Field Performance of Bifacial PV Modules and Systems

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3-Yr Bifacial Research Project (2016-2018)

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)

Task 2: Develop Performance Models

Irradiance modeling
- Ray tracing simulations
  [github.com/cdeline/bifacial_radiance](github.com/cdeline/bifacial_radiance)
- 2D view factor method for conventional arrays
  [github.com/cdeline/bifacialVF](github.com/cdeline/bifacialVF), SAM, PVsyst
- 3D view factor method for cell-by-cell irradiance
  [pvpmc.sandia.gov/pv-research/bifacial-pv-project/](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)
Bifaciality: a module property

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

From 65% to 95%

LG NeON* Sunpreme* Prism Solar* Silfab* Adani* Longi** JA Solar** SolarWorld* Lumos*

* 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
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)**
  \[ \frac{E_{\text{bifacial}}}{E_{\text{monofacial}}} = 1 + \text{BG} \]

- Normalize rated capacity to compare between systems, i.e.,
  \[ \text{BG} = \frac{\sum P_{\text{bifacial}}(t) / P_{0\text{bifacial}}}{\sum P_{\text{monofacial}}(t) / P_{0\text{monofacial}}} - 1 \]

- **BG** varies with bifaciality, but also with **rear surface irradiance**:
  - 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 – 0.3
• White = 0.5 – 0.6

Vermont – summer

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

Vermont – winter

Measured Albedo
• Natural = 0.2
• White = 0.3
BG(power) varies significantly by time of day.
Annual energy (fixed tilt in NM, NV)

New Mexico 01-Jan-2017 through 31-Dec-2017

Albedo

0.55  0.25
~32%  ~20%

~40%

0.55

~23%  ~20%  ~29%

Nevada 05-Jan-2017 through 04-Jan-2018

Albedo

0.3  0.2
~23%  ~20%  ~29%
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
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

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

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

Adjustment Factor

Ayala, Silvana et al. "Model and Validation of Single-Axis Tracking with Bifacial PV." 7th WCPEC, Waikoloa, HI (submitted to JPV)
Measured PR was 9.4% higher for HIT bifacial vs. xSi monofacial

Question: How much of the gain was from bifaciality?

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

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 11:00 EST

Photo from Jan 1, 2018 14:15 EST
Bifacial performance modeling

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

- 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

Measured rear surface irradiance

Rear irradiance across a 1m x 2m module

Rear irradiance across a row
Modeled rear surface irradiance

Solar noon on the spring equinox.

Effect of module position

Note difference in scale
Rear Irradiance Distribution and Mismatch loss

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%)

\[
\text{Energy loss} = \frac{kWh_{\text{avg}} - kWh_{\text{detailed}}}{kWh_{\text{avg}}}
\]
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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