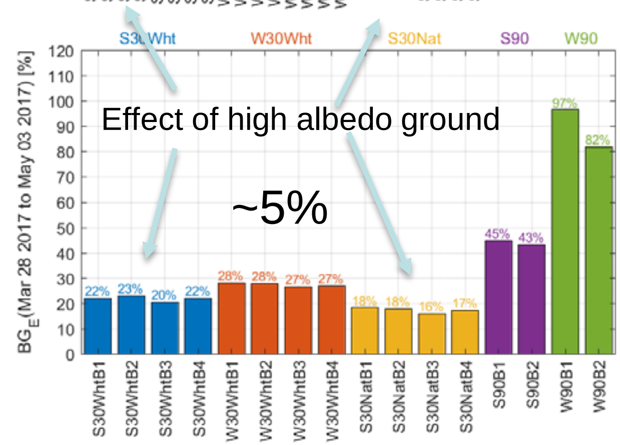


Prism Solar Results from Vermont





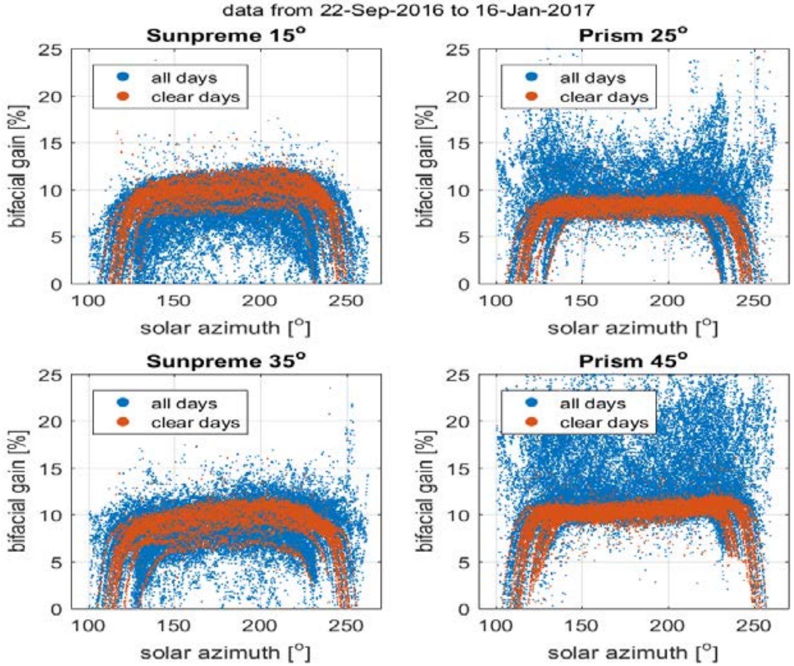




- Bifacial modules outperformed monofacial in all cases (energy).
- Bifacial energy gains ranged from 16%-97% in VT
- Effect of high albedo ground can be observed directly since the S30Wht and S30Nat orientations are the same.
  - Result of high albedo ~5% additional energy gain!
- Gains are expected to increase with Summer data is included. (direct irradiance behind the arrays)

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 interspersed so rear-side, spatial irradiance bias is minimized.
- Two types of bifacial modules are used:
  - Prism Solar (n-Type c-SI)
  - SunPreme (HJT/HIT)
  - Monofacial modules are from SolarWorld
- Shading effect seen in AM and PM
  - Due to monofacial modules are thicker and shade adjacent bifacial modules (we are going to fix this in the future)



Fixed-tilt String-level Arrays

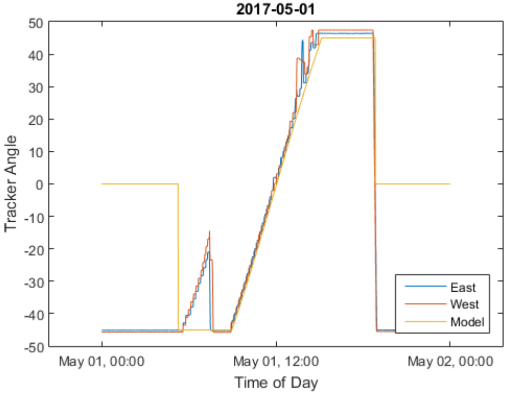
Preliminary Results

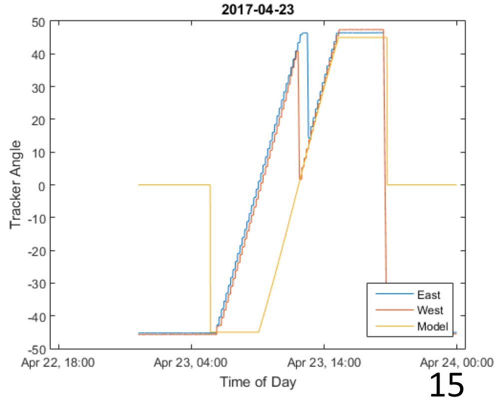
- Prism Solar BG = 6%-10%+, better performance on cloudy days
  - Prism cells have pyramidal texturing, which increases performance in diffuse light.
- SunPreme performance is more variable during clear days and lower on cloudy days. Two possibilities:
  - HIT cells have lower Temp coef than reference modules
  - Lack of cell texturing may reduce diffuse performance
- Bifacial performance appears to benefit significantly from module scale MPPT
  - Non uniform rear side irradiance
- Multi-row array includes self shading effects.
  - Multiple rows
  - Multiple modules per row

Stein, J. S., D. Riley, M. Lave, C. Deline and F. Toor (2017). Outdoor Field Performance from Bifacial Photovoltaic Modules and Systems. 44th IEEE PVSC. Washington, DC. Accepted as oral presentation.

Bifacial Single Axis Tracker (NM)

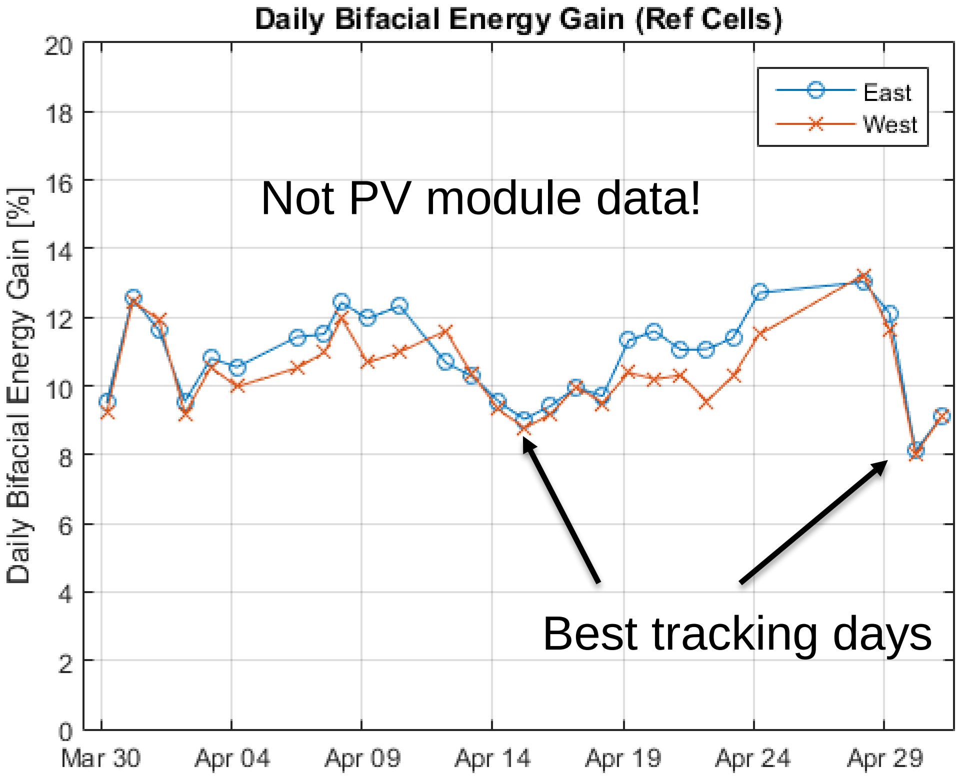
- Module and Inverters installed
  - Row 1: String 1: Sunpreme
  - Row 1: String 2: TBD
  - Row 2: String 1: Prism Solar
  - Row 2: String 2: TBD
- Inclinometers, front and back reference cells on each tracker
- Tracking issues
  - Three photodiodes with shade block control tracker movement
  - We are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



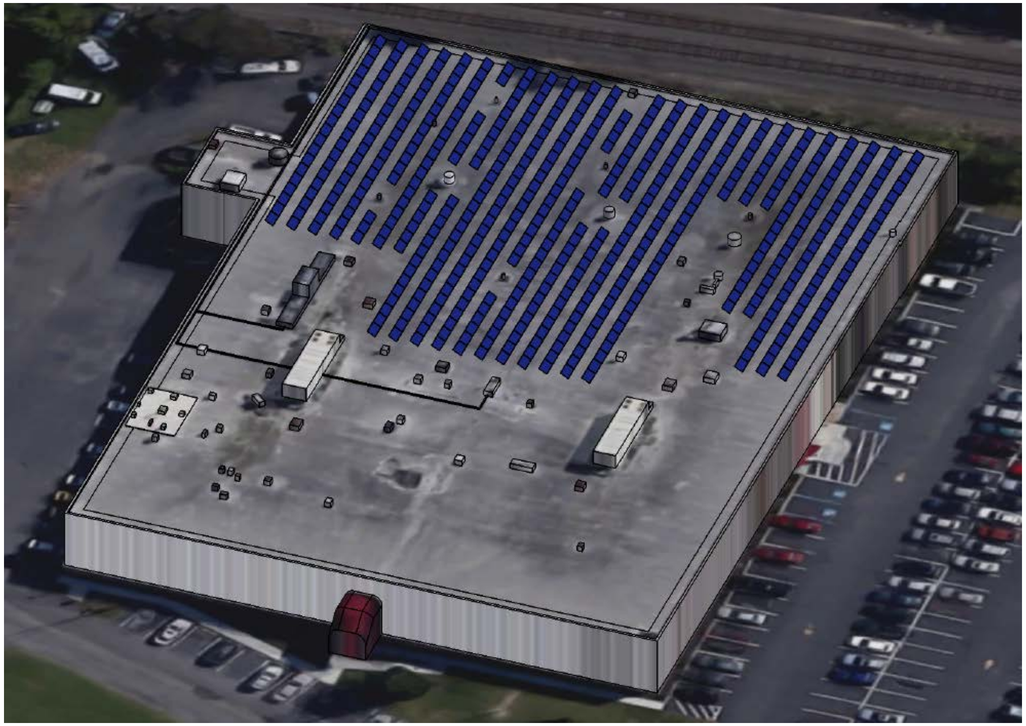


Bifacial Single Axis Tracker (NM)

- Potential bifacial energy gains were estimated from front and rear irradiance measurements using reference cells.
  - $BG_E = \frac{\sum(Front+Rear)}{\sum Front} - 1$
- Potential gains are lowest when tracker is "on-track" ~8%.



Commercial Bifacial System



String level DC performance will be measured on four strings on this NY commercial rooftop bifacial system.

Summary and Future Work

- Bifacial PV offers and delivers significant extra energy per m^2 of array.
- Bifacial gains vary as a complex function of module characteristics, sun position, tilt and azimuth angles, albedo, system size, and backside obstructions.
- Project goals for 2018 include:
  - Develop and validate predictive models that can evaluate system performance and LCOE. – Balance detail with speed of calculations
  - Publish design guidelines for bifacial PV systems.
  - Publish and compare bifacial performance for different applications.

Questions?

Joshua S. Stein

jsstein@sandia.gov