Realistic Yield Expectations for Bifacial PV Systems – an Assessment of Announced, Predicted and Observed Benefits

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Bifacial PV Modules and Systems

Bifacial gain

Ratio of additional “rear side” kWh to “front only” kWh

$$BG = \frac{E_{\text{rear}}}{E_{\text{front}}}$$
Bifacial PV Modules and Systems
Bifacial gain

Some bifacial gain values from literature (mainly experimental / test systems):

- bSolar 2014: 24%
- bSolar 2014: 15%
- Sanyo 2009: 22%
- ISC Konstanz 2014: 22%
- EdF R&D 2014: 57%
- ECN 2014: 20%
Bifacial PV Modules and Systems

Bifacial gain

- Is the bifacial gain a module property?
- Is it around 20%?
- What about large commercial installations?
AGENDA

- Efficiency and Power: Definitions
- Predicting Bifacial Yields
- Exemplary Results
- Conclusion
# Bifacial PV Modules and Systems

## Influence on bifacial gain

Yield depends on with monofacial with bifacial modules

- **STC power**: ++ ++
- **module properties**: + ++
- **tilt angle**: + ++
- **height**: o ++
- **albedo**: + ++
- **mounting structure**: o +

... and other factors

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Bifacial Efficiency and Power
A Straight Forward Approach

Yield ~ \( G(\text{front}) \times \text{eff}(\text{front}) + G(\text{rear}) \times \text{eff}(\text{rear}) \)

= \( G(\text{front}) \times \text{eff}(\text{front}) + G(\text{rear}) \times \text{eff}(\text{front}) \times BF \)

- STC value
  - 18% ... 22%
- Optical gain
  - 5% ... 50%
- Bifaciality factor
  - 75% ... 95%

These factors determine bifacial gain

- Module property (laboratory)
- System property (software)
- Module property (laboratory)
Predicting Bifacial Yields
Predicting Optical Gains

- No commonly used software available (the current versions of e.g. PVSYST, PV*SOL, and NREL’s SAM cannot predict optical gains)
- Numerical methods from physics and optics offer different approaches:
  - View factor method
  - Ray tracing method
Predicting Bifacial Yields

The view factor method

The view factor $F(1,2)$ is the proportion of the radiation which leaves surface 1 that strikes surface 2.
Predicting Bifacial Yields

The view factor method

The view factor $F_{1 \rightarrow 2}$ is the proportion of the radiation which leaves surface 1 that strikes surface 2.

$$F_{1 \rightarrow 2} = \frac{1}{A_1} \int_{A_1} \int_{A_2} \frac{\cos \theta_1 \cos \theta_2}{\pi s^2} dA_2 dA_1$$
Predicting Bifacial Yields
The ray tracing method

...traces the path of light through pixels in an image plane and simulates the effects of its encounters with virtual objects.

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Predicting Bifacial Yields

Predicting Optical Gains

- View factor method:
  - easy to implement for simple geometries
  - becomes complex task for realistic systems

- Ray tracing method:
  - less easy to implement
  - time consuming
  - delivers rear side irradiance, rear side inhomogeneity, mutual (front side) shading, influence of mounting structure...
Predicting Bifacial Yields
Rendering with Radiance

Features:
- Backward ray tracing
- Arbitrary surface properties
- Artificial light sources
- Natural light sources (sun & sky)
- Results in units of W/m²sr or W/m²
- Operates in an Unix environment
- No contemporary user interface
Predicting Bifacial Yields
Rendering with Radiance

- Artificial light ...
Predicting Bifacial Yields
Rendering with Radiance

- Natural light ...

- See also: Ch. Reise, A. Kovach: *PV Shading Analysis in Complex Building Geometries*, 13th EUPVSEC, Nice (FR), 1995
Predicting Bifacial Yields
Rendering with Radiance
Predicting Bifacial Yields
Rendering with Radiance

An example:

- Bifacial modules
- Mounting Structure
- Albedo properties
- Sky radiance distribution

... human view
Predicting Bifacial Yields
Rendering with Radiance

An example:
- Bifacial modules
- Mounting Structure
- Albedo properties
- Sky radiance distribution

... aerial view
Predicting Bifacial Yields
Rendering with Radiance

An example:

- Bifacial modules
- Mounting Structure
- Albedo properties
- Sky radiance distribution

... mouse view
Predicting Bifacial Yields

Validation I

The prototype:
Bifacial module test installation, monitored by Fraunhofer ISE in 2009
Predicting Bifacial Yields

Validation I

System model validation results (235 days in 2009):

<table>
<thead>
<tr>
<th></th>
<th>height</th>
<th>tilt angle</th>
<th>albedo</th>
<th>bifacial Gain DC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement</td>
<td>0.2 m</td>
<td>15</td>
<td>0.64</td>
<td>21.9%</td>
</tr>
<tr>
<td>Model</td>
<td>0.2 m</td>
<td>15</td>
<td>0.64</td>
<td>21.1%</td>
</tr>
</tbody>
</table>
Predicting Bifacial Yields

Validation II

Single module model validation...
Predicting Bifacial Yields
Validation II

Single module model validation results: irradiation vs. tilt angle
Predicting Bifacial Yields

Validation II

Single module model validation results: $I_{sc}$ vs. tilt angle
Exemplary Results

- Bifacial modules will be installed in commercial PV projects.
- Commercial PV projects will follow or extend traditional installation schemes, therefore, some contradictions will arise:
  - Module height vs. wind load with rooftop systems.
  - Optical gain vs. space requirements (GCR).
  - Increased albedo vs. maintenance effort.
- Most probably, commercial PV projects will show lower bifacial gains than test or demonstration installations.
Exemplary Results

Some bifacial gain values from our consulting work:
Exemplary Results

First example values for a rooftop system:

<table>
<thead>
<tr>
<th>type</th>
<th>height</th>
<th>tilt angle</th>
<th>albedo</th>
<th>GCR</th>
<th>Country</th>
<th>bifacial Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>rooftop</td>
<td>0.1 m</td>
<td>20</td>
<td>0.40</td>
<td>0.40</td>
<td>DE</td>
<td>6%</td>
</tr>
<tr>
<td>rooftop</td>
<td>0.3 m</td>
<td>20</td>
<td>0.40</td>
<td>0.40</td>
<td>DE</td>
<td>11%</td>
</tr>
<tr>
<td>rooftop</td>
<td>0.5 m</td>
<td>20</td>
<td>0.40</td>
<td>0.40</td>
<td>DE</td>
<td>14%</td>
</tr>
<tr>
<td>rooftop</td>
<td>0.3 m</td>
<td>20</td>
<td>0.20</td>
<td>0.40</td>
<td>DE</td>
<td>6%</td>
</tr>
<tr>
<td>rooftop</td>
<td>0.3 m</td>
<td>20</td>
<td>0.40</td>
<td>0.40</td>
<td>DE</td>
<td>11%</td>
</tr>
<tr>
<td>rooftop</td>
<td>0.3 m</td>
<td>20</td>
<td>0.60</td>
<td>0.40</td>
<td>DE</td>
<td>16%</td>
</tr>
</tbody>
</table>
Summary

- Bifacial modules show a big potential for increased yield and/or reduced electricity costs
- Bifacial gain is not a module property
- Bifacial module characterization needs some proper definitions
- Each system layout needs an individual assessment
- Small experimental or demonstration systems show bifacial gains of 15% to 25%
- With larger commercial systems, realistic bifacial gains are expected in a range from 5% to 15%
- Optimization of mounting geometry and mounting structure is essential in order to draw the full benefits from bifacial PV modules
Thank you for your attention!

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