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

ECN › TNO innovation for life

ISC International Solar Energy Research Center Konstanz

PVSYST PHOTOVOLTAIC SOFTWARE

Zurich University of Applied Sciences zh aw School of Engineering IEFE Institute of Energy Systems and Fluid Engineering

Measured data compared to simulations

ECN.TNO - Gaby Janssen, Teun Burgers

ISC Konstanz - Djaber Berrian, Joris Libal

PVsyst - Bruno Wittmer, André Mermoud

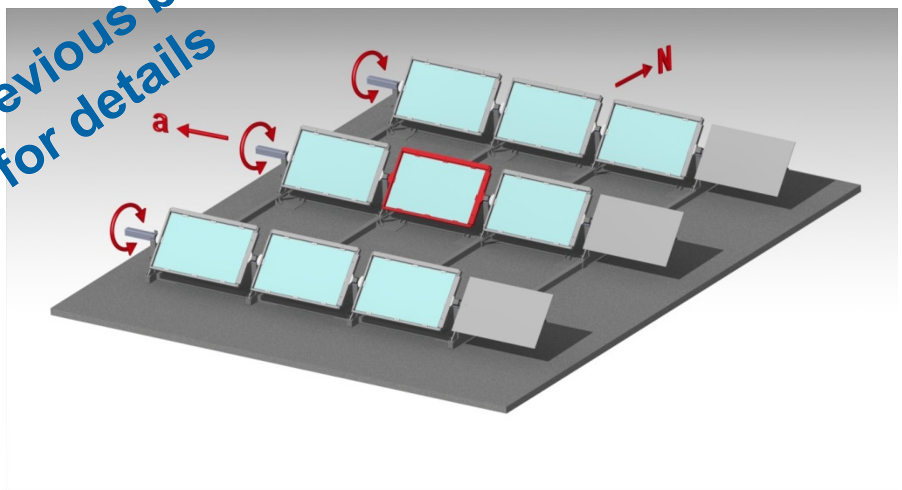
ZHAW - Markus Klenk, Hartmut Nussbaumer, Marco Morf, Franz Baumgartner

Amsterdam, bifi PV 2019

Retrospection and motivation

Zurich University of Applied Sciences
zhaw School of Engineering
IEFE Institute of Energy Systems and Fluid Engineering

See previous bifi PV for details



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

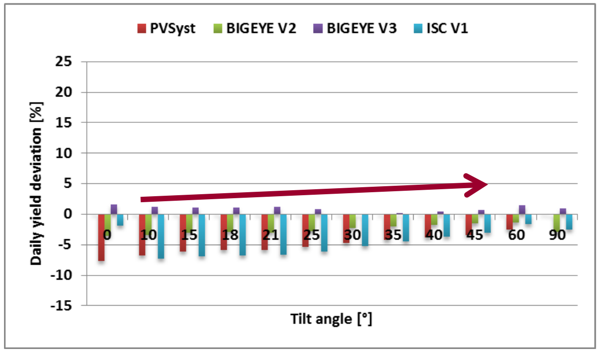
Retrospection and motivation

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

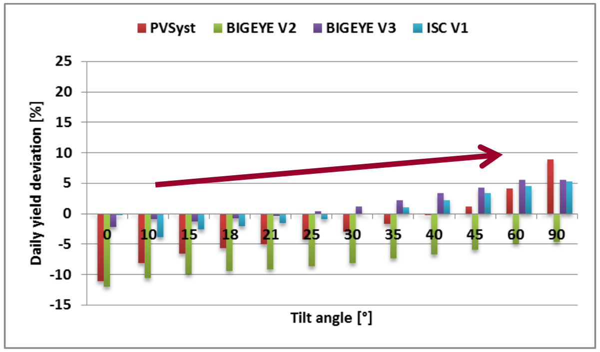
Three characteristic irradiation conditions and tilt angle variation

See previous bifi PV for details

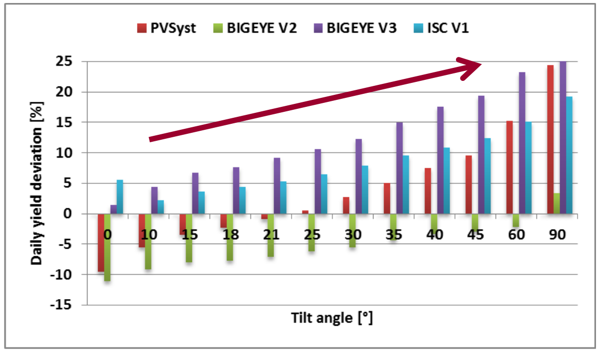
Results (deviation of daily yield vs. tilt angle)



GHI ↑; direct irradiance ↑



Mixed conditions



GHI ↓; direct irradiance ↓

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_{rear}
  - "Effective" $I_{SC,rear}$
  - Bifacial gain (current)
  - Power
- Summary

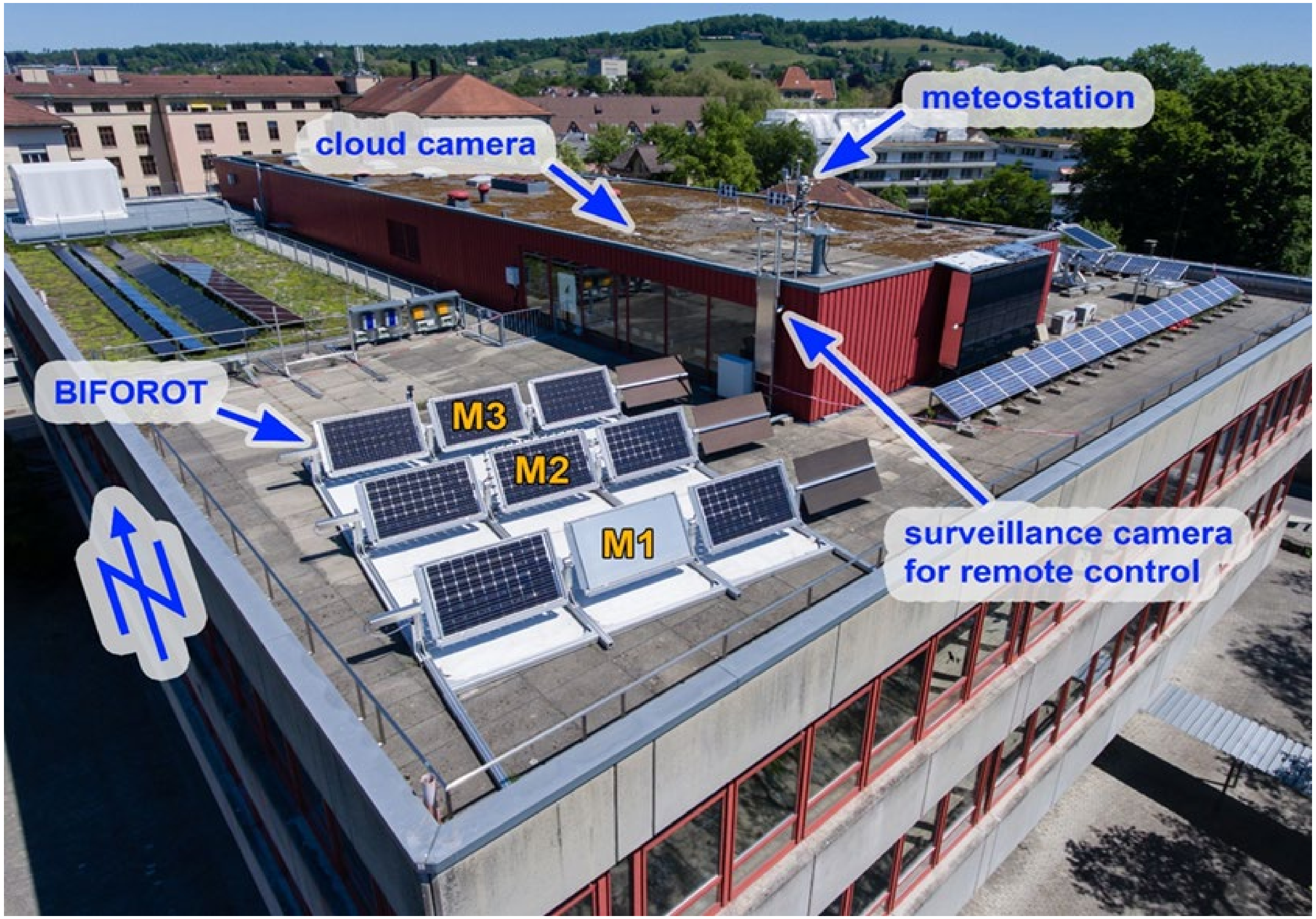
More detailed information → Paper submitted to «Solar Energy»

Setup and general aspects

Zurich University of Applied Sciences
zh aw School of Engineering
IEFE Institute of Energy Systems and Fluid Engineering

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

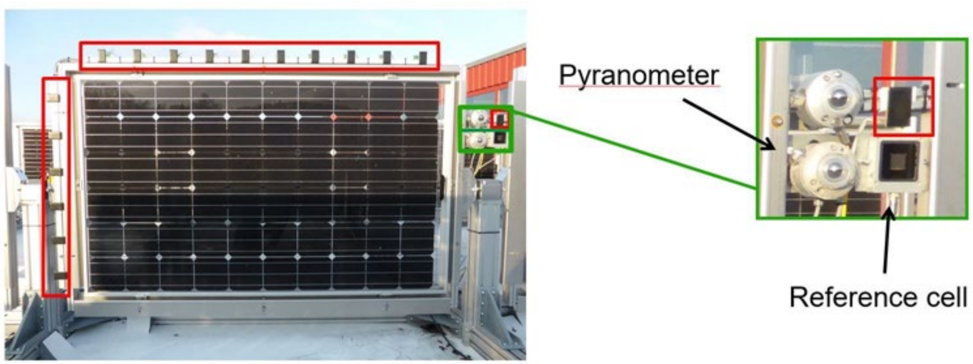
Setup and general aspects

Zurich University of Applied Sciences
zh aw
School of Engineering
IEFE Institute of Energy Systems and Fluid Engineering

Irradiation data from various sensors

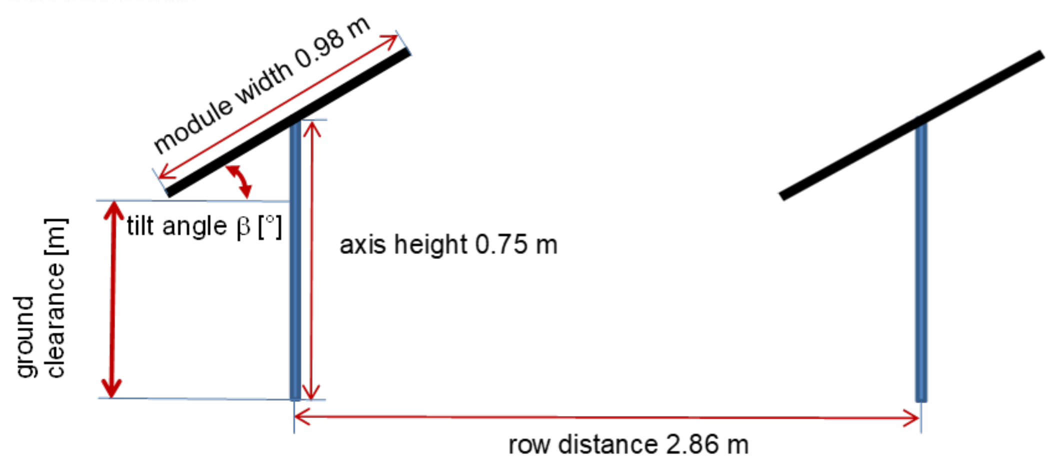
Rooftop: GHI and DHI by pyranometer + pyrheliometer + horizontal reference cell

Rotating with module M2: Pyranometer + reference cell



Red frames:

Sensors not used in this work

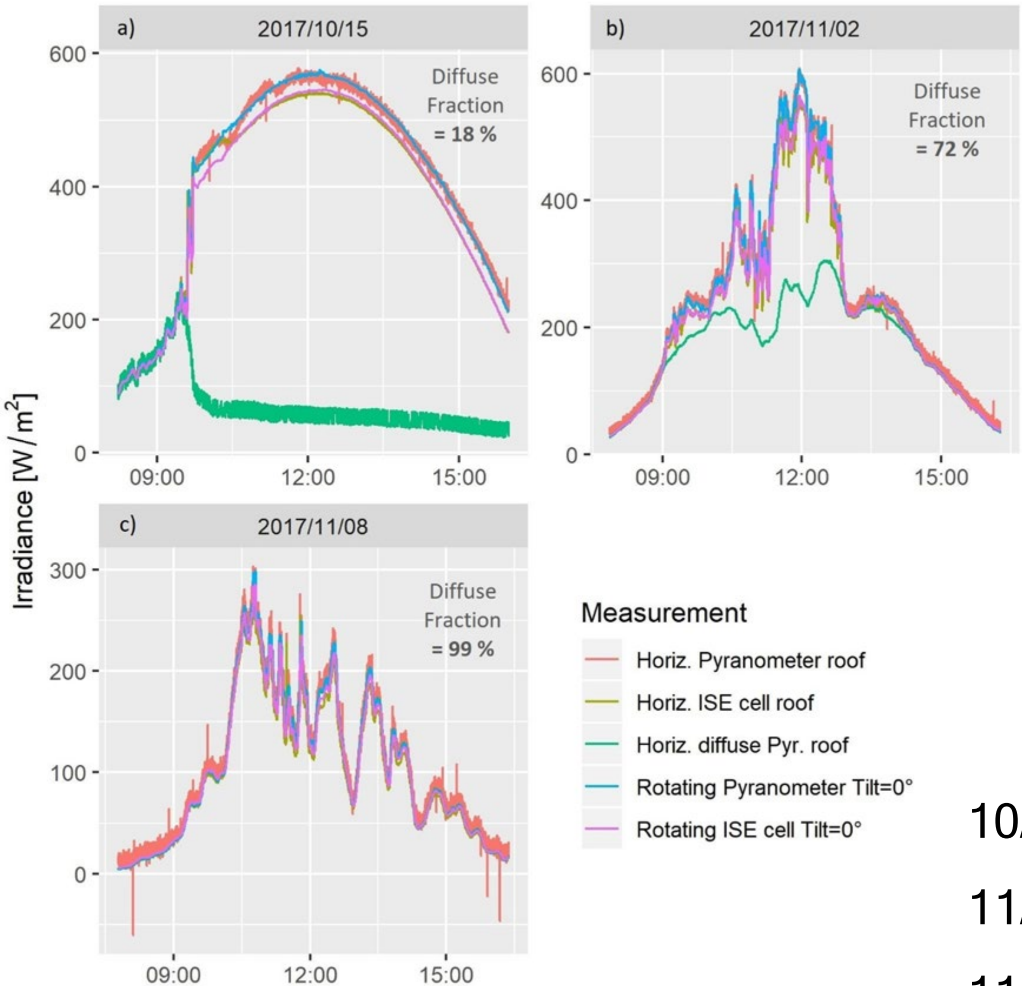


Remark:

Axis height fixed; not ground clearance

Setup and general aspects

Zurich University of Applied Sciences
zh aw School of Engineering
IEFE Institute of Energy Systems and Fluid Engineering



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 $\Rightarrow$ paper

Measured data compared to simulations

Front side irradiation G

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

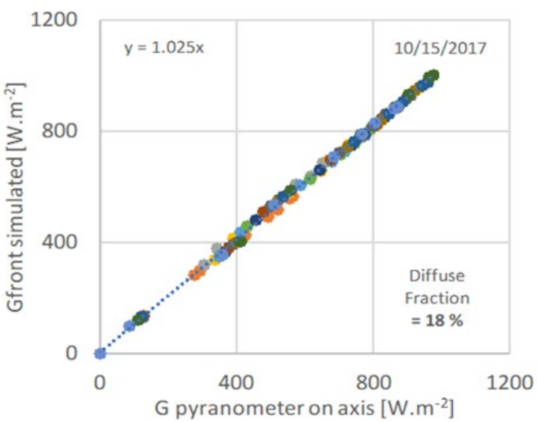
Front side irradiation G

Zurich University of Applied Sciences
zh aw School of Engineering
IEFE Institute of Energy Systems and Fluid Engineering

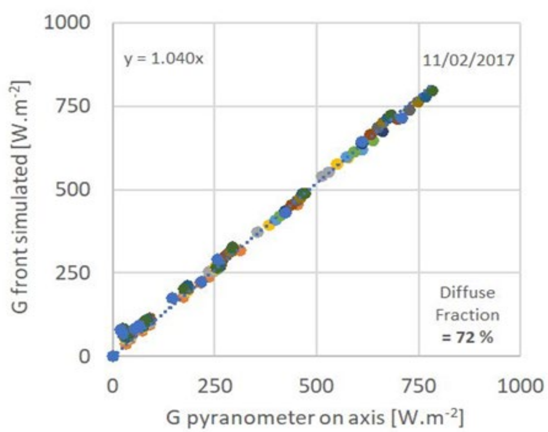
Calculation with BIGEYE from ECN.TNO

Similar results for all three simulation tools

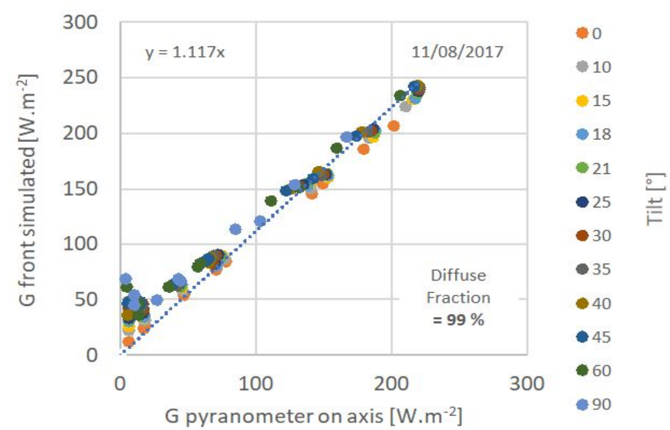
"G_{front} simulated" based on GHI data recorded with the pyranometer on the roof



Diffuse fraction: 18%



Diffuse fraction: 72%



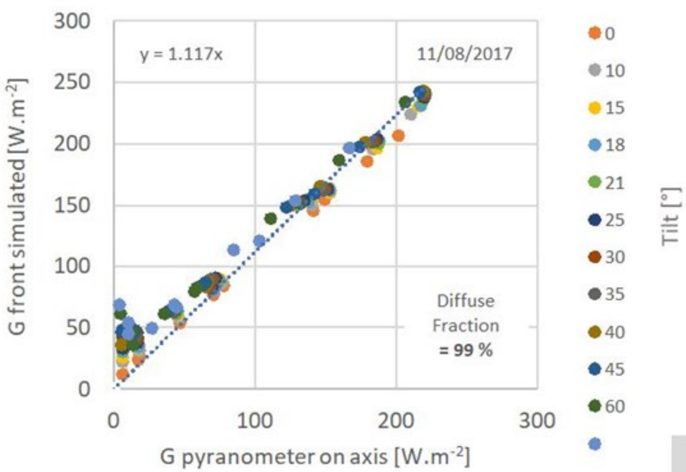
Diffuse fraction: 99%

Significant deviations only for low irradiance

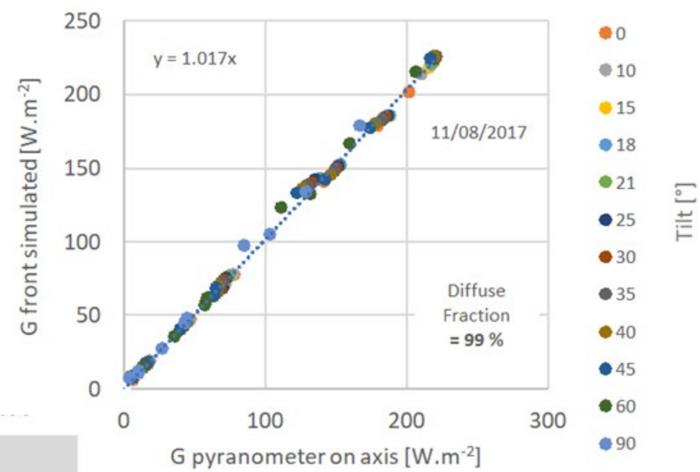
Front side irradiation G

Zurich University of Applied Sciences
School of Engineering
IEFE Institute of Energy Systems and Fluid Engineering

GHI for simulation, pyranometer on roof

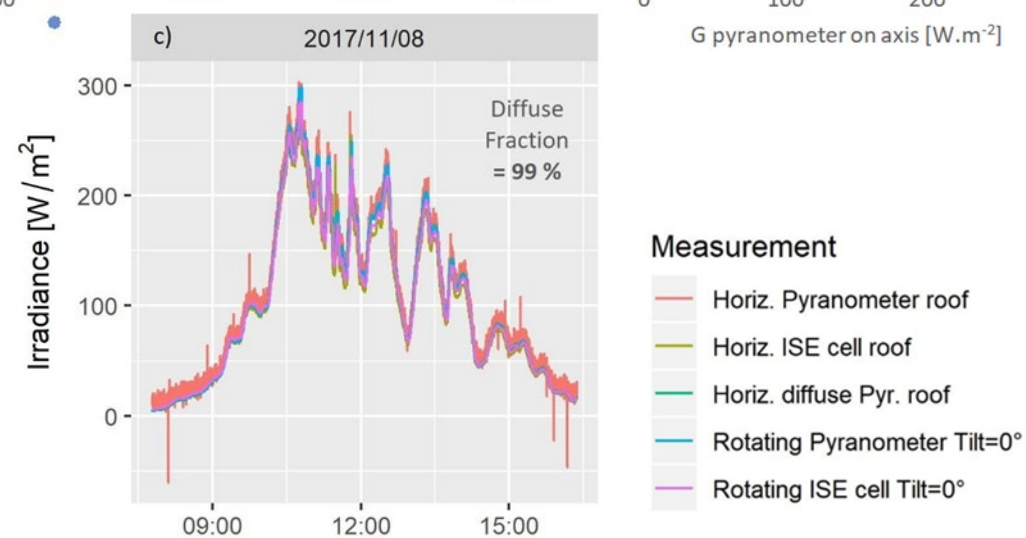


GHI for simulation, pyranometer on axis at 0° tilt



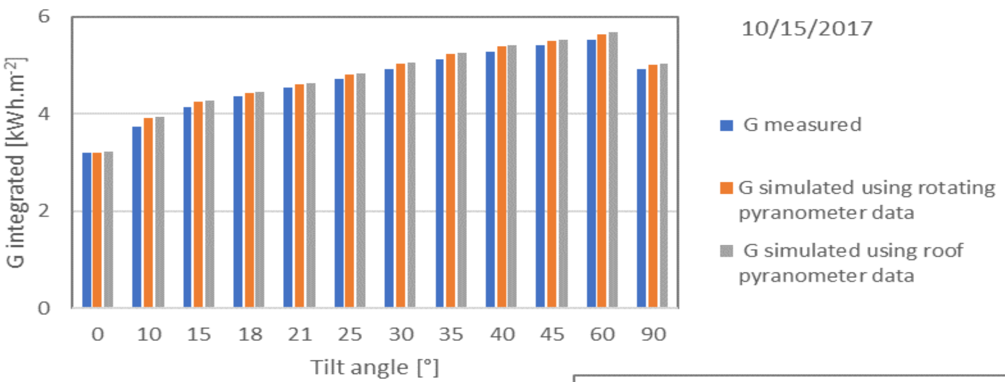
Apparently good congruence of the irradiation data →

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



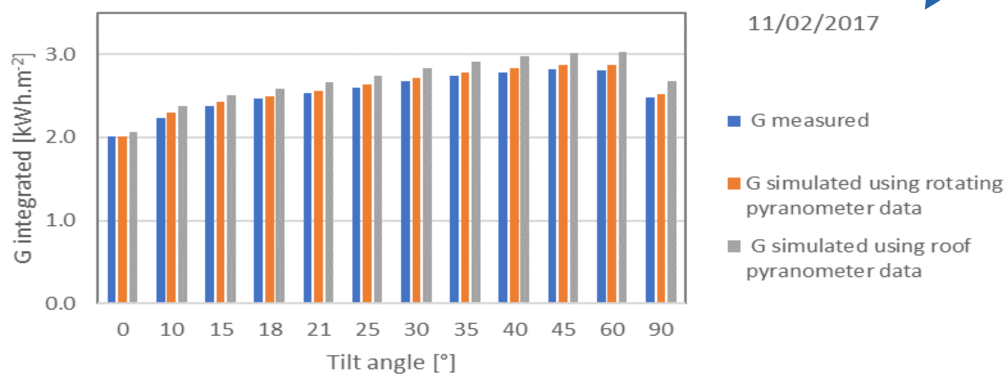
Front side irradiation G

Diffuse fraction: 18%



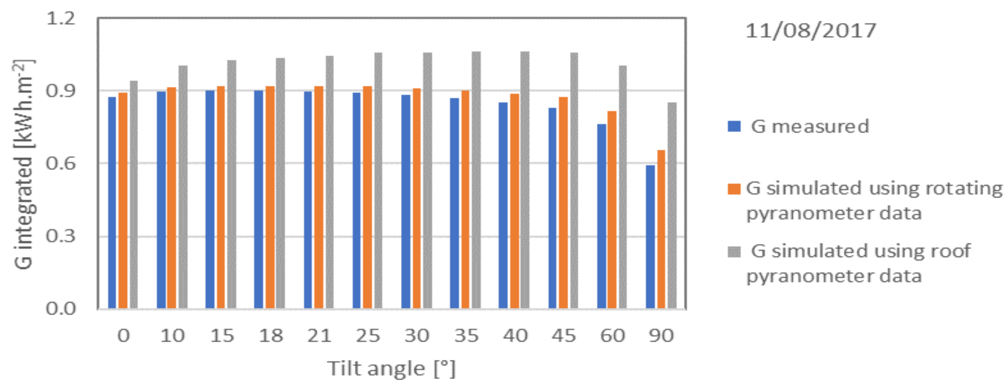
Diffuse fraction: 72%

Calculations with BIGEYE



Diffuse fraction: 99%

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)

Front side irradiation G

Analysis of observed behaviour

'rotating pyranometer' gives lower GHI,

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

Detailed description and analysis $\Rightarrow$ 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

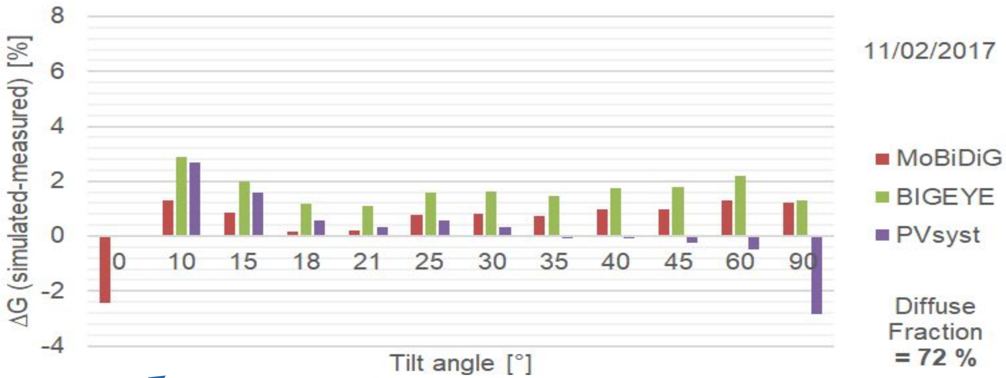
Zurich University of Applied Sciences
zh aw School of Engineering
IEFE Institute of Energy Systems and Fluid Engineering

Deviation ΔG (sim.-meas.) to meas.

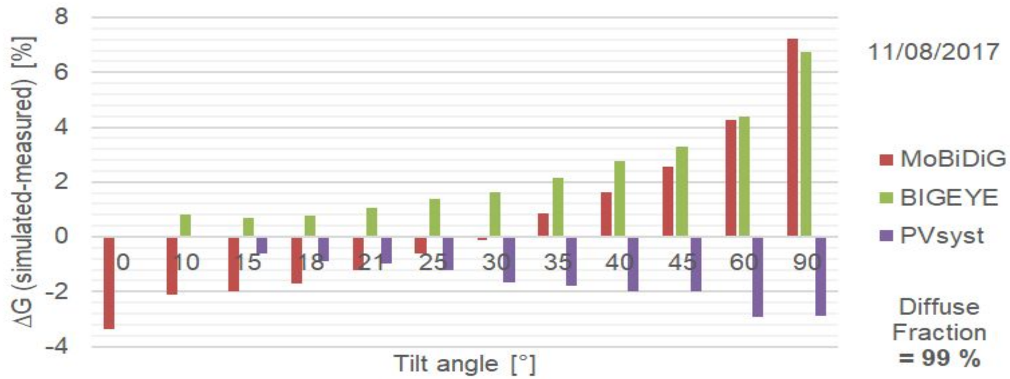
All three simulation tools

GHI by turning pyranometer at 0°

Diffuse fraction: 18%



Diffuse fraction: 72%



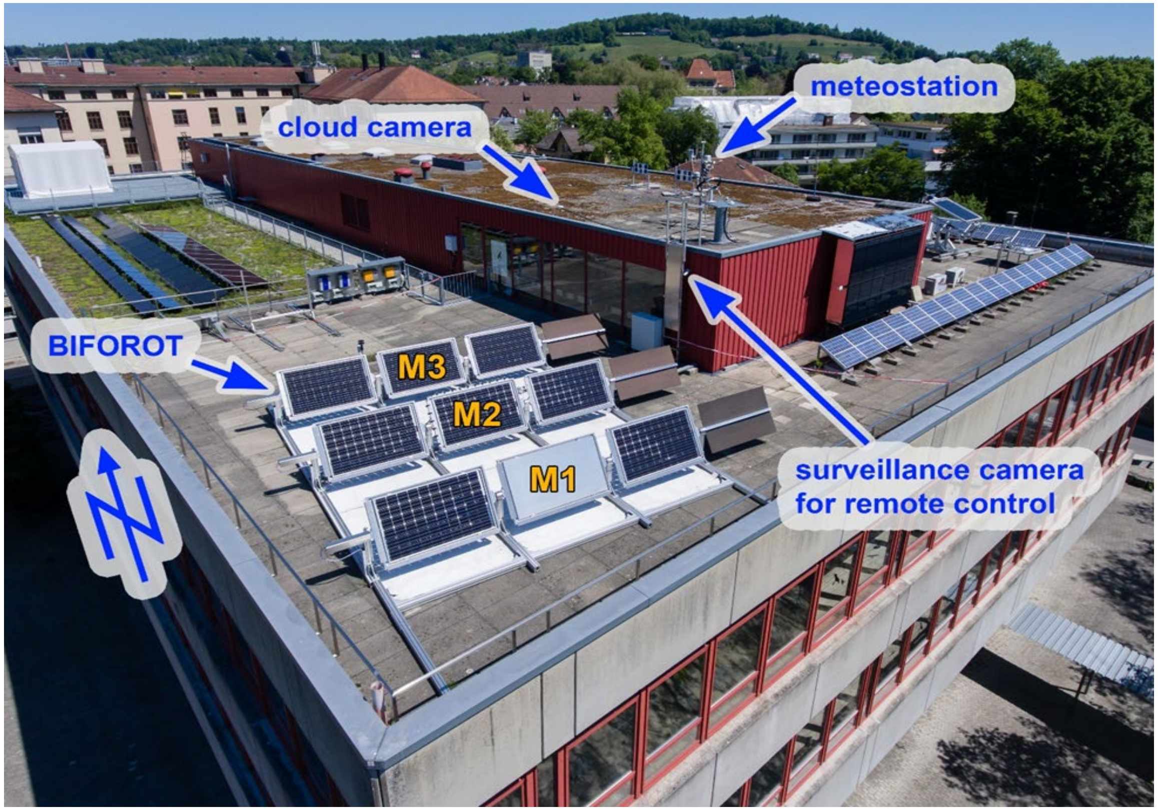
Diffuse fraction: 99%

Rear side irradiation G_{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

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

Correlation of $I_{SC,rear}$ with simulated G_{rear}

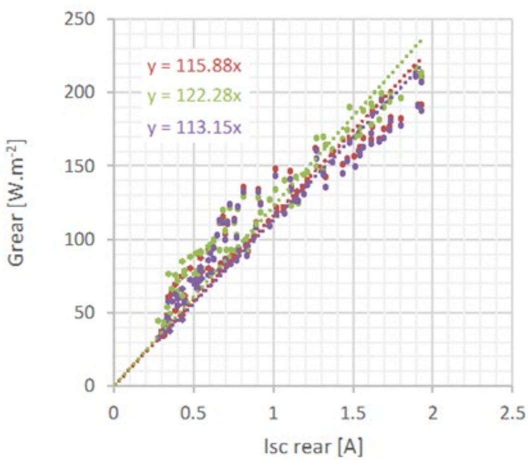
→

Rear side irradiation G_{rear}

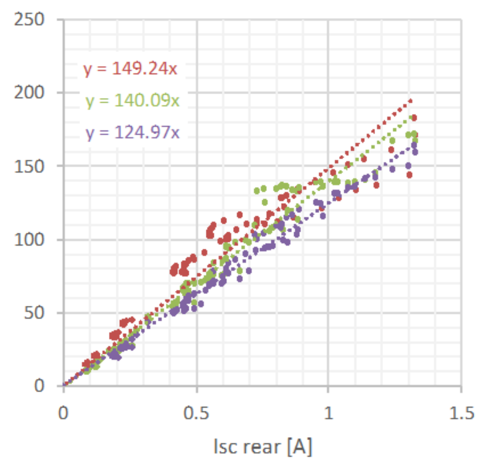
Zurich University of Applied Sciences
zhaw School of Engineering
IEFE Institute of Energy Systems and Fluid Engineering

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

~ G_{rear} : averaged over module plane

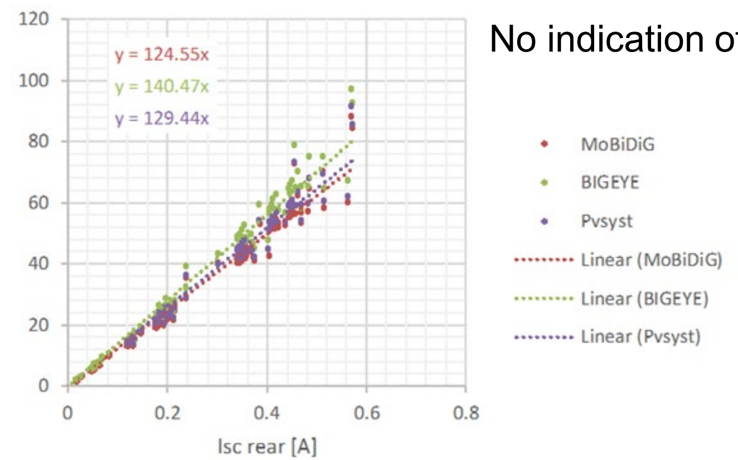


Diffuse fraction: 18%



Diffuse fraction: 72%

No indication of tilt



Diffuse fraction: 99%

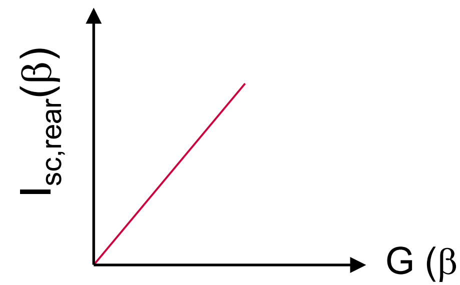
- Compared to front side: Less linear relationship
- Increased differences between the three tools reflect the complexity of the calculation of the rear side irradiance, and the different choices made in the simulation codes
- Deviations and nonlinearities smaller for low irradiation, high diffuse fraction

"Effective" $I_{SC,rear}$

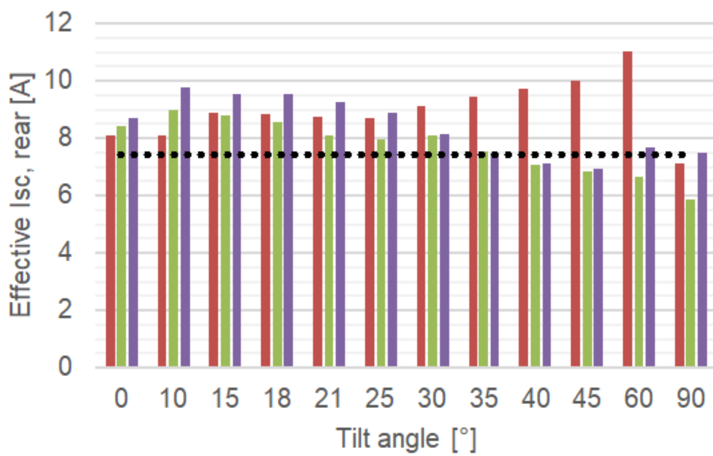
Zurich University of Applied Sciences
zhaw School of Engineering
IEFE Institute of Energy Systems and Fluid Engineering

$$Isc,rear = I_{sc,rear}^{Eff} \frac{G_{rear}(\beta)}{E^0}$$

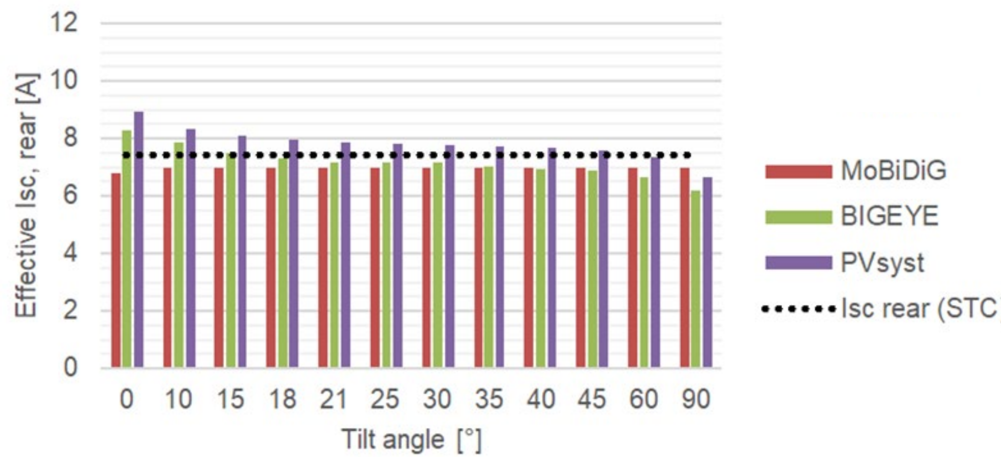
E_0 irradiation at STC



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



Diffuse fraction: 18%



Diffuse fraction: 99%

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

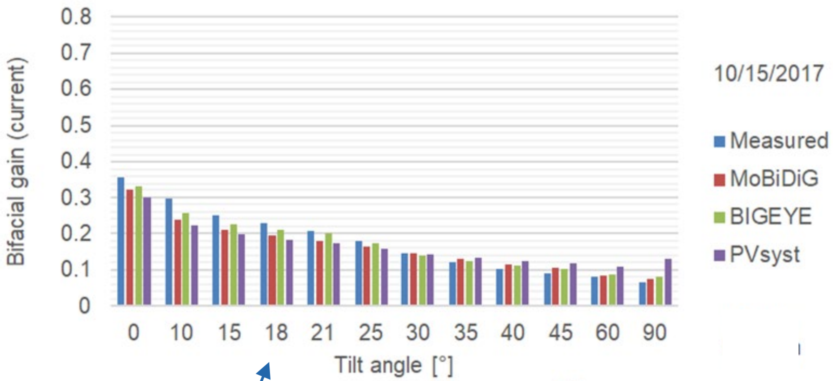
Bifacial gain (current)

Zurich University of Applied Sciences
zhaw School of Engineering
IEFE Institute of Energy Systems and Fluid Engineering

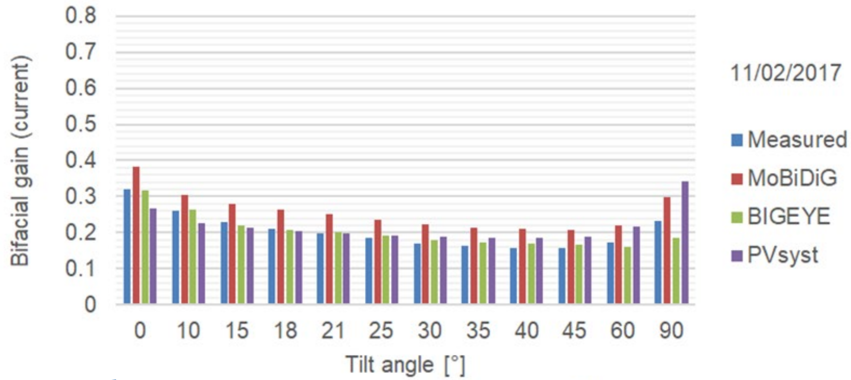
$$BG_{I,meas} = \frac{I_{SC,rear}}{I_{SC,front}}$$

$$BG_{I,sim} = \frac{G_{rear}}{G_{front}} \cdot \varphi_I$$

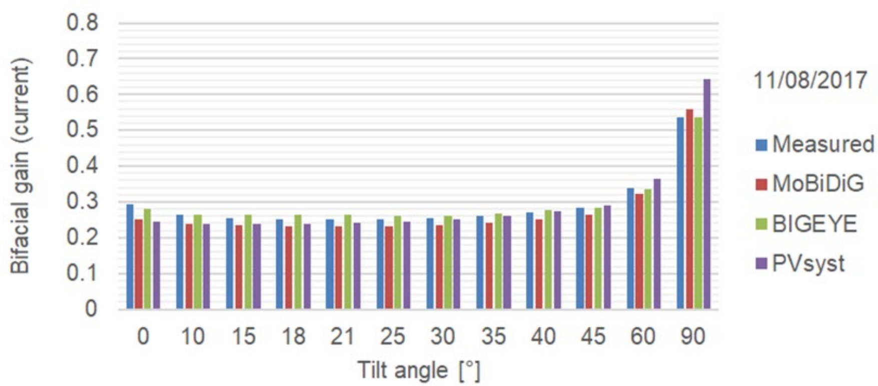
φ_I : STC bifaciality factor



Diffuse fraction: 18%



Diffuse fraction: 72%

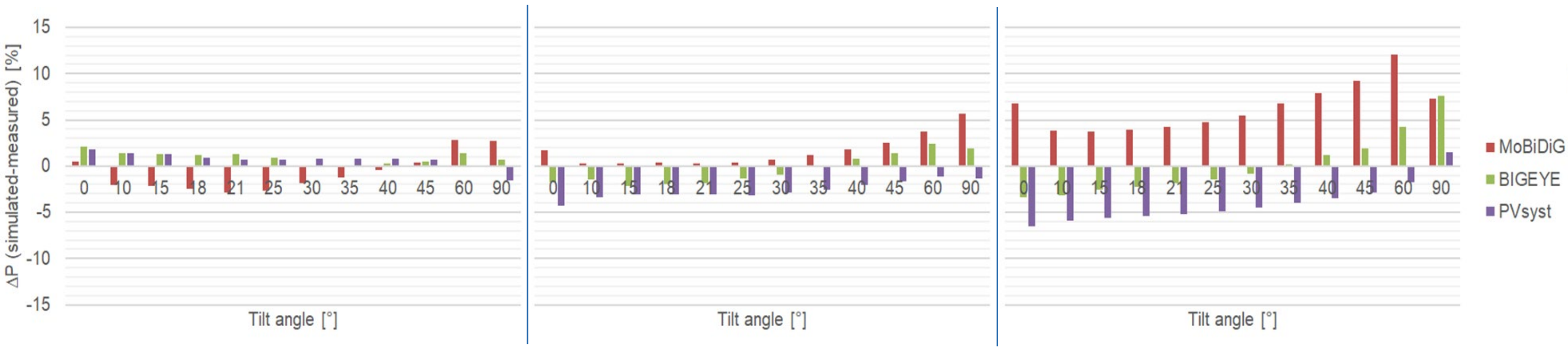


Diffuse fraction: 99%

Power

Zurich University of Applied Sciences
School of Engineering
IEFE Institute of Energy Systems and Fluid Engineering

Deviations ΔP in integrated power output, (simulated-measured) to measured



Diffuse fraction: 18%

Diffuse fraction: 72%

Diffuse fraction: 99%

ΔP low for moderate tilt

30° to 45° ΔP < ± 2 %
mostly well below ± 1 %

ΔP ↑ towards 0° and 90°
but within ± 3 %

“Slope” and “offset”

Δ P max for 0° or 90°

Per tool: Δ P < 6 %
All tools: Δ P ~ ± 5 %

“Slope” and “offset” ↑

ΔP max for 0° or 90°

Per tool: Δ P < 10 %
All tools: Δ P ~ ± 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

Zurich University of Applied Sciences
zh aw School of Engineering
IEFE Institute of Energy Systems and Fluid Engineering

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

Irr.: ↑; diffuse fraction: 18%

ΔP low for moderate tilt

30° to 45° ΔP < ± 2 %
mostly well below ± 1 %

ΔP ↑ towards 0° and 90°
but within ± 3 %

Irr.: ↔; diff. fraction: 72%

“Slope” and “offset”

Δ P max for 0° or 90°

Per tool: Δ P < 6 %
All tools: Δ P ~ ± 5 %

Irr.: ↓; diff. fraction: 99%

“Slope” and “offset” ↑

ΔP max for 0° or 90°

Per tool: Δ P < 10 %
All tools: Δ P ~ ± 10 %

Results shows that bifacial yield modeling is reaching a stage of maturity

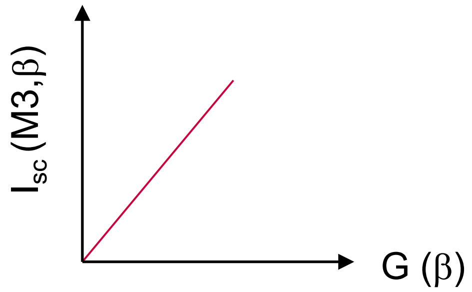
Our aim is to present the analysis of long-term data in a future study

Additional slides

“Effective I_{sc}” front side

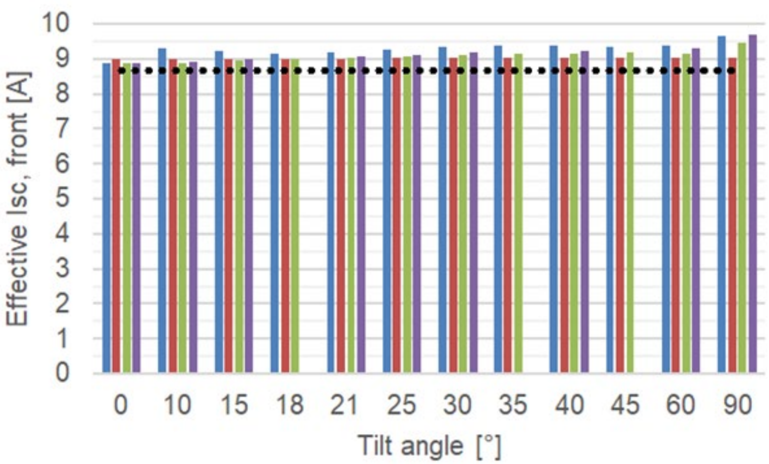
Other concept, the «effective I_{sc}»

Good linear relation: I_{sc} (β) of M3 and G(β)

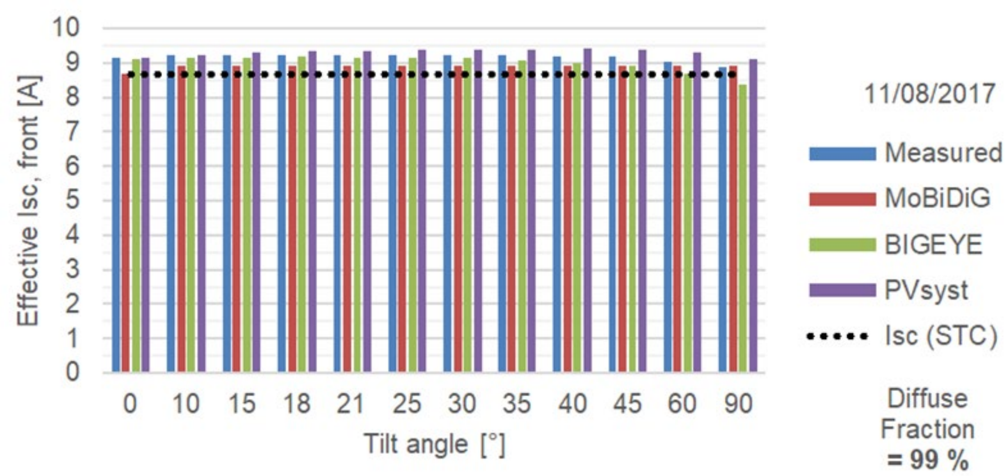


$$Isc(M3,\beta) = I_{sc,front}^{Eff} \frac{G(\beta)}{E^0}$$

G(β) measured or simulated effective I_{sc}
E_0 irradiation at STC



Diffuse fraction: 18%



Diffuse fraction: 99%

"Effective I_{sc}" front side

Fair agreement with the STC $I_{SC,front}$. Deviations expected :

- Module: additional and tilt dependent reflection losses. Irradiance on module less as on pyranometers $\Rightarrow I_{SC.front}^{eff}$ < Isc (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 $I_{SC.front}^{eff}$. Averaging of temp. due to rotation. Measured values > STC values, but deviations > than temp. effect.
- Inaccuracies in the measured irradiance and current. Measured $I_{SC.front}^{eff}$ 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

Zurich University of Applied Sciences
zh aw School of Engineering
IEFE Institute of Energy Systems and Fluid Engineering

Analysis of observed behaviour

'rotating pyranometer' gives lower GHI,

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

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

θ: angle of beam incidence, *θz*: sun zenith angle, *γ*: ground reflection coefficient

F_1 and F_2: Perez coefficients depending on ϵ and the sky brightness

VF_{sky} ↓ with tilt angle ↑

Any uncertainty in horizontal beam component (GHI-DHI) or in F1, a parameter determining the circumsolar fraction, will be magnified at larger tilt angles