Performance testing of bifacial PV modules according to IEC TS 60904-1-2:

A route towards bifacial reliability

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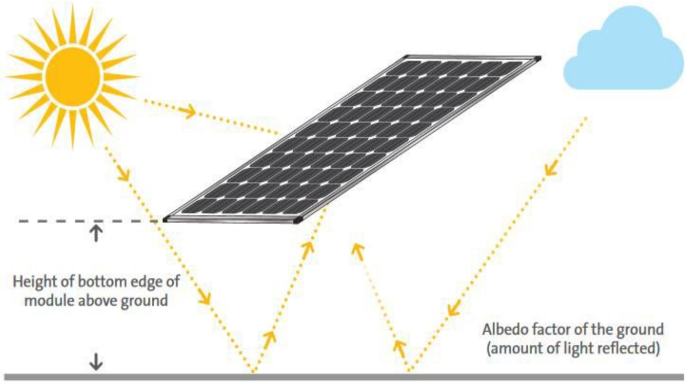
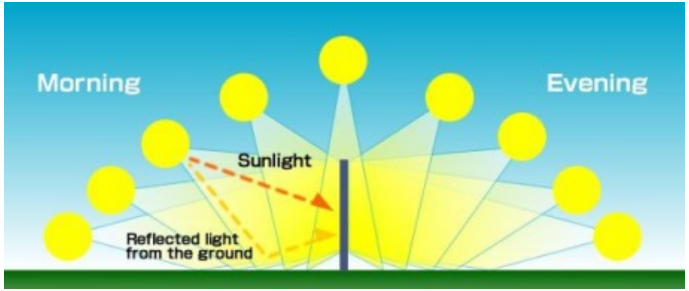
Outline

- Introduction: Challenges – Barriers
- How to measure a bifacial PV module correctly? IEC TS 60904-1-2
- Measuring bifacial PV modules at ESTI:
    - Single-side illumination
    - Double-sided illumination
    - Outdoor
- Outdoor test field – Stand alone module and test array
    - Performance, Rear irradiance and Operating temperature
- Key messages

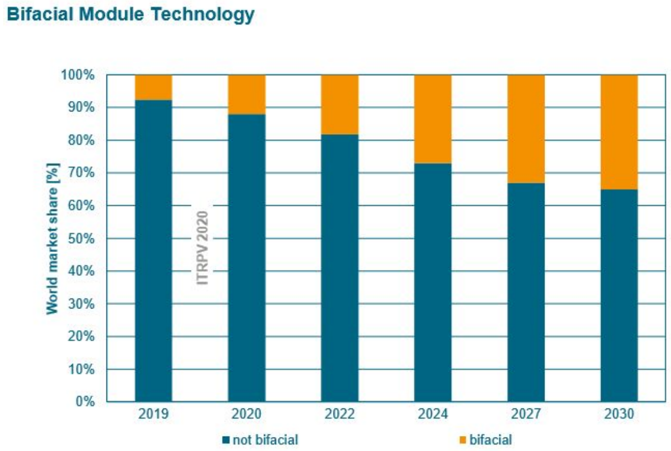
Introduction

- **Bifacial silicon PV modules**: both sides of the cell/module absorb solar radiation, using scattered light from ground and surroundings
- Increase performance in comparison to traditional monofacial PV modules
- No new concept (1954-1960): Rediscovering 2000’s, mass production 2010’s
- New system integration: advantages
- Indoor or outdoor measurements corrected to standard test conditions (STC) to assess performance and quality
- *Basis for module comparison and reliable “beginning of life” value for long-term degradation*





Introduction



Source: International Photovoltaic Technology Roadmap (ITRPV), 2019 Results-Eleventh Edition, April 2020

- ❑ Shift the focus from power (€/Wp) to (the more suited) energy (€/kWh) mentality.
- ❑ Low energy cost (LCOE – Levelized Cost of Energy) is the key factor

1.25 MW Japan

2 MW Germany

2.5 MW Chile (megacell)

12.8 MWp USA (Sunpreme)

- Pictures from Radovan Kopecek and Joris Libal, Bifacial PV world 2018, bifiPV2018, Denver September 10

Introduction: Challenges – Barriers - Objectives

Standards

Lack of standards

Reproducible and accurate measurements ⇒ Assess long-term degradation rates and reliability

Modelling

Commercially available PV system simulation programs need to be improved for bifacial conditions

Bankability

Lack of standards and reliable forecast modelling

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Introduction: Challenges – Barriers -Objectives

IEC TS 60904-1-2:
Measurement of current-voltage characteristics of bifacial photovoltaic (PV) devices

Measurement -output power determination:

- IEC 60891
- IEC 60904-X

Product qualification testing

- Design: IEC 61215-X,
- Safety: IEC 61730

FDIS (Final draft) 06/2020

- *61215:*
Bifacial Standard Test Conditions (BSTC):
$GE = 1000 + \varphi * 135\ W/m^2$ *

- *61730:*
Current application is revised to account for $GE = 1000 + \varphi * 300\ W/m^2$
$I_{mpp} \rightarrow I_{mpp} @ G_E$

*Rear side irradiance lies in the range 120-135 W/m² for parameters given in the table using Radiance software (C. Deline et al. (2017) J. Photovoltaics Vol. 7, 2)

Examples:
Part 1. Power matrix with G_E
Part 2. SR data of the rear side
Part 4. AoI for new 4 planes (E,W,S vertical and rear of inclined plane)
Part 4. Wind speed at rooftop height.
New orientations:

- Rooftop: β=20º,S-N, ρ=60%
- Vertical E/W, ρ = 20%

Energy Rating:

- IEC 61853-X

PV materials and components

- IEC 62852
- IEC 62790
- IEC 62930

No changes

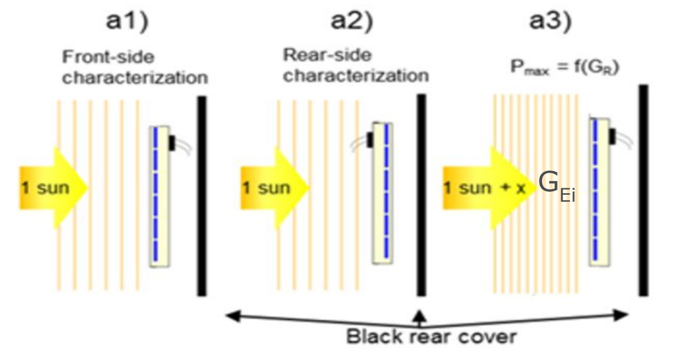
How to measure a bifacial PV module: IEC TS 60904-1-2

Published:
Jan 29th 2019

Solar simulator

Outdoor

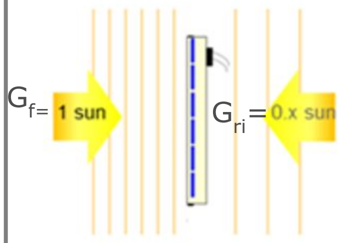
Single-side illumination

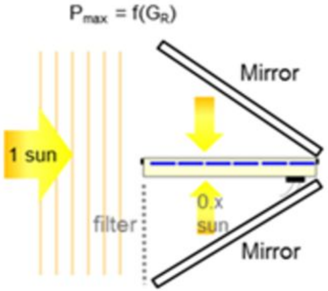


- Non-irradiated background (non-exposed side G_r<3 W/m², at any point)
- Non-uniformity <5%
- $G_{Ei} = 1000$ W/m²$+\varphi * G_{ri}$,

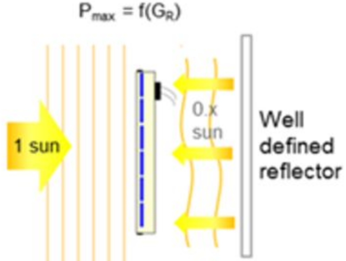
with $\varphi = Min\ (\varphi I_{sc}, \varphi P_{max})$

Double–sided illumination

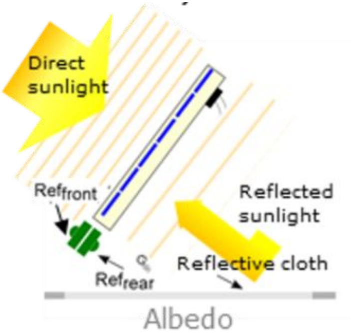




G_f=front side irradiance
G_r=rear side irradiance



- Non-uniformity <5% on both sides
- G_f=1000 W/m² & G_{ri}



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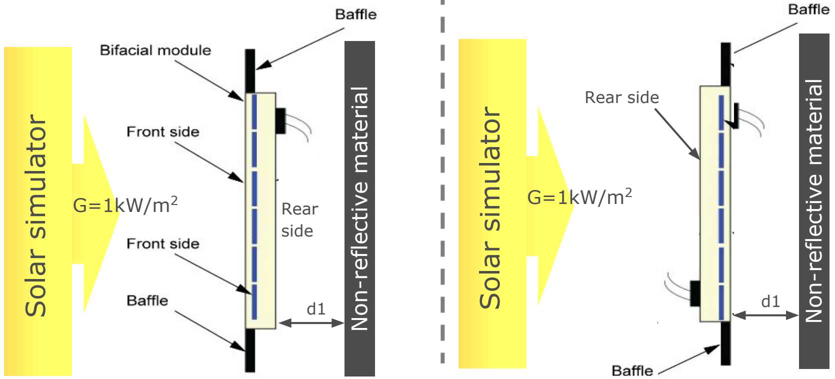
How to measure a bifacial PV module: IEC TS 60904-1-2

❑ **Bifacialities @STC**

Front side (f) characterisation | Rear side (r) characterisation



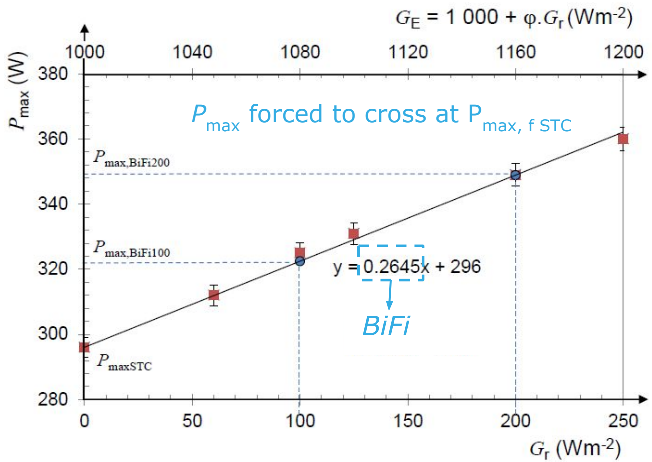
d_1, "suitable distance‟ from its non-exposed side

$$\varphi_{Pmax}\ (\%) = \frac{P_{max\ REAR}}{P_{max\ FRONT}};\ \varphi_{Isc}\ (\%) = \frac{I_{sc\ REAR}}{I_{sc\ FRONT}}$$

❑ **Equivalent irradiance level G_{Ei}** *on the front side*

$$G_{E_i} = 1000\ W/m^2 + \varphi * G_{r_i}$$
$$\varphi = Min(\varphi_{Isc}, \varphi_{Pmax})$$

❑ **Rear irradiance driven power gain yield, *BiFi***:
linear fit's slope of the P_{max} versus G_R data series.

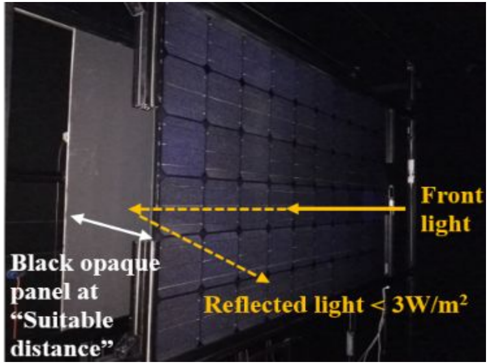


Calculated (from GE) or measured (if double-sided)

❑ **Specific P_{max}** ⇒ linear interpolation:

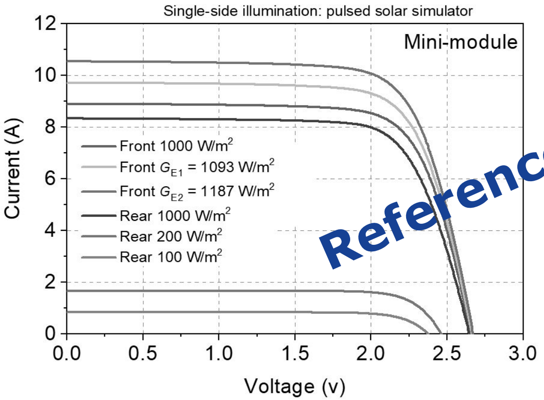
$$P_{max\ BiFi100} = P_{maxSTC} + BiFi * 100$$
$$P_{max\ BiFi200} = P_{maxSTC} + BiFi * 200$$

Measuring bifacial PV modules at ESTI: *Single-side illumination*



- Bifacial PV modules calibration
- International intercomparisons
- Pre-normative research for improvements/amendments to IEC TS 60904-1-2

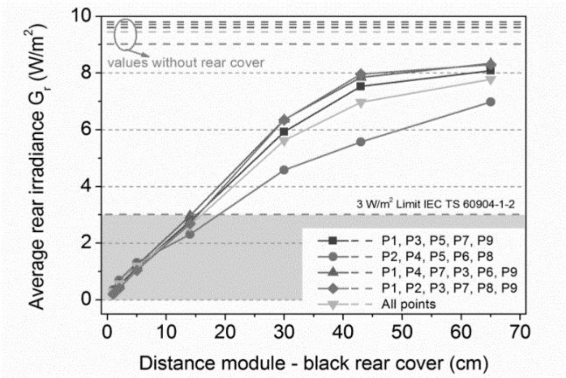
Reference method for bifacial PV characterisation

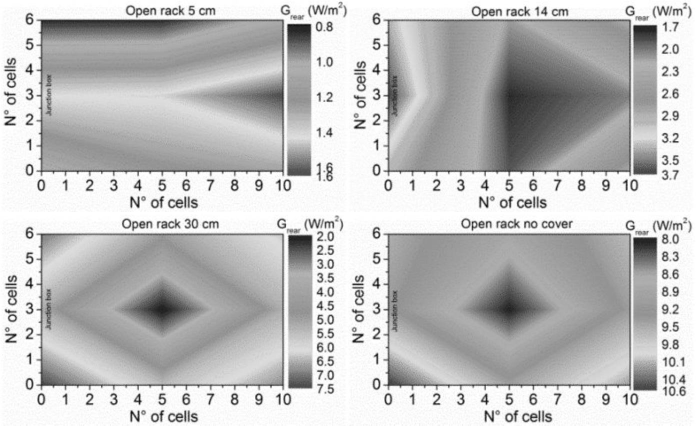


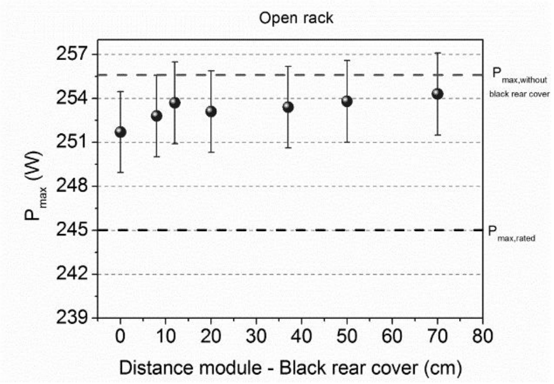
ESTI ISO/IEC 17025: 1st accredited calibration laboratory worldwide for calibration of bifacial PV devices at STC (IEC TS 60904-1-2) - Single-side illumination using equivalent irradiance method.

Measuring at ESTI: *Single-side illumination*

- ❑ IEC TS 60904-1-2 amendments: i.e. $G_r < 3\ W/m^2$, at any point, on the non-exposed side achieved by:
  - ❑ Non-reflective material at a “suitable distance”
  - ❑ Recommendation: Baffles ⇒ limit test area size







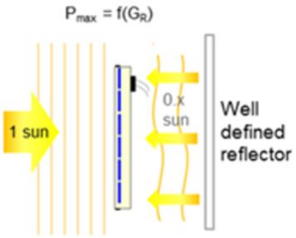
✔ Larger suitable distance between module and rear cover using baffles to fulfil the TS

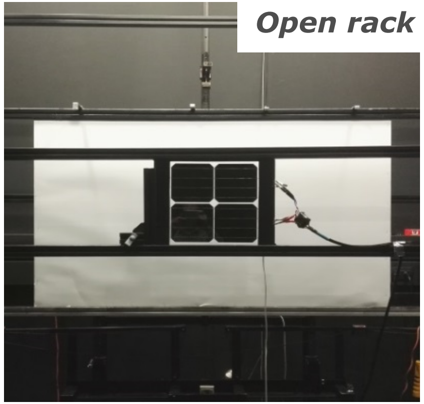
✔ No significant influence on P_{max} with deviation from G_r requirement of $3\ W/m^2$

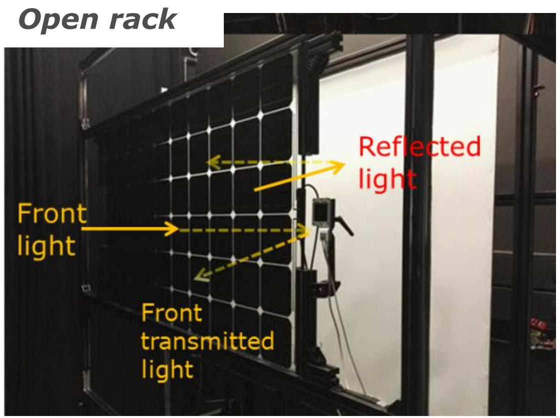
J. Lopez-Garcia, et al, "Assessment of the Rear Irradiance on Bifacial Silicon PV Modules", 36th EU-PVSEC, Marseille, France, 9-13 September 2019, pp. 901-908

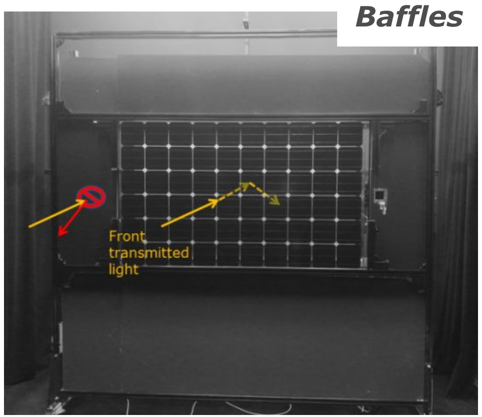
Measuring at ESTI: *Double-sided illumination – Rear reflector*

- ❑ Double-sided illumination with a single source
- ❑ Adjustable irradiance levels by changing distance and reflective panel size
- ❑ Module size flexibility



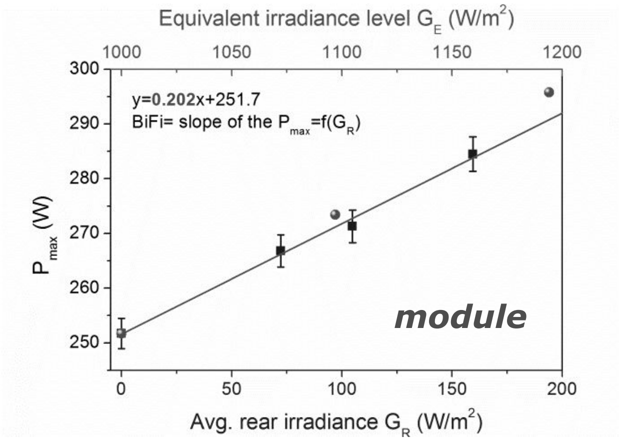




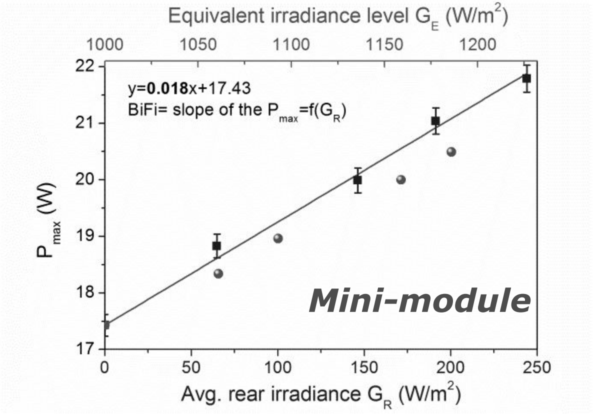


J. Lopez-Garcia, et al "Electrical performance of bifacial silicon PV modules under different indoor settings affecting the rear reflected irradiance", Solar Energy 177 (2019) 471482

Measuring at ESTI: *Double-sided illumination – Rear reflector*



- Despite non-uniformity, P_{max} single-side ~ P_{max} double-sided
- Non−uniform G_{rear} affects I_{sc} and V up to V_{mpp} but to a much lesser extent the P_{max}



ϕ (%)	G_R (W/m^2)	G_E (W/m^2)	P_{max} G_E (W)	P_{max} $BiFi_{GR}$ (W)	ΔP_{max} (%)
98	0	1000	251.7	251.7	+0
	100	1098	273.4	271.9	+0.5
	200	1196	295.8	292.1	+1.3

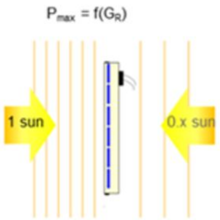
ϕ (%)	G_R (W/m^2)	G_E (W/m^2)	P_{max} G_E (W)	P_{max} $BiFi_{GR}$ (W)	ΔP_{max} (%)
93	0	1000	17.43	17.43	+0
	100	1093	18.96	18.88	+1.4
	200	1187	20.49	20.78	+2.6

× Non-uniformity <5% ⇒ Improvement reflector with isotropic/Lambertian surface

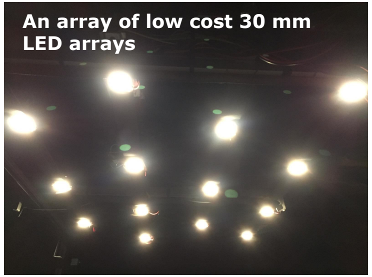
✔ Adjustable rear irradiance G_R (100-200 W/m^2)

Suitable method for bifacial PV modules characterisation?

Measuring at ESTI: *Double-sided illumination – Double source*



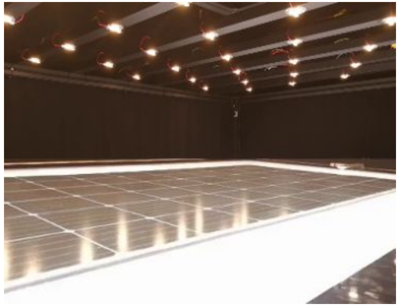
- Simultaneous double-sided illumination with two light sources:
  - Front long **pulsed solar simulator** + **LED-based bias light**



Prototype for minimodules

- Homemade low cost - Rear steady state prototype 14 (CoB) LEDs
- Adjustable irradiance (0-400 W/m^2)
- Area 40x40 cm^2

Full size upscaling

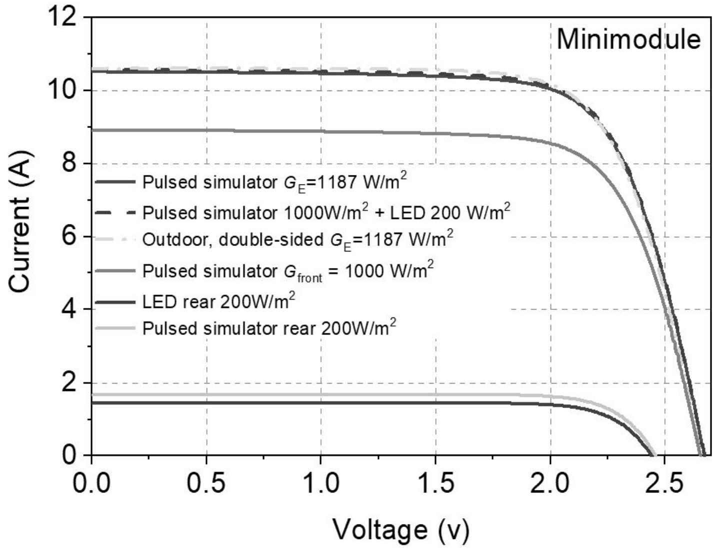


- Low cost, homemade, Rear steady state prototype 55 LEDs
- Adjustable irradiance (0-500 W/m^2)
- Area 200 x 120 cm^2
- Irradiance Non-uniformity <5%

Measuring at ESTI: *Double-sided illumination – Double source*

40x40 cm^2 prototype

- ✔ Temporal stability: Class "A"
- ✔ Pulse to Pulse repeatability ~ 0.5%
- ✔ Irradiance non-uniformity: 4.45% Class "B"
- × Spectral match: worse than class "C"



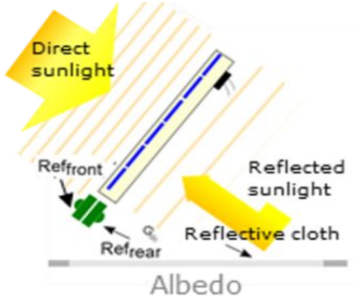
✔ compensated by mismatch correction, or using the effective irradiance method (IEC 60904-7)

mini-module G-G frameless36 x 36 cm^2 ϕ ~ 93%	ΔI_{sc} [%]	ΔP_{max} [%]
PIIIb 1187 W/m^2 Reference single-side illumination	-	-
PIIIb 1000 W/m^2 + LED 200 W/m^2	0.60	0.77
PIIIb 1000 W/m^2 + LED 200 W/m^2 corrected	0.20	0.29

D. Shaw, J. Lopez-Garcia, R.P. Kenny, L. Pinero-Prieto and E. Ozkalay, "Design study of a double-side illumination solar simulator for bifacial silicon PV modules characterisation based on low-cost LED bias light", 35th EU-PVSEC, (2018), 1001 - 1005.

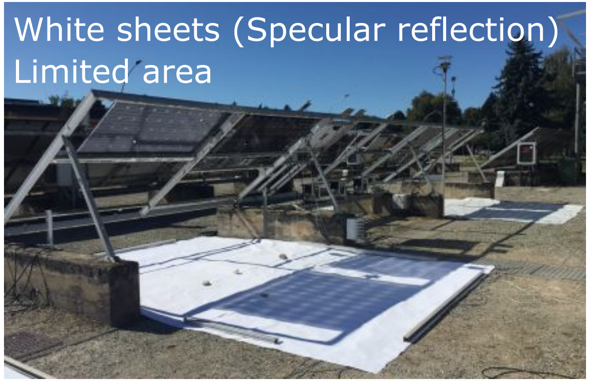
Measuring at ESTI: Outdoor - *Double-sided illumination*

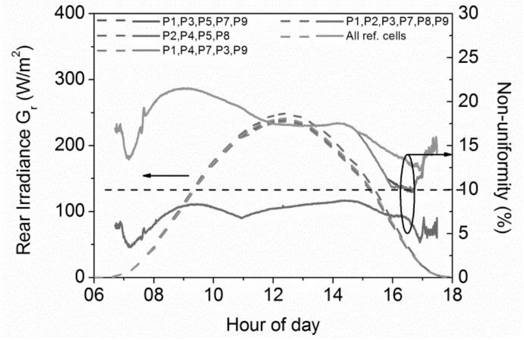
IEC TS 60904-1-2:

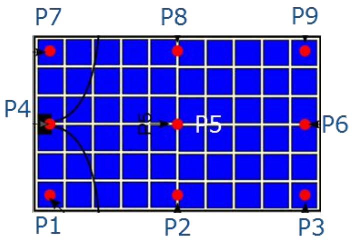


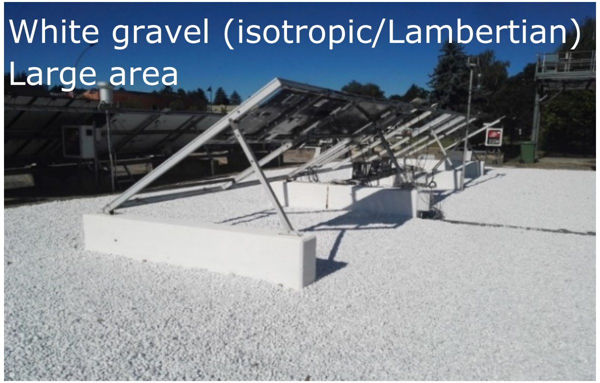
- ❑ Non uniformity G_r < 10% (< 5% indoor)
- ❑ Mean value of the irradiance at the backside
- ❑ A matt, reflective cloth to increase the reflection uniformity on the surface behind DUT

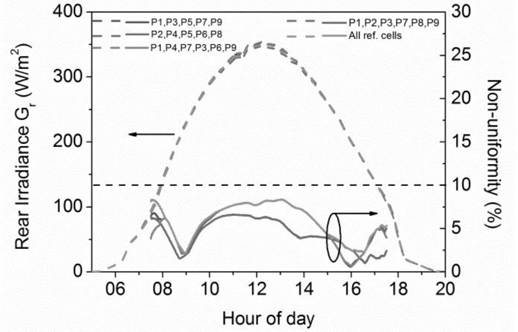
Measuring at ESTI: Outdoor - *Double-sided illumination*











✔ **Rear irradiance**
✗ **Non-uniformity**

✔ **Rear irradiance**
✔ **Non-uniformity**

R. Kenny, E. Garcia-Menendez, J. Lopez-Garcia and B. Haile, " Characterising the operating conditions of bifacial modules", AIP Conference proceedings, 1999 (2018) 020014

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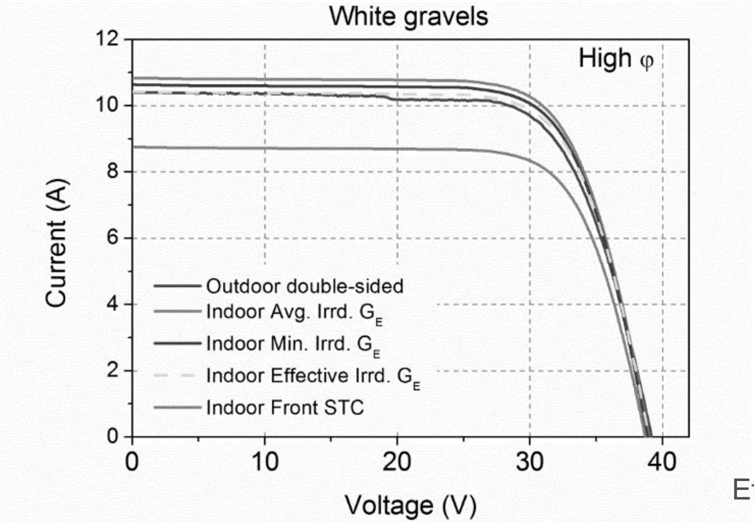
Measuring at ESTI: Outdoor - *Double-sided illumination*

Set-up	Avg. G_{rear} Non-uniformity (%)
Black curtains + steel laminates	31
Black wooden panels	13
White gravel	8
Black curtains	5

Noon time in summer



- ❑ I-V curve kink due to G_r non-uniformity
- ❑ ΔP_{max} due to ΔFF and ΔI_{mpp} between indoor and outdoor measurement for similar G_E
- ❑ Outdoor double-side I-V curve similar to indoor equivalent irradiance at outdoor effective G_r

Effective $G_r = I_{sc\_rear\ only,outdoor} / I_{sc\_rear\ indoor\ STC} \times 1000\ W/m^2$

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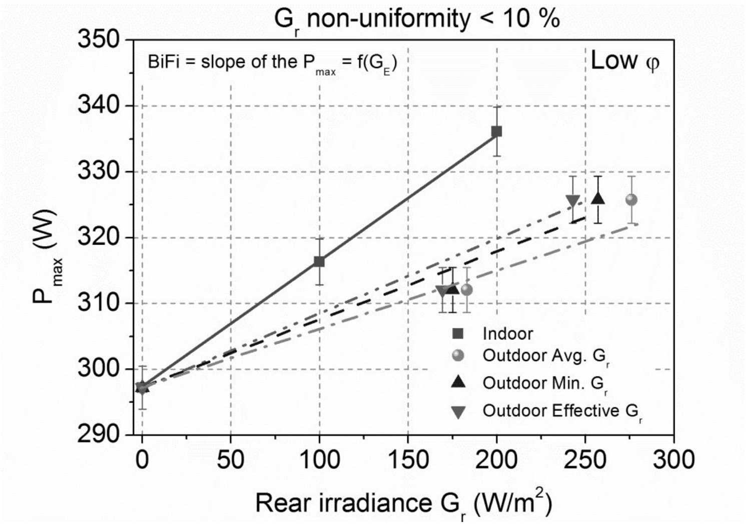
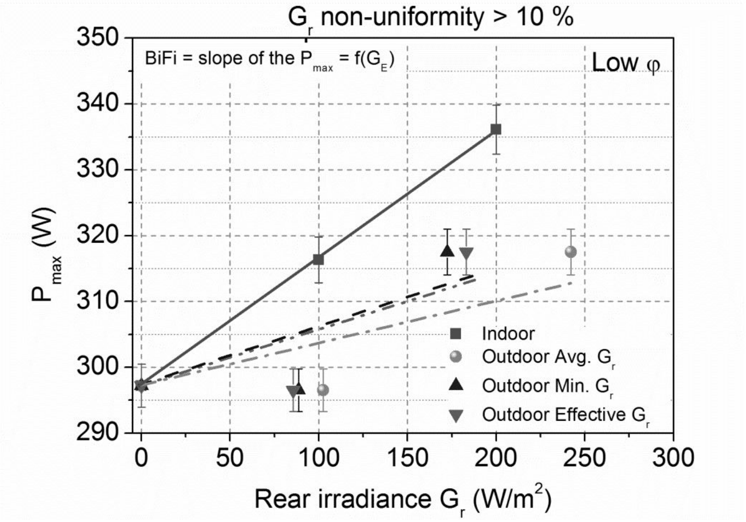
Measuring at ESTI: Outdoor - *Double-sided illumination*





Deviation from indoor *BiFi* increases with G_r non-uniformity
BiFi for effective and Min. G_r more similar to indoor
Lower deviation from indoor reference BiFi for higher bifacialities
G_r determination influence *BiFi* for outdoor measurements according to TS

J. Lopez-Garcia, et al, "Assessment of the Rear Irradiance on Bifacial Silicon PV Modules", 36th EU-PVSEC, Marseille, France, 9-13 September 2019, pp. 901-908

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Measuring at ESTI: Outdoor - *Double-sided illumination*

IEC TS 60904-1-2:

- ❑ Non uniformity G_r < 10%
- ❑ Mean value of the irradiance at the backside
- ❑ A matt, reflective cloth to increase the reflection uniformity on the surface behind DUT

- ✔ Difficult control of outdoor measurement conditions requested by the TS
- ✔ G_r determination and G_r non-uniformity impact on BiFi and P_{max} of outdoor characterisation
- ✔ Disagreement between actual measurements and TS requisites and recommendations
- ✔ Different indoor and outdoor results:
  - ✔ Indoor method is more reproducible and controllable to determinate Bifi and P_{max}

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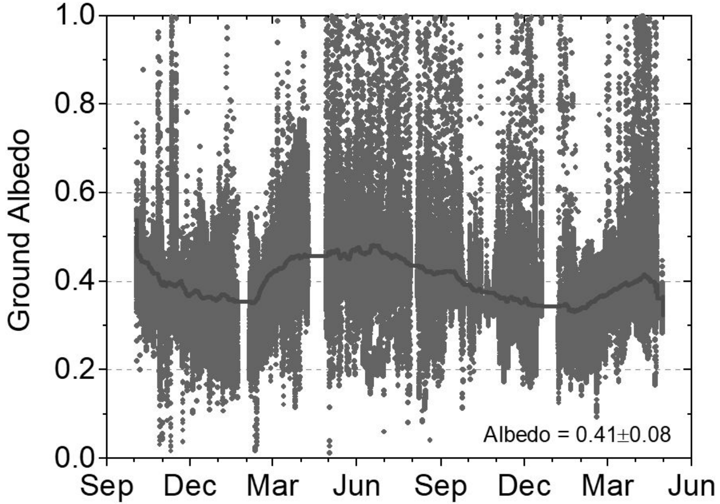
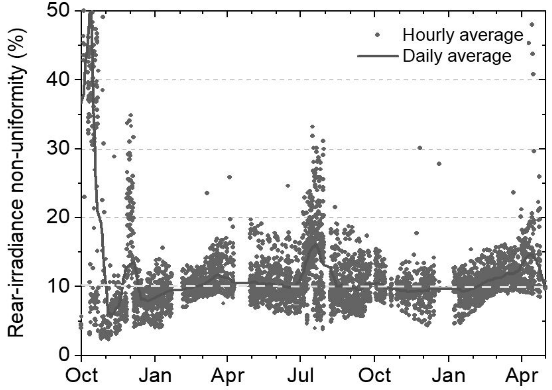
Outdoor test field: Stand alone modules – setup

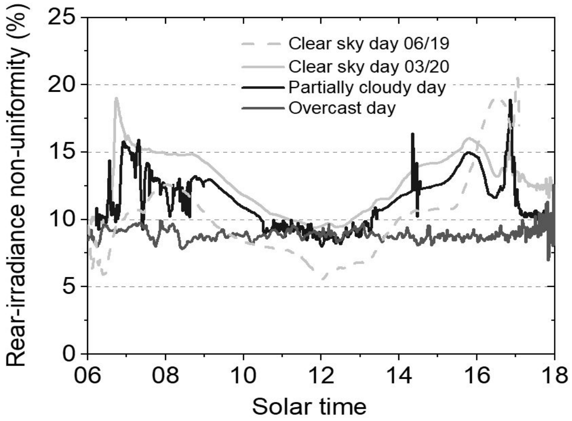


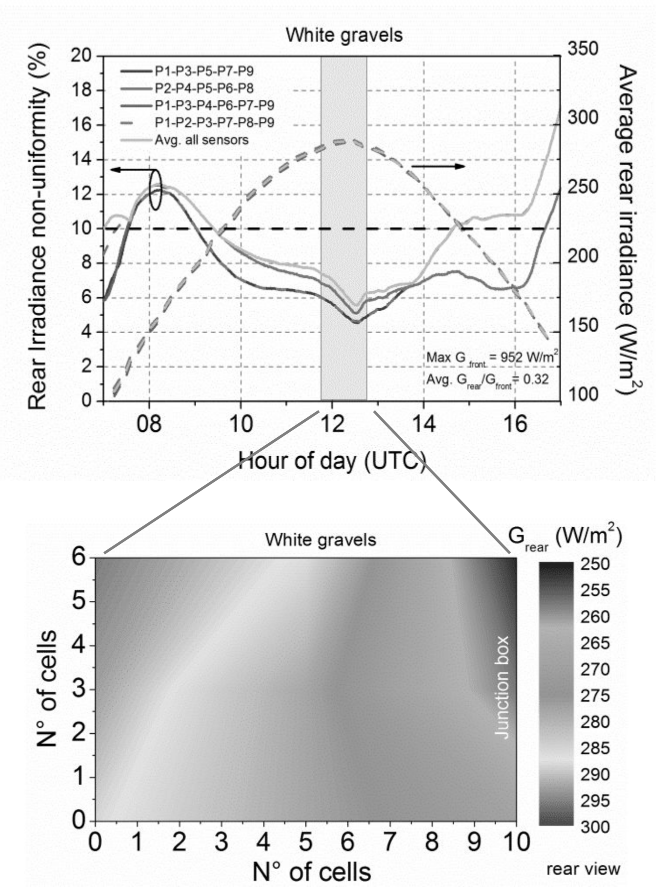
Type	ϕ_{Pmax} (%)	Frame	Technology	Laminate
1	98	N	n-PERC??	Glass-glass 3.2mm
2	67	N	p-PERC	Glass-Glass 2.5 mm
3	68	Y	n-PERT	Glass-foil 2.5 mm

- ❑ Variable ground albedo: Energy forecast tools

Outdoor test field: Stand alone modules – set-up



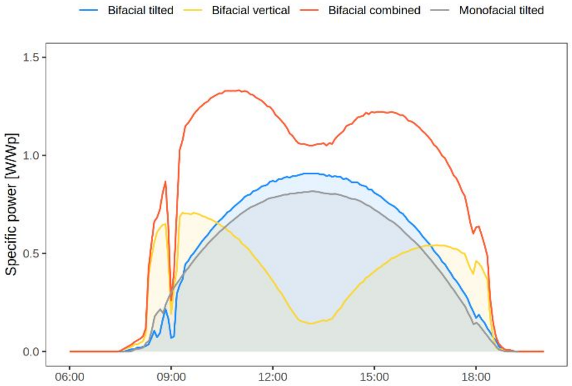




- Variable G_r non-uniformity ≈ 10%, Seasonal dependant and uniform on overcast days
- G_r non-uniformity value depends on sensor number, position and time of the day

Outdoor test field: Test Array - Setup

Type	2
ϕ_{Pmax} (%)	67
Frame	N
Tech.	p-Perc
Laminate	Glass-Glass



- ❑ Fixed vertical E-W oriented + tilted equator facing ~ solar tracking systems
- ❑ Design for specific production requirements
- ❑ Need of high bifacialities and good module designs

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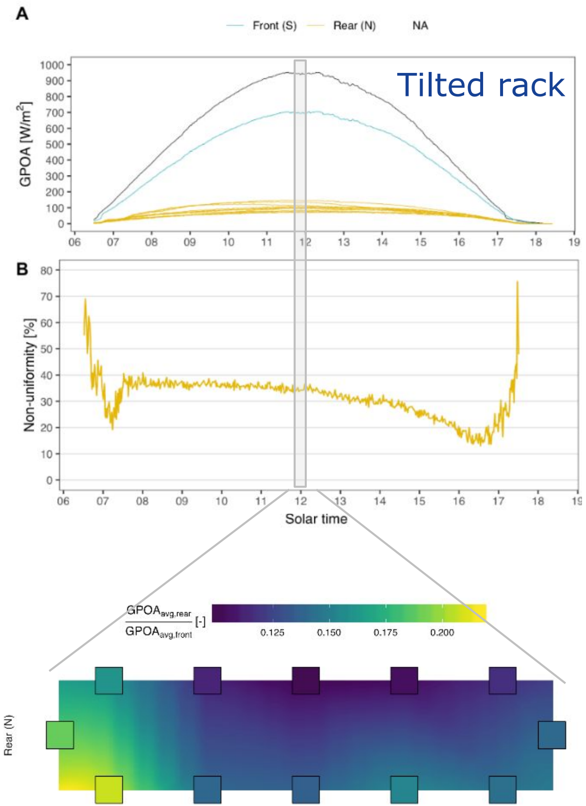
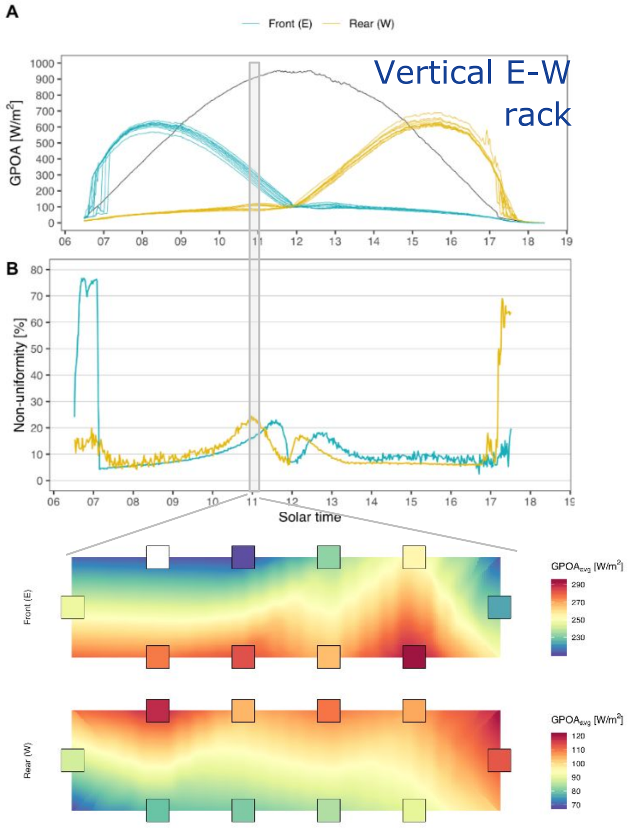
Outdoor test field: Test Array





In addition:

- ❑ G_r non-uniformity uniform for overcast days
- ❑ G_r non-uniformity <10% for vertical rack

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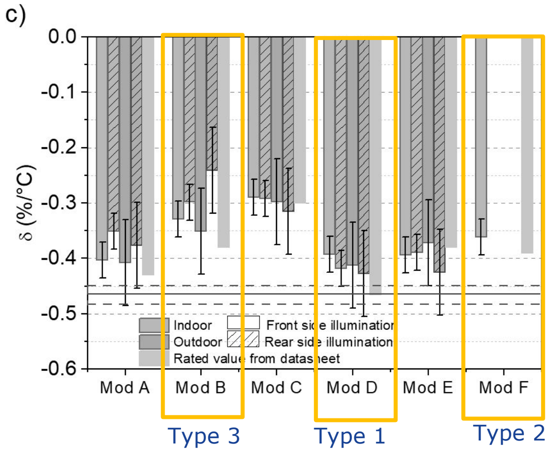
Outdoor test field: Real operating temperature

- Assumption:
  - Bifacial ⇒ Higher output ⇒ Extra light absorption ⇒ Higher T°

- Heat balance:
  - Absorbed, transmitted or reflected irradiance
  - Conversion losses (thermalisation, entropy generation, recombination or parasitic absorbance)
  - Heat losses by radiation and convection (High (IR) light transmission through the module)

- Bifacial modules: lower temperature coefficients



J. Lopez-Garcia, D. Pavanello, and T. Sample, "Analysis of temperature coefficients of bifacial silicon PV modules", J. Photovoltaic, 8(4) (2018), 960-968

Higher or lower Temperature?

- In general, $T_{bifa} < T_{mono}$ depending on several factors[3,4,5]:
  - If no extra irradiation [2]
  - For solar cells due to decrease of internal heat absorption (BSF)
  - For relatively high irradiance (>400 W/m²) [1]

1) Lamers, MWPE et al., Solar Energy Materials and Solar cells, 185 (2018) 192-197
2) Zhang, Z et al., Renewable Energy 155 (2020) 658-668
3) Mittag, M et al,. 36th EUPVSEC 2019, Marseille, France.
4) Hezel, R., High Efficiency low cost photovoltaic, Springer, 2009
5) J. Bonilla, Bifacial PV modules – Output power characterization and energy yield measurements, webinar TUV Reihnland 2020

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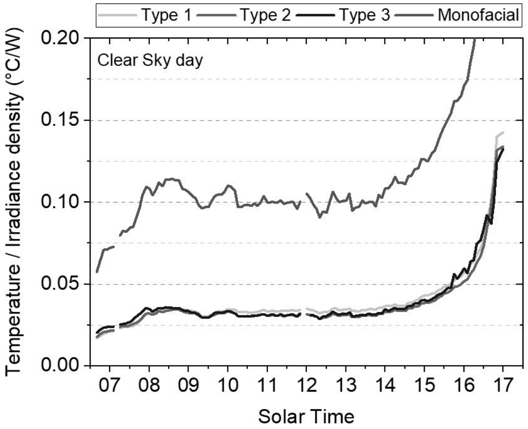
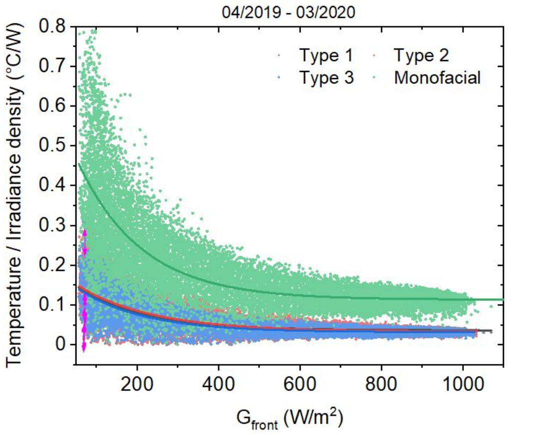
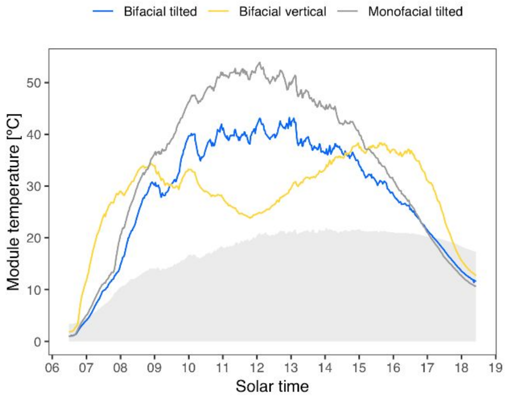
Outdoor test field: Real operating temperature

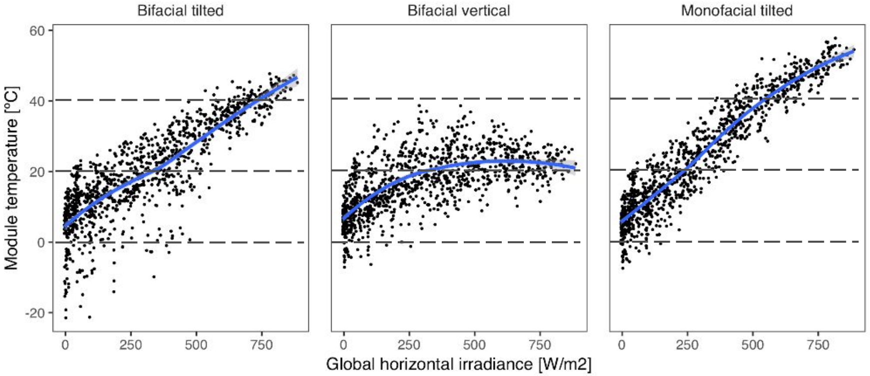
Stand alone modules





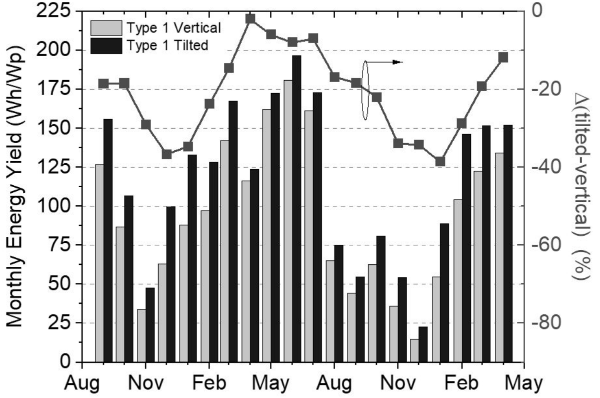
Test array





$T_{bifa} - T_{mono} / T_{mono}$ *100 ≈ -20%

Outdoor test field: Stand alone modules

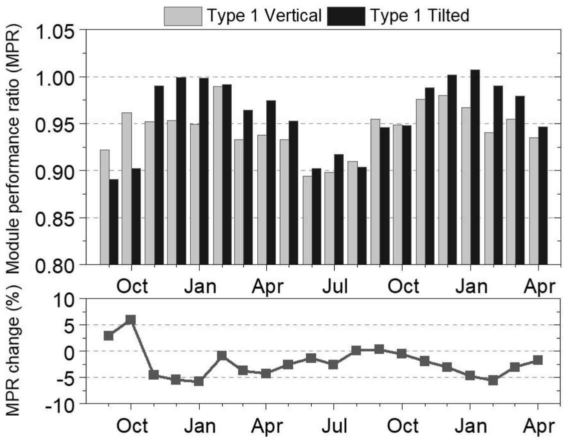


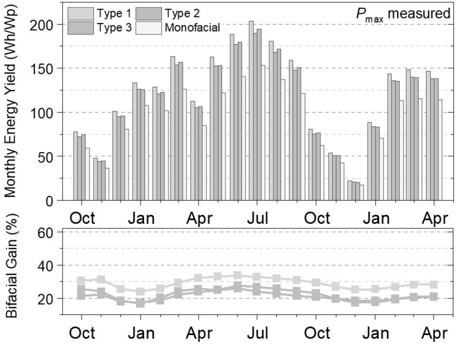
$$MPR = \frac{\sum P_h(W)}{\sum G_{T,h}(W/m^2)} \cdot \frac{1000\ (W/m^2)}{P_{\max STC}(W)}$$

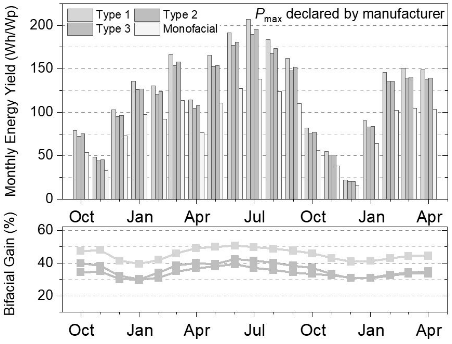
ΔTotalEY (Vertical$_{\text{measured-declared}}$)=-2.2%

ΔTotalEY (Tilted$_{\text{measured-declared}}$)=-1.7%

ΔTotalEY ($_{\text{vertical-tilted}}$)=-18.7%

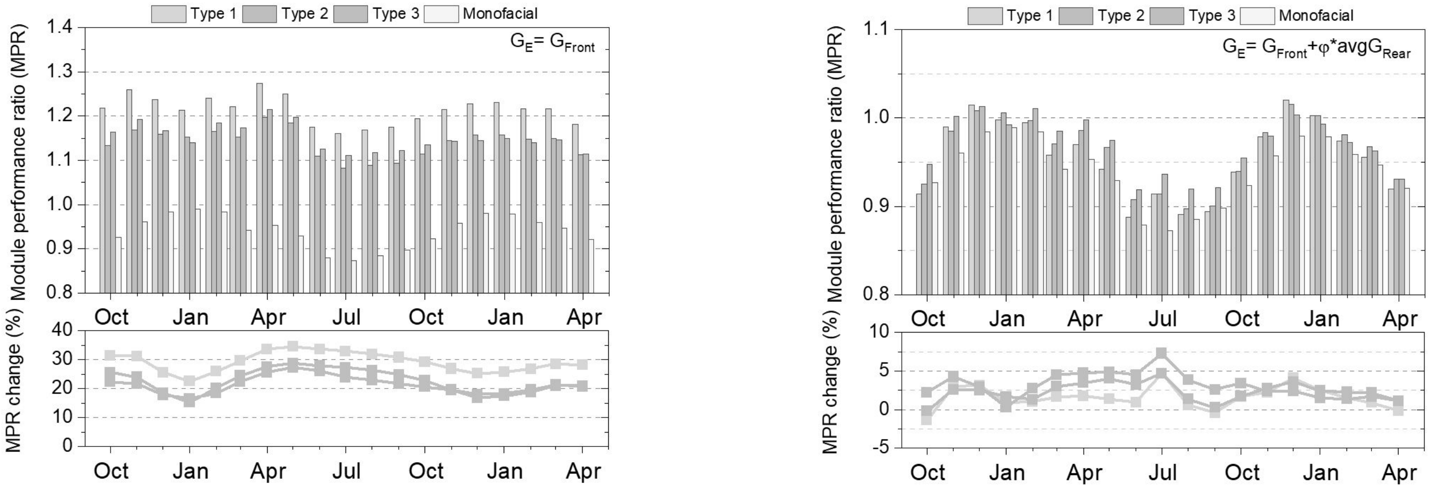






A. Gracia-Amillo, J. Lopez-Garcia, R. P. Kenny and T. Sample, "Energy yield analysis of bifacial PV modules: different technologies and configurations",36th EU-PVSEC, Marseille, France, 9-13 September 2019, pp. 1165-1170

Outdoor test field: Stand alone modules



- ❑ Relevance of a good rear irradiance characterisation
- ❑ Notably differences in MPR depending on the avg. global irradiance:MPR change Min G_{rear} > MPR change Mean G_{rear}

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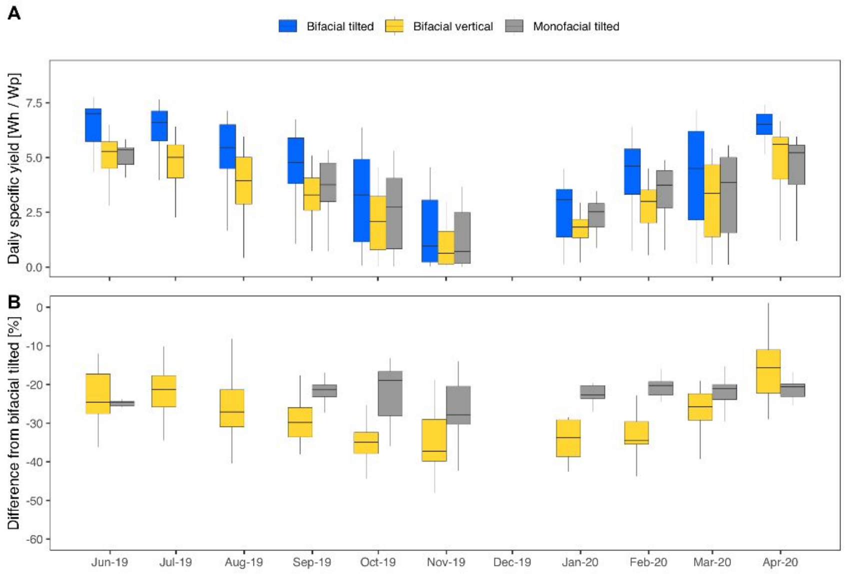
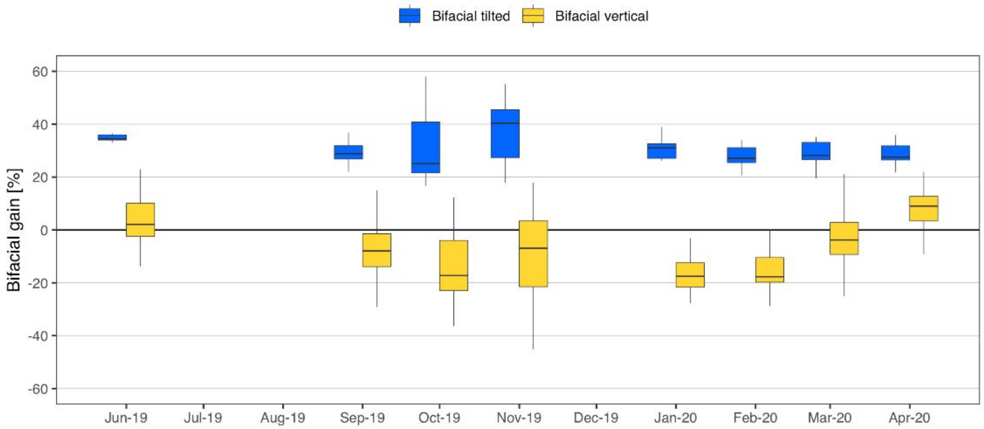
Outdoor test field: Test array



- ❑ Bifacial tilted outperforms vertical and monofacial
- ❑ Bifacial vertical outperforms monofacial in two months



- ❑ Bifacial gain > 22%

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Key messages

- ✔ Bifacial PV market development needs of reliable standards and modelling tools.

- ✔ Analysis of suitability of different characterisation methods for bifacial PV modules (IEC TS 60904-1-2)

  - ✔ Single-side illumination main approach: Non-irradiated background flexibility → increase of uncertainty

  - ✔ Alternative indoor double-sided illumination approach
    - ✔ Based on rear reflector → Gr non-uniformity issues.
    - ✔ Double-source illumination: LED and pulsed solar simulator → Fulfil most of IEC requirements
  - ✔ Outdoor approach: Difficult control of outdoor measurement conditions requested by the TS, G_r determination and G_r non-uniformity impact on *BiFi* and P_{max} of outdoor characterisation

- ✔ Real operating conditions:

    - ✔ Tilted equator facing and vertical E-W oriented: Stand alone modules and test array (3kWp)
    - ✔ Variable operating conditions (albedo, Gr non-uniformity)
    - ✔ Lower operating temperature of bifacial modules
    - ✔ Bifacial outperformed monofacial (BG ≈ 20-30%)
    - ✔ Accurate initial measurements is the only way to assess long-term degradation rates

Thank you

Any questions?

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PV-Enerate

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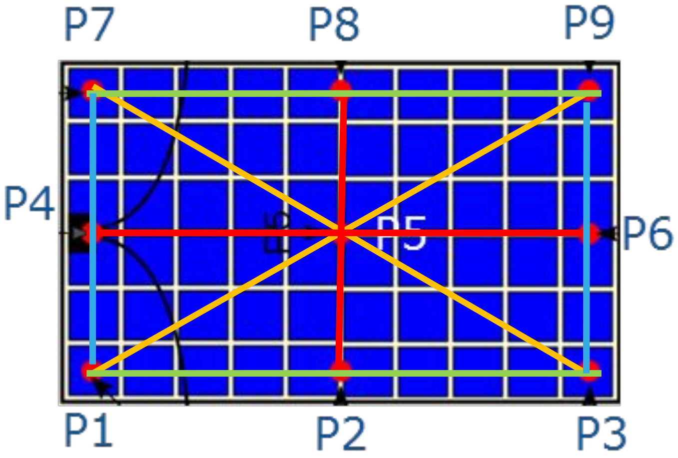
Annex

- Measurement of the irradiance on the non-exposed side for all methods:

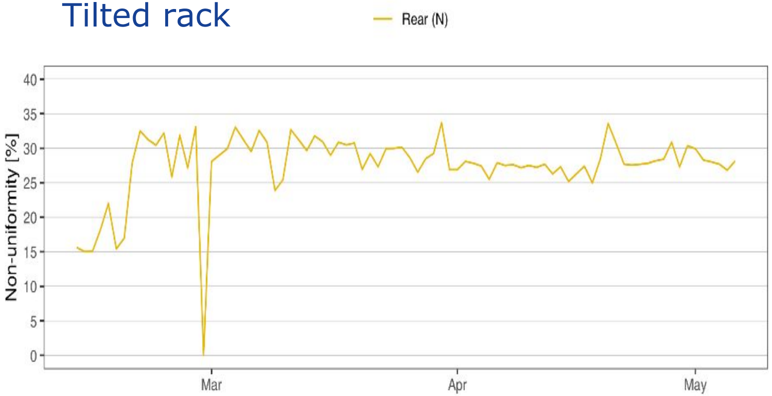
  - G_r measured with 2x2 cm^2 c-Si reference cell; UC (k=2) = 0.48% at 9 points:
  - choose at least 5 points with symmetrical distribution, for instance:

    - P1-P3-P5-P7-P9, P2-P4-P5-P6-P8, P1-P2-P3-P7-P8-P9, P1-P3-P4-P6-P7-P9

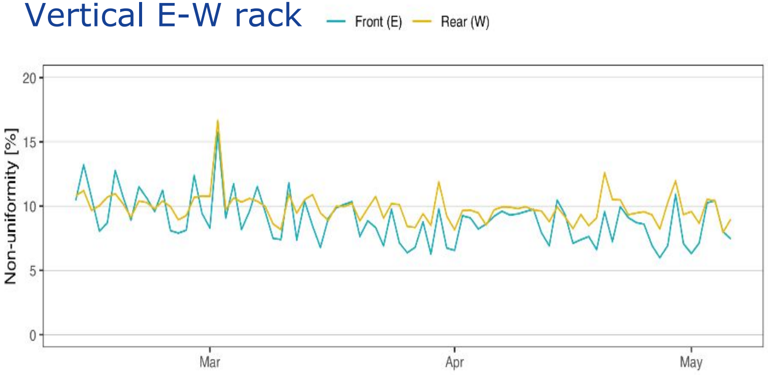


Annex: Outdoor test field: Test array

Tilted rack



Vertical E-W rack



In addition:

- ❑ G_r non-uniformity uniform for overcast days
- ❑ G_r non-uniformity <10% for vertical rack