Accuracy of Simulated Data for Bifacial Systems with Varying Tilt Angles and Share of Diffuse Radiation

Measured data compared to simulations

ECN.TNO - Gaby Janssen, Teun Burgers
ISC Konstanz - Djaber Berrian, Joris Libal
PVsyst - Bruno Wittmer, André Mermoud
ZHAW - Markus Klenk, Hartmut Nussbaumer, Marco Morf, Franz Baumgartner

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Retrospection and motivation

Measurement results obtained with the BIFOROT

- BIFOROT - Bifacial Outdoor Rotor Tester
- Focus on central module(s)

Continuously varying tilt angle (automated, 1-minute cycle 0° - 90°, 12 steps)

No tracker ⇒ South-oriented, variable mounting parameters
Retrospection and motivation

Simulation tools from PVsyst, ISC Constance and ECN.TNO (2 models)

Three characteristic irradiation conditions and tilt angle variation

Results (deviation of daily yield vs. tilt angle)

Deviations dependent on irradiation conditions and tilt angle

Results sparked the interest in a closer analysis
Retrospection and motivation

Setup and general aspects

Measured data compared to simulations
  - Front side irradiation $G$
  - Rear side irradiation $G_{\text{rear}}$
  - “Effective” $I_{\text{SC,rear}}$
  - Bifacial gain (current)
  - Power

Summary

More detailed information → Paper submitted to «Solar Energy»
Power measurement of central bifacial module M2; 12 tilt angles per minute
\( I_{SC} \) measurement of M1 and M3 reveal contribution of front and rear side

M3 bifacial
Rear side blocked
\( I_{SC} \) frontside

M2 bifacial
\( P_{MPP} \) bifacial

M1 bifacial
Front side blocked
\( I_{SC} \) rearside

Albedo: 0.5
Setup and general aspects

Irradiation data from various sensors

Rooftop: GHI and DHI by pyranometer + pyrheliometer + horizontal reference cell

Rotating with module M2: Pyranometer + reference cell

Red frames:
Sensors not used in this work

Remark:
Axis height fixed; not ground clearance
Setup and general aspects

Three days with characteristic irradiation conditions

Mid-October to early November

10/15 Irradiation ↑ diffuse fraction: 18%
11/02 Mixed conditions; diff. fraction: 72%
11/08 Irradiation ↓ diffuse fraction: 99%
Setup and general aspects

Three simulation tools for monofacial and bifacial applications (also tracking)

- ECN.TNO: “BIGEYE” V3
- ISC Konstanz: “MoBiDiG” (Modelling of Bifacial Distributed Gain)
- PVsyst V6.81: Renown commercial simulation tool

Differences mainly in the irradiation model

Details ⇒ paper
Measured data compared to simulations
Simulation of the front side well established in the simulation of monofacial modules

Why should front side simulation be of interest for bifacial modules?

- In the course of the data analysis → the sensitivity of the output at specific conditions (low irradiation and steep tilt angle) to the irradiation measurement was highlighted
- Tilt angles that can be a reasonable choice for bifacial installations also include conditions that are rarely applied to monofacial systems (e.g. vertical installation)

Analysis of G: Irradiation on front side module plane

Other approach for front side analysis: “Effective Isc” → Paper
Front side irradiation $G$

Calculation with BIGEYE from ECN.TNO

Similar results for all three simulation tools

“$G_{\text{front simulated}}$” based on GHI data recorded with the pyranometer on the roof

- **Diffuse fraction:** 18%
- **Diffuse fraction:** 72%
- **Diffuse fraction:** 99%

Significant deviations only for low irradiance
Front side irradiation G

GHI for simulation, pyranometer on roof

GHI for simulation, pyranometer on axis at 0° tilt

Apparently good congruence of the irradiation data

Nevertheless, significantly improved simulation if GHI from rotating pyranometer at 0° tilt is used
Calculations with BIGEYE

The relative error increases for conditions with low irradiance and for higher tilt angles.

Simulation results can be very sensitive to the horizontal irradiance input at cloudy days with low horizontal beam component (GHI-DHI).
Analysis of observed behaviour

‘rotating pyranometer’ gives lower GHI,

⇒ lower beam component (GHI-DHI) and clearness parameter $\epsilon$ for Perez model

Detailed description and analysis ⇒ Paper

Any uncertainty in horizontal beam component (GHI-DHI) or the circumsolar fraction, will be magnified at larger tilt angles

If horizontal beam component is overestimated, the overestimation blows up at high tilt angles
Front side irradiation $G$

Deviation $\Delta G$ (sim.-meas.) to meas.

All three simulation tools GHI by turning pyranometer at $0^\circ$

Diffuse fraction: 18%

Diffuse fraction: 72%

Diffuse fraction: 99%
Rear side irradiation $G_{\text{rear}}$

Rear side irradiance

Obvious: Relate to measurement data of M1 (I_{sc})

However shading of front row @ direct Irr. during relevant period (construction crane)

Other option

$I_{sc,\text{rear}} = I_{sc} (M2) - I_{sc} (M3)$

Correlation of $I_{sc,\text{rear}}$ with simulated $G_{\text{rear}}$
Rear side irradiation $G_{\text{rear}}$

$I_{SC,\text{rear}}$ vs. $G_{\text{rear}}$ (simulated)

$G_{\text{rear}}$: averaged over module plane

- Compared to front side: Less linear relationship
- Increased differences between the three tools reflect the complexity of the calculation of the rear side irradiance, and the different choices made in the simulation codes
- Deviations and nonlinearities smaller for low irradiation, high diffuse fraction

No indication of tilt

Diffuse fraction: 18%
Diffuse fraction: 72%
Diffuse fraction: 99%
"Effective" $I_{SC,\text{rear}}$

$$I_{sc,\text{rear}} = I_{sc,\text{rear}}^{Eff} \frac{G_{\text{rear}}(\beta)}{E_0}$$

E_0 irradiation at STC

Correlate simulated $G(\beta)$ and $I_{sc}(\beta)$ of M1 → approx. linear ⇒ simulated effective $I_{sc}$;

Diffuse fraction: 18%

Diffuse fraction: 99%

Effective $I_{SC,\text{rear}} > I_{SC,\text{rear}}$ (STC) values indicate (< and > $I_{SC,\text{rear}}$ (STC) observed):

- The simulation underestimates the irradiance on the rear
- $I_{SC}(M2) - I_{SC}(M3)$ is overestimating the contribution of the rear side to total $I_{SC}$
Bifacial gain (current)

- Diffuse fraction: 18%
- Diffuse fraction: 72%
- Diffuse fraction: 99%

\[ BG_{I,meas} = \frac{I_{SC,\text{rear}}}{I_{SC,\text{front}}} \]
\[ BG_{I,sim} = \frac{G_{\text{rear}}}{G_{\text{front}}} \cdot \varphi_I \]

\( \varphi_I \) : STC bifaciality factor
Power

Deviations $\Delta P$ in integrated power output, (simulated-measured) to measured

- Diffuse fraction: 18%
  - $\Delta P$ low for moderate tilt
  - 30° to 45° $\Delta P < \pm 2\%$
  - mostly well below $\pm 1\%$
  - $\Delta P \uparrow$ towards 0° and 90° but within $\pm 3\%$

- Diffuse fraction: 72%
  - “Slope” and “offset”
  - $\Delta P$ max for 0° or 90°
  - Per tool: $\Delta P < 6\%$
  - All tools: $\Delta P \sim \pm 5\%$

- Diffuse fraction: 99%
  - “Slope” and “offset” $\uparrow$
  - $\Delta P$ max for 0° or 90°
  - Per tool: $\Delta P < 10\%$
  - All tools: $\Delta P \sim \pm 10\%$

Deviations at overcast conditions for the annual yield: only small total contribution
Summary

Front side

Significant deviations (measured to simulated) only for overcast conditions

- Results very sensitive at conditions with small beam component (GHI-DHI)
- Small uncertainties in beam component enhanced for steeper tilt angles
- Mono- and bifacial affected.
  - Bifi installations: wider range of applied tilt angles
  - Very low error for tilt angles that are typical for monofacial modules
- Typical south-oriented bifi installations → front side related effects dominate

“Simulated front side irradiance is as good as the irradiance data enables”

Rear side

Deviations particularly at conditions with high direct irradiation share

- Measurements more affected by inhomogeneities and shading by the mounting
- Causes for deviations still not fully understood

More distinct differences between the three simulation tools
Summary

Bifacial gain and total electrical output → Well predicted by all three models

Power: Particularly for high irradiation, low diffuse share remarkably small deviations

Overcast conditions → comparatively small contribution to the annual yield

<table>
<thead>
<tr>
<th>Irr.: ↑; diffuse fraction: 18%</th>
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Results shows that bifacial yield modeling is reaching a stage of maturity

Our aim is to present the analysis of long-term data in a future study
Additional slides
Other concept, the «effective $I_{sc}$»

Good linear relation: $I_{sc} (\beta)$ of M3 and $G(\beta)$

$$I_{sc}(M3, \beta) = I_{sc, \text{front}}^\text{Eff} \frac{G(\beta)}{E^0}$$

$G(\beta)$ measured or simulated effective $I_{sc}$

$E_0$ irradiation at STC

Diffuse fraction: 18%  Diffuse fraction: 99%
Fair agreement with the STC $I_{SC\text{,front}}$. Deviations expected:

- **Module**: additional and tilt dependent reflection losses. Irradiance on module less as on pyranometers $\Rightarrow I_{SC\text{,front}}^{\text{eff}} < I_{\text{sc (STC)}}$. According to results no major influence.

- Slight current increase with temperature (3-4 mA.K$^{-1}$). Should be similar for all tilt angles and lead to higher effective $I_{SC\text{,front}}^{\text{eff}}$. Averaging of temp. due to rotation. Measured values > STC values, but deviations > than temp. effect.

- Inaccuracies in the measured irradiance and current. Measured $I_{SC\text{,front}}^{\text{eff}}$ always larger than the STC value indicates underestimation of $G$ or an overestimation of the front side current.

- Non-uniform irradiance distribution on the module. The cell with smallest irradiance will limit the current leading to smaller measured currents.
Front side irradiation $G$

Analysis of observed behaviour

‘rotating pyranometer’ gives lower GHI,

$\Rightarrow$ lower beam component (GHI-DHI) and clearness parameter $\epsilon$ for Perez model

$$G_{\text{front}} = (GHI - DHI + DHI \cdot F_1) \frac{\cos \theta}{\cos \theta_z} + DHI \cdot \left[ (1 - F_1) \cdot VF_{\text{sky}} + F_2 \cdot \sin \beta \right] + \gamma \cdot GHI \cdot VF_{\text{ground}}$$

$\theta$: angle of beam incidence, $\theta_z$: sun zenith angle, $\gamma$: ground reflection coefficient

$F_1$ and $F_2$: Perez coefficients depending on $\epsilon$ and the sky brightness

$VF_{\text{sky}} \downarrow$ with tilt angle $\uparrow$

Any uncertainty in horizontal beam component (GHI-DHI) or in $F_1$, a parameter determining the circumsolar fraction, will be magnified at larger tilt angles