Bifacial PV Modules: Performance Characterization and Energy Yield Measurements

pv magazine Webinar: New approach for bifacial modules and yield expectations

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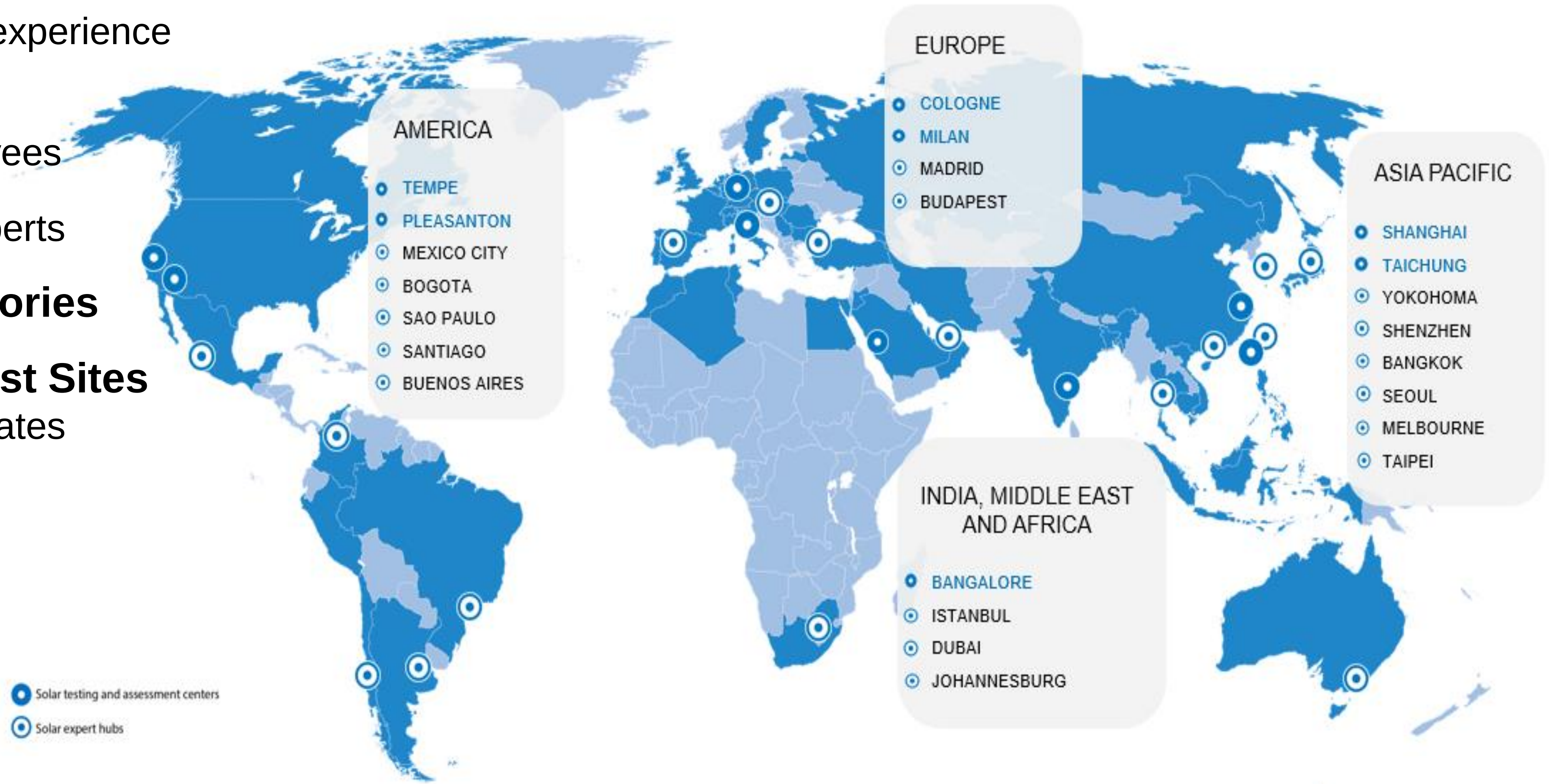

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Agenda

1. State of the art in output power characterization of bifacial PV modules
2. Electrical performance of bifacial PV Modules
   - Laboratory measurements
   - Outdoor energy yield performance measurements
4. Results of outdoor exposure
   - Cologne
   - Saudi Arabia
   - India

1. State of the art in output power characterization of bifacial PV modules

Overlook

IEC TS 60904: Photovoltaic devices – Part 1-2:

Measurement of I-V characteristics of **bifacial** photovoltaic (PV) devices

Publication: January 29th 2019

Technical Specification →  3 years → International Standard

Objectives:

1. Bifacialities determination
2. Output power determination for variable rear side irradiance

- Solar simulator
  - Single-side illumination
  - Double-side illumination
- Natural sunlight
  - 2 additional PV reference devices for rear irradiance

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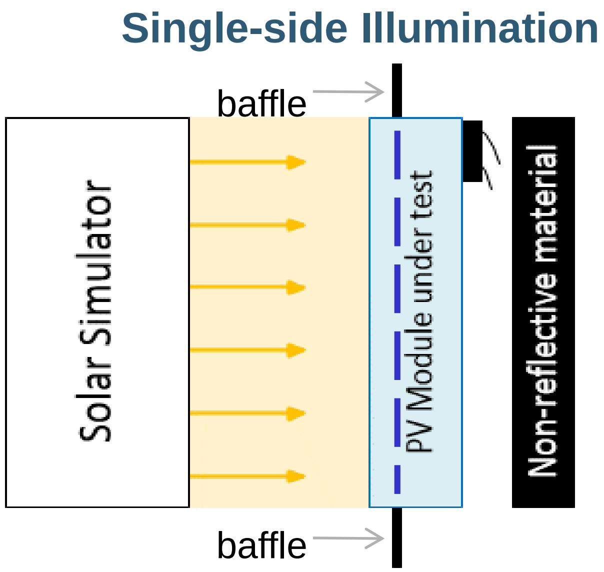
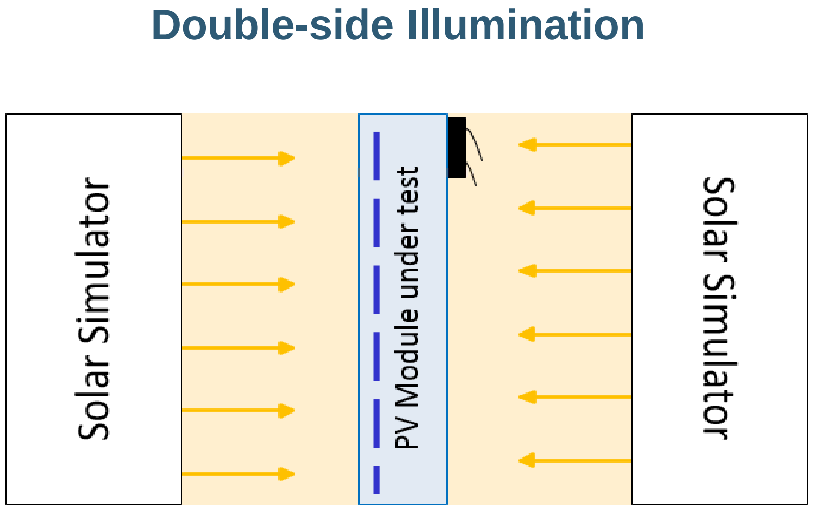
1. State of the art in output power characterization of bifacial PV modules

Approaches with a solar simulator





Single-side Illumination	Double-side Illumination
Irradiance levels >1000 W/m^2 **„typically“** up to 1200 W/m^2	Different levels on both sides
Non-irradiating background (non-exposed side <3 W/m^2 at any point)	
Non-uniformity <5% (Class B)	Non-uniformity <5% (Class B) on both sides

1. State of the art in output power characterization of bifacial PV modules

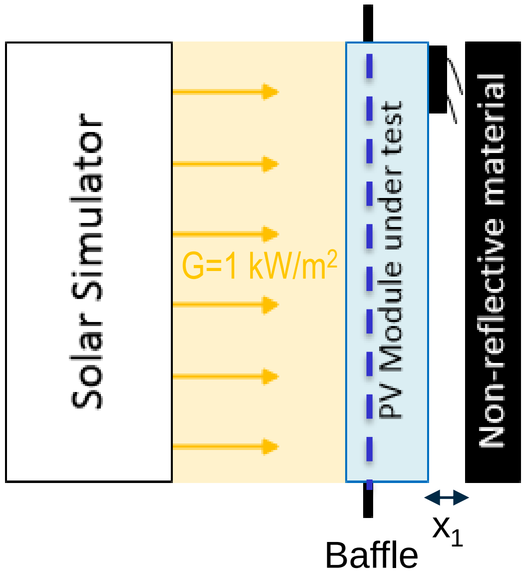
Characterization procedures with a solar simulator

Step 1:

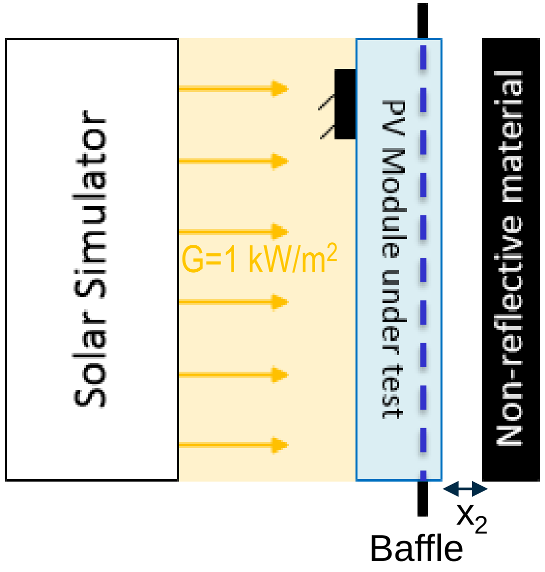
Bifacialities at STC

I-V Measurements on front side (f) & rear side (r)

1.1 front side (f) characterization



1.2 rear side (r) characterization



1.3 Bifacialities determination

$$\varphi Isc = \frac{Isc\ r}{Isc\ f}$$

$$\varphi Voc = \frac{Voc\ r}{Voc\ f}$$

$$\varphi Pmax = \frac{Pmax\ r}{Pmax\ f}$$

X_1 and X_2 „suitable distance“ from its non-exposed side

- ❑ Procedure applicable either for single or double side-illumination method.
- ❑ Spectral mismatch correction shall be applied when the front and rear side have different spectral response

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1. State of the art in output power characterization of bifacial PV modules

Characterization procedures with a solar simulator

Step 2:

Bifacial power gain „**BiFi**“ determination

Step 3:

$P_{maxBiFi100}$ & $P_{maxBiFi200}$

Single-side illumination

$\boldsymbol{Pmax}$ with **at least two** different equivalent irradiances (G_E).

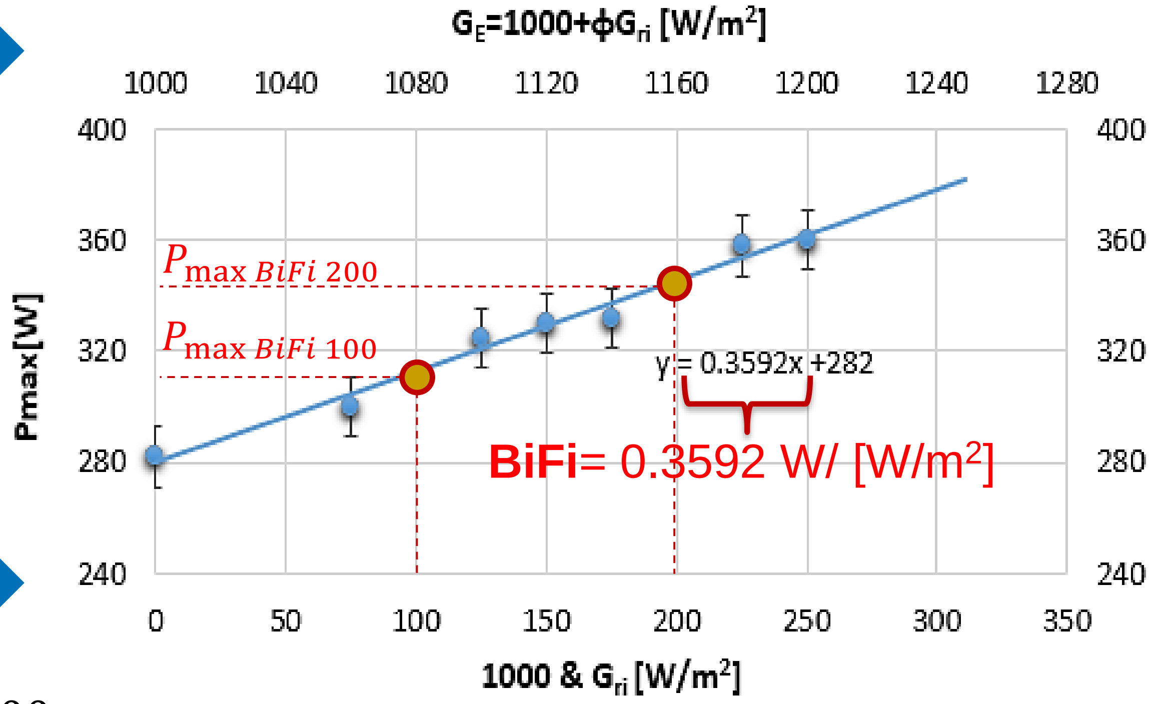
Double-side illumination

$\boldsymbol{Pmax}$ with G_f=1000 W/m² **& at least two** different G_r

$$P_{max\ BiFi\ 100} = P_{max_{STC}} + BiFi * 100$$

$$P_{max\ BiFi\ 200} = P_{max_{STC}} + BiFi * 200$$

$\boldsymbol{\varphi} = Min\ (\boldsymbol{\varphi_{Isc}}, \boldsymbol{\varphi_{Pmax}})$



$P_{max\ BiFi\ 100}$= 282+0.3592*100=317.9 W

$P_{max\ BiFi\ 200}$=282+0.3592*200=353.8 W

BiFi: rear irradiance driven power gain yield

$\boldsymbol{G_f}$= front side irradiance

$\boldsymbol{G_r}$=rear side irradiance

1. State of the art in output power characterization of bifacial PV modules

Characterization procedures with a solar simulator

IEC TS 60904 Part 1-2

Report

- Bifacialities φIsc, $\varphi Voc, \varphi Pmax$
- Isc, Voc & $Pmax$ at different G_r
- BiFi
- $P_{maxBiFi100}$ & $P_{maxBiFi200}$

Reference bifacial device

Power Labeling?

Bifacial Standard Test Condition (BSTC) [1]

$$G_f = 1000\ W/m^2$$
$$G_r = 135\ W/m^2$$
$$G_E = 1000 + \varphi * 135\ W/m^2$$

Electrical Data		
	STC	BSTC
Nominal Power	300 W (±3%, k=2)	330 W (± 3.5%, k=2)
Open-Circuit Voltage (Voc)	38.5 V (± 1%, k=2)	39 V (± 1.2%, k=2)
Short-Circuit Current (Isc)	9.4 A (± 2.8%, k=2)	10.2 A (± 3%, k=2)
Bifaciality (φ)	0.7 (± 0.05, k=2)	
Maximum System Voltage	1000 V IEC	
Maximum OC Protection Rating	20 A	
Power Temp Coef. (Pmpp)	-0.4% / K (±0.05%, k=2)	
Voltage Temp Coef. (Voc)	-0.31% / K (±0.02%, k=2)	
Current Temp Coef. (Isc)	0.05% / K (±0.01%, k=2)	

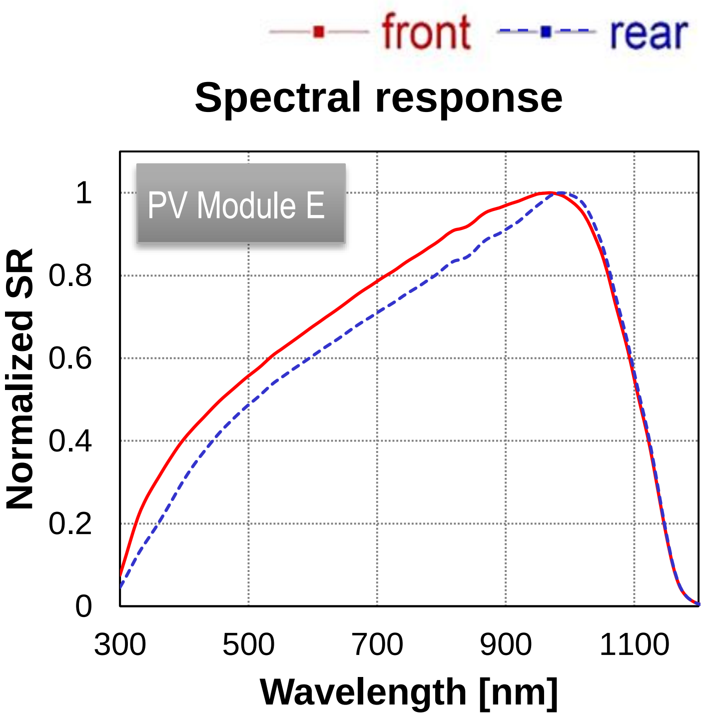
STC: AM1.5G; Temp. = 25°C; Irradiance = 1000 W/m²
BSTC: AM1.5G; Temp. = 25°C; Irradiance = 1000+ φ·135 W/m²

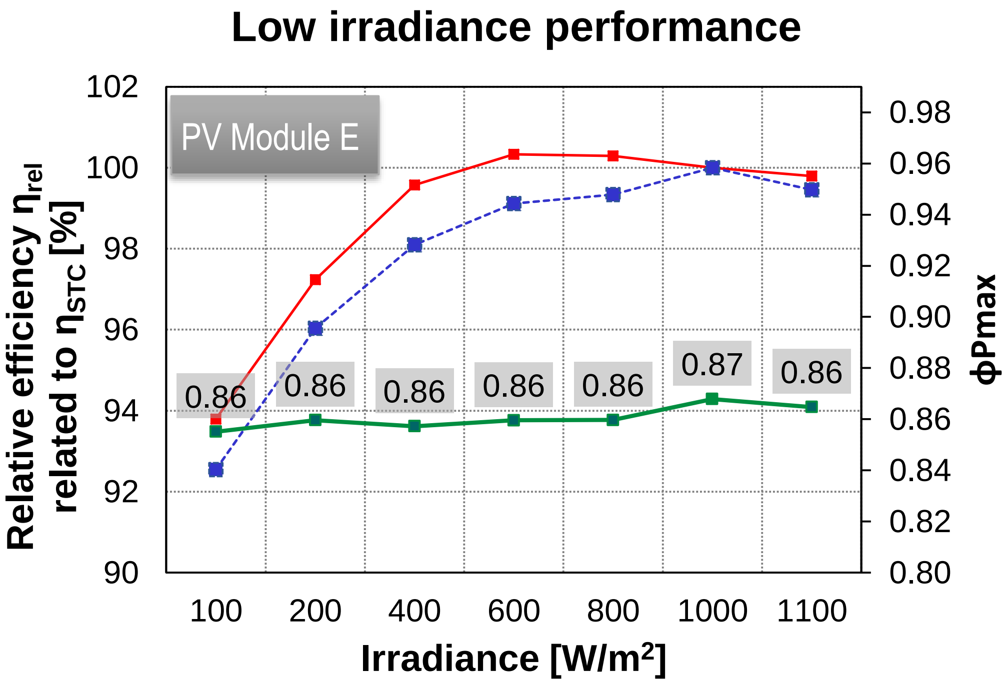
[1] 2PfG 2645/11.17: Measurement of *I-V* characteristics of bifacial photovoltaic devices and label requirements

2.Electrical Performance of Bifacial PV Modules

Characterization in our laboratories

- STC with class AAA pulsed solar simulators
- Bifaciality coefficients
- Temperature coefficients
- Spectral Response
- Angular Response
- Low Irradiance





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2.Electrical Performance of Bifacial PV Modules

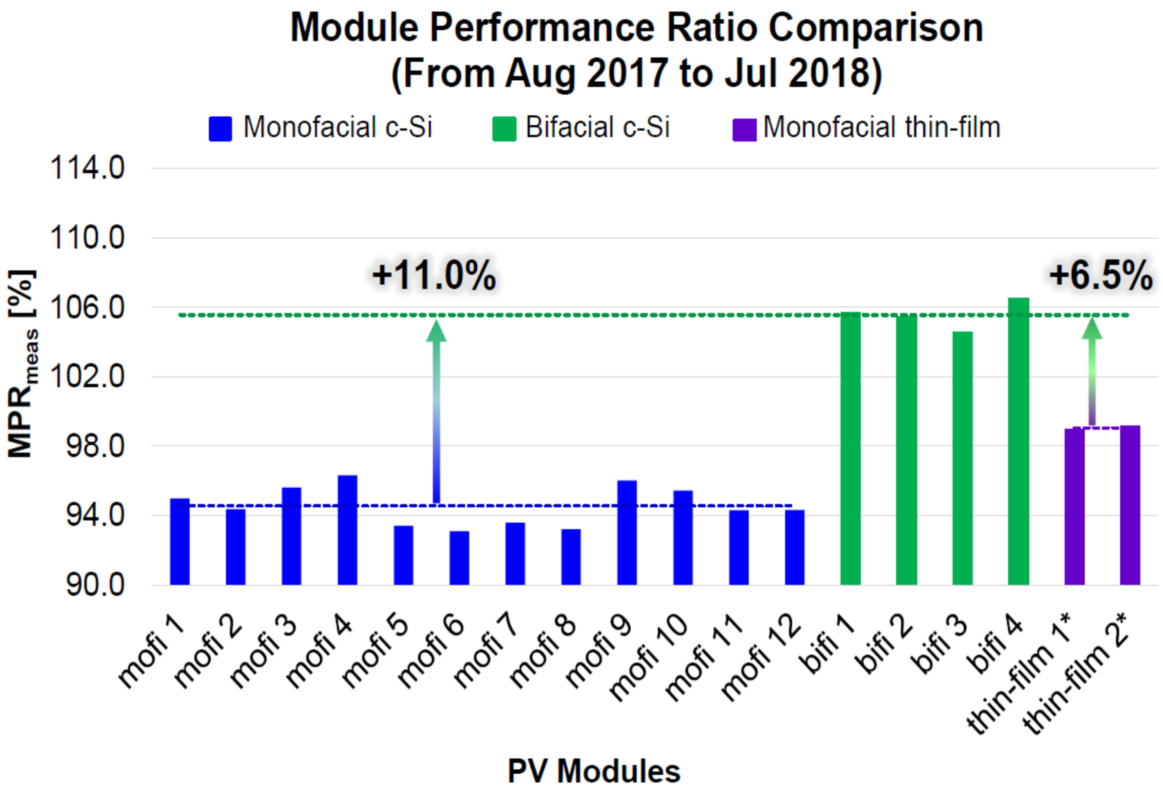
Outdoor energy yield performance in different climates

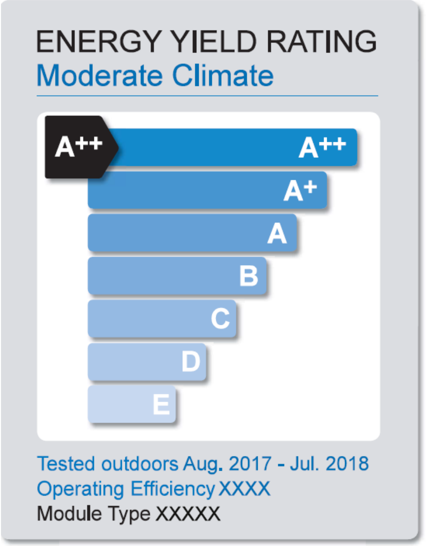
- MPP tracking (30 sec)
- I-V curve (10 min)
- Temperature of the back of the module, T_{BoM} (30 sec)
- In plane spectral irradiance (1min)
- Meteorological data (30 sec)
- G_r pyranometers (30 sec)

3.Results of Outdoor Exposure

Results Cologne

Height above ground	1.5 m
Tilt angle	35° South
Mounting conditions	Gravel (albedo 28%)
Annual in-plane solar irradiation $H_{POA, Annual}$	1231.1 kWh/m²
Annual in-plane rear irradiation $H_{rear, Annual}$	169.4 kWh/m²





** Values referred to label P_{MPP}. All others PV modules are referred to indoor P_{MPP} at STC with SMM correction and were electrically stabilized*

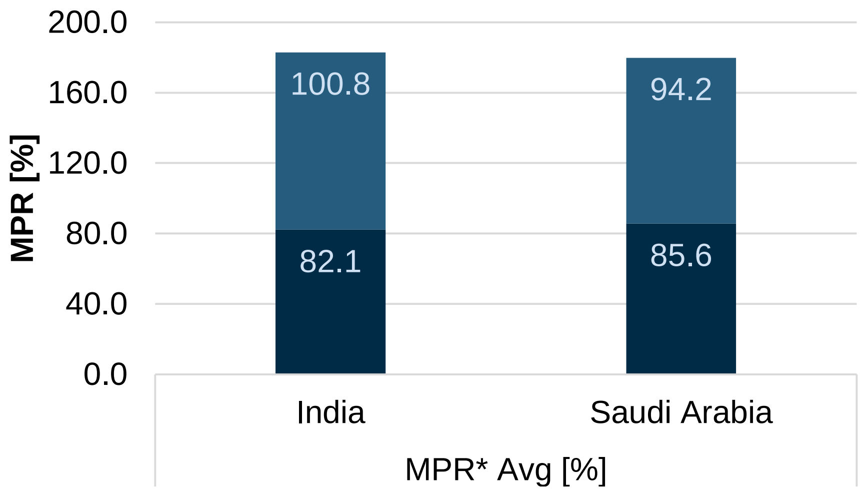
[2] Bonilla J. et al (2018): Energy Yield Comparison between Bifacial and Monofacial PV Modules: Real World Measurements and Validation with Bifacial Simulations, EUPVSEC 2018.

3.Results of Outdoor Exposure

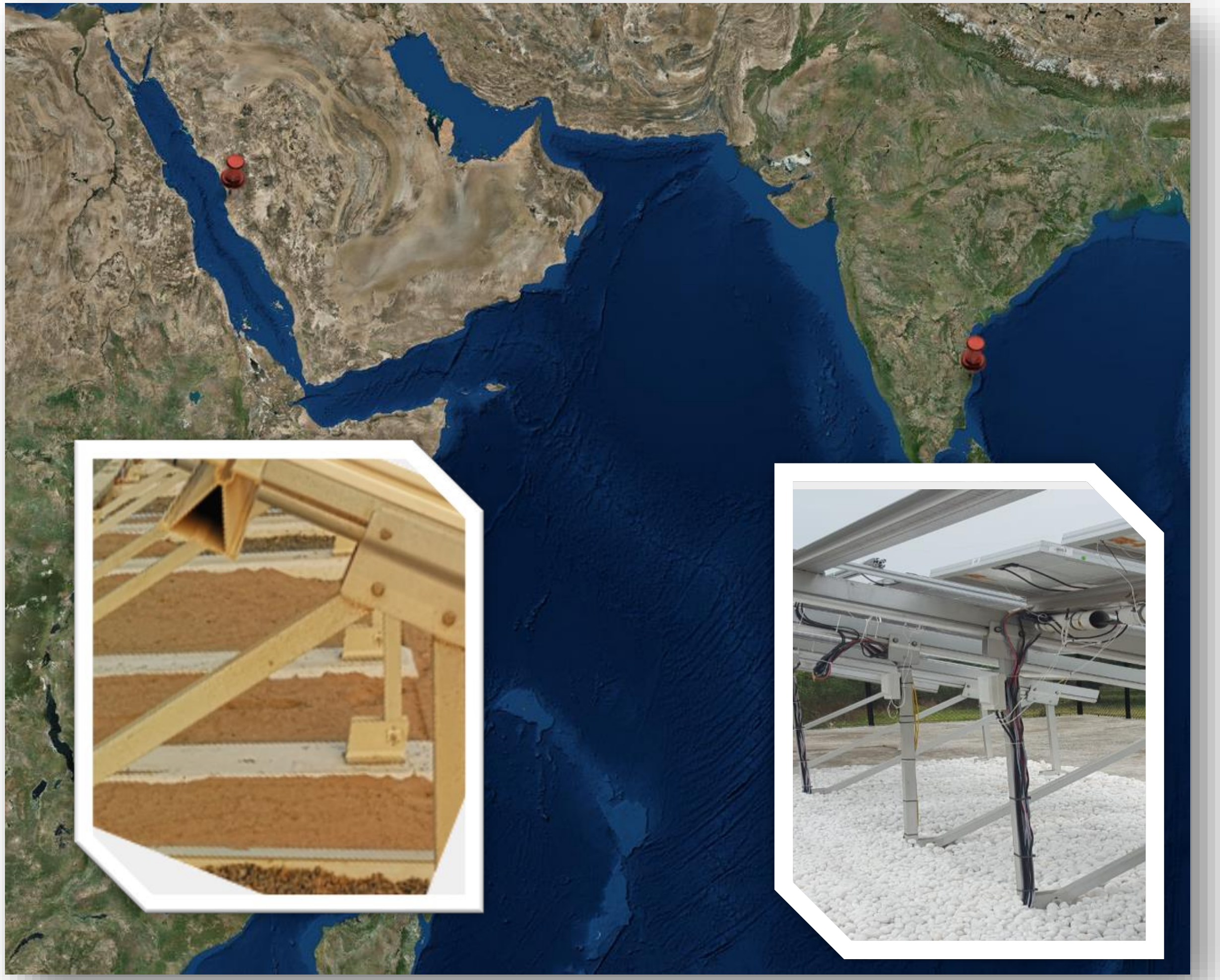
Results Saudi Arabia and India

	India	Saudi Arabia
Surface	White Stones	Desert Sand
Albedo	~60%	~35%
G_{rear}/ G_{front}	33%	21%
Bifacial Gain	23%	10.1%

Module performance ratio comparison



*Peliminary results of 6 months



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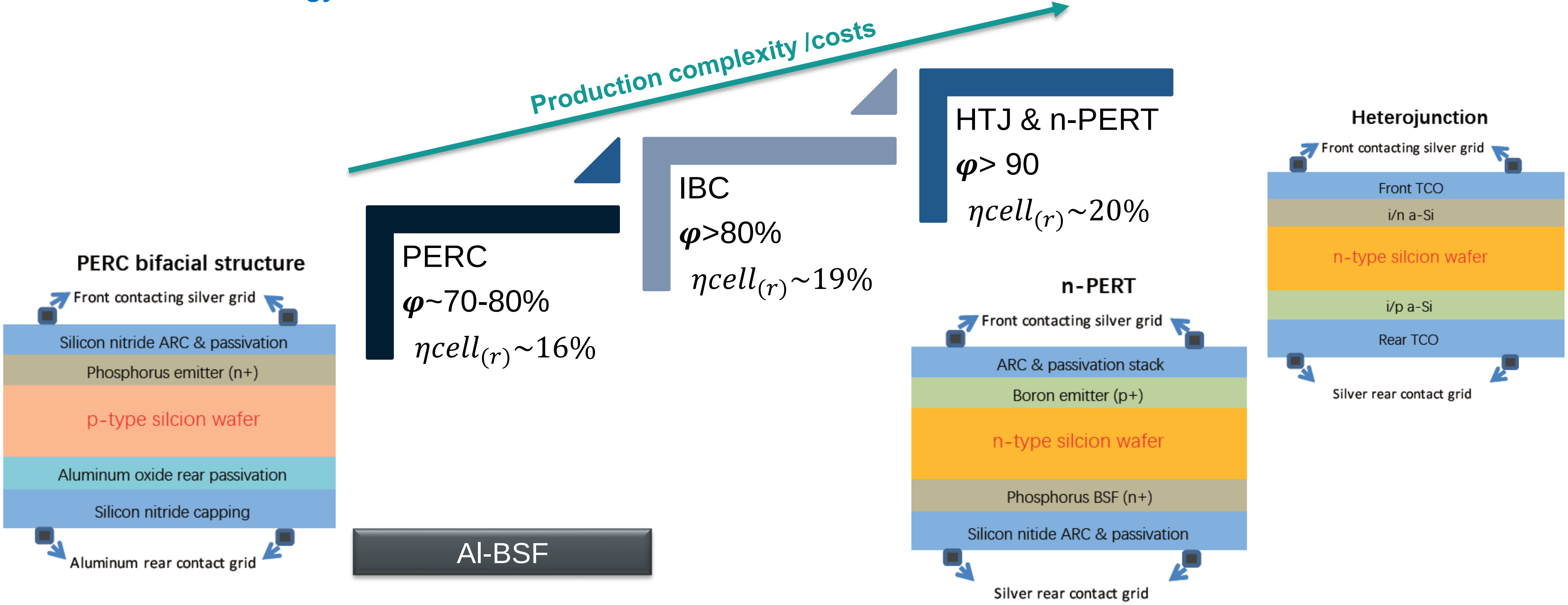
Annex

Bifacial cell Technology and efficiencies



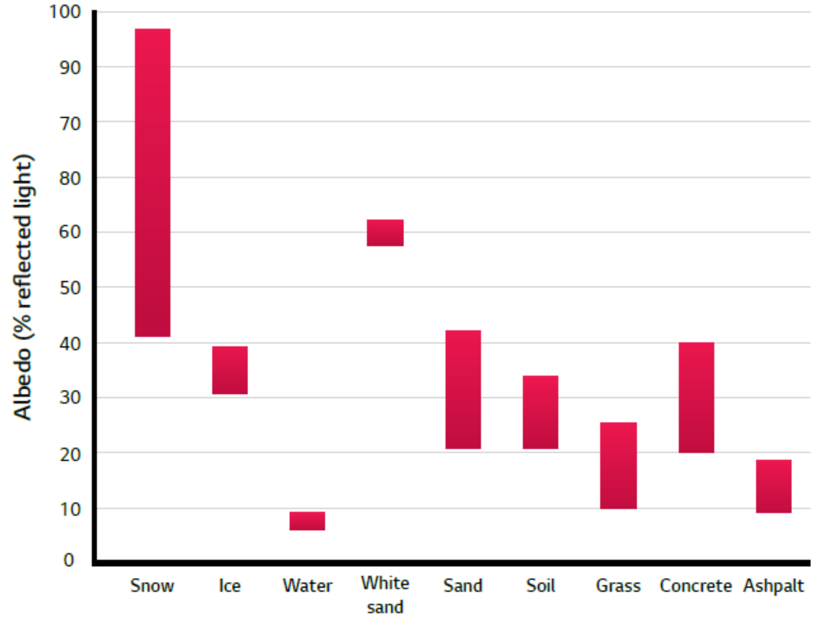
Images: TAIYANGNWES 2017; Bifcial Solar Module Technology Report

More about cell technology: TAIYANGNWES (2017); Bifcial Solar Module Technology Report and Veschetti Y. (2016) Cell Session Introduction at BifiPV Workshop-Miyazaki 29-30/09/2016

Annex

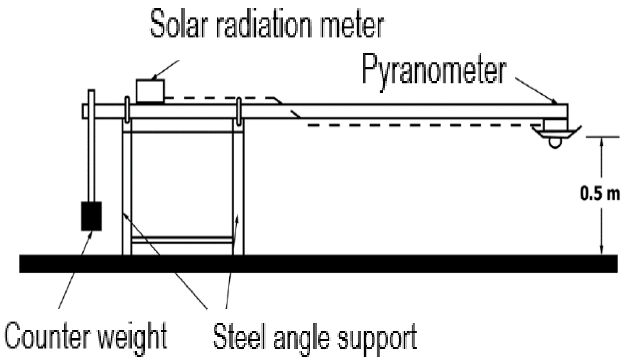
Ground Reflectance (Albedo ρg)

$$\text{Albedo} = \frac{\text{Reflected Light}}{\text{Incident Light}}$$



* Source : Helmholtz Alfred-Wegener Institute and the National Renewable Energy Laboratory (NREL)

ASTM E 1918-16: Standard Test Method for Measuring Solar Reflectance of Horizontal and Low-Sloped Surfaces in the Field.



Material	Reflectance*(R)	Grear at 1000Wm-2 front
Asphalt	0.1	70 Wm-2
Light soil	0.21	130 Wm-2
Concrete	0.28	170 Wm-2
Beige built-up roofing	0.43	250 Wm-2
White EPDM roofing	0.8	430 Wm-2

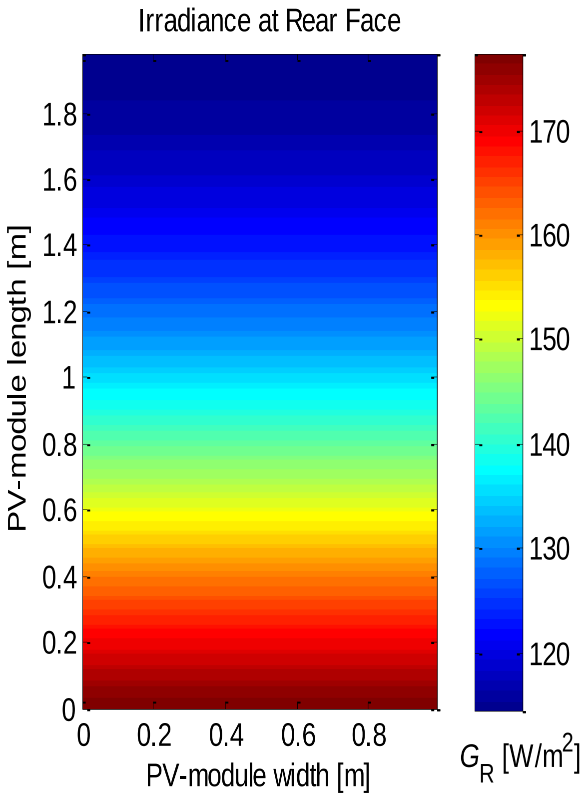
Source : Deline et al., IEEE PVSC 2016; Deline et al., IEEE JPV (submitted) (National Renewable Energy Laboratory)

Annex

Influences on Energy Yield: Bifacial PV Modules

(Surface) Albedo → Rear irradiance (G_{rear}) → Bifacial Gain

Non-Uniformity of Irradiance [2]



[3] Monokroussos C. et al (2018): Rear Face Spectral Irradiance at 1-Sun and Application to Bifacial Module Power Rating, EUPVSEC 2018

Annex

Solar simulator requirements for bifacial characterization

	Single-side illumination		**Double-side illumination**	
General Requirements	IEC 60904-1 (Class BBB or better)			
Irradiance levels	>1000 W/m^2 **„typically“** up to 1200 W/m^2		Different levels on both sides	
Non-uniformity	Measured at the irradiance levels **used** and those values used for corrections (such as SMM) and uncertainty evaluation	<5%	Measured on both sides when the test area is simultaneously illuminated on both sides	<5% on both sides at used irradiance levels and those values used for corrections (such as SMM) and uncertainty evaluation
Spectral distribution		Spectral match 0.6-1.4 STI <2% LTI<5%		Spectral match 0.6-1.4 STI <2% LTI<5%
Temporal instabilities				

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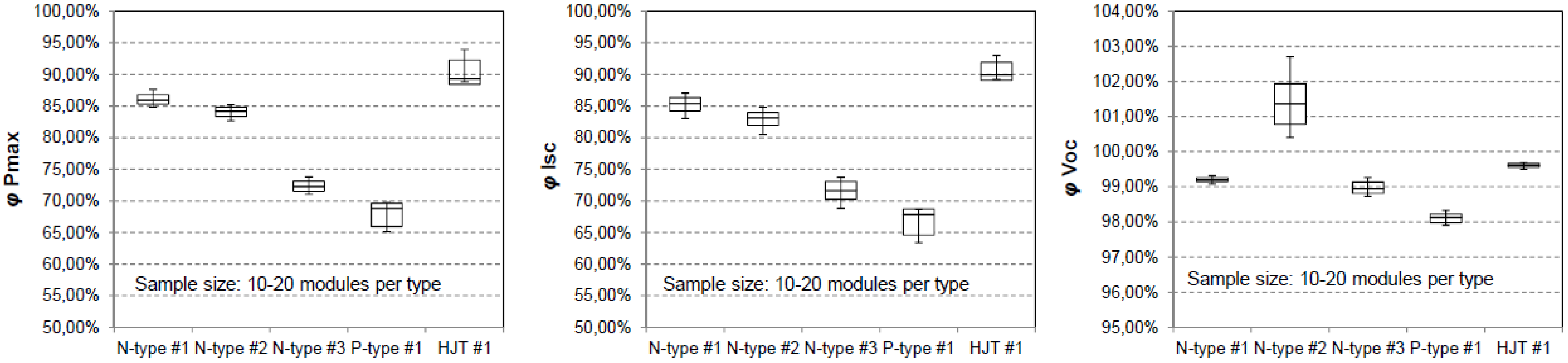
2.Electrical Performance of Bifacial PV Modules

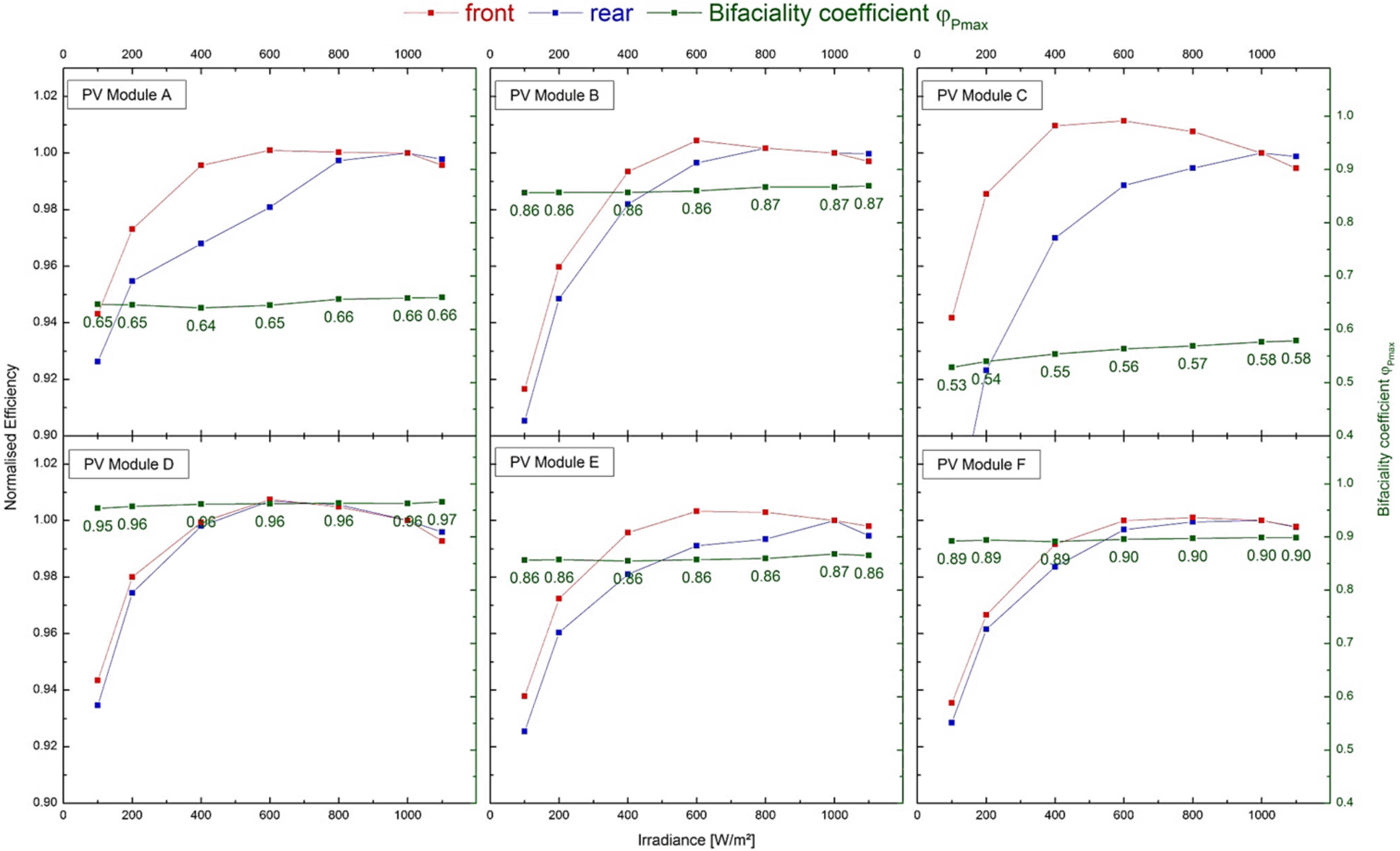
Bifaciality Coefficients Dispersion seen in Production



- The **variation** of **bifaciality coefficients, *φ***, was evaluated by measuring a series of modules in **production** (**10-20 modules per type**).
- **Bifaciality** depends strongly on **technology.** Coefficients may vary from **60%** to **90%**.
- **Bifaciality coefficients** may **vary** from **±2.0%** to **±5.0%** (k=2) in production for as-produced modules of the same family.

2.Electrical Performance of Bifacial PV Modules

Bifaciality coefficient-Results of six bifacial PV modules measured in laboratory



Partial shading of the cells by the label, junction boxes, bus bars or cables must be avoided!

Evitar sombreado parcial de celdas

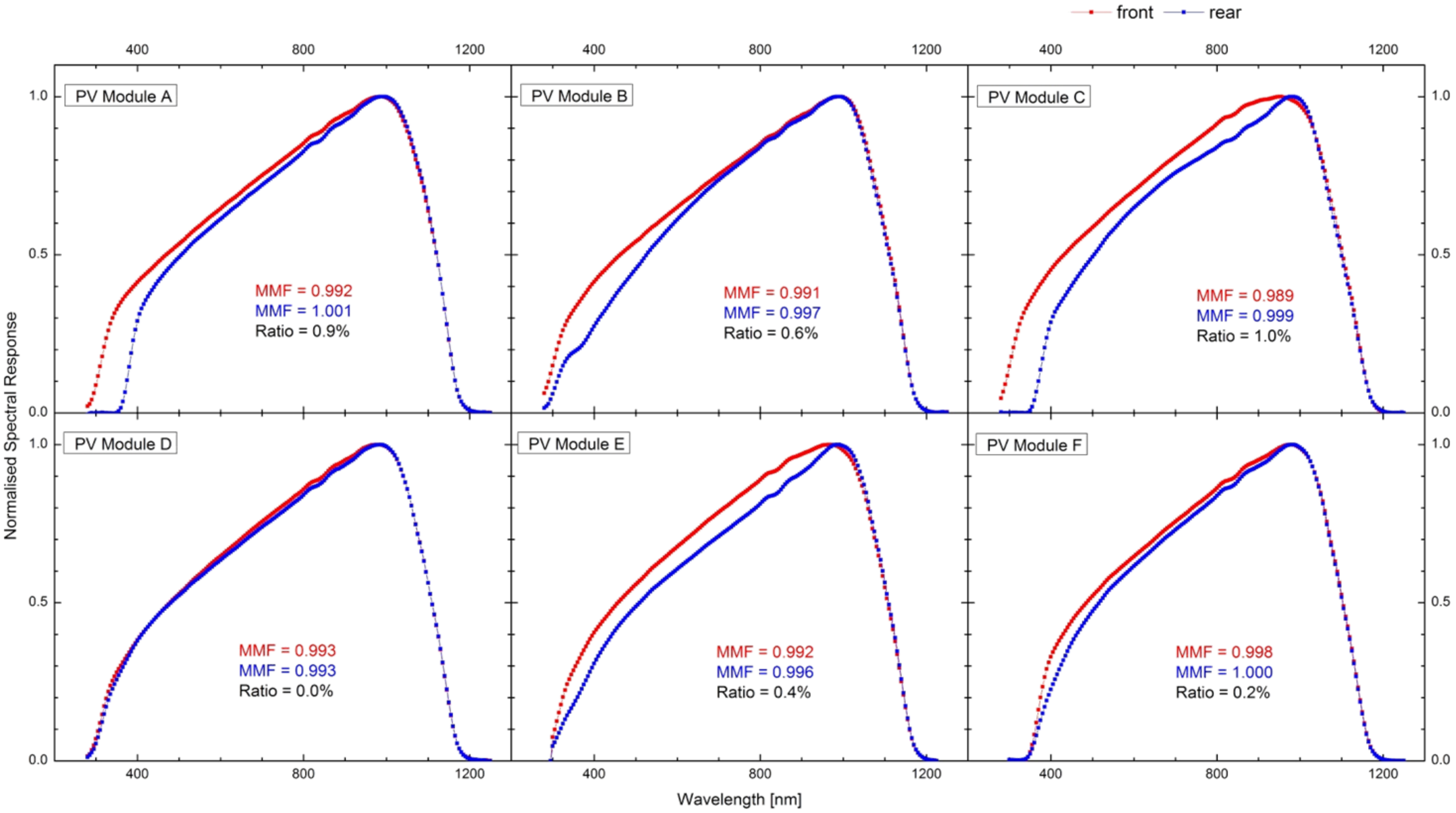
$$\varphi_{P\max} = \frac{P\max_r}{P\max_f}$$

Low depedency on irradiance

Baja dependencia en irradiancia

2.Electrical Performance of Bifacial PV Modules

Spectral Response-Results of six bifacial PV modules measured in laboratory

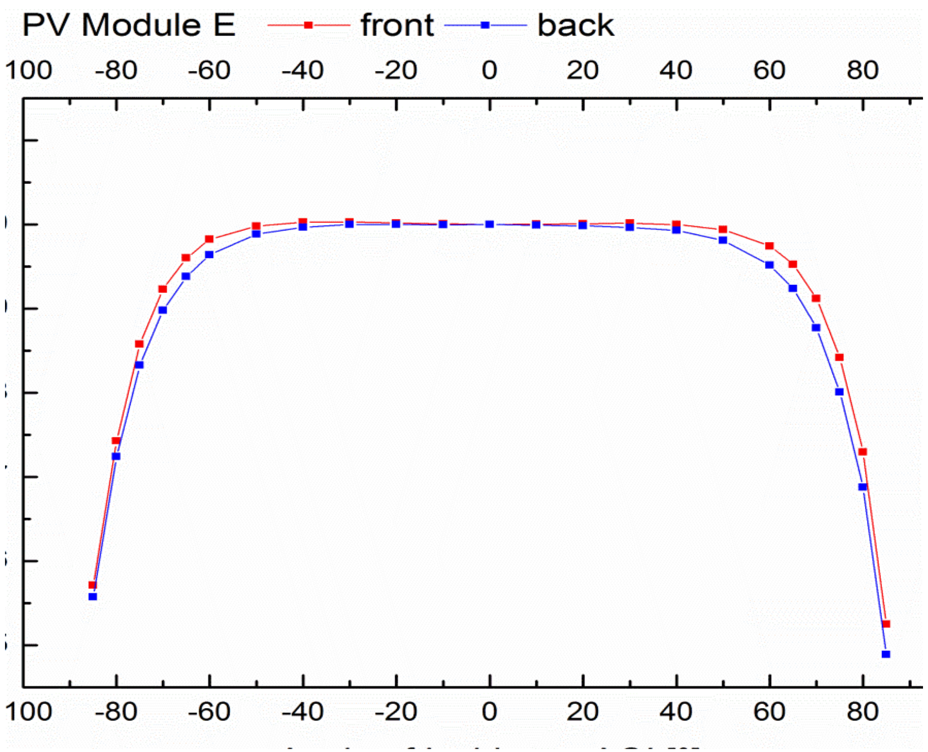


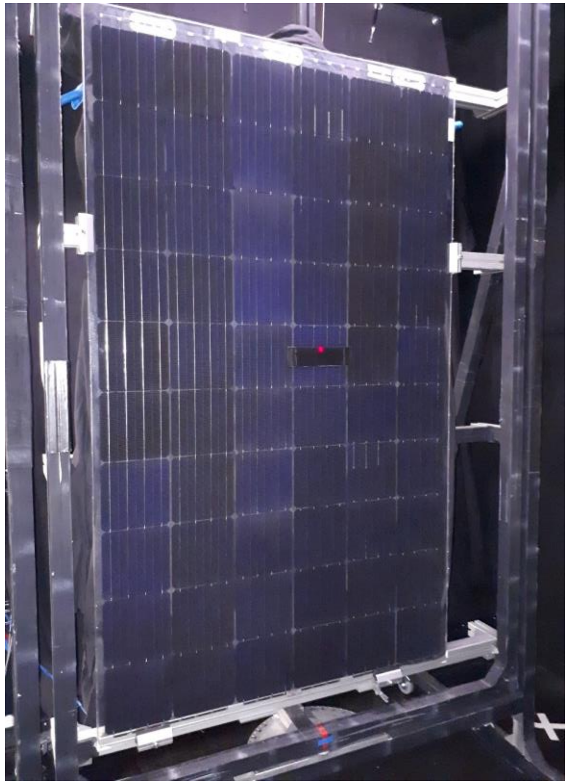
Different compensation of spectral mismatch

2.Electrical Performance of Bifacial PV Modules

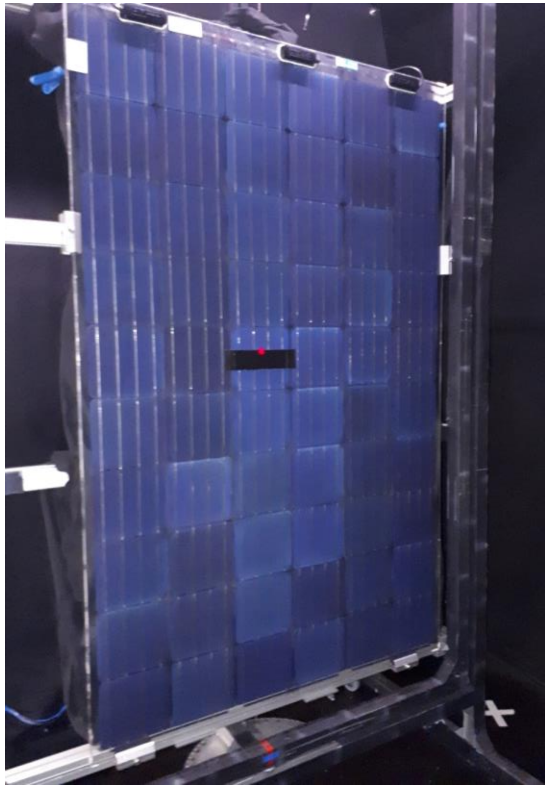
Angular Response-PV Module *E* measured in Laboratory

Non-destructive test method[4]: Isc under partially shading





front side (f) characterization



rear side (r) characterization

[4] W. Herrmann: Solar Simulator Measurement Procedures for Determination of the Angular Characteristic of PV Module, EUPVSEC 2014.

[5] Schweiger, M (2017): Electrical Performance of Bifacial PV Modules: Comparative Measurements of Market-Ready Products, at Proceedings of the 27th European Photovoltaic Solar Energy Conference EU PVSEC

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1. State of the art in output power characterization of bifacial PV modules

Characterization procedures with a solar simulator

Step 2:

Bifacial power gain **„BiFi“** determination

Single side illumination	Double side illumination
1. STC : G_f=1000 W/m², G_r=0 W/m², AM1.5 and 25°C. G_f within ±10% with corrections acc. to IEC 60891.	
2. $\boldsymbol{Pmax}$ with **at least two** different equivalent irradiances (G_{E_i}). G_{E_i} = 1000 W/m² + $\boxed{\varphi}$ * G_{r_i} ; $\boldsymbol{\varphi} = Min\ (\boldsymbol{\varphi_{Isc}}, \boldsymbol{\varphi_{Pmax}})$	2. $\boldsymbol{Pmax}$ with G_f=1000 W/m² **& at least two** different G_r ; G_f= 1000 W/m² & G_{r_i}
3. **BiFi** determination as the **slope from linear fit** $\boldsymbol{Pmax}$ **vs** $\boldsymbol{G_r}$	

$$G_{r_{i\,(i=1,2,3..)}} \begin{cases} 0 < G_{r_i} < 100\,W/m^2 \\ 100 \leq G_{r_i} < 200\,W/m^2 \\ G_{r_i} \geq 200\,W/m^2 \end{cases}$$

BiFi: rear irradiance driven power gain yield
$\boldsymbol{G_f}$= front side irradiance
$\boldsymbol{G_r}$=rear side irradiance

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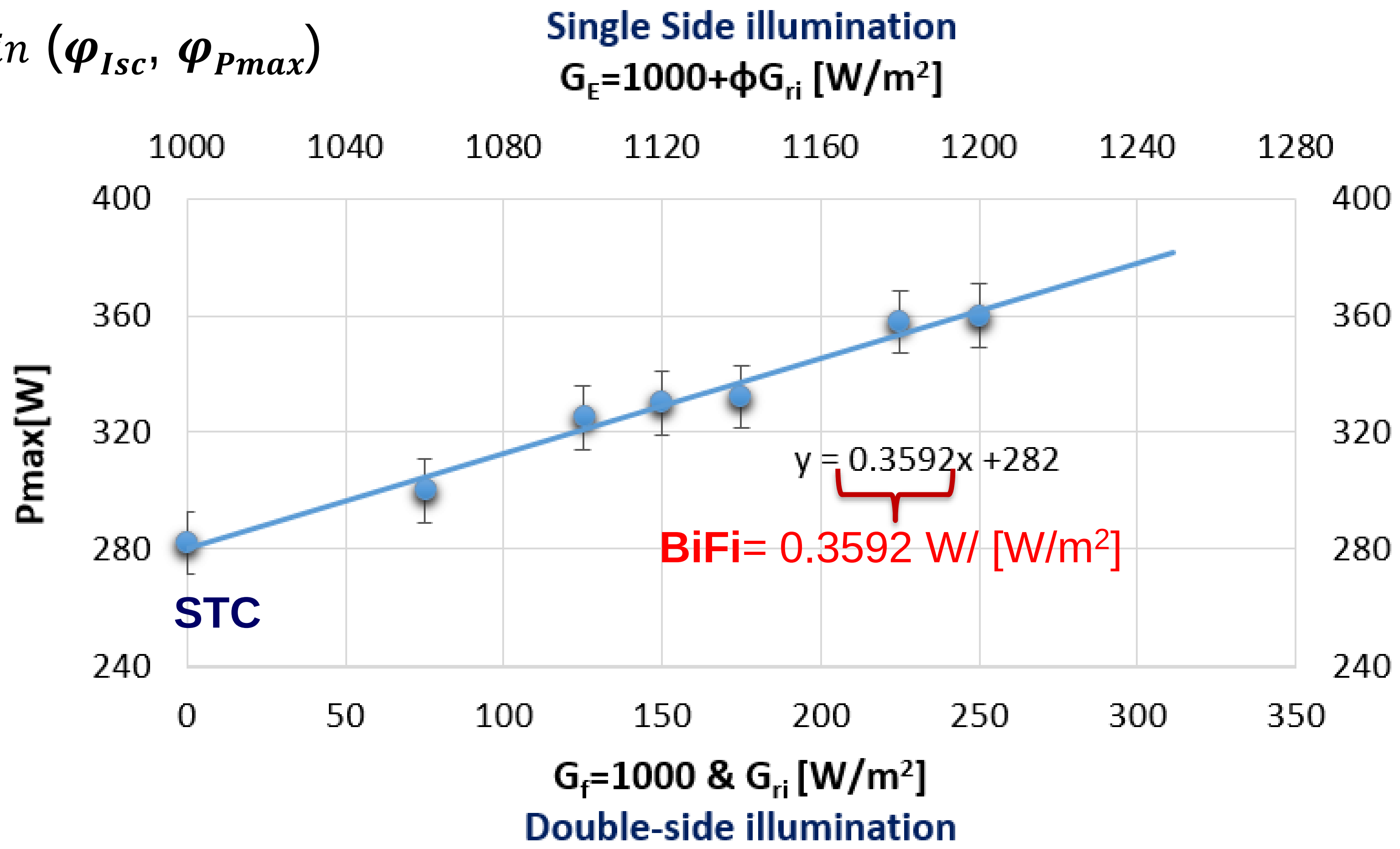
1. State of the art in output power characterization of bifacial PV modules

Characterization procedures with a solar simulator

Bifaciality		φ=0.8	
G_f [W/m²]	G_r [W/m²]	G_E [W/m²]	P_{max} [W]
1000	0	1000	282
1000	25	1020	
1000	50	1040	
1000	75	1060	300
1000	100	1080	
1000	125	1100	325
1000	150	1120	330
1000	175	1140	332
1000	200	1160	
1000	225	1180	358
1000	250	1200	360
1000	275	1220	
1000	300	1240	

Single-side double-side

$$\varphi = Min\ (\varphi_{Isc},\ \varphi_{Pmax})$$



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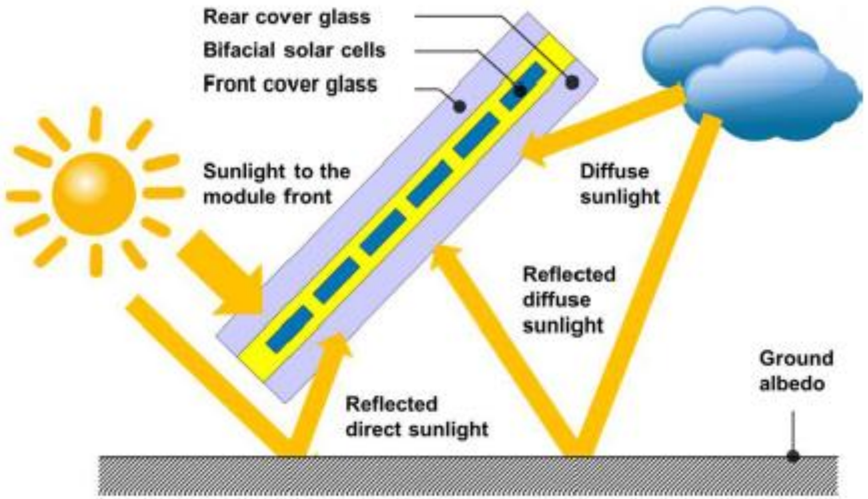
BSTC



Field parameter	Bifacial reference conditions
Albedo	0.21 (light soil)
Height above ground	1 m
Inclination angle	37°
Front side irradiance	1000 W/m^2

Field parameter	Bifacial reference condition
Beam & Circumsolar Irradiance	- As defined in IEC 60904-3
Diffuse Irradiance	- As defined in IEC 60904-3 - Isotropic diffuse
Ground Albedo	- Lambertian diffuse reflector - Light sandy soil with spectral albedo as given in SMARTS v. 2.9.5
Air Mass	1.5
Inclination angle	37°
Front side irradiance	1000 W/m^2
Shading	No near shading
PV-array design	Single row, >10 modules
Height above ground	**1 m**
Module Transmission	**Spectral transmission data for Glass/EVA/Glass structures of bifacial modules**

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Annex

Outdoor Operation: Equipment and frequency of field measurements

Parameter	Equipment/Technique	Frequency
TBoM	2 PT100 temperature sensors	30 sec
I-V curve measurements	Electronic loads	10 min
PMPP	MPP tracker	30 sec
Current and Voltage	4T sensing of one second speed	10 min
GPoA	Pyranometer	30 sec
G rear	Pyranometer	30 sec
Tambient, Precipitation and humidity	Sensors (instantaneous measurements)	30 sec
Spectral irradiance	Spectrometer (300-1600nm)	1 minute

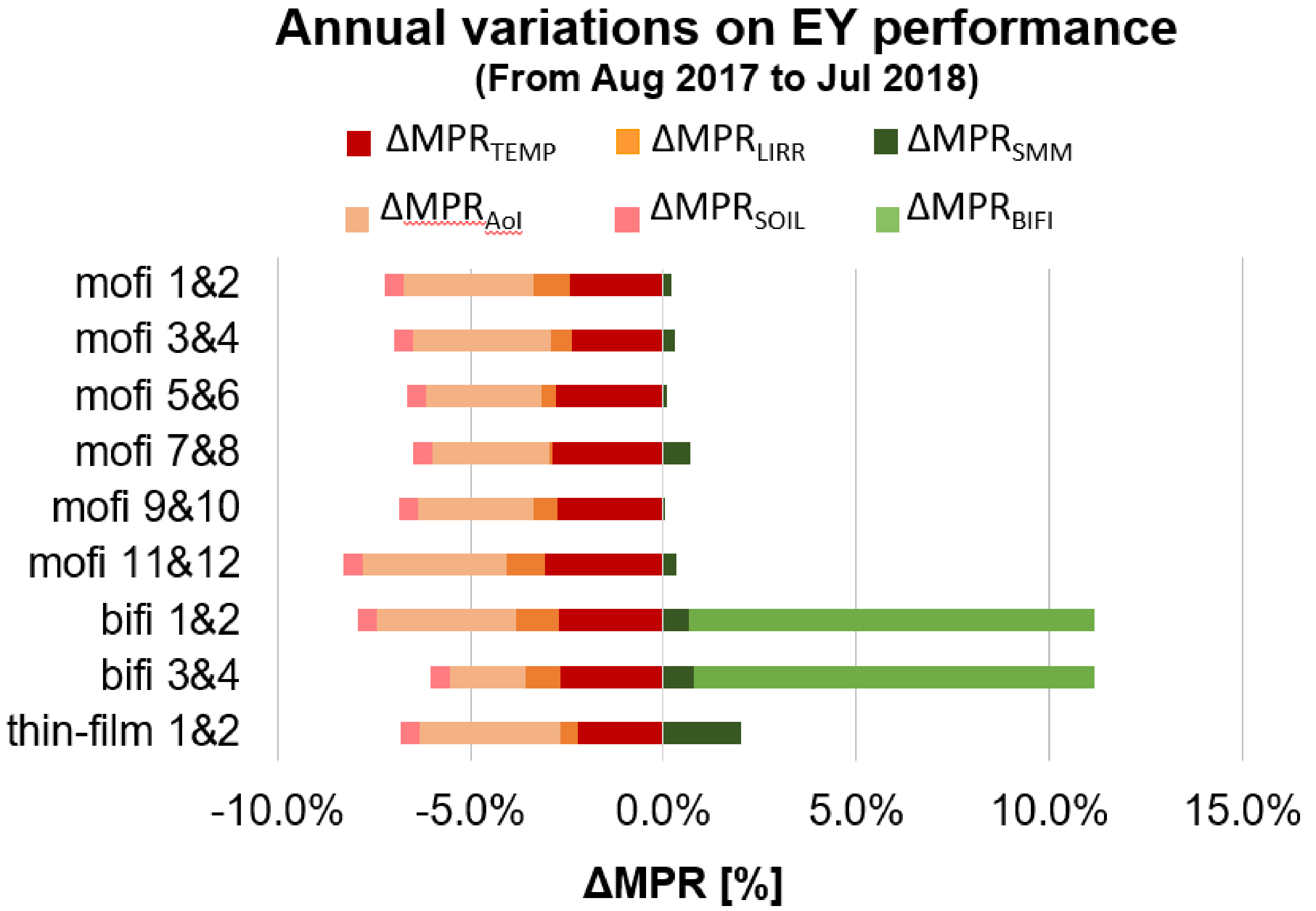
Annex

Results of Outdoor Exposure: Quantification of Energy Losses/Gain:

The combined loss mechanisms resulted in a calculated PV module performance ratio (MPR_{CAL})

$$MPR_{CAL} = 100\% - \Delta MPR_{TEMP} \pm \Delta MPR_{LIRR} - \Delta MPR_{SOIL} \pm \Delta MPR_{SMM} - \Delta MPR_{AOI} + \Delta MPR_{bifi}$$

$$\Delta MPR_{bifi} = \frac{\varphi_{bifi} * Hrear\ [kWh/m^2]}{Hpoa\ + Hrear\ [kWh/m^2]}$$



For all PV modules ΔMPR_{SOIL} = -0.5% was considered, based on the measurements of two reference cells, one soiled and one regularly cleaned.

Energy Yield: Looking beyond the Standard Test Conditions

Energy Yield Rating Label for PV modules

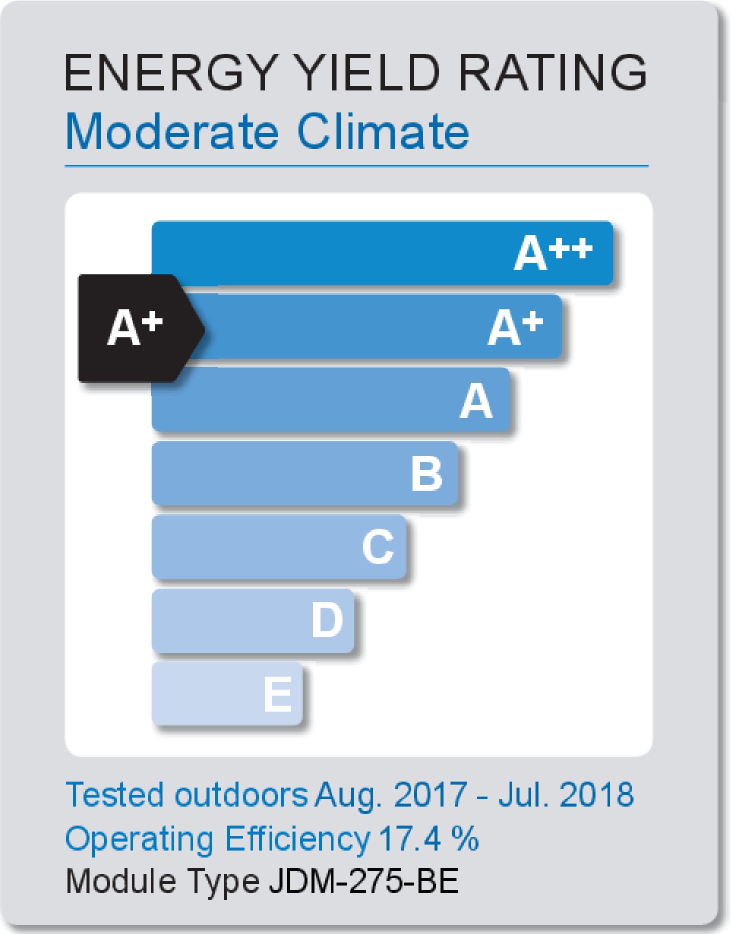
- 7 performance classes: E to A++
- 4 reference climates available:

  1. Moderate Climate, 2. Semi-Desert Climate,

  3. Desert Climate, 4. Tropical Climate
- Informative: Period of measurement and operating efficiency

Higher rating means higher energy yield per W_P STC power for a certain climate.

+ All relevant impact factors on energy yield are incorporated
+ Lowers risks, also due to performance degradation
+ High precision and lower uncertainty than simulation



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Energy Yield: Looking beyond the Standard Test Conditions

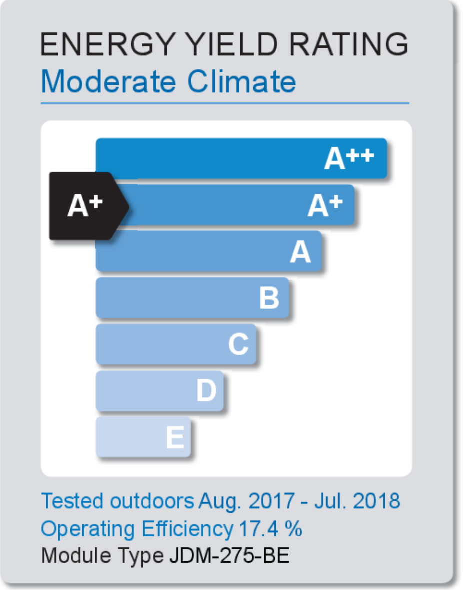
Energy Yield Rating Label for PV modules

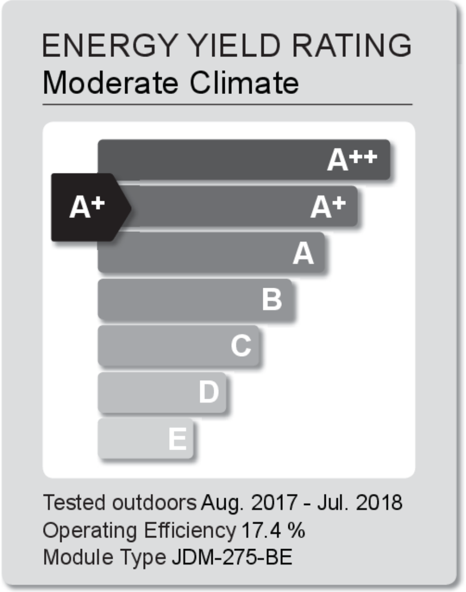
Based on Module Performance Ratio Index (MPRI):

$$MPRI = \frac{MPR_{\mathrm{Sample}}}{MPR_{\mathrm{Reference}}} - 1$$

- PV module energy yield performance is **referenced to a standard c-Si PV module** (60 cells, glass/EVA/backsheet design)
- **Monitoring basis:** One year side-by-side measurement, open-rack mounted
- **Rated output power** of test module must fulfil manufacturers specification (validated by lab measurement)

Classification	E	D	C	B	A	A+	A++
MPRI interval	< -10%	< -5%	< -3%	< -1%	-1% – 1%	> 1%	> 3%
Issued	0	0	1	2	3	2	2





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