Field Performance of Bifacial PV Modules and Systems

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SAND2018-8876 C

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

Task 1: Measure Outdoor Bifacial Performance

- Module scale
  - Adjustable rack (height, tilt, albedo, and backside shading effects)
  - Spatial variability in backside irradiance
  - Effects of backside obstructions

- String scale
  - Fixed tilt rack (tilt, mismatch effects)
  - Single axis tracker (ongoing)
  - Two-axis tracker

- System scale
  - String level monitoring on commercial systems (validation data)

Stein, J. S., D. Riley, M. Lave, C. Deline, F. Toor and C. Hansen (2017). Outdoor Field Performance of Bifacial PV Modules and Systems. 33rd European PV Solar Energy Conference and Exhibition. Amsterdam, Netherlands. SAND2017-10254

3-Yr Bifacial Research Project (FY16-18)

## Task 2: Develop Performance Models

Irradiance modeling

- Ray tracing simulations
  github.com/cdeline/bifacial_radiance
- 2D view factor method for conventional arrays
  github.com/cdeline/bifacialVF, SAM, PVsyst
- 3D view factor method for cell-by-cell irradiance
  pvpmc.sandia.gov/pv-research/bifacial-pv-project/

Module performance models

- Work in progress: cell-by-cell mismatch is outstanding issue
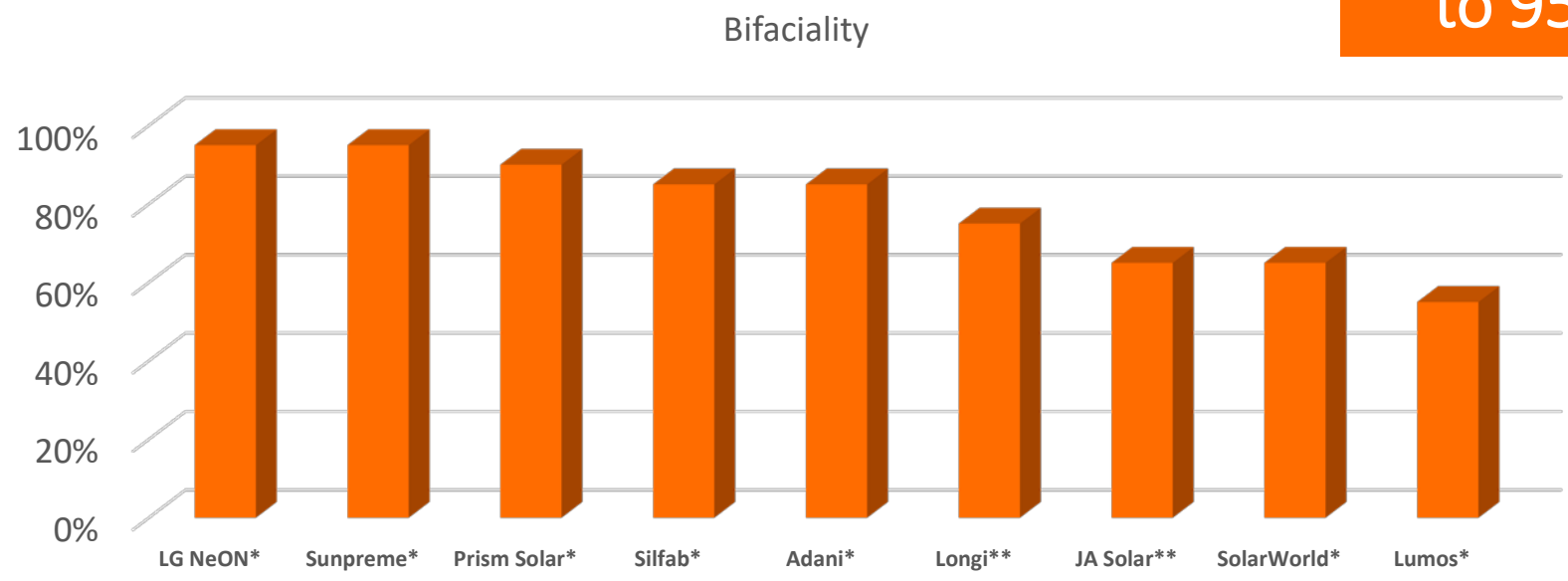
Task 3: Support Rating Standards

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

Back surface irradiance by cell (W/m²)

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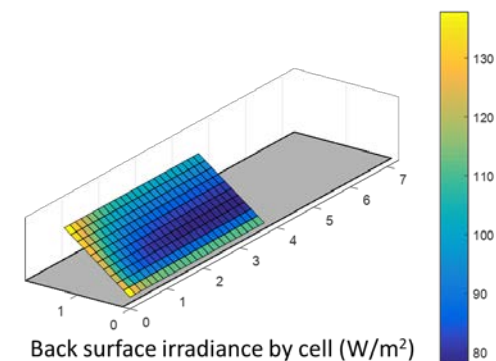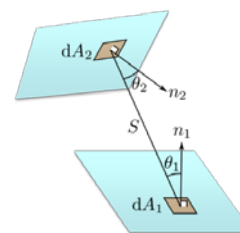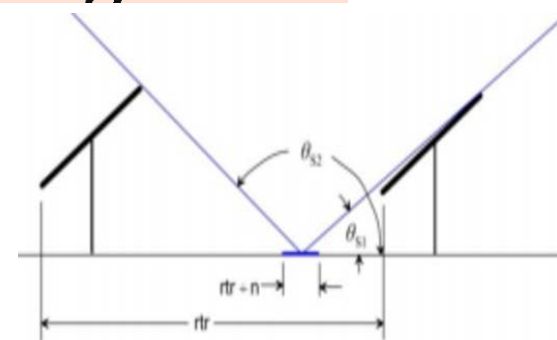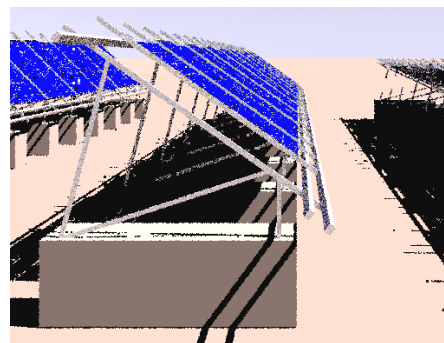
Bifaciality : a module property

$$\text{Bifaciality} = P_{MP} \text{ (rear)} / P_{MP} \text{ (front)}$$

From 65% to 95%

Bifaciality

* Info from Bifacial PV Systems Solar Professional Magazine

** Info from manufacturer datasheet

Soltec webinar, "Bifacial PV tracking: the simulation and optimization of yield gain", April 17 2018

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Quantifying Bifacial System Performance

- We compare bifacial modules to similar monofacial modules in the same mounting and orientation (e.g., fixed tilt, south-facing) using *bifacial gain BG (energy or power)*

  - $E_{bifacial}/E_{monofacial} = 1 + \text{BG}$

- Normalize rated capacity to compare between systems, i.e.,

  - $BG = \dfrac{\sum \text{P}_{\text{bifacial}}(\text{t}) \,/\, \text{P0}_{\text{bifacial}}}{\sum \text{P}_{\text{monofacial}}(\text{t})/\text{P0}_{\text{monofacial}}} - 1$

- BG varies with bifaciality, but also with <u>rear surface irradiance</u>:

  - Rear-surface irradiance (mostly ground reflected irradiance) is not proportional to front-side plane-of-array irradiance

    - Albedo can change with time of day and season

    - Shadows from nearby objects

    - Nearby obstructions (e.g., racking)

  - Power is not always proportional to total irradiance (front + back)

    - Mismatch effects from spatially variable rear-surface irradiance

Prism Solar Modules in NM, NV and VT

New Mexico

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

Nevada

Measured Albedo
- Natural = 0.2
- White   = 0.3

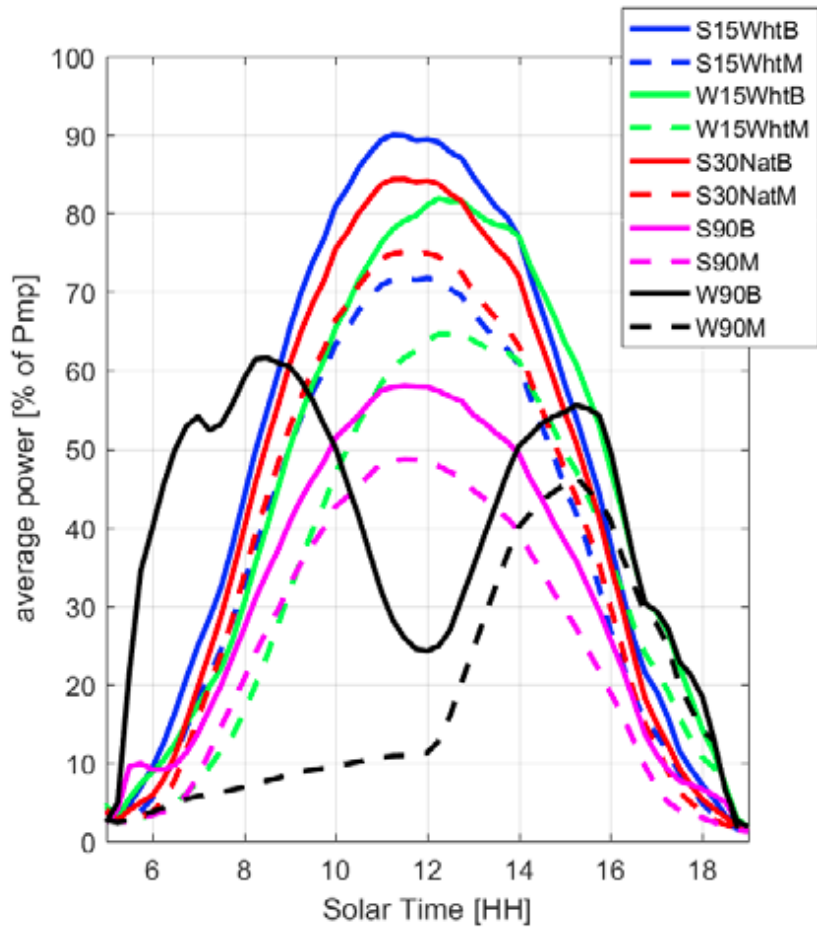Vermont – summer

Measured Albedo
- Natural = 0.1 (Summer)
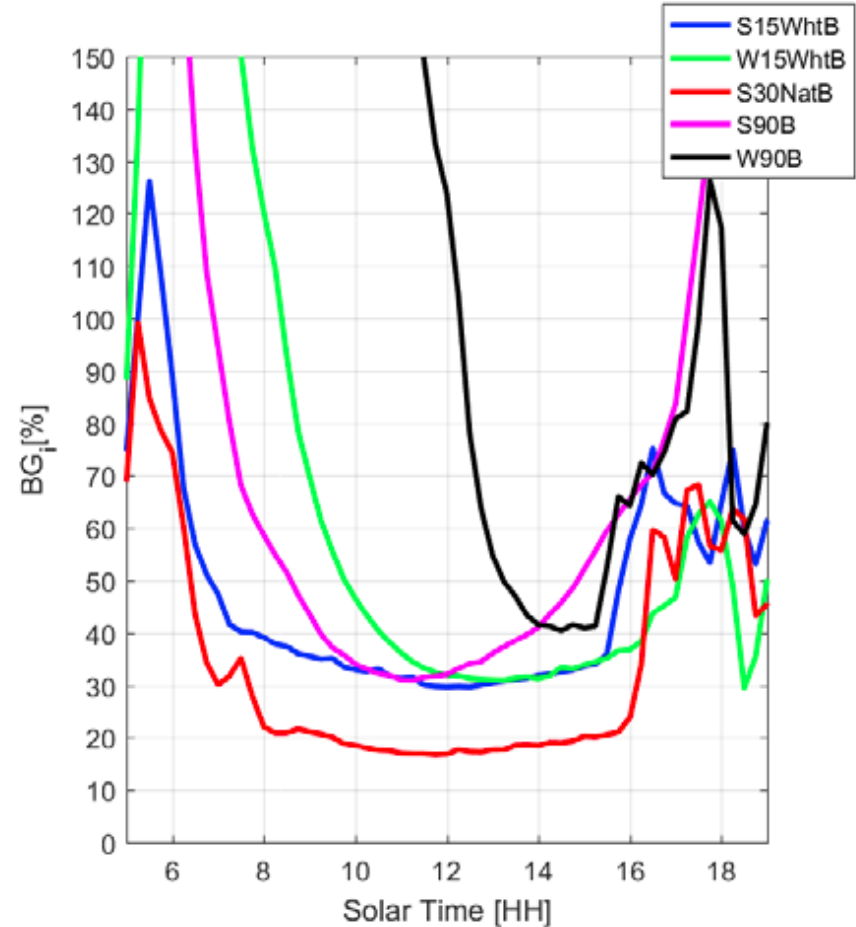- White   = 0.2 (Summer)
- Winter = 0.2 – 0.8

Vermont – winter
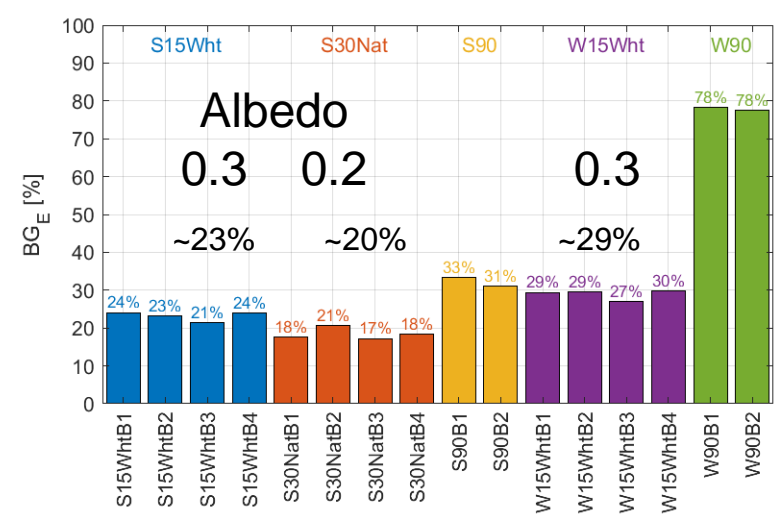
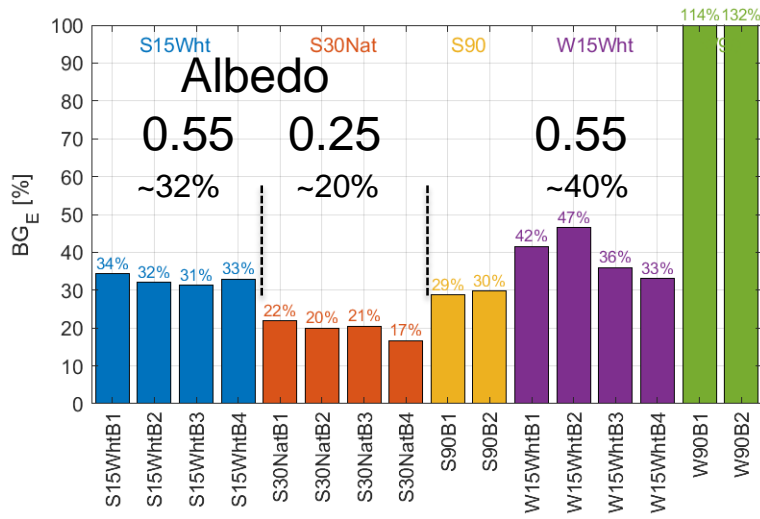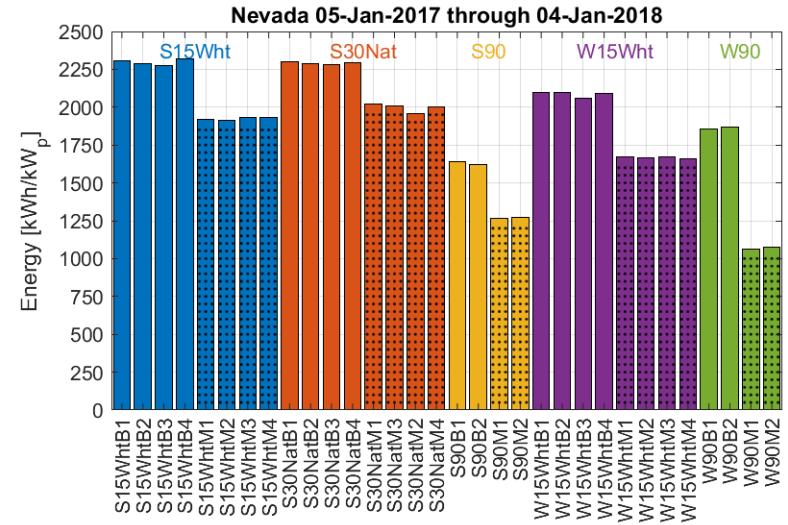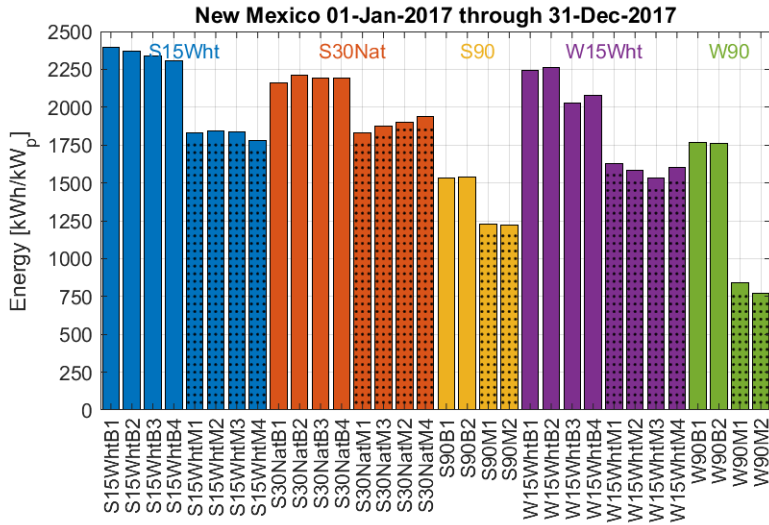# BG(power) varies significantly by time of day

Average power for one year

Average BG(power) for one year

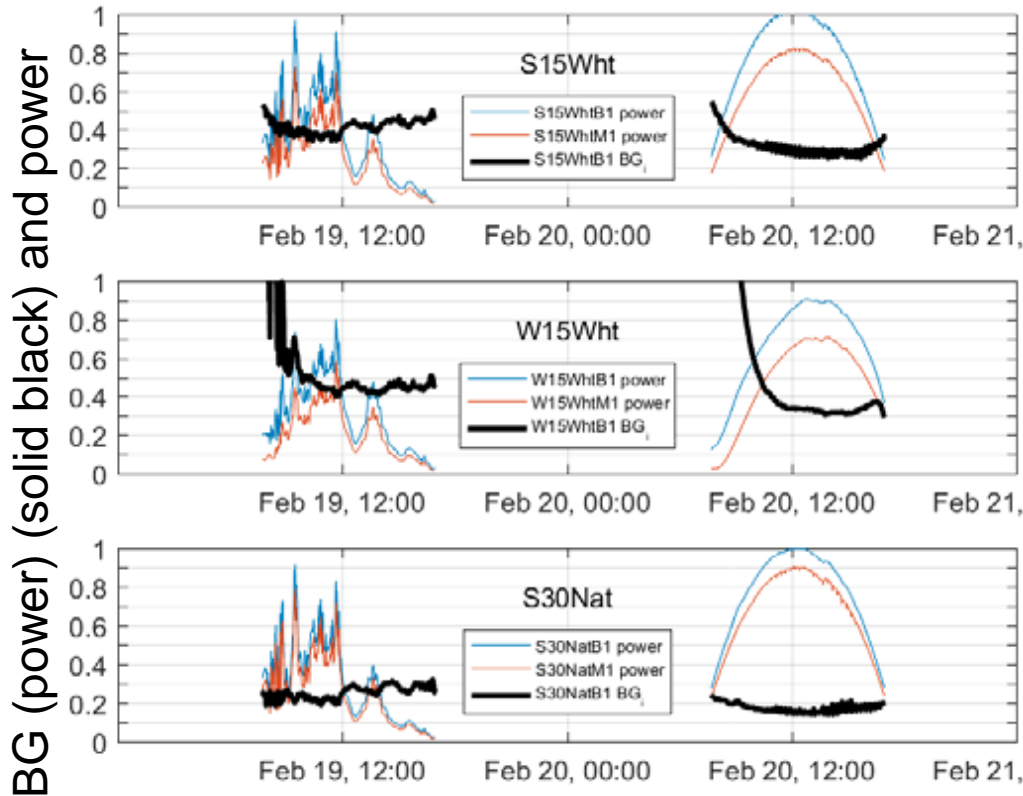# Annual energy (fixed tilt in NM, NV)
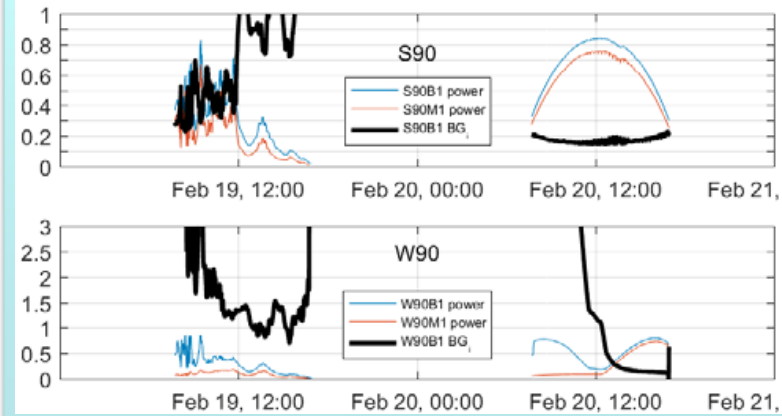
BG(power) vs. weather condition

BG relatively stable for south and west tilted systems

Cloudy day   Clear day
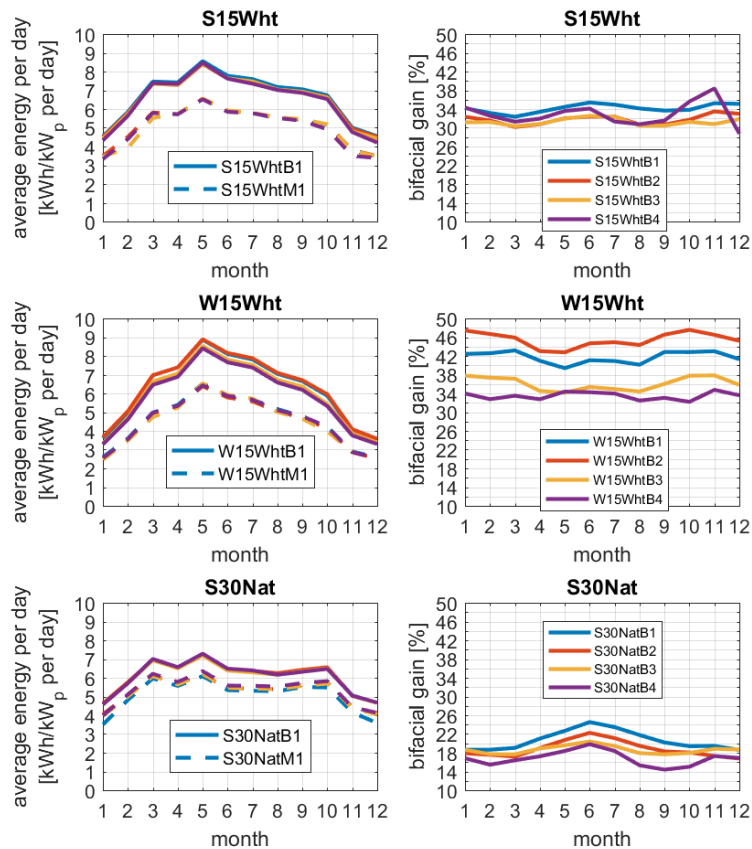

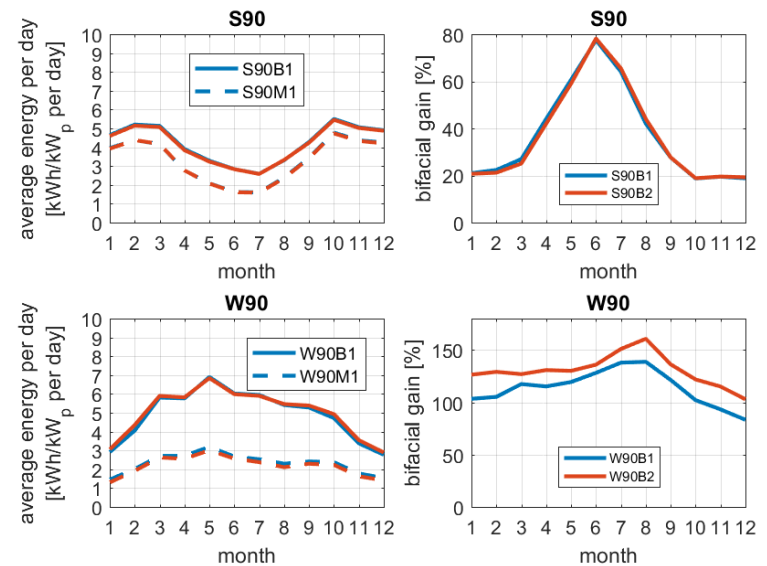BG varies significantly with weather for vertical orientations

Monthly energy for Prism modules (NM)

BG(energy) relatively stable over seasons, except for vertical orientation

South and west tilted systems

Vertical oriented systems

Small-system Performance

Four fixed-tilt single string arrays

- Four rows at 15˚, 25˚, 35˚,and 45˚ tilt.
- Each row has one bifacial and one monofacial string of 8 modules.
- Modules alternate to minimize backside spatial irradiance bias.
- Bifacial: Prism Solar (n-Type c-SI) : Rb ~93%
- Bifacial: SunPreme (HJT/HIT) : Rb ~95%
- Monofacial: SolarWorld

- BG less for system than for single modules
- BG increases with tilt – seasonal effect (summer)

BG ~ 20% for 30-deg single module
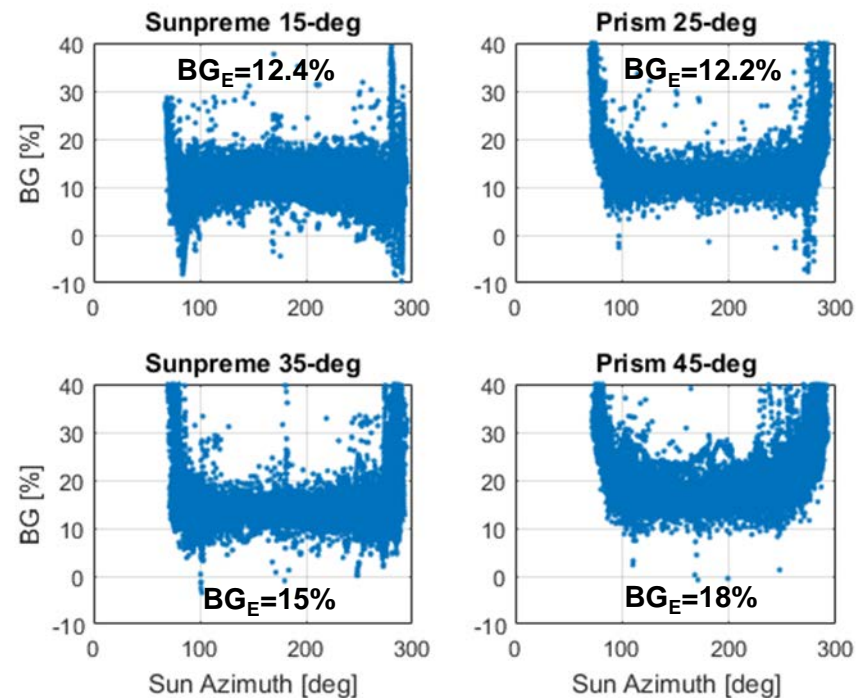
Data from June 1 – Aug 31, 2017 11

Bifacial on Single Axis Trackers

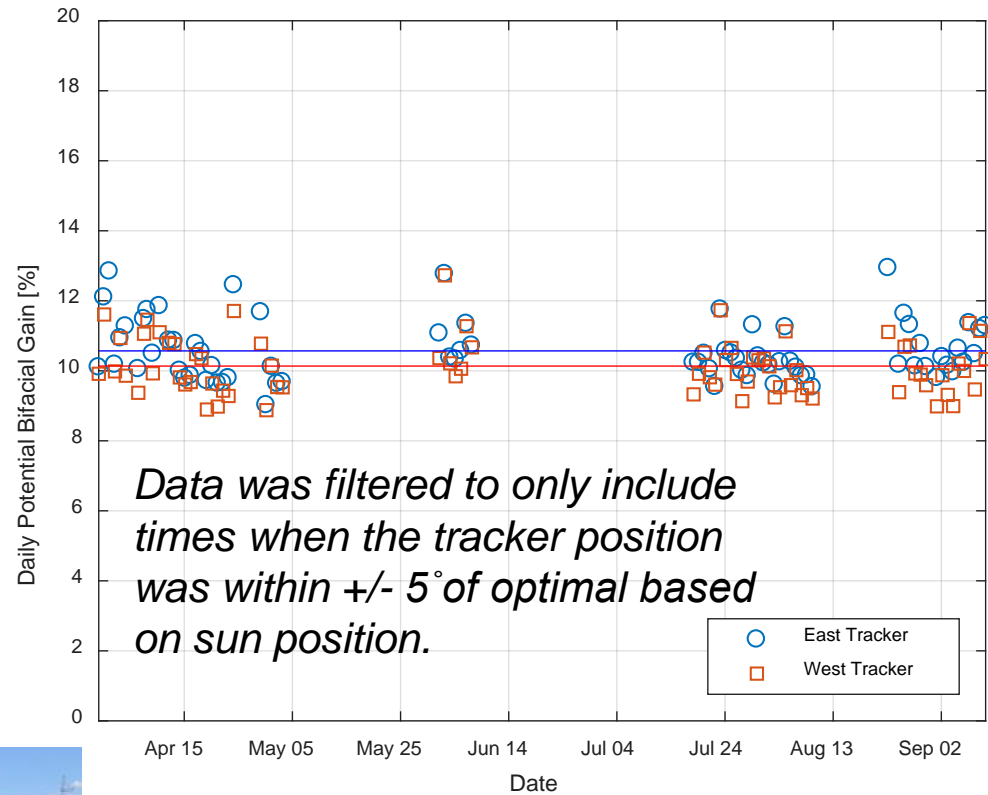- Daily *Potential* Bifacial Gain (Energy) is estimated from front and back irradiance data using reference cells.

Data was filtered to only include times when the tracker position was within +/- 5° of optimal based on sun position.

100kw systems on 1-axis trackers

- Side by side systems (eastern Oregon)
- Different module types: HIT bifacial vs xSi monofacial
- Comparable field IV curve measurements

100kW bifacial   100kW monofacial
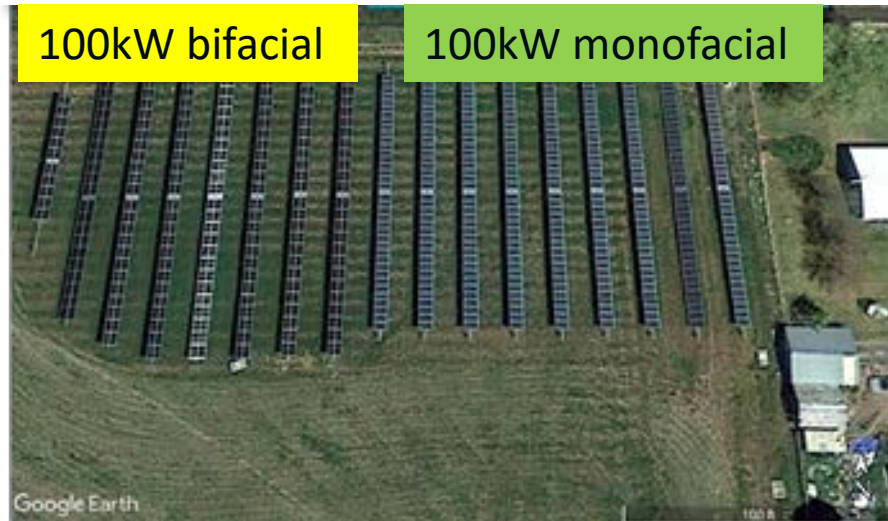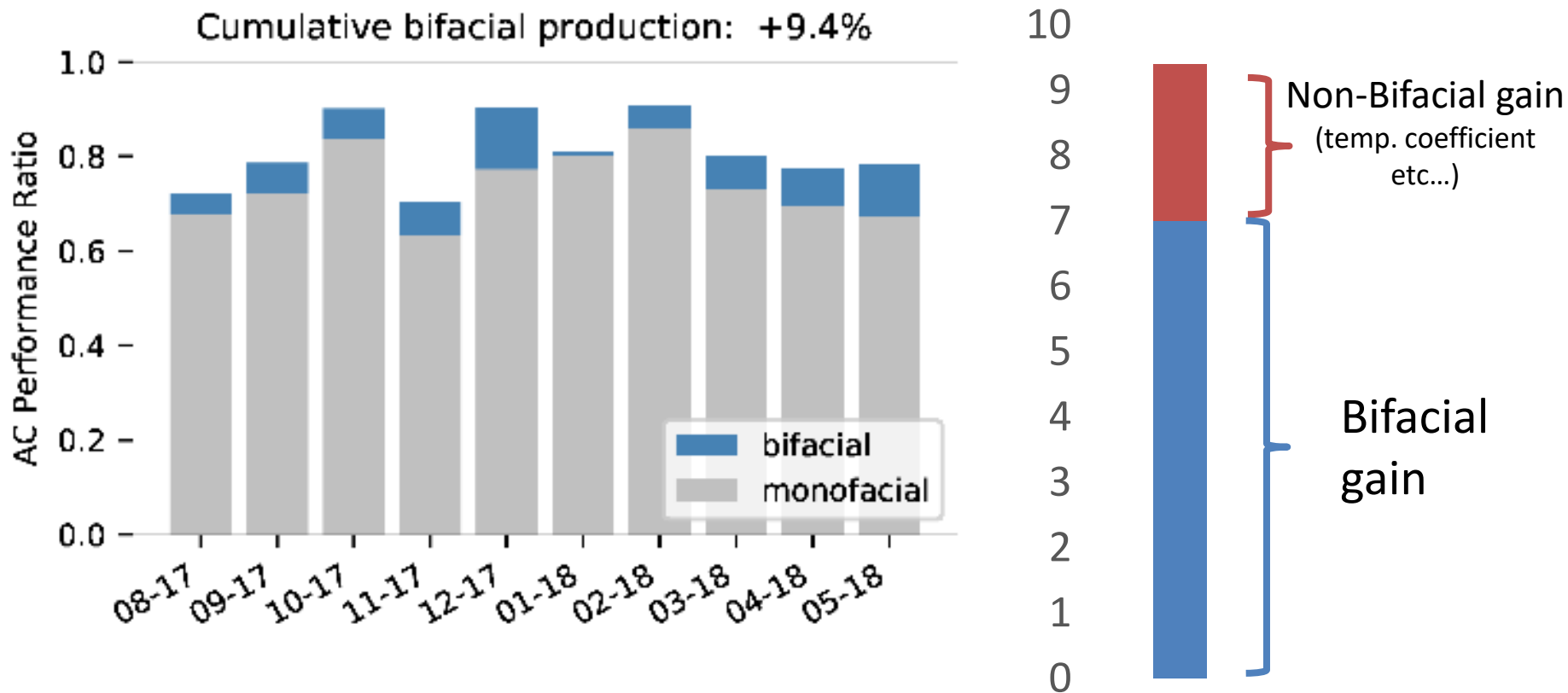
Un-like module types require adjustment for non-bifacial factors such as temp coeff. and low-light performance

$$BG_{\mathrm{Meas},bifacial} = 100\% \times \left(\frac{PR_{bifi}}{PR_{mono}} \frac{PR_{mono,model}}{PR_{bifi,model}} - 1 \right)$$

Adjustment Factor

Ayala, Silvana et al. "Model and Validation of Single-Axis Tracking with Bifacial PV." 7th WCPEC, Waikoloa, HI (submitted to JPV)

1-axis tracking field comparison: bifacial HIT vs mono xSi

Measured PR was 9.4% higher for HIT bifacial vs. xSi monofacial
Question: How much of the gain was from bifaciality?


Cumulative bifacial production: +9.4%

Bifacial gain comparison with model: Measured: +7%. VF model: 6.7%

Ayala, Silvana et al. "Model and Validation of Single-Axis Tracking with Bifacial PV." 7th WCPEC, Waikoloa, HI (submitted to JPV)

Bifacial on 2-Axis Trackers (VT)

- Two 2-axis trackers each have two **strings** (one of monofacial and one of bifacial)
- Significant obstructions behind bifacial modules from tracker rack

Bifaciality ~0.93

BG ~10% before snowy weather
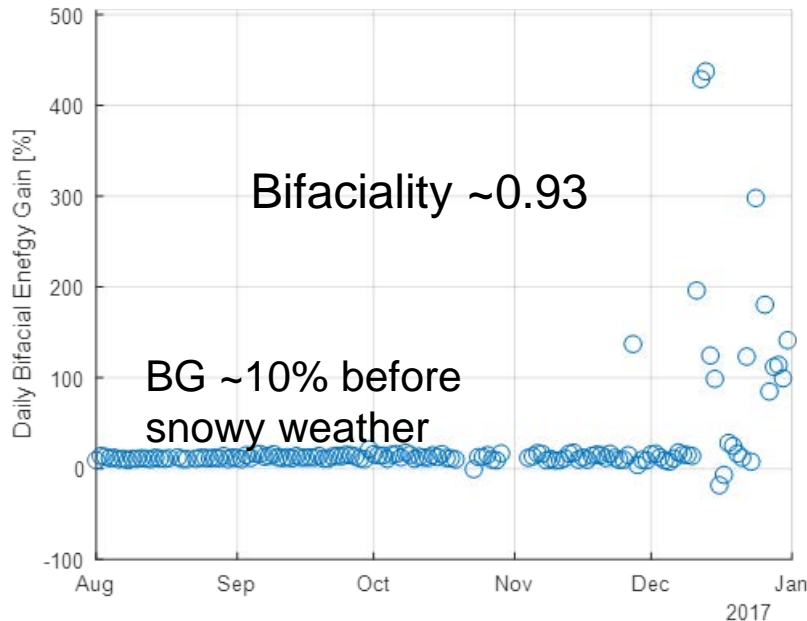
Performance advantage during snow:
- Albedo increase
- Bifacial modules often shed snow more rapidly
- Rear side is generally clear
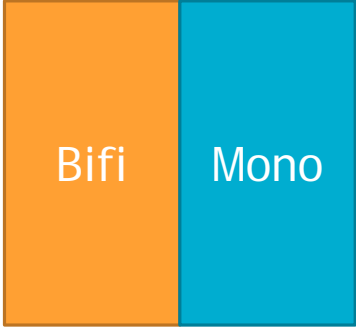
Example of snow shedding advantage

Photo from Jan 1, 2018 10:45 EST

Photo from Jan 1, 2018 14:15 EST

Photo from Jan 1, 2018 11:00 EST

Bifi	Mono

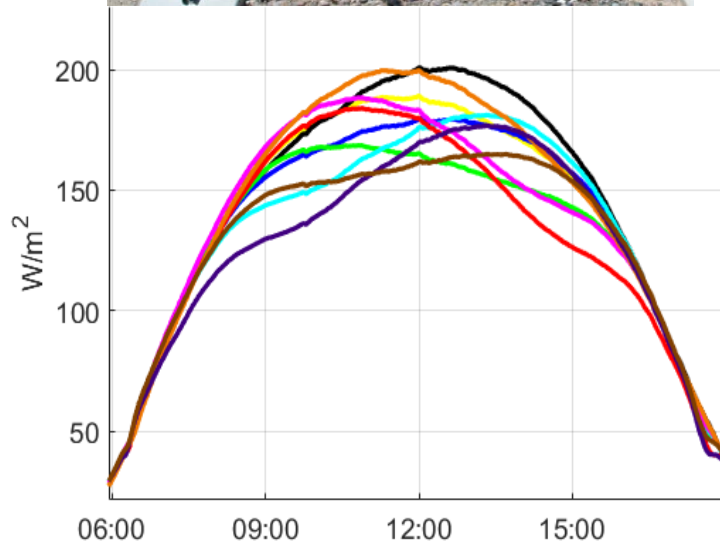SolarWorld

Mono	Bifi

Prism

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Bifacial performance modeling

- Desired: <u>annual simulation at hourly or better resolution </u>with <u>accuracy comparable to irradiance measurement uncertainty</u> within a <u>minute on commodity PC</u>

- Available:
  - Fast 'infinite row' 2D view factor model
  - Fast ray tracing (bifacial_radiance) – calculates annual energy only
  - Detailed models: 3D cell-by-cell view factor, ray tracing

- The primary technical challenges are:
  - Modeling rear-surface irradiance accounting for nearby structures
  - Obtaining accurate values of local ground albedo
  - Modeling the effect of irradiance non-uniformity on power
  - Computationally efficient implementations

Stein et al. (2017) "Comparison of modeling methods and tools for bifacial PV performance", 9th PV Performance Modeling and Monitoring Workshop, Weihai, China.
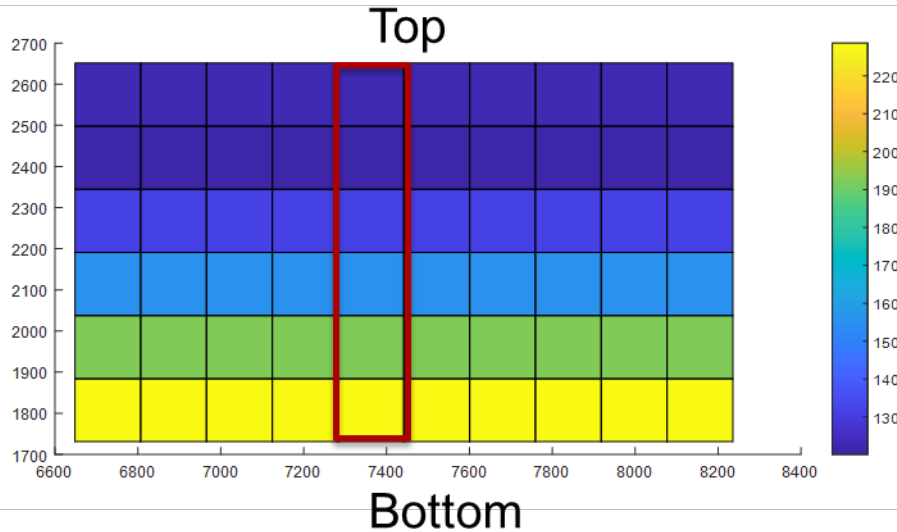
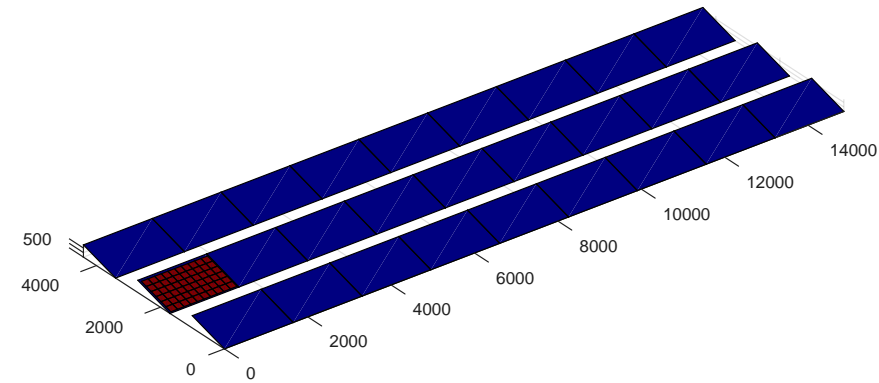# Measured rear surface irradiance

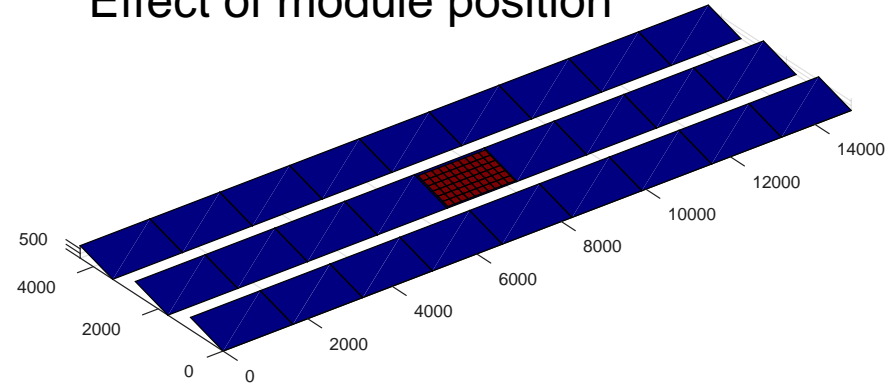Rear irradiance across a 1m x 2m module

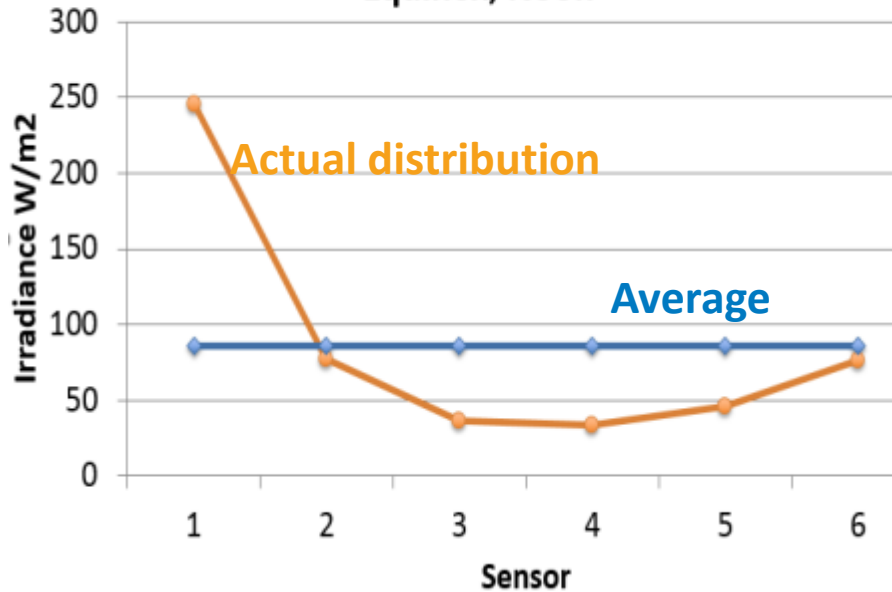Rear irradiance across a row
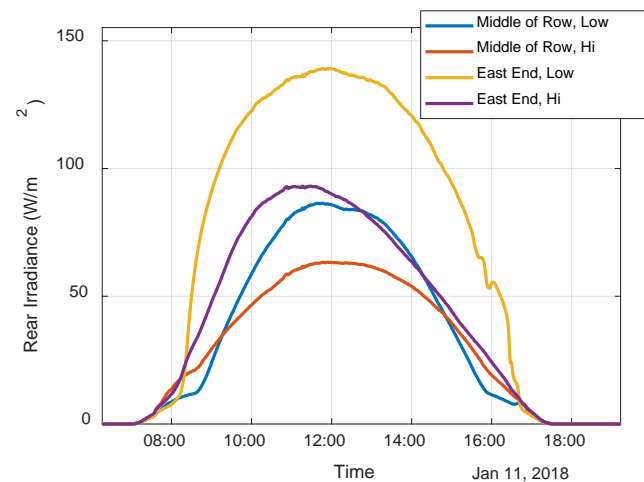
Modeled rear surface irradiance

Top

Bottom
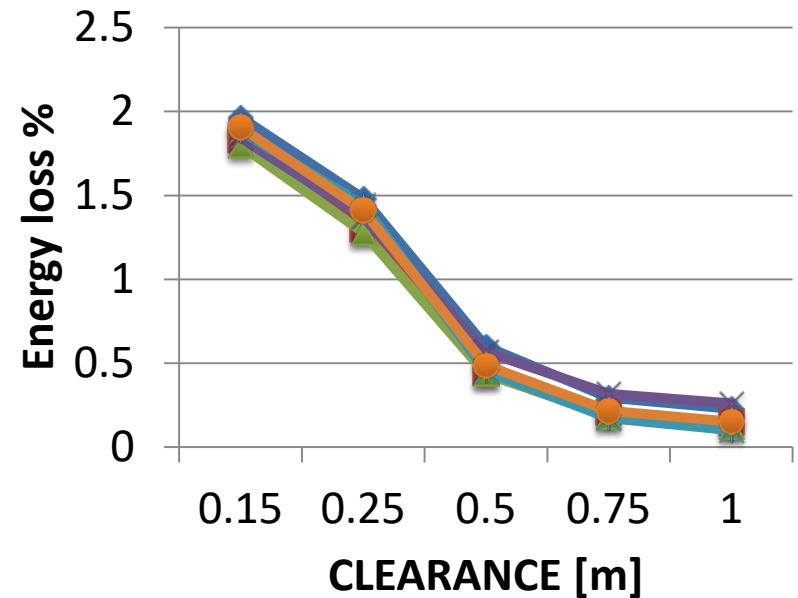
Effect of module position

Note difference in scale
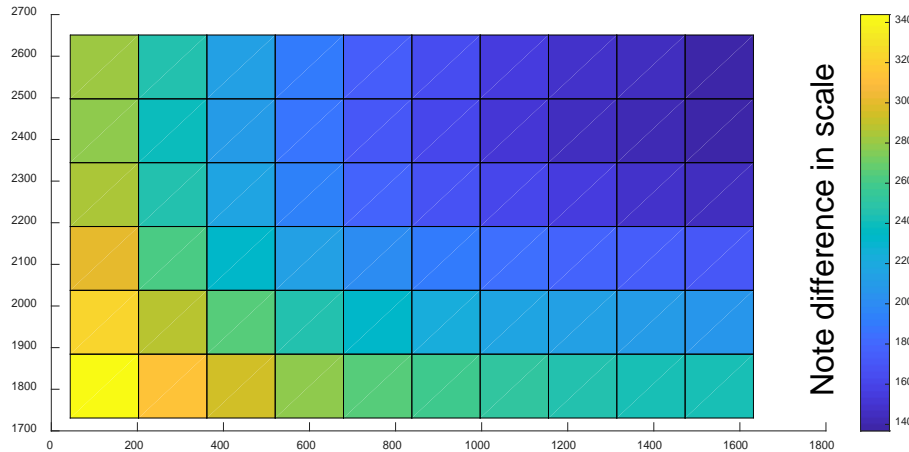
Solar noon on the spring equinox.

Rear Irradiance Distribution and Mismatch loss

Back Irradiance Spatial Distribution on Spring Equinox, Noon

Actual distribution

Average

C. Deline et al., Bifacial PV Performance Models: Comparison and Field Results, BiFiPV 2017 Workshop – Konstanz Germany

$$Energy\ \%loss = \frac{kWh_{avg} - kWh_{detailed}}{kWh_{avg}}$$

- **Current models only return an average value**. This doesn't capture additional shading or distribution mismatch loss.

- **Spatial distribution of rear irradiance** increases for low ground clearance

- **Energy loss can be significant** (e.g. 10% bifacial gain -> 8%)

Conclusions

Bifacial performance always exceeds monofacial performance in the same orientation

- 10% seems to be a floor value for Bifacial gain (for a bifacial module with Rb ~ 93%) – perhaps 10% x Bifaciality could be a rule of thumb
- Bifacial advantage (measured by BG) increases substantially (and unfairly) when monofacial modules are not optimally deployed
- Extreme example: vertical, E-W bifacial modules have similar yield as latitude tilt, southward monofacial modules

Observations

- Bifacial advantage decreases from single modules (BG ~20%) to systems (BG ~12-15%) due to shading of nearby ground from the modules themselves
- Bifacial gain (BG) is not an ideal metric
  - LCOE may be more meaningful for two systems each designed to optimize yield within the same constraints (area, budget, obstructions)
- Optimizing bifacial yield will require careful attention to system design effects such as shadowing, mismatch mitigation and local albedo

Questions?

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