Bifacial modeling with the BIFOROT

BIFOROT: Bifacial Outdoor Rotor Tester

ZHAW: Markus Klenk, Hartmut Nussbaumer, Marco Morf, Thomas Baumann, Franz Baumgartner

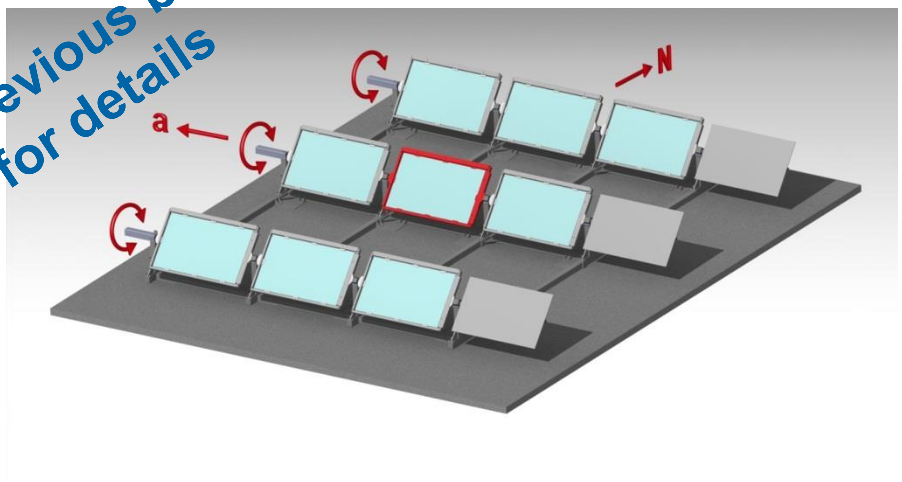
ISC Konstanz: Djaber Berrian, Joris Libal

ECN part of TNO: Gaby Janssen, Ashish Binani, Teun Burgers

Denver, bifi PV 2018

BIFOROT set-up

See previous bifi PV for details



- Real world conditions as in actual bifacial PV system
  - Array instead of stand-alone module
  - Focus on central module(s)
- **Continuously varying tilt angle (automated, 1-minute cycle 0°- 90°, 12 steps)**
- South-oriented, variable mounting parameters and additional features

Some BIFOROT features

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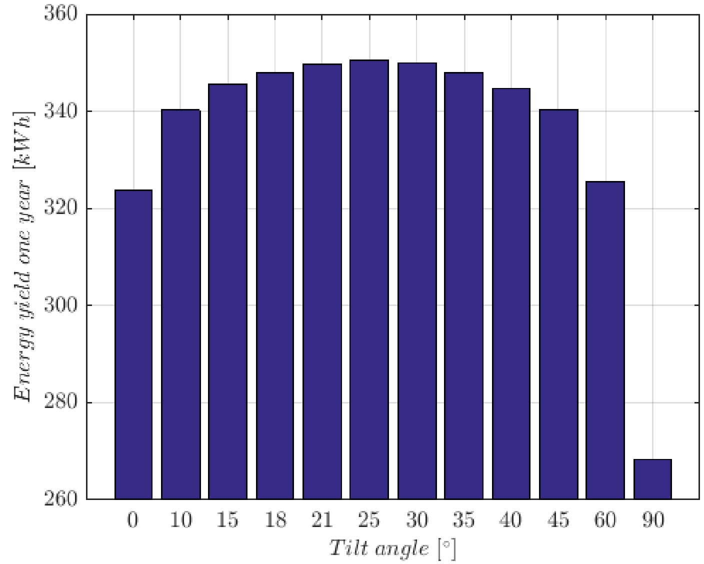
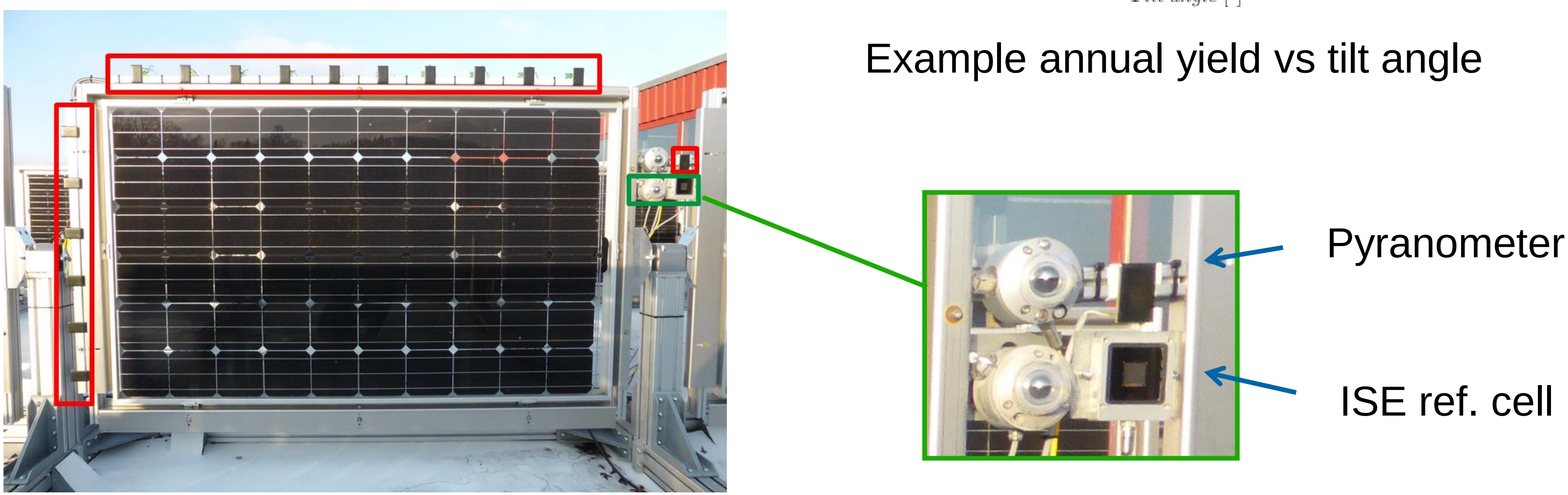


Example annual yield vs tilt angle



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Measured data compared to simulations

Miniaturized test rig

Measurement data compared to simulations

Commercial simulation tool: PVSyst

Simulation by institutes: ECN > TNO & ISC Konstanz

(SAM simulation tool from NREL → not included yet but welcome)

ECN > TNO

«BIGEYE» V2: Analytical, quasi 3D view factor; Hay-Davies-Klucher-Reindel model

«BIGEYE» V3: Full 3D numerical view factor; Perez model with 1990 coefficients

ISC Konstanz: «MoBiDig» quasi 3D view factor. Perez model with 1990 coefficients

Joint publication with ISC Konstanz and ECN > TNO is planned

Irradiance, daily yield and deviation

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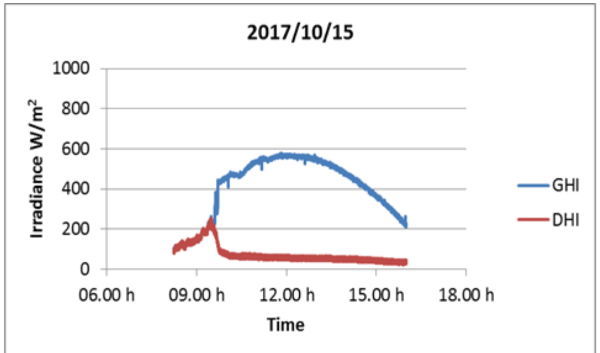
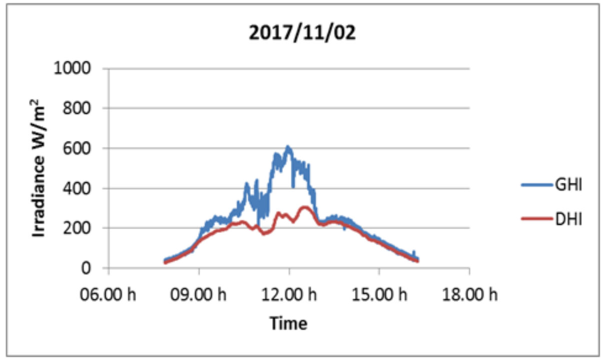
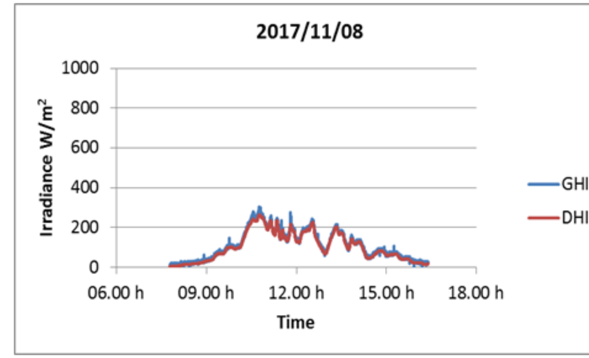
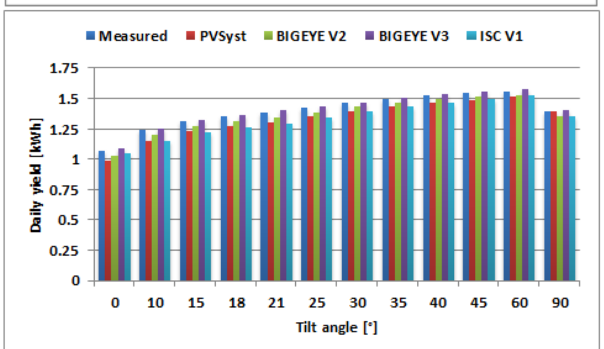
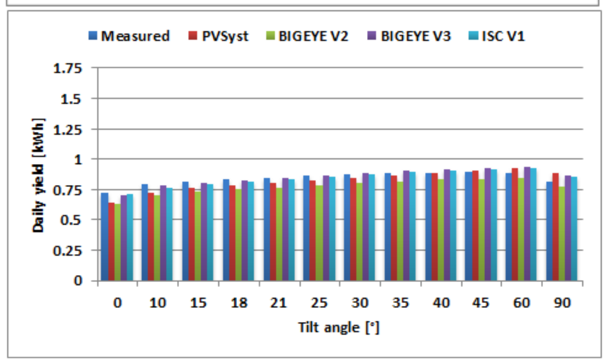
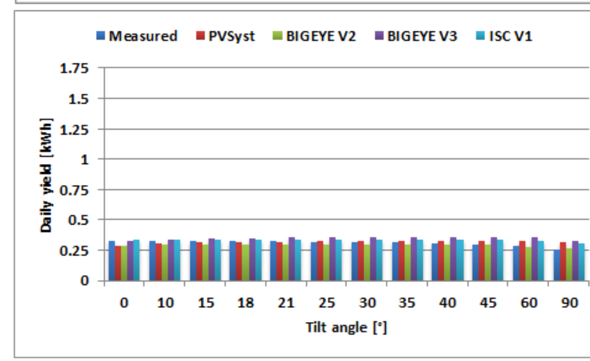


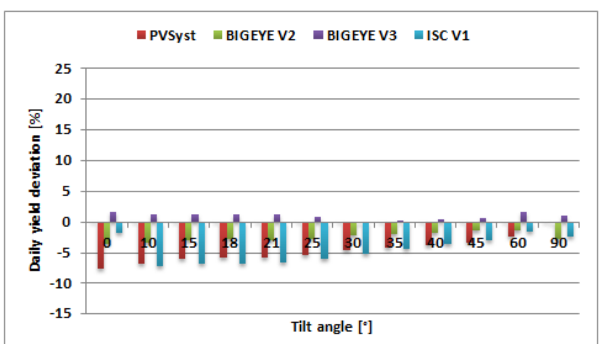


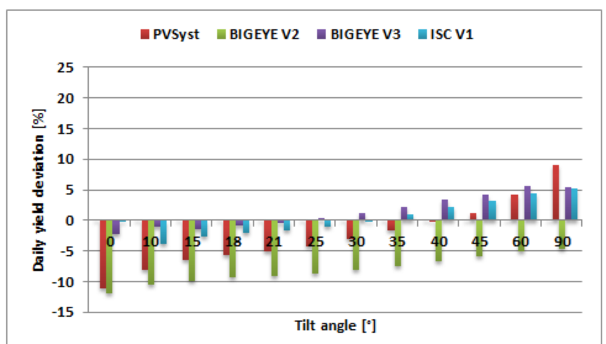


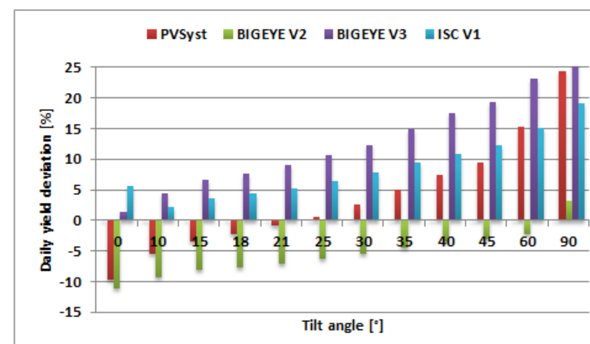








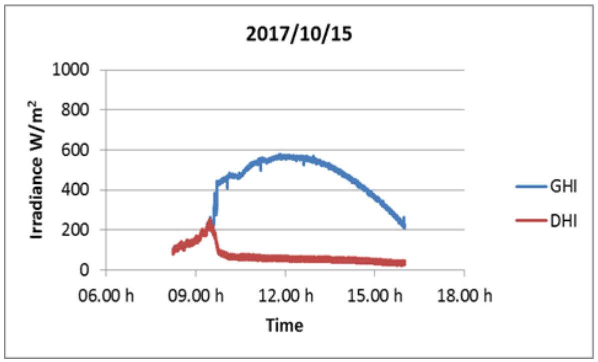


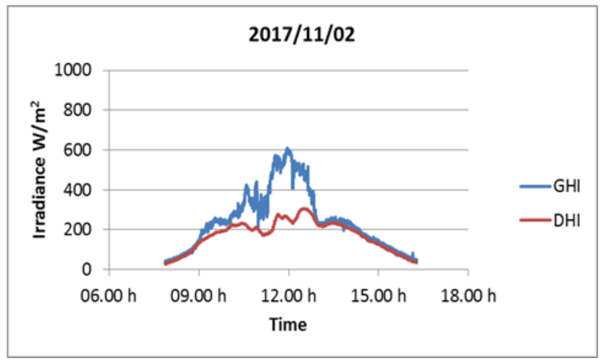


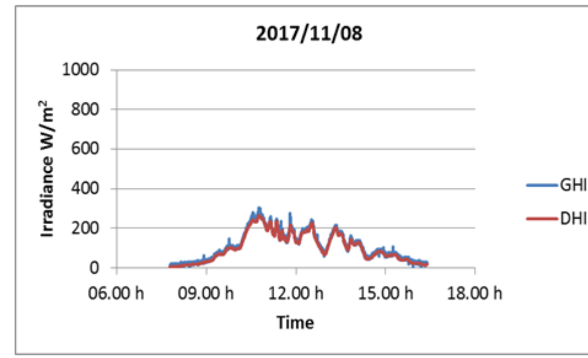
Irradiance, daily yield and deviation

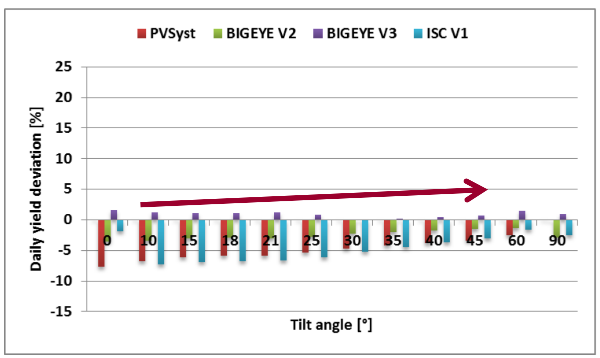
∆ KWh measured/ simulated: Absolute deviations comparable for differing irradiance

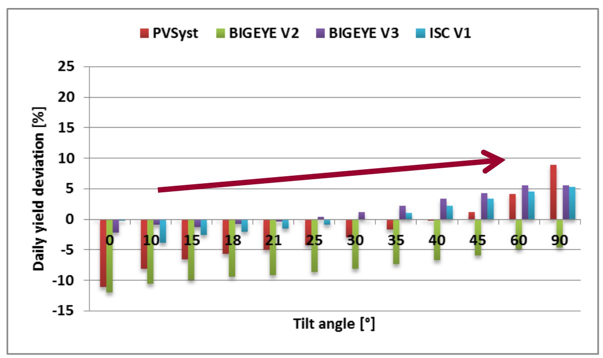
Relative deviation dependent on intensity

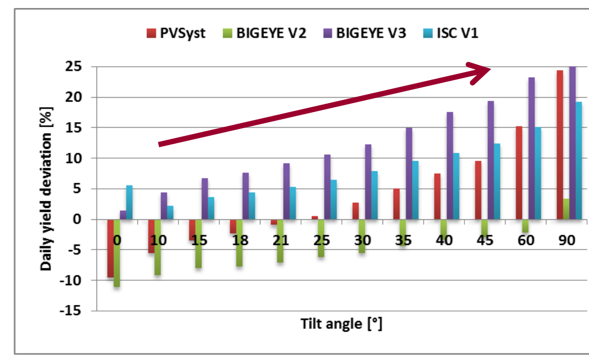












Comparatively low deviations for typical irradiation conditions and moderate tilt!!!

Deviations of the simulations qualitatively show the same «slope», but different «offset»

Remark: PVSyst states that bifacial simulation is not well suited for vertical installations

Comparison: Radiation on module front plane

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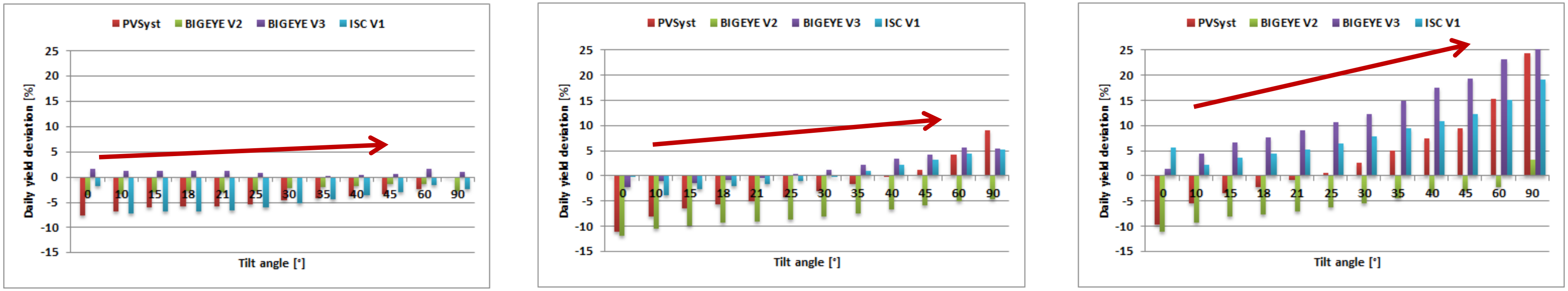
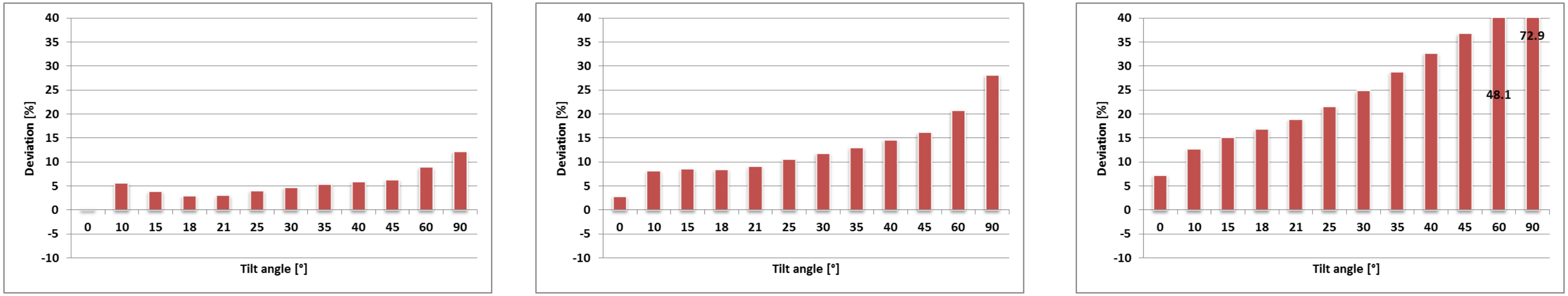


Deviation: Measured (CMP21) and PVSyst Simulation – Global Irradiation on module front plane – same trend



Observed deviation «trend» in bifacial modelling dominated by front side irradiation

Numerous publications dealing with irradiation models such as Perez, Hay,.... Also selectable in PVSyst

Relevance of extreme conditions?

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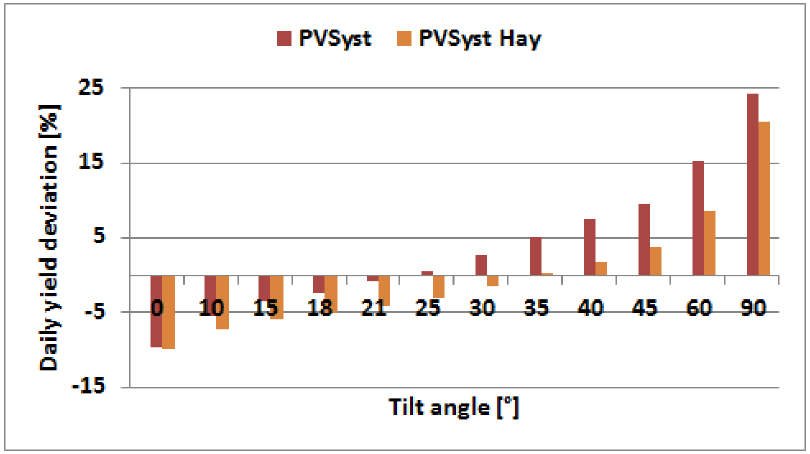
Example PVSyst (2017/11/08, worst case):

Application of Hay- instead of Perez model



Improvement for low direct radiation and steep tilt

Worsening for shallow tilt

General trend («slope») is still observable

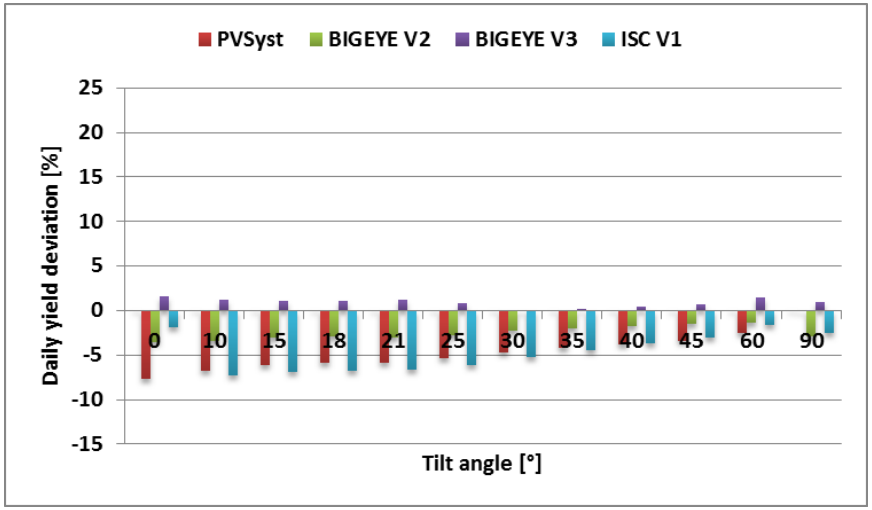
Relevance of extremely low direct radiation share?

Significance for annual yield limited for «normal» tilt

Relevant for shallow and steep tilt angles

High direct radiation share and moderate tilt

→ **Quite good correspondence**



Also other factors (bifi) have to be addressed

→ Suppression of front side irradiance effects

→ Bi- and monofacial comparison, «bifacial gain»

→ Reveal impact of real bifacial effects

Summary and Outlook Part 1

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For typical irradiation conditions and moderate tilt

⇒ Simulations of bifacial modules show comparatively low deviations

Low direct irradiation and steep or shallow tilt result in more pronounced deviations

⇒ Corresponding deviations of frontside irradiance and yield dominate

Further improvement of the models ongoing

Joint publication with ECN > TNO and ISC Konstanz is planned

BIFOROT proofed its suitability as data soucre and to validate simulation results

ZHAW appreciates suggestions for joint projects or cooperations with the BIFOROT !

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Measured data compared to simulations

Miniaturized test rig

Miniaturized test rig / basic idea

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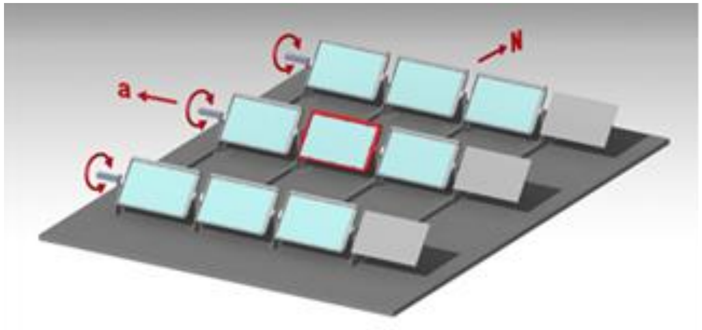
BIFOROT: Long term measurements

- Fast tilt angle variation: 12 angles per minute
- But adjustment of height, row distance and albedo slow



Miniaturized rig (1:12) as a more flexible solution

- Parameter varied quickly→ nearly identical conditions
- Multiple rigs → vary at identical conditions !!!
- Multiple rigs → directly compare locations !!!

Prerequisite: Assignable measurement data

Miniaturized Test Rig

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Miniaturized Test Rig

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Miniaturized Test Rig

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Surprising correspondence

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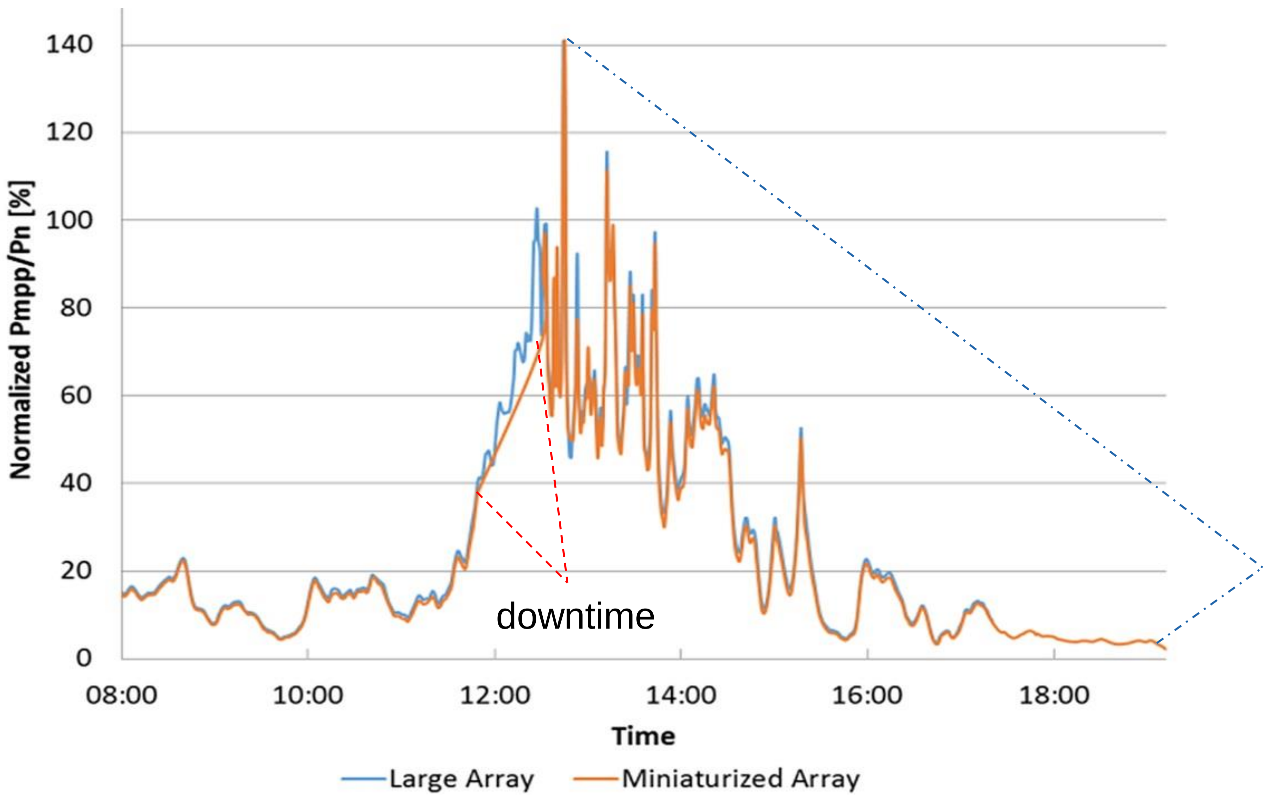
Typical example: P_{MPP}; 1 day; arbitrarily selected tilt angle of 35°

- 8:00 am to 7:00 pm ⇒ 11 hours ⇒ 660 P_{MPP} values per rig and tilt angle



Same cell type & ambient conditions

- V_{OC}: ☑
- I_{SC}: ☑
- FF: ??!!

Surprising correspondence for varying

- Irradiation intensity
- Temperature

How to quantify the correspondence?

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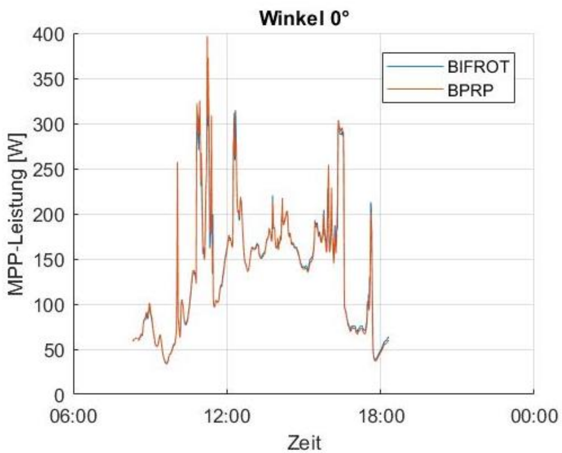
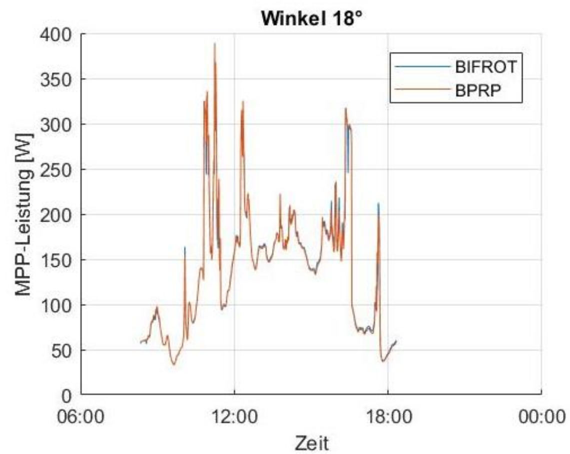
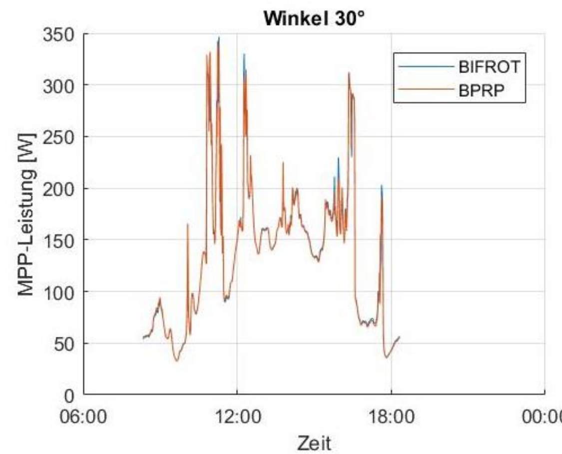
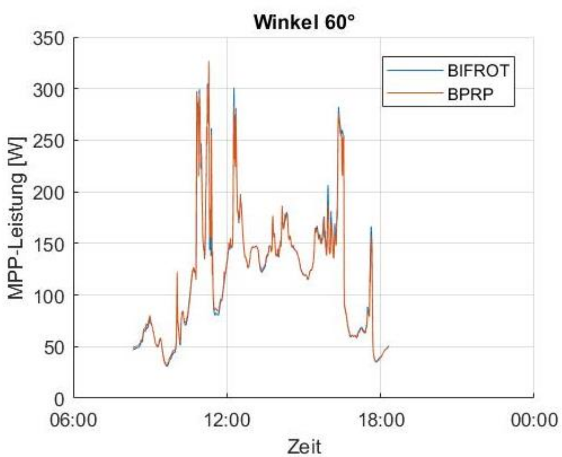
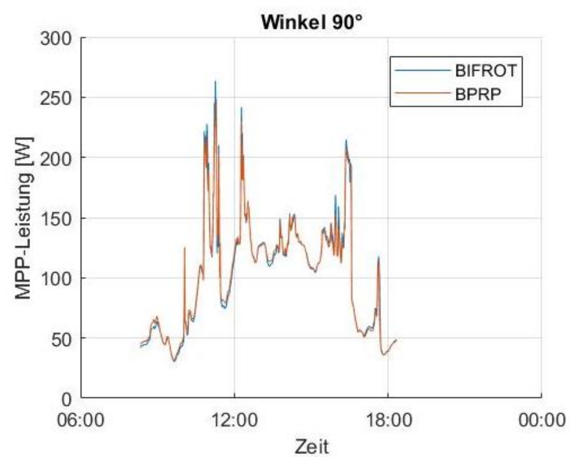
Example: 05/09/2017 ; 5 out of 12 tilt angles







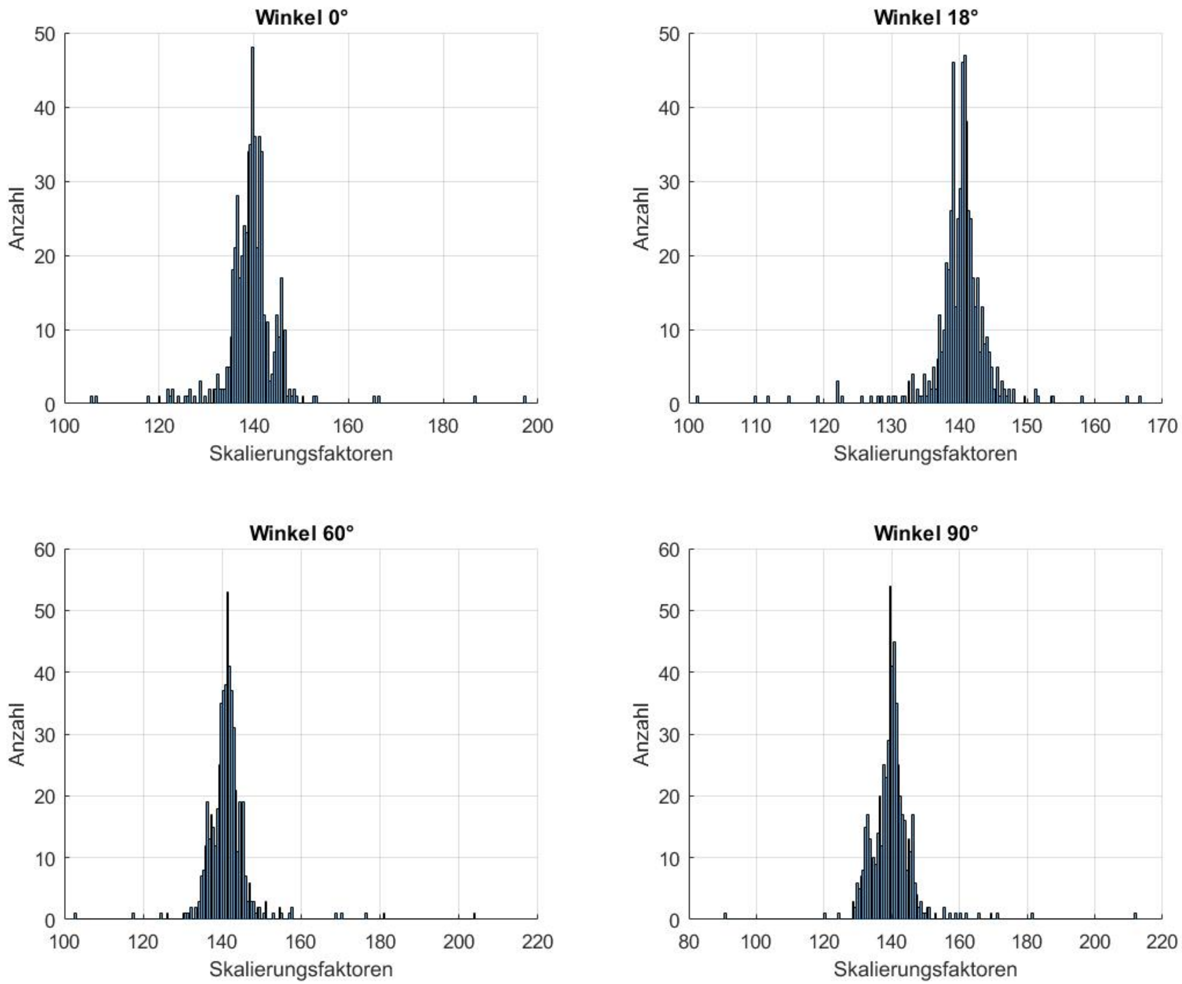




Approach: Determine a correlation factor for each data point / time stamp (for each 1-minute cycle)

$\Rightarrow$

How to quantify the correspondence?



- This approach reveals short-term fluctuations
- Mean values as correlation factor
- Tilt angle variation
  → no grave differences

Long-term – stable correlation factor?

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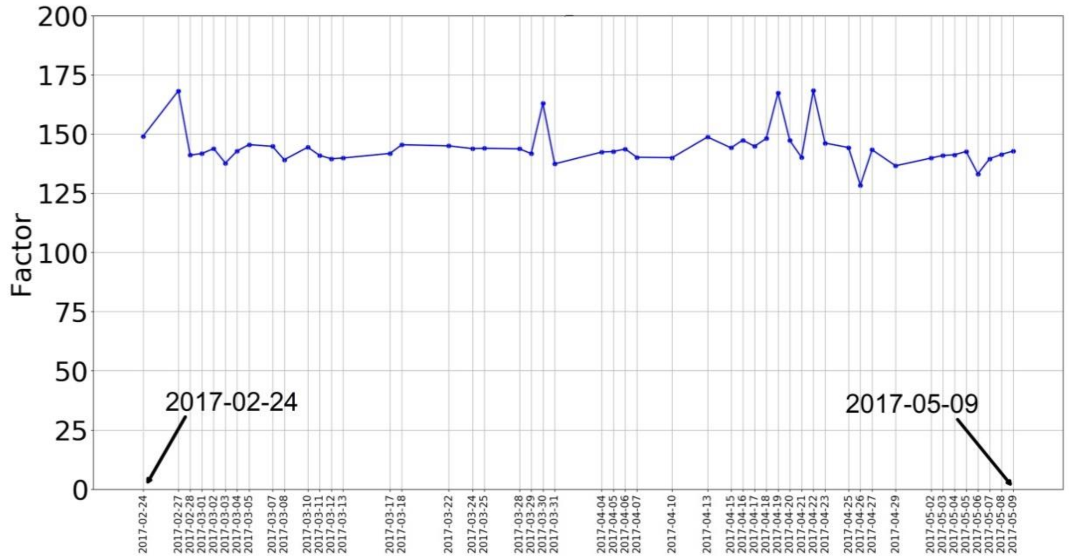
Test duration with unchanged conditions from 02/24 – 05/09/2017

- Improvised character of small test rig caused repeated downtime
- Define daily correlation factor to directly express P_{MPP} deviation of both test devices



Daily correlation factor

$$= \frac{\int \mathrm{Pmpp}_{\mathrm{BIFOROT}}\, dt}{\int \mathrm{Pmpp}_{\mathrm{Miniaturized\ Array}}\, dt}$$

Example: 1 of 12 tilt angles

Course of the plot indicates quite stable mean value, but also shows distinct peaks / deviations

Long-term – stable correlation factor?

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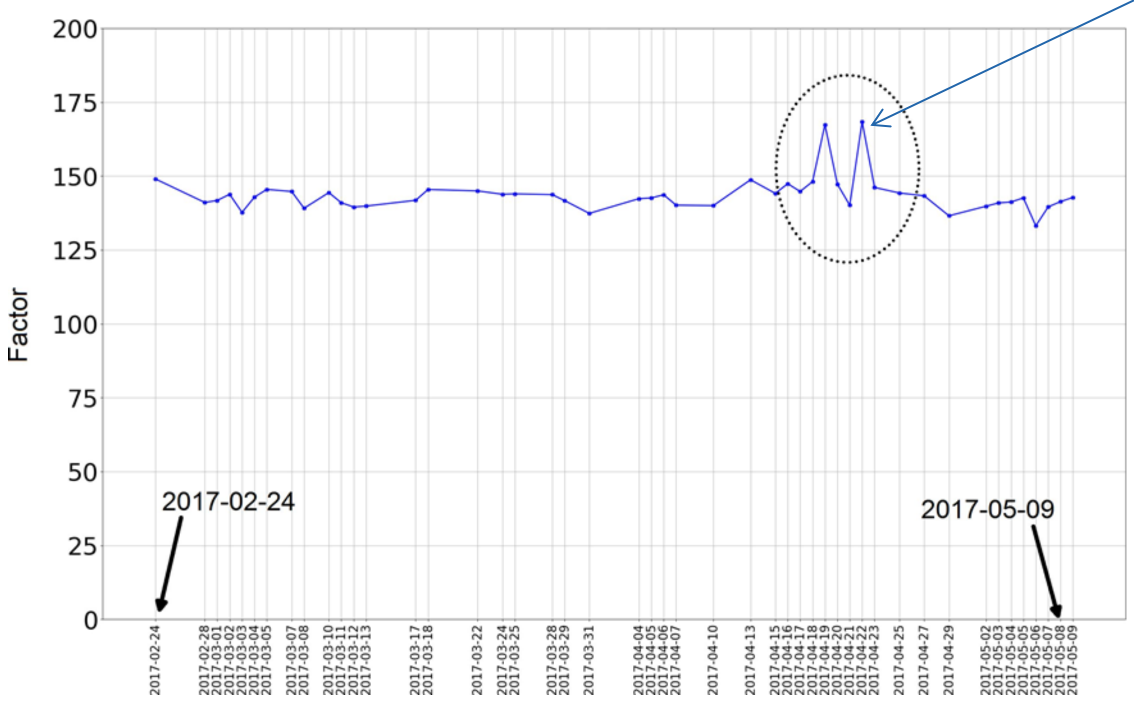
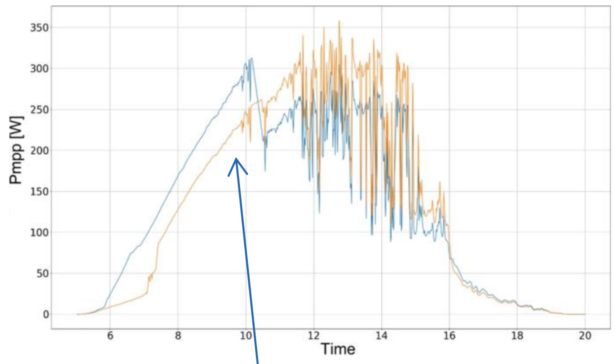
Define rules → Aim: automated data selection instead of checking each individual day

- Detect downtime and snip data from both test rigs
- Joint measurement time of at least six hours

⇒ Course clearly smoother





Off-set: origin unknown

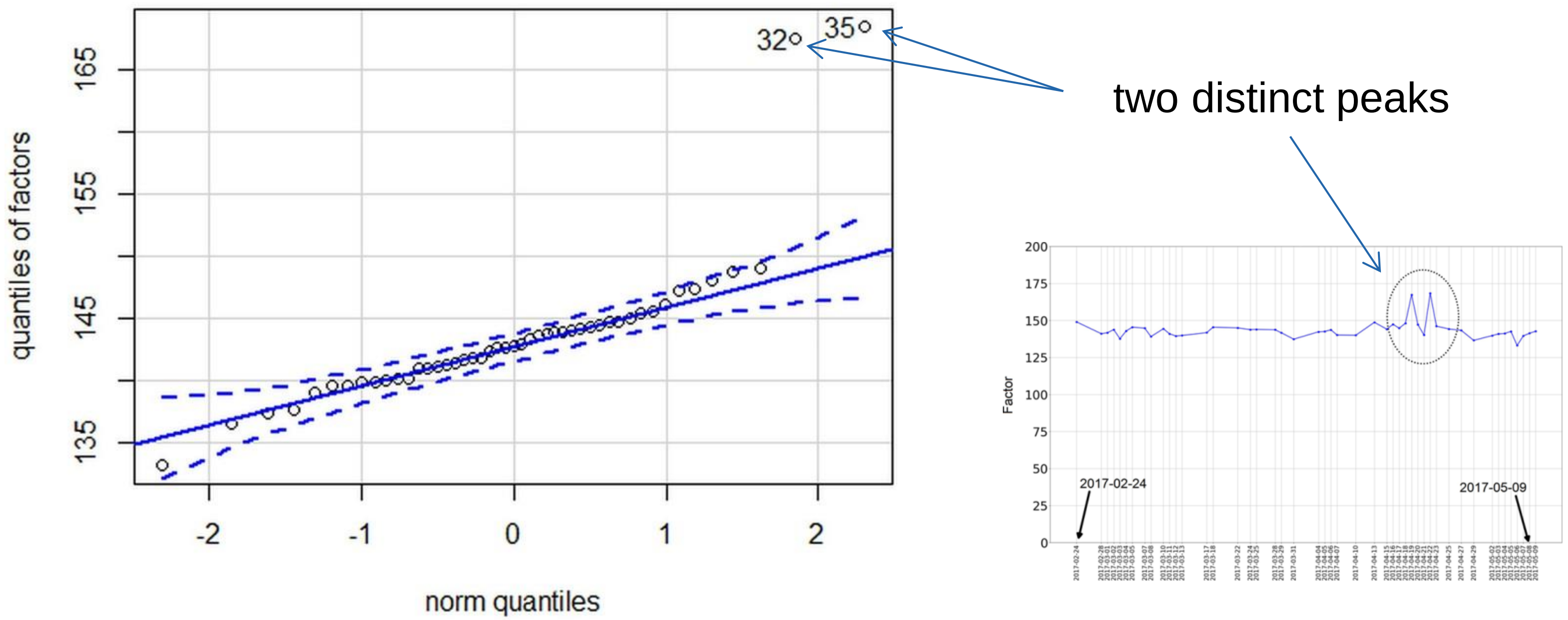
Remaining distinct peaks

- Define algorithms
- Individual check
- Apply statistics

Normally distributed correlation factors

"Normal probability plot" of the daily scaling factors

- Data points inside dotted lines: normal distribution can be assumed



- Data is predominantly normally distributed
- Grave outliners can be considered as probably caused by specific events

Estimation of the prediction accuracy

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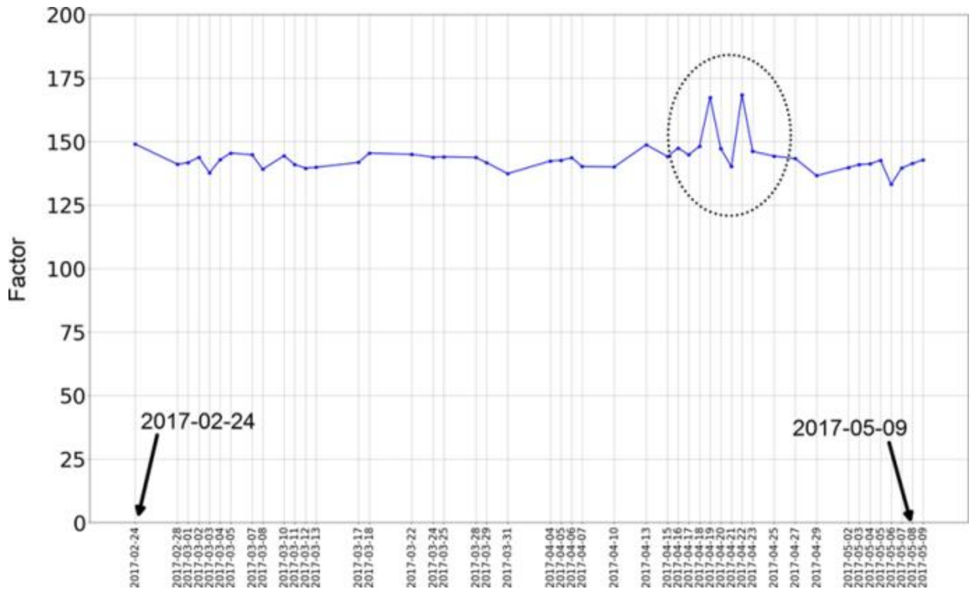
- Data is predominantly normally distributed
- Grave outliners can be considered as probably caused by specific events

One option: Apply statistical tools to suppress the impact of outliers

Example: Application of the “Huber M-Estimator”



Tilt angle	Mean	StdDev	Mean Huber M-Estimator	StdDev Huber M-Estimator
0°	143.6	6.1	142.8	3.3 (2.3%)
15°	145.5	5.9	144.8	4.2 (2.9%)
30°	145.6	5.5	145.3	4.2 (2.8%)
45°	146.4	8.2	145.6	5.2 (3.6%)
90°	144.7	11.3	143.8	9.2 (6.4%)

StdDev.: Single future data point with probability of 68% (95%) within ± 1 σ (2σ)

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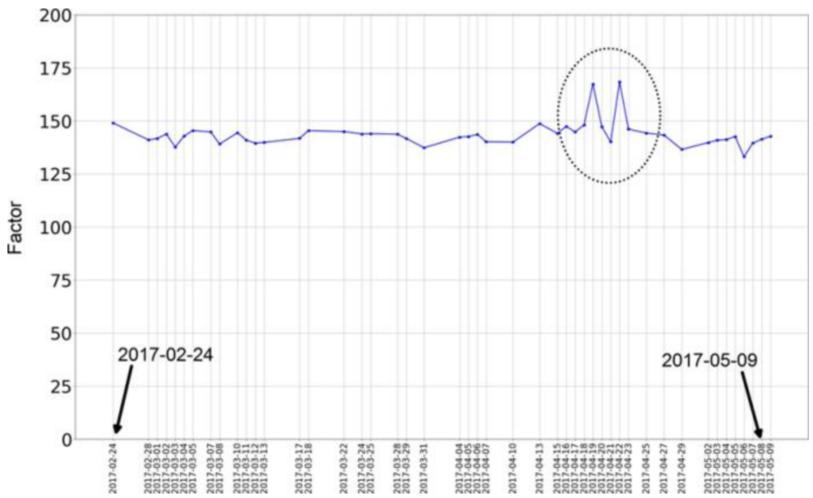
Estimation of the prediction accuracy

Standard error of the mean (SEM) for normally distributed data

- Measures dispersion of sample mean values from subgroups around “true” mean value
- Improves with increasing amount of data points



The approximated SEM can be calculated as:

$$s_{\bar{x}} = \frac{s}{\sqrt{n}}$$

$s_{\bar{x}}$: SEM (approximated)
n: amount of selected data points (days)
s: standard deviation of the selected subgroup

- **Already low «normal» standard deviation**
- **Measuring for several days improves the correlation factor determination and accuracy**

Planned: Mobile test platform

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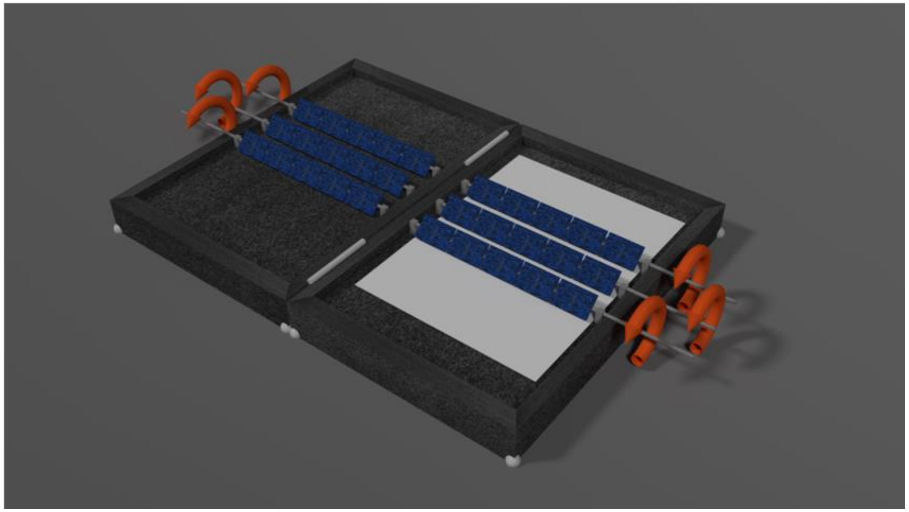
Miniaturized rig - more flexible solution

Parameters varied quickly→ nearly identical conditions

- Multiple cheap rigs → vary at identical conditions !!!
- Multiple cheap rigs → directly compare locations !!!

→ **Product for EPC`s, Institutes,...?!**



Current idea: Improved version with two systems as mobile test platform

Summary and Outlook Part 2

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- Output of a downscaled, miniaturized test rig can be assigned to the one of a corresponding large, real test field ⇒ Suitable as measurement tool!

- Superior accuracy to presently available simulation tools in several regards

- Assignabilty is still surprising. Extended trials with new hardware desirable
  - Is correspondance of FF (series resistance, etc.) by chance?
  - Height variation probably not critical (rotation causes height variation)
  - Tested set-up with comparatively large row spacing
  - (Both test rigs placed with considerable distance (6.5 m))
  - ...

- First version of the system was improvised test rig, not suitable for outdoor use

- Extremely promising results motivate construction of a new, improved test array

- Other options could be implemented, such as multiple elements instead of a single solar cell to represent cell strings in the modules

- **ZHAW is open for joint projects or cooperations with the BIFOROT and the miniaturized rig!**

Additional Slides

Additional slides

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- Data is predominantly normally distributed
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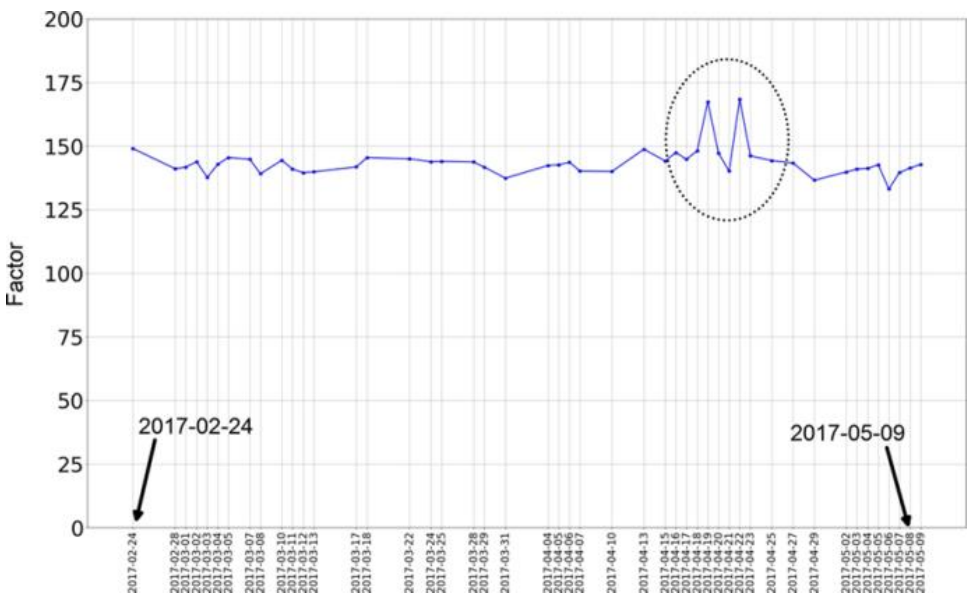
One option: Apply statistical tools to suppress the impact of outliers as

Example: Application of the “Huber M-Estimator”



	Mean value	Standard deviation
All data as in figure	**143.6**	**6.1**
Without the two distinct outliners	**142.6**	**3.3**
All data after application of the Huber M-Estimator	**142.8**	**3.3**

Additional slides

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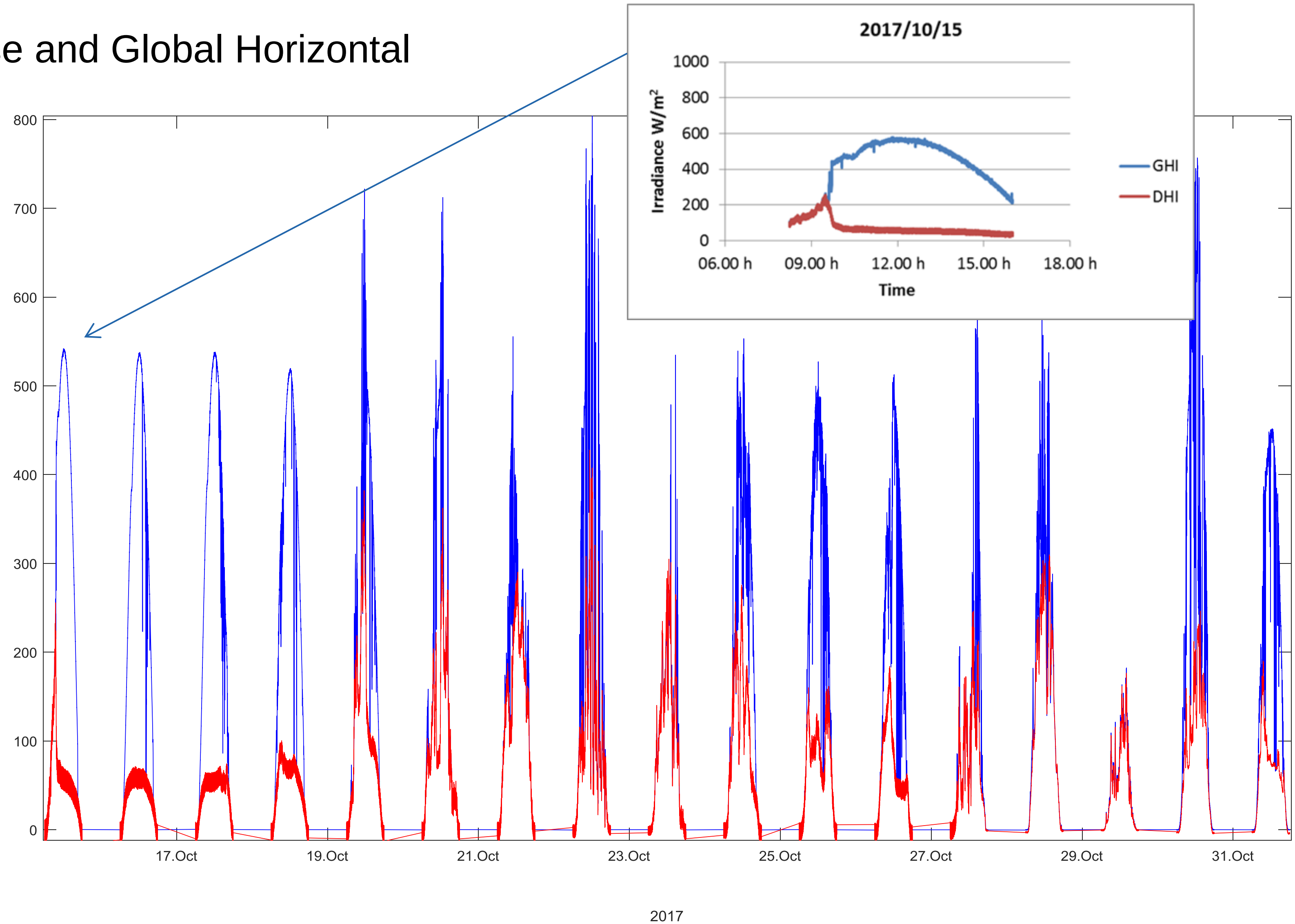
Diffuse and Global Horizontal



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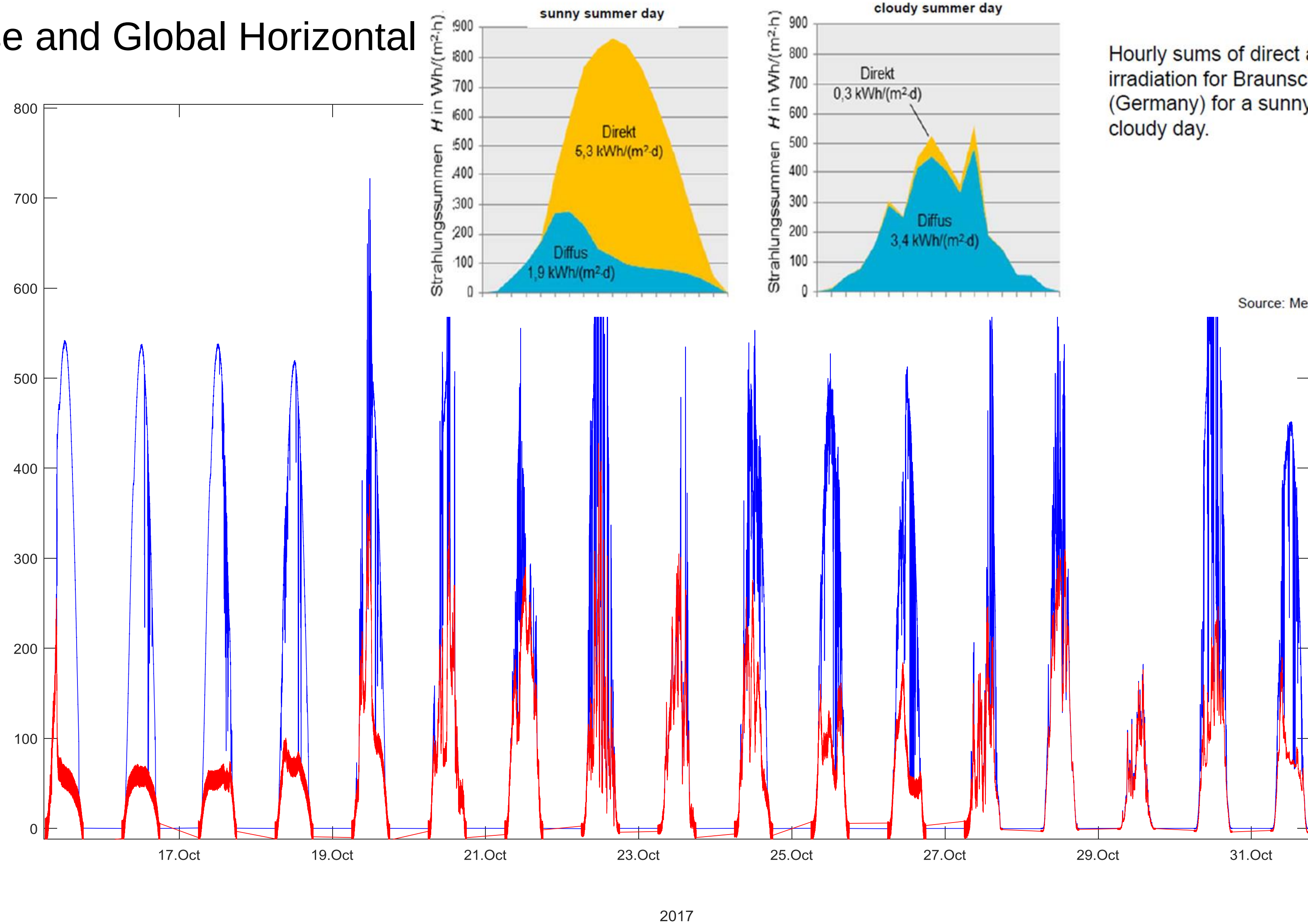
Diffuse and Global Horizontal



Hourly sums of direct and diffuse irradiation for Braunschweig (Germany) for a sunny and a cloudy day.

Source: Mertens (2013)

Example: Impact of irradiance model

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