Bifacial PV System Performance: Separating Fact from Fiction

Chris Deline, Silvana Ayala Peláez, Bill Marion, Bill Sekulic, Michael Woodhouse, and Josh Stein (Sandia National Labs)

PVSC-46, Chicago, IL 2019
Bifacial PV in the news

Bifacial beats Trump’s tariffs
Federal trade authorities have ruled that bifacial solar modules are no longer subject to the Section 201 ruling, which currently apply a 25% tariff to most solar modules imported to the United States.

JUNE, 2019 JOHN WEAVER

Canadian Solar Secures Its Largest Order as Bifacial Modules Gain Traction
EDF Renewable Energy will buy 1.8 gigawatts of modules from Canadian Solar as the Investment Tax Credit phases down, in a sign that developers are growing more comfortable with two-sided solar technology.

KARL-ERIK STROMSTA | MAY 29, 2019

Georgia will be home to largest solar PV project in the US to use bifacial modules and tracking

February 25, 2019

By Renewable Energy World Editors
Historic & projected PV market

Different cell technology

- Al-BSF
- PERC
- SHJ

Bifacial cell in world market

- Bifacial cell in world market
- Monofacial cell in world market

World market share [%]

PERC cell technology – easily bifacial

Module bifaciality $\phi = \frac{P_{Rear}}{P_{Front}}$

- 0.65-0.80 (p-PERC)
- 0.75-0.90 (n-PERT)
- 0.85 – 0.95 (Si Heterojunction)

Monofacial vs Bifacial module manuf. cost

Bifacial Performance Modeling

Photo credit: Prism Solar
Bifacial total irradiance

\[ G_{Total} = G_{Front} + (G_{Rear} \times \text{bifaciality}) \times (1 - \eta_{Loss}) \]

Module bifaciality \( \phi_{Bifi} = \frac{P_{mp0 \, rear}}{P_{mp0 \, front}} \)
Modeling Rear Irradiance

\[ G_{\text{rear}} = G_{\text{diffuse, r}} + G_{\text{reflected, r}} + G_{\text{beam, r}} \]
Modeling Rear Irradiance

\[ G_{\text{rear}} = G_{\text{diffuse},r} + G_{\text{reflected},r} + G_{\text{beam},r} \]
What bifacial gain can be expected?

Bifacial Plus Tracking Boosts Solar Energy Yield by 27 Percent

Recent testing shows bifacial PERC modules can significantly increase energy yields.

Bifacial energy gain $BG_E$

$$= \frac{E_{Bifacial}}{E_{Mono}} - 1$$

= ??
Surface Albedo has a big effect

Rear irradiance, single module at STC
(1kWm\(^{-2}\) frontside)

Ground reflectance (R)

R. Kopecek and J. Libal, Bifacial Photovoltaics: Technology, applications and economics, IET publishing, 2019
System $G_{\text{Rear}}$ experiences self-shading

C. Deline et al., Assessment of Bifacial Photovoltaic Module Power Rating Methodologies – Inside and Out, J. Photovoltaics 7, 2017
Bifacial Performance

Models
Complicated geometries possible, including racking and terrain.

Radiance uses backward ray-trace to evaluate the irradiance (W/m²) at the modules.

Field validation shows good agreement with close-mount rooftop mockup.

View Factor Model for Rear Irradiance

Simple
basic geometry

Fast
computationally inexpensive

Common

Behind
SAM, Pvsyst, and others

PVSyst v6.75
$G_{\text{rear}}$ is summed over 180° field-of-view:

$$G_{\text{rear}} = G_{\text{DNI,rear}} + \sum_{i=1}^{180^\circ} VF_i \cdot F_i \cdot G_i ;$$

$$VF_i = \frac{1}{2} \cdot [\cos(i - 1) - \cos(i)];$$

$$F_i = \text{Incidence angle modifier}(\Theta)$$

$$G_i = \text{Irradiance} \left[ G_{\text{sky}}, G_{\text{hor}}, \rho \cdot G_{\text{ground}} \right];$$

Irradiance sources: sky, ground (shaded or unshaded)

B. Marion et al., A Practical Irradiance Model for Bifacial PV Modules, 2017
B. Marion, Numerical method for angle-of-incidence correction factors for diffuse radiation incident photovoltaic modules, 2017
NREL SAM Model

Bifacial trackers, 75 kW
5 bifacial technologies
### Bifacial system configuration

- **20 modules (7.5 kW) / row**
- 4 PERC, 1 SHJ Bifacial strings
- 3 PERC monofacial strings
- Module electronics / monitoring
- String kWh\textsubscript{DC} monitoring
- Front, rear POA irradiance
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**Front, rear POA irradiance**

- = Front POA
- = Rear POA
Initial field results – bifacial trackers

1-axis tracker - cloudy & sunny day

\[ \text{BG}_E = \frac{E_{\text{bifacial}}}{E_{\text{mono}}} - 1 \]
Initial field results – bifacial trackers

\[ BG_E = \frac{E_{bifacial}}{E_{mono}} - 1 \]
More diffuse = higher $BG_E$
Initial field results – bifacial trackers

\[ BGE = \frac{E_{bifacial}}{E_{mono}} - 1 \]

Annual power histogram

50% energy production
Modeled vs Measured $P_{DC}$ Power

Monofacial PERC
Mean model error: 1.88%. RMSE: 18.0%

Bifacial PERC
Mean model error: 1.75%. RMSE: 19.9%

*SAM v2018.11 using 15-minute measured DNI, DHI, albedo from SRRL BMS. Andreas, A.; Stoffel, T.; (1981). NREL Solar Radiation Research Laboratory (SRRL): Baseline Measurement System (BMS); Golden, Colorado (Data); NREL Report No. DA-5500-56488. Bifacial systems assume 5% shading loss, 5% mismatch loss, 0% transmission factor
Bifacial modeling sensitivity

3 sensitivity cases:

<table>
<thead>
<tr>
<th></th>
<th>Ground albedo</th>
<th>PERC $\phi_{Bifi}$</th>
<th>Si-HJT $\phi_{Bifi}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>High case</td>
<td>0.30</td>
<td>0.75</td>
<td>0.95</td>
</tr>
<tr>
<td>Average case</td>
<td>0.20</td>
<td>0.7</td>
<td>0.90</td>
</tr>
<tr>
<td>Low case</td>
<td>0.15</td>
<td>0.65</td>
<td>0.85</td>
</tr>
</tbody>
</table>

PERC bifacial gain 4-8%

Si-HJT bifacial gain 6.5-11%

Field test results to date

$BG_e = \frac{E_{bifacial}}{E_{mono}} - 1$

Market Analysis
Assumptions: 100MW system, 1.2 DC-AC ratio, 0.35 GCR
LCOE Analysis for Monofacial and Bifacial PV Systems

Assumptions: 100MW system, 1.2 DC-AC ratio, 0.35 GCR
## LCOE Analysis for Monofacial and Bifacial PV Systems

**POST-TARIFF Bifacial vs Monofacial LCOE at various US sites**

6% Nominal Discount Rate. Single Owner and Unlevered Pro Forma with 30% ITC

<table>
<thead>
<tr>
<th>Site</th>
<th>kWh/kW annual (monofacial)</th>
<th>Monofacial LCOE</th>
<th>PERC Bifacial</th>
<th>SHJ Bifacial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seattle, WA</td>
<td>1,200</td>
<td></td>
<td>$1.05/W</td>
<td>$1.05/W</td>
</tr>
<tr>
<td>Kansas City, MO</td>
<td>1,450</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miami, FL</td>
<td>1,700</td>
<td>$1.05/W</td>
<td>$1.09/W</td>
<td></td>
</tr>
<tr>
<td>Daggett, CA</td>
<td>1,950</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


Assumptions: 100MW system, 1.2 DC-AC ratio, 0.35 GCR
Conclusions:

• Bifacial PV is becoming mainstream with GW’s of installed projects

• Energy gain depends on the site configuration and surface albedo. Models like SAM, PVSyst and Bifacial_Radiance can assist with system design and power estimation.

• 1-axis tracker validation is underway at NREL, showing good initial match with model, and energy gain of 6% and 9% annually for PERC and Si-HJT.

• LCOE of bifacial systems is competitive with monofacial systems now, even with initial cost adder of 5-6 ¢/W. Post-tariff, bifacial is a clear winner.
Look for more

**WEDNESDAY, 10:30A:** (Sheraton 4-5)
- B. Lee, J. Wu: Bifacial PERC cells. 11A & 11:30A

**THURSDAY, 8:30A:** (Chicago 8)
- A. Asgharzadeh: Benchmarking models. 8:30A
- M. Waters: Bifacial Capacity Testing. 8:45A
- K. McIntosh: Bifacial mismatch loss 9:00A

**THURSDAY 10:30A:** (Sheraton 1)
- M. Patel, R. Bailey: Albedo. 10:30 & 10:45A
- S. Ayala: Shading effects on bifacial trackers. 11A

**36th EU PVSEC (Marseille)**
**6th Bifi PV Workshop (Amsterdam)**
- S. Ayala: Electrical mismatch and shading
- B. Marion: Ground albedo measurements
- J. Stein: HPC Optimization of Bifacial Systems

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Modeling Rear Irradiance

- Albedo
- Row-to-row spacing
- Clearance
- Tilt

**Irradiance Model**
- Location
- Weather
- Sky Diffuse Model

**Others:**
- Spacing between cells
- #rows, #panels
- Mounting Structure
- Other scene elements
LCOE Analysis for Monofacial and Bifacial PV Systems

Assumptions: 100MW system, 1.2 DC-AC ratio, 0.35 GCR
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