Bifacial PV: Field results from the US on bifacial gains from modules, strings, and systems

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PVPerformance MODELING COLLABORATIVE

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Sandia National Laboratories

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Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Bifacial PV Research Motivation and Approach

- Bifacial PV may be one of the most cost effective ways to increase energy generation from PV systems.
  - Bifacial gain (% increase in power (or energy) over monofacial in same orientation) needs to be determined as it varies due to many factors.
  - Designs and BOS are not designed for bifacial PV
  - Bifacial performance models are immature and not validated.
- Sandia, NREL, and UIowa have a three year research project focused on:
  - Bifacial field data covering different spatial scales and applications
  - Bifacial PV rating standards
  - Bifacial PV Performance Models

Field Test Beds : Applications

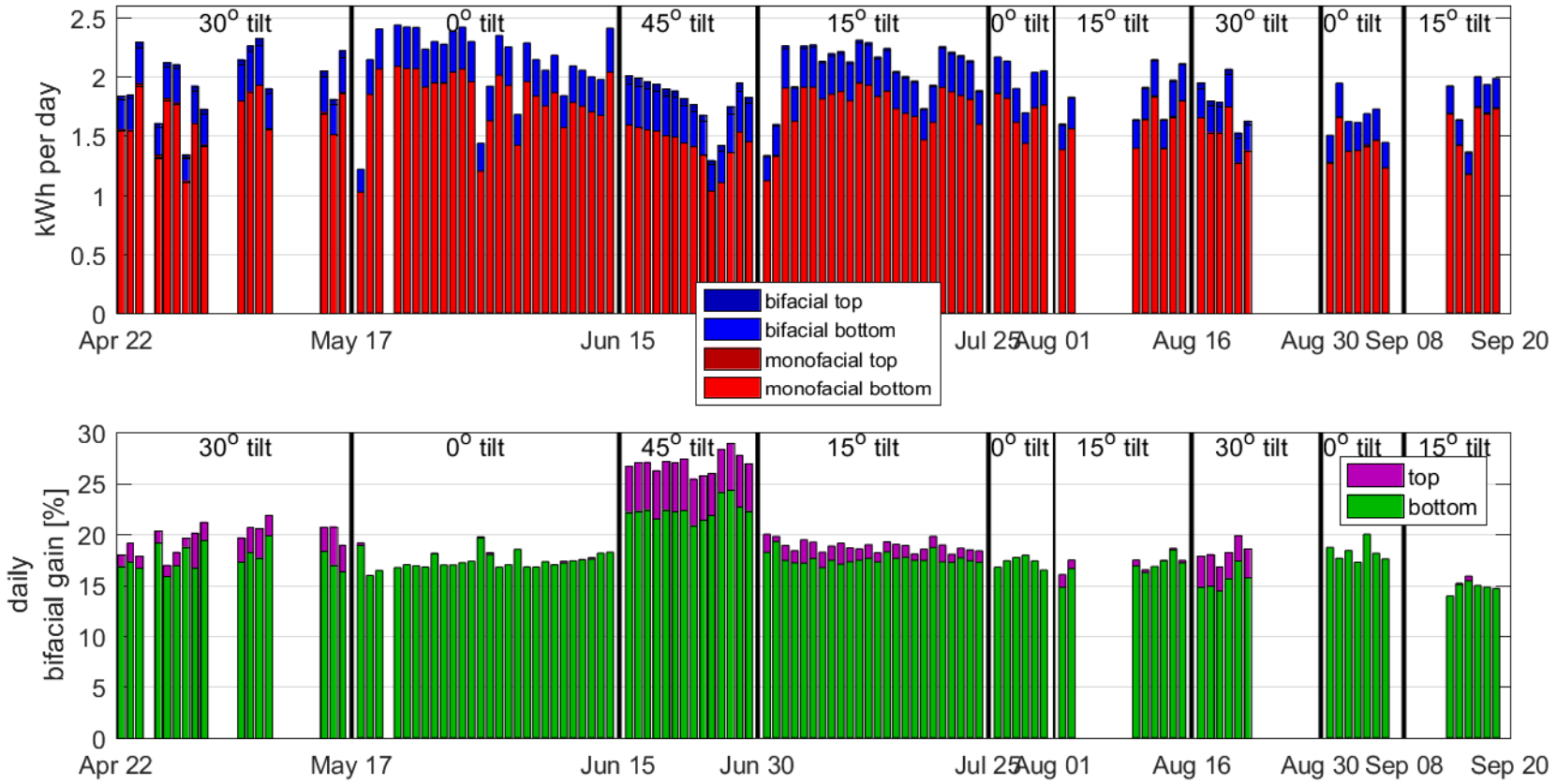
- Single module behavior
  - Adjustable rack (2016)
  - Rear side irradiance mapping (2016)
  - Prism Solar arrays (2016)
- String performance
  - Fixed tilt rack (2016)
  - Single-axis tracker – (2016)
- System performance
  - White rooftop system (~150kW) – (2017)
  - Ground mount system (<0.5 MW) 30 deg fixed tilt system – (2017)

Adjustable-tilt/height Module IVs

Fixed-tilt String-level Arrays

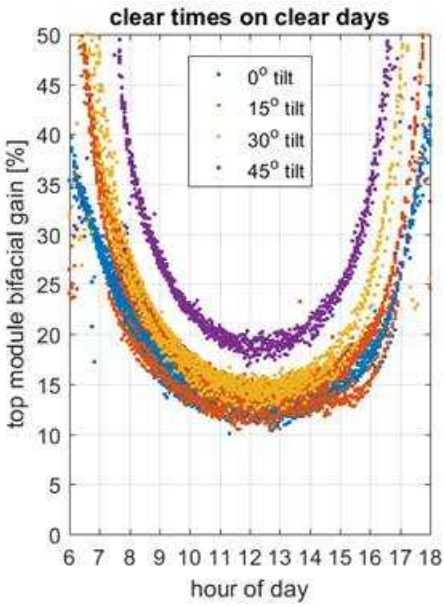
Adjustable Rack

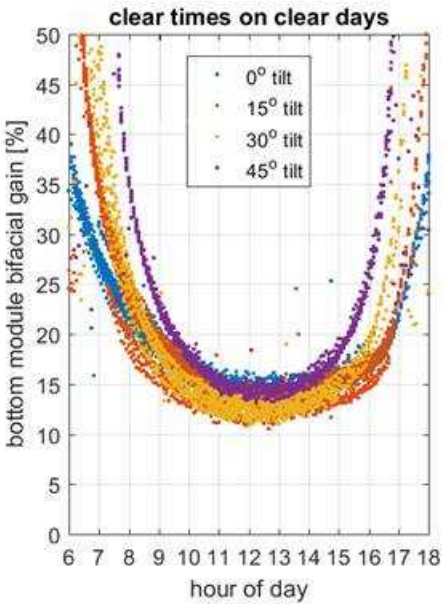
Adjustable Rack Results

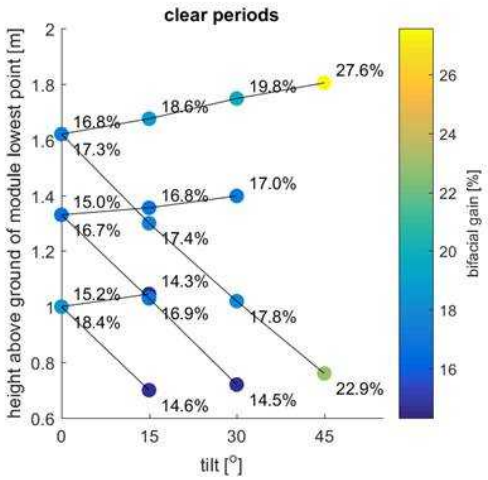


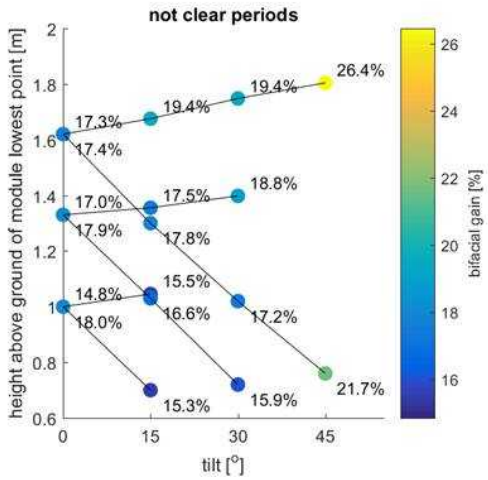
Adjustable Rack Results

- Bifacial gains are higher for larger tilt angles and heights above ground.
- These results may change with season as sun position changes.
- Future work will look at rear side shading effects from racking, cables, etc.





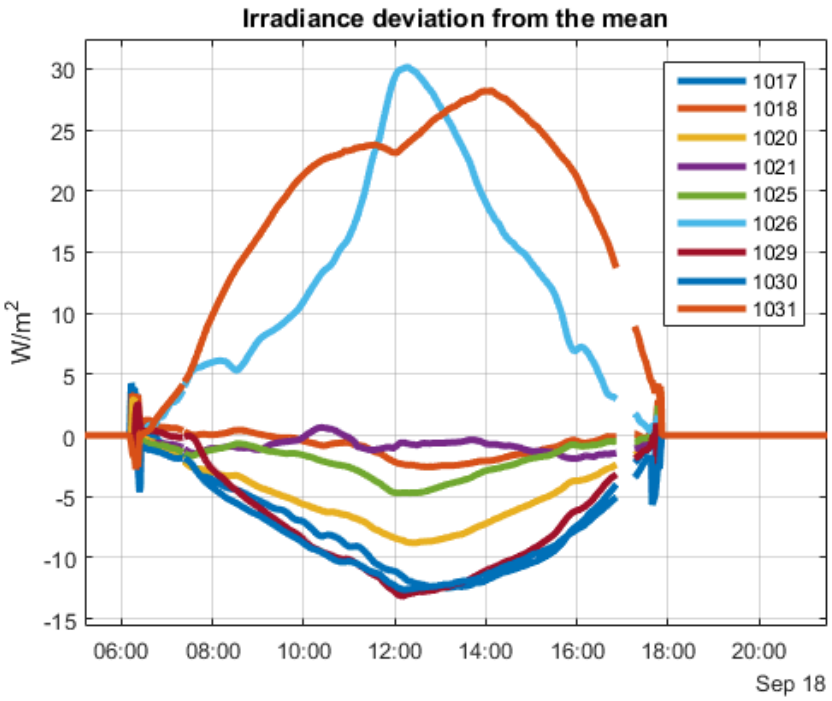




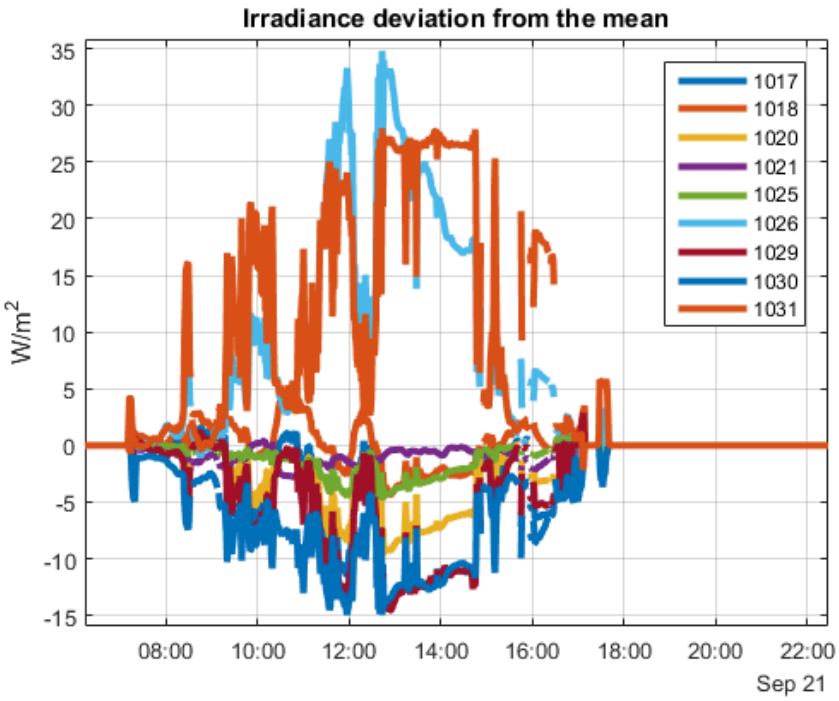
Rear Side Irradiance Mapping

- 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

Rear Side Irradiance Mapping



Sunny Day



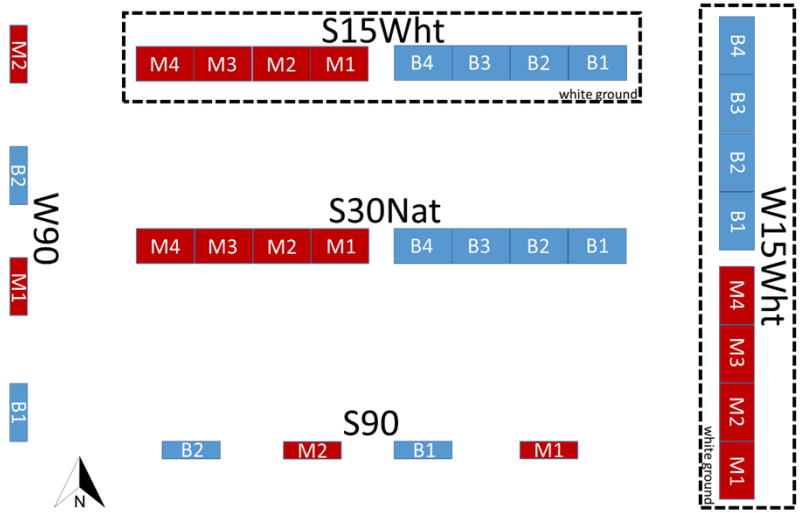
Highly Variable Day

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

Prism Solar Field Test

Five orientations:

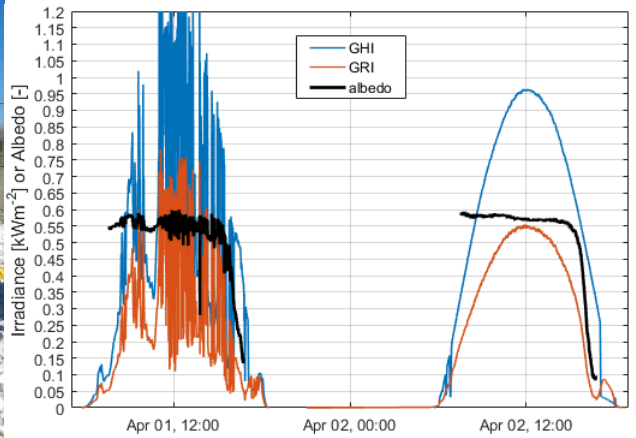
- 32 modules
  - 16 bifacial
  - 16 monofacial
  - Two ground surfaces (Nat & Wht)
- Microinverters hold modules at MPP.
- DC monitoring measuring I & V each module
- Module Temperatures
- Front and rear POA irradiance.

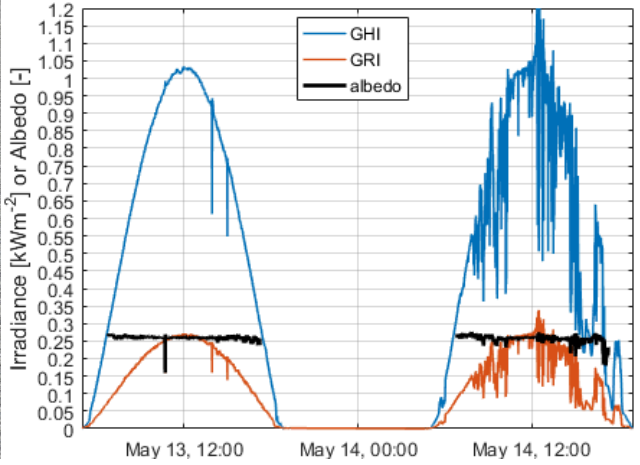


Albedo

- Albedo influences bifacial performance gains.
- Albedo was measured with two pyranometers
  - White gravel ~0.58
  - Grey gravel ~0.26

- These values were used for modeling bifacial gain



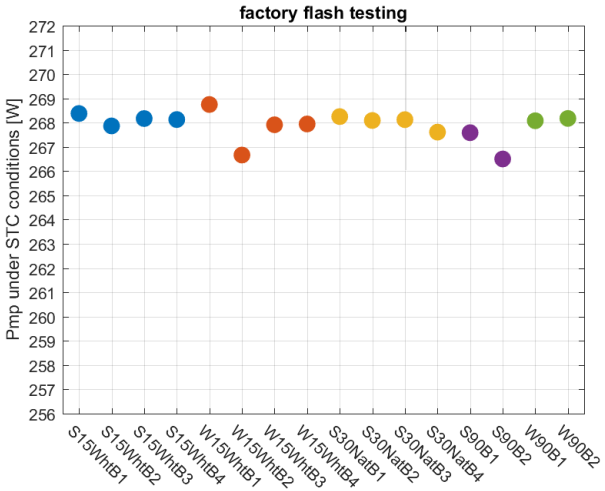


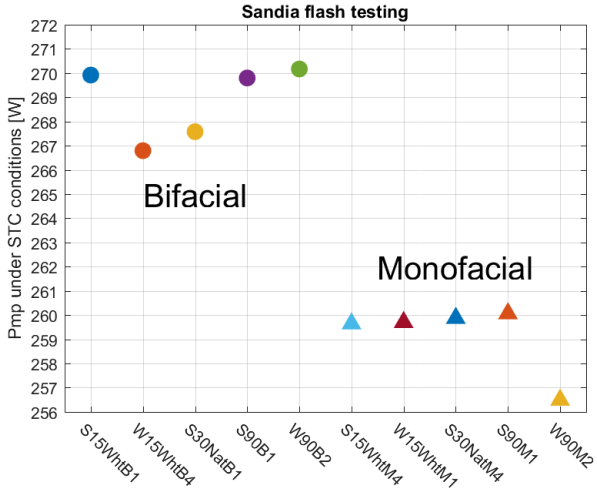
Flash Testing

- Bifacial modules were initially flash tested it the factory.
- Front side flash was performed with back covered.
  - 268W average rating on front
  - Back side is about 90% of front

- After being deployed in the field for several months, one module from each orientation was flash tested at Sandia.
  - 5 bifacial
  - 5 monofacial
  - Sandia flash test results match within uncertainty (~3-4%)
  - Monofacial modules (nameplate = 265W) flashed nearer to 260W.

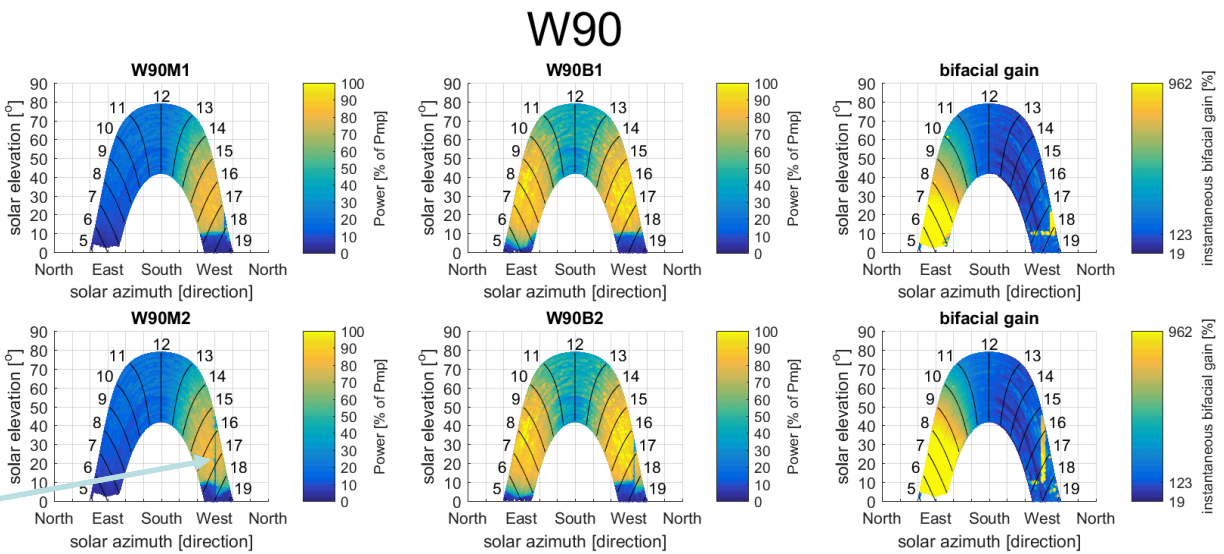
- All data was normalized by 268W for bifacial and 260W for monofacial.





Power over Sun Positions

- Pole shading affected some of the modules and arrays for short periods in the late afternoon.

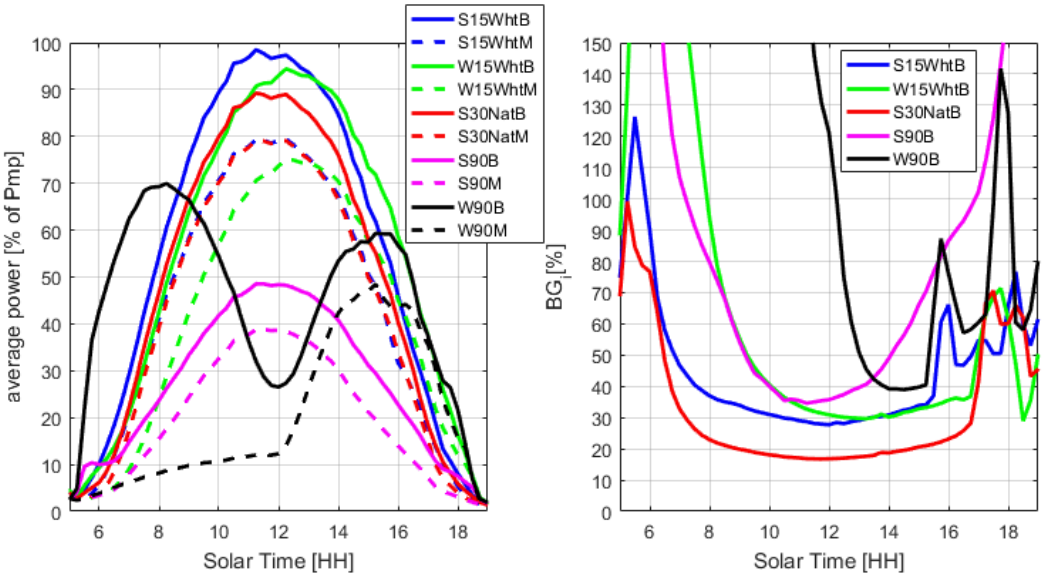


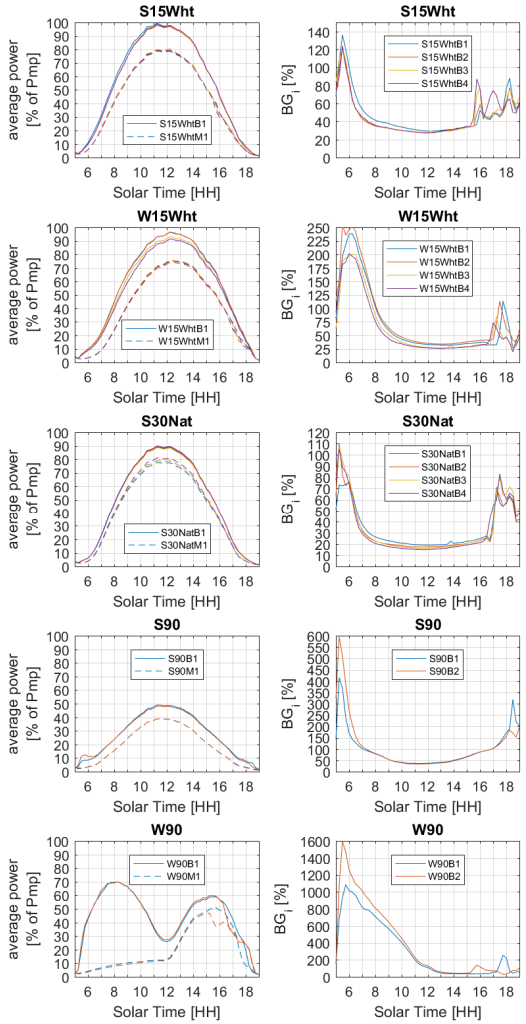
Time Dependent Performance

Bifacial "Power" Gain

$$BG_i(t) = 100\% \times \left(\frac{P_{bifacial}(t) \ / \ Pmp_{bifacial}}{P_{monofacial}(t) \ / \ Pmp_{monofacial}} - 1 \right)$$

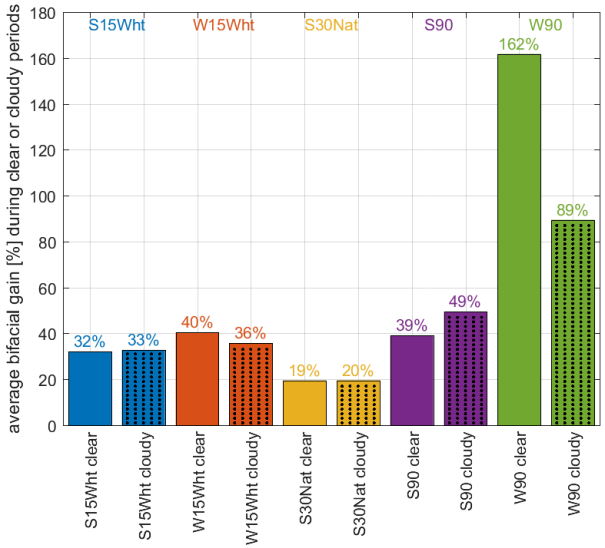
- BG is highest away from solar noon.
- BG depends greatly on array azimuth and orientation
  - Greatest for "non" optimal monofacial orientations.

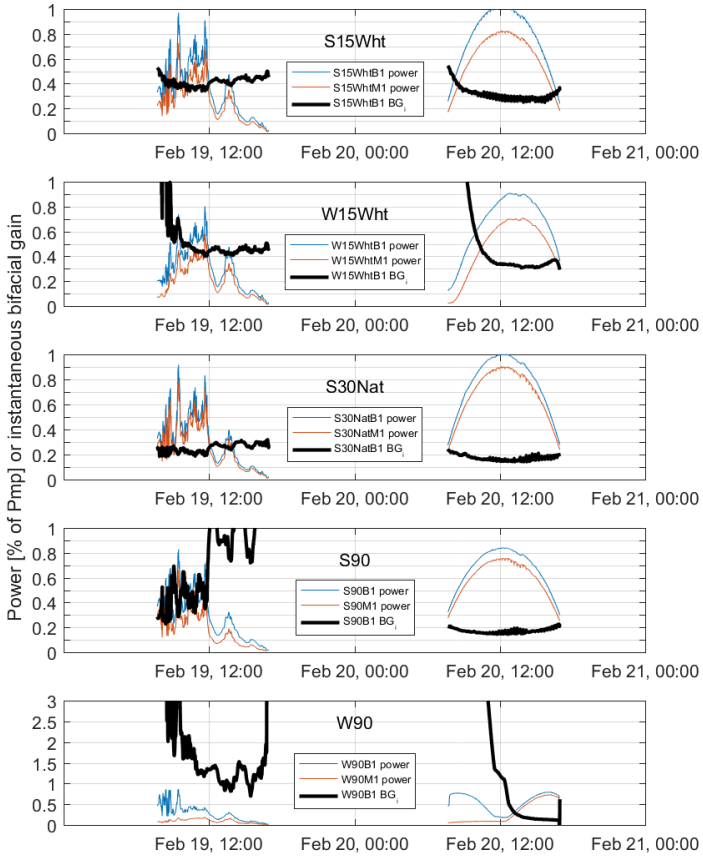




Effects of Clouds

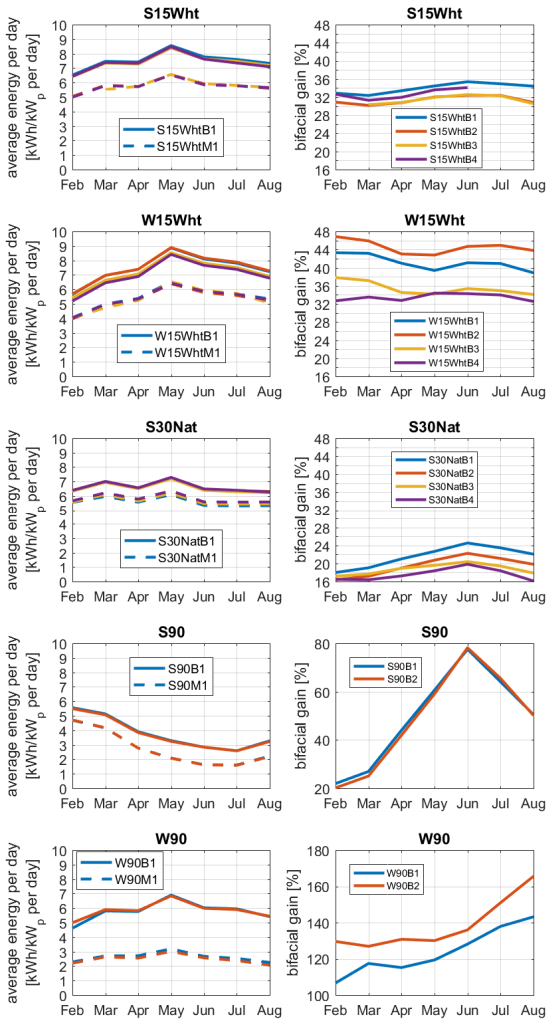
- BG increases during cloudy days for S-facing arrays.
- BG is equal or slightly less on cloudy days for non-South-facing array orientations.
  - Direct sun on module back is more important than greater diffuse irradiance.





Monthly Results

- BG appears to not vary that much for low tilt arrays over the 6-month period of study.
- S30Nat and S90 peaked in June (most direct irradiance on module back in morning and evening).
- W90 peaked in August

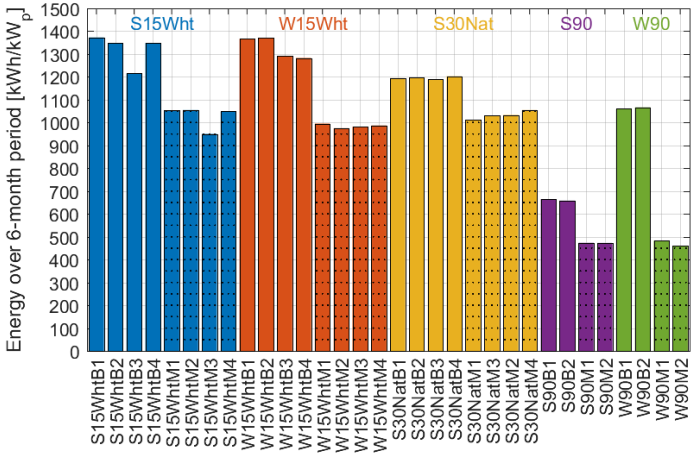


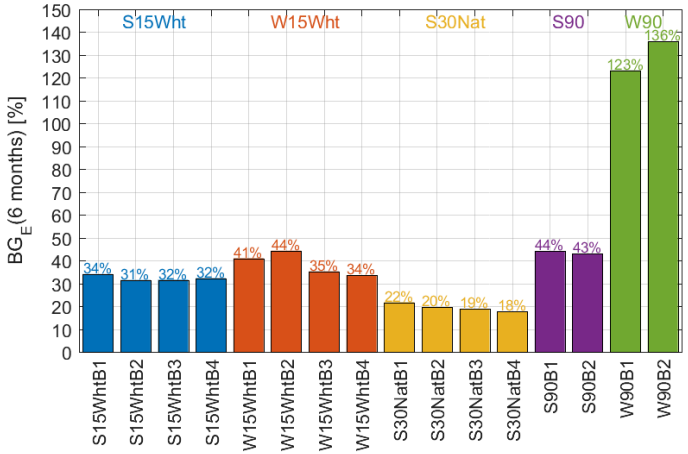
Six Month Energy Results

Bifacial "Energy" Gain

$$\mathrm{BG_E}(6\ \mathrm{months}) = 100\% \times \left(\frac{\sum_{6\ months} \mathrm{P_{bifacial}} / \mathrm{Pmp_{bifacial}}}{\sum_{6\ months} \mathrm{P_{monofacial}} / \mathrm{Pmp_{monofacial}}} - 1\right).$$

- Bifacial modules consistently out performed monofacial modules in the same orientation.
- W90 modules outperformed ALL monofacial modules in the testbed!
- BG in Energy ranged from 18-136%





Prism BG Model Comparison

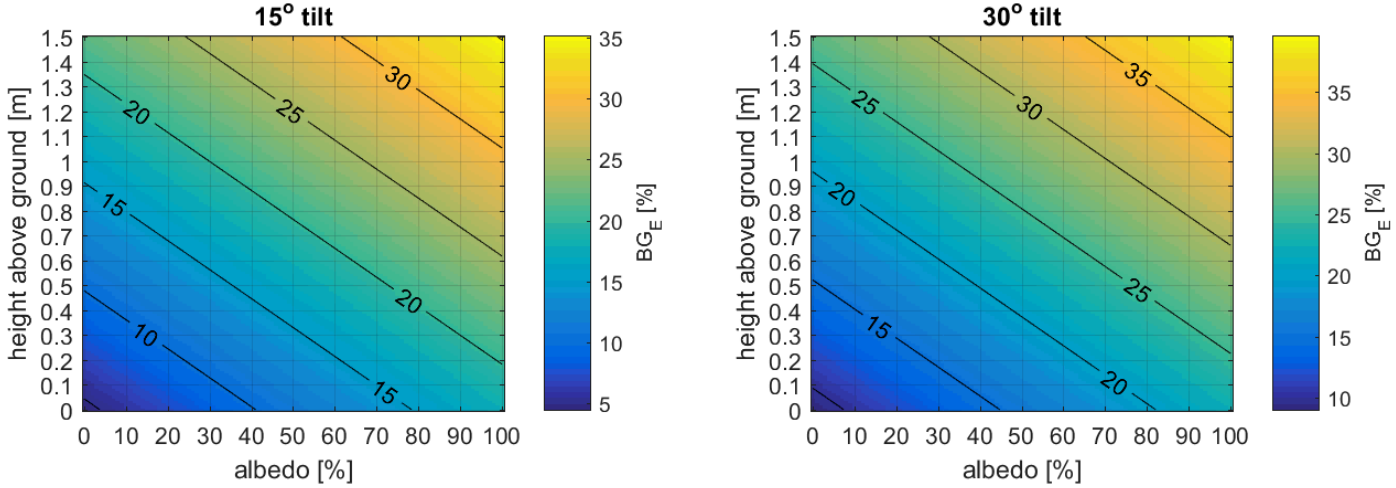
Prism Solar BG Model

$$BG_E(1\ \text{year}) = 0.3 \times \theta + 11.5 \times h + 0.134 \times \alpha,$$

θ= tilt angle (degrees)
h = height (m)
α= albedo

- Prism Solar has suggested an empirical model to represent bifacial energy gain (over an entire year)
- Sandia compared measurements with this model (6 months)

Prism BG Model Examples



Prism BG Model Comparison

- Model and measurements were quite consistent.

	Tilt (θ)	height (h)	albedo (α)	azimuth correction factor	Predicted BG_E(1 year)	Measured BG_E(6 months)
S15Wht	15˚	1.08m	55-60%		24-25%	34%
						31%
						32%
						32%
W15Wht	15˚	1.08m	55-60%	162%	38-40%	41%
						44%
						35%
						34%
S30Nat	30˚	1.03m	20-30%		24-25%	22%
						20%
						19%
						18%
S90	90˚	0.89m	20-30%		40-41%	44%
						43%
W90	90˚	0.86m	20-30%		~90%	123%
						136%

Prism Solar Study Conclusions

- Bifacial gains change through the day
- Bifacial modules perform especially well in non-optimal orientations (e.g., not facing the equator) and can outperform monofacial modules optimally orientated
- Highest bifacial gains from vertical W-facing modules
- Bifacial gains depend on the sky condition
- Empirical models appear to match bifacial performance for small systems.
- Next question is how much will these gains be reduced as the systems become larger?

Future Work

- Investigation of rear side shading effects.
- The project team will investigate string performance differences between monofacial and bifacial arrays
  - Fixed tilt
  - Single axis tracking

- We will instrument larger commercial bifacial systems in the next year to try and address the effects of system size on expected bifacial gains.
- We are working with several modeling approaches to be able to estimate the back side irradiance contribution for bifacial systems.
- We will deliver additional results over the next two years. Stay tuned!

Sandia National Laboratories

Thank You

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