This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 792059

goPV

Oct. 27th

PV Modules: Bifacial technology

(14:30-16:30)

GLOBAL OPTIMIZATION OF INTEGRATED PHOTOVOLTAIC SYSTEM FOR LOW ELECTRICITY COST

Daniel Valencia, TECNALIA
Paul Berthelemy, CEA INES

PV Modules: Bifacial technology

Index of the session

- 14:30 – Introduction to bifacial technology [D. Valencia - TECNALIA]
- 14:50 – Current status of bifacial technology [D.Valencia – TECNALIA]
- 15:05 – Bifacial modules developed in GOPV project: beyond the market status [Paul Berthelemy - CEA]
- 15:40 – 15 min BREAK
- 15:55 – Bifacial PV production software options [D.Valencia – TECNALIA]
- 16:05 – Bifacial PV production: practical case [D.Valencia – TECNALIA]

PV Modules: Bifacial technology

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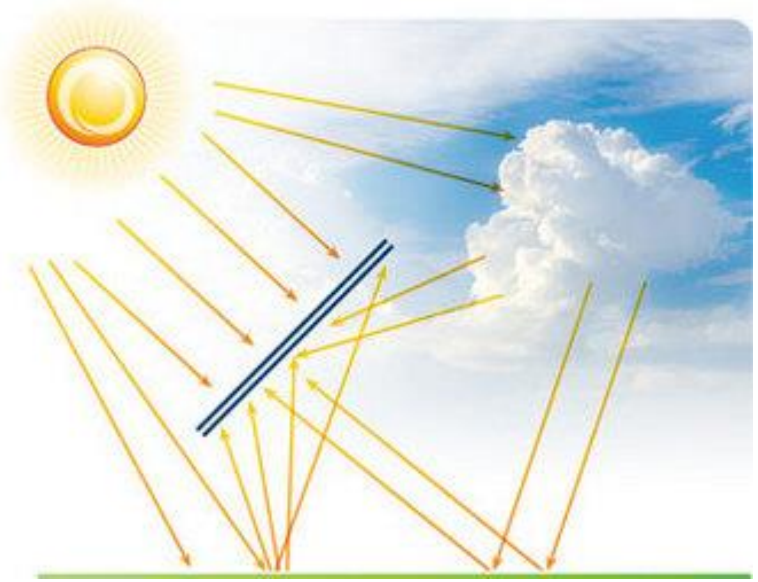
Introduction

Key Ideas

- **Monofacial PV**: **only frontside** of the photovoltaic (PV) module produces electricity using incident solar radiation. **Traditional concept**.
- **Bifacial PV**: **both frontside and backside** of the photovoltaic (PV) module produce electricity from solar incident radiation.
- Compared to monofacial, **bifacial** PV technology have an **additional electricity production** thanks to extra radiation received at the backside.
- The **cost of bifacial** PV modules are **slightly higher**. Also some additional expenses are required by bifacial PV plant.
- The **extra production normally compensates the extra cost**. However, every case should be analyzed in detail.



Understanding energy gain in bifacial PV systems. PV-Tech.org. Sep 2017

Introduction

tecnalia Inspiring Business

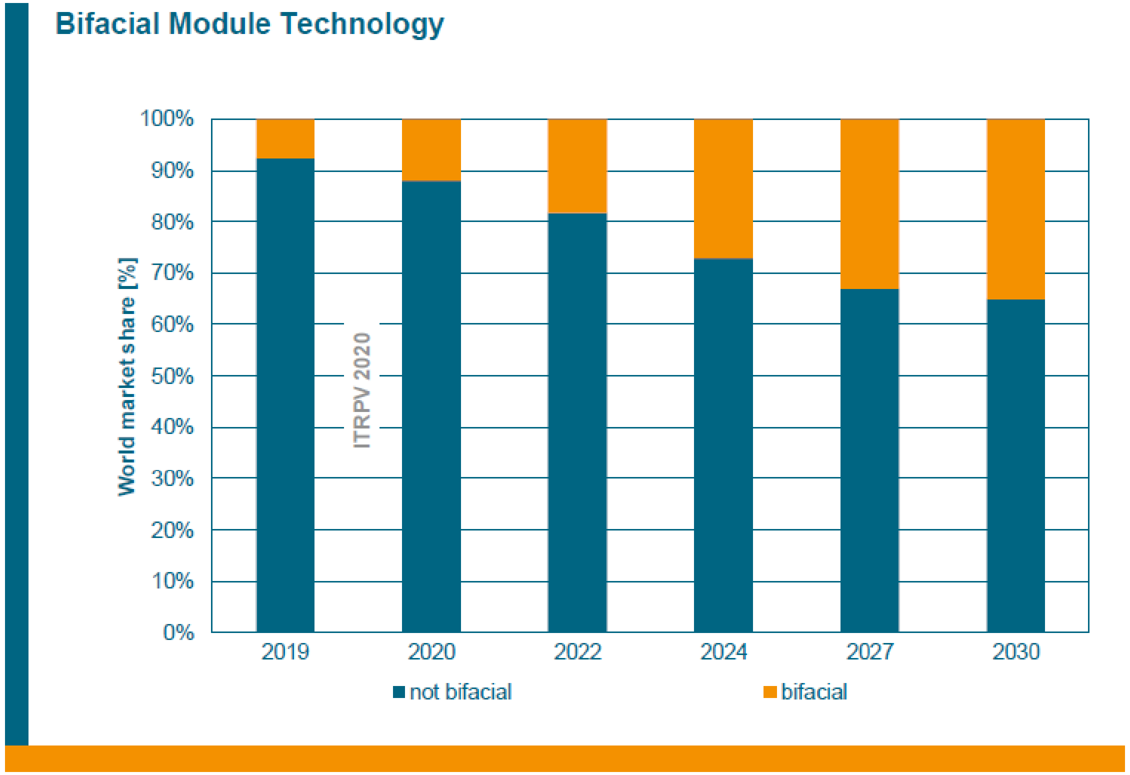
Key Ideas

"**Bifacial solar modules**, which generate power on the front and back, is the technology that **will help bring down LCOEs of solar power plants the most in the short-run**. This results in power gains between 5% and up to 30%, depending on the solar cell technology used, location, and system design."

$$\text{LCOE} = \frac{Installation+operation\ cost}{Total\ energy\ produced}$$

SolarPower Europe

Global Market Outlook For Solar Power / 2020 - 2024

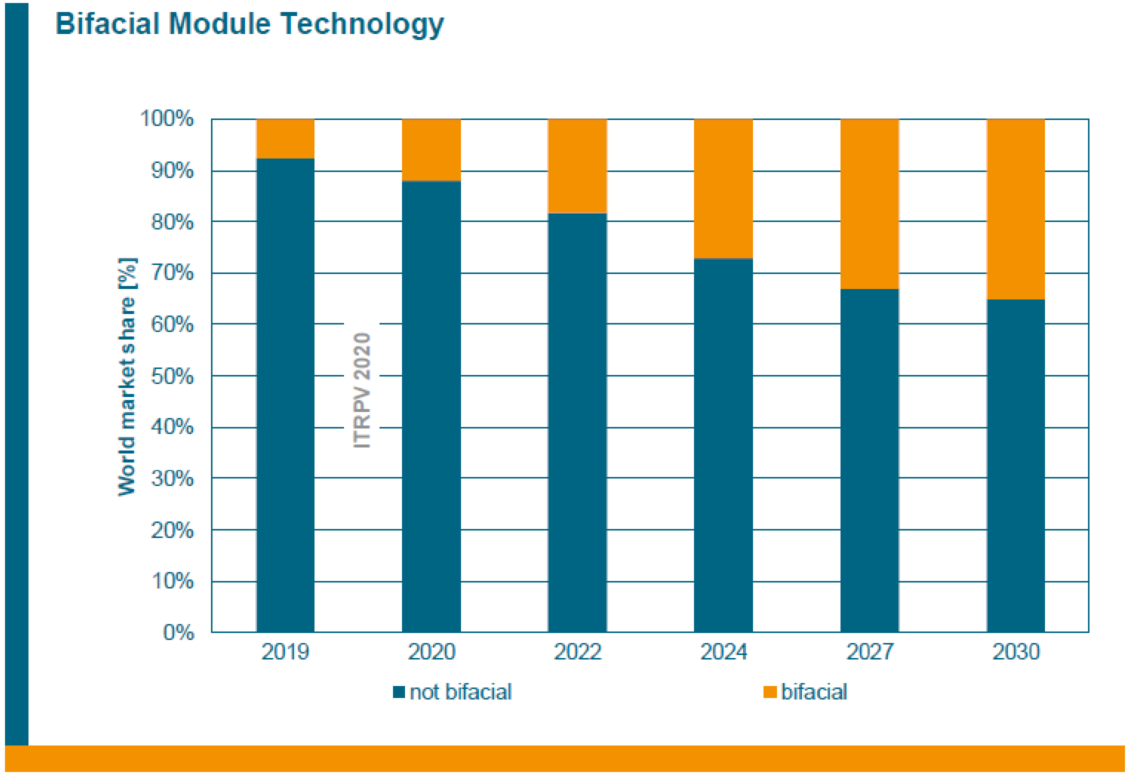


ITRPV 2020 Report. Oct 2020

Introduction

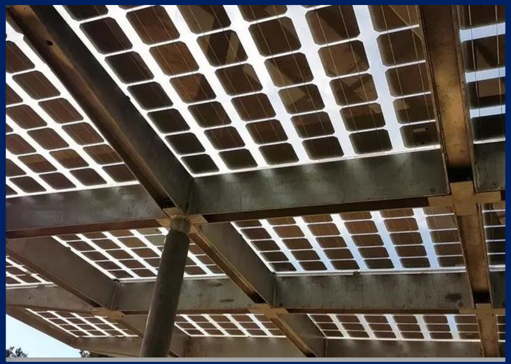
Key Ideas

- Since about 2012, **interest** in **bifacial** PV has been constantly **increasing**
- Some of the new solar cell technologies, which are currently being implemented in **industrial production**, allow a comparatively simple **adaptation to a bifacial layout**
- General trend **towards glass/glass** modules with superior reliability
- A major issue is the **uncertainty regarding the additional 'bifacial' yield**, which is due to the more complicated irradiation conditions and the power rating of bifacial modules.
- **Standardized measurement** conditions for bifacial modules published in 2019: IEC TS 60904-1-2
- Starting from today's 12% bifacial market share the ITRPV roadmap 2020 predicts an **increase** to **around 33% by 2027**.



ITRPV 2020 Report. Oct 2020

Introduction



Utility scale

- LCOE reduction due to backside production
- Fixed systems or 1-axis tracking

PV Integration

- New applications and products
- More production per m2 with low cost increase

Combined uses: Agro-PV and Floating PV

- Better use of soil for PV and agriculture
- More production in floating PV

Images from Soltec, Onyx Solar, Next2Sun

Introduction

New parameters that impact on bifacial extra production

- Bifacial ratio:
  - **Irradiation ratio received by the backside of the modules compared to frontside** of the module during one period time (hourly, monthly, yearly …).
  - Depends on module installation parameters, ground albedo (i.e. ground reflection) and irradiation conditions (direct or diffuse).

$$Bifacial\ Ratio = \frac{G_{back}}{G_{front}}$$

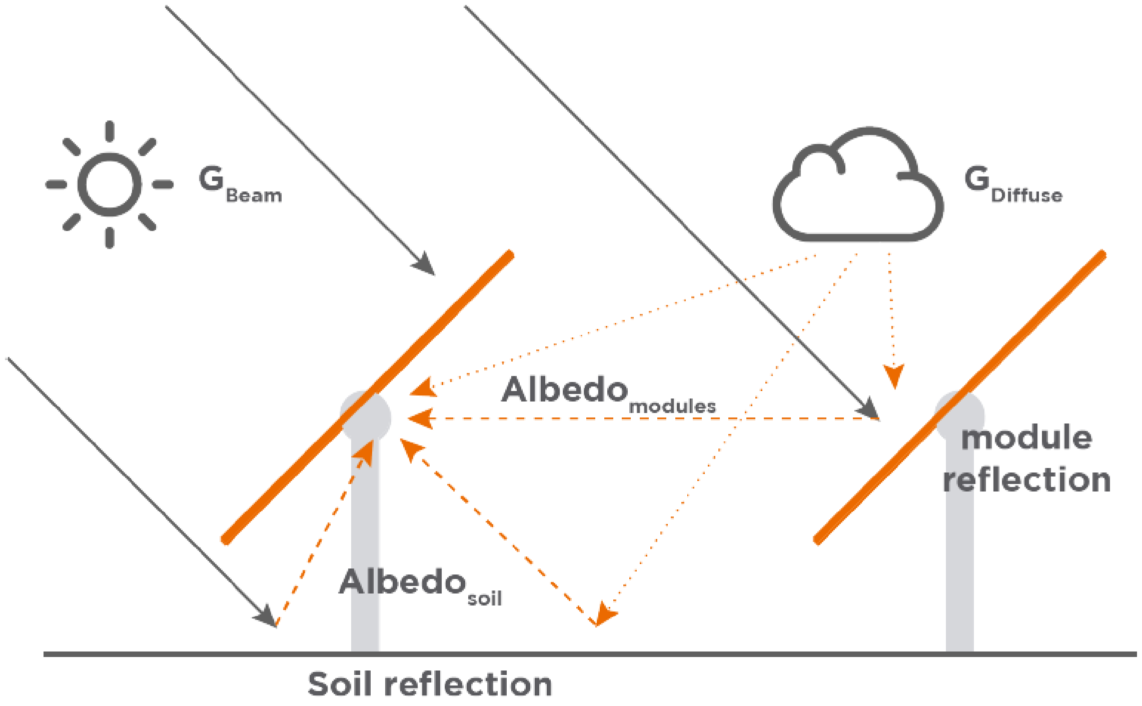
- Module bifaciality:
  - The backside of the bifacial module is not as efficient as frontside.
  - Is the ratio of **backside module peak power compared to the front side**.
  - Depends on mainly PV technology. It is normally indicated in module datasheet.

$$Module\ Bifaciality = \frac{P_{mpp\ back}}{P_{mpp\ front}}$$

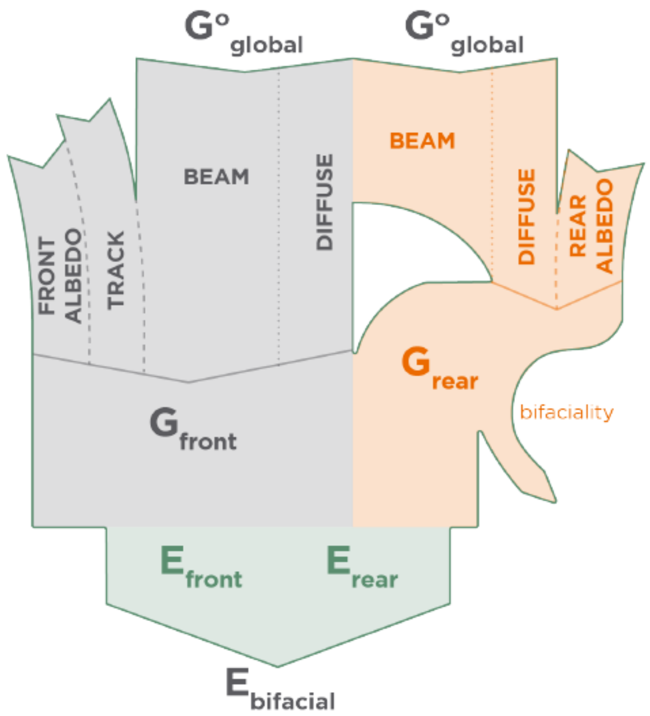
- Bifacial Gain:
  - **Energy gain increase due to backside electricity production** compared to the front side

$$Bifacial\ Gain = \frac{E_{back}}{E_{front}} = Bifacial\ Ratio\ * Bifaciality$$

New parameters that impact on bifacial extra production



$$G_{rear} = G_{diffuse} + G_{reflected}\,(albedo)$$



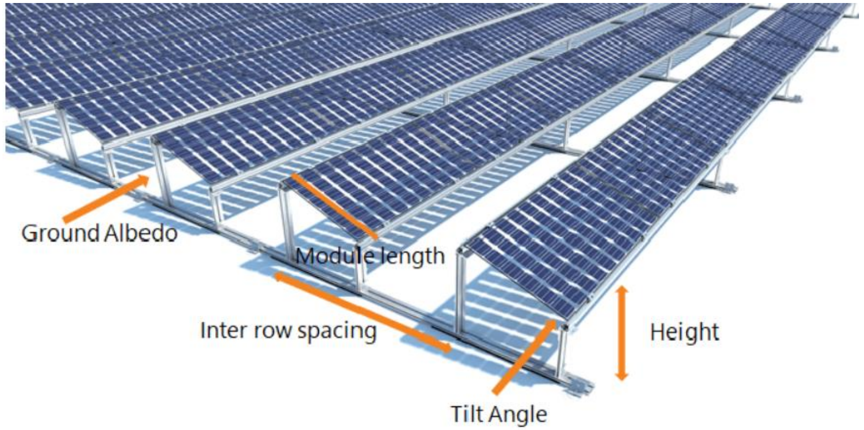
Bifacial PV Tracking: The Simulation and Optimization of Yield Gain. Soltec webinar. Apr 2018

Introduction

Bifacial Ratio (BR) – Irradiation at the backside

$$Bifacial\ Ratio = \frac{G_{back}}{G_{front}}$$

- **Albedo** is the diffuse radiation reflected by the soil out of the total solar radiation. Normally goes from 10% to 40%. Higher albedo means higher BR. It strongly impacts the bifacial ratio with nearly linear behavior.
- Row-to-Row spacing (aka pitch) is the distance between rows. BR increases when this distance increase. It is related with GCR (Ground Coverage Ratio).
- Clearance height is the distance between the bottom of the modules and the ground. Higher clearance means higher BR.
- Tilt of the modules also affects the BR value.



Nadweh, Safwan & Ghazaly, Nouby & Hadi, Husam. (2024). Using Grey Wolf Optimization Algorithm and Whale Optimization Algorithm for Optimal Sizing of Grid-Connected Bifacial PV Systems. 5. 733-745. 10.18196/jrc.v5i3.21777.

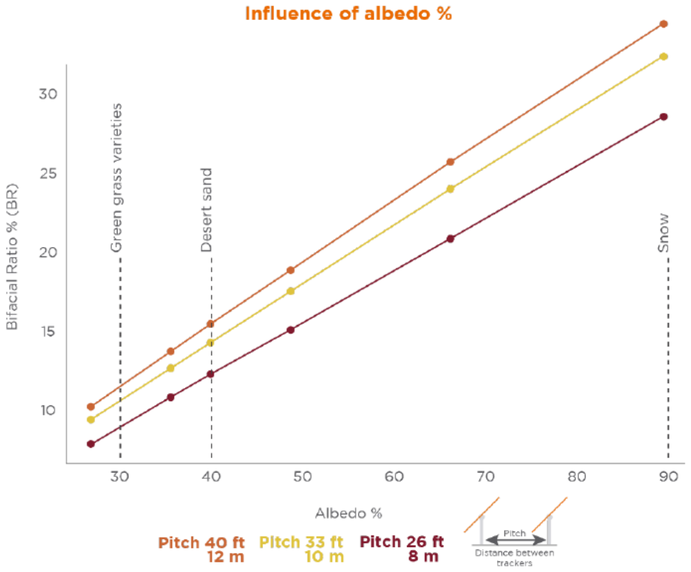
Material	Reflectance*(R)	Grear at 1000Wm-2 front
Asphalt	0.1	70 Wm-2
Light soil	0.21	130 Wm-2
Concrete	0.28	170 Wm-2
Beige built-up roofing	0.43	250 Wm-2
White EPDM roofing	0.8	430 Wm-2

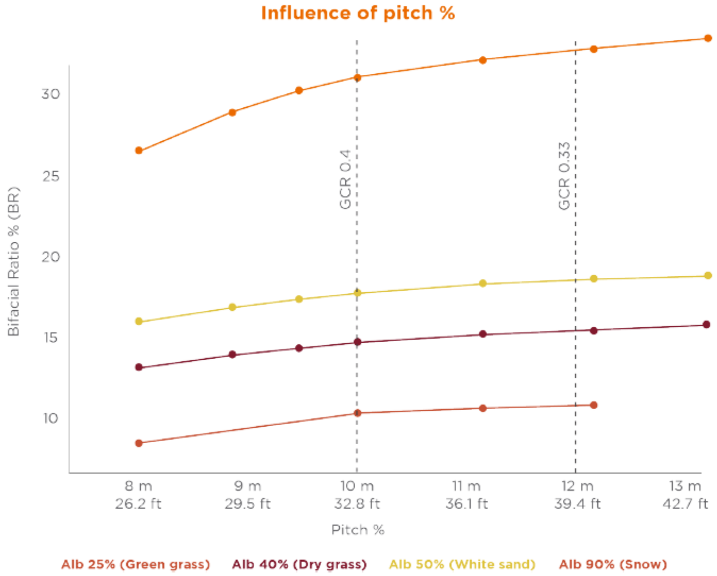
Deline et al., IEEE PVSC 2016; Deline et al., IEEE JPV (submitted) (National Renewable Energy Laboratory)

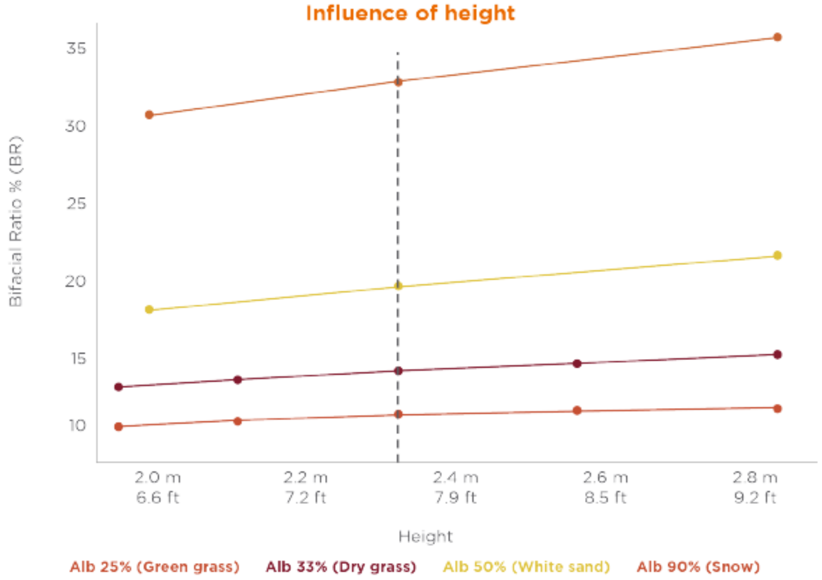
Introduction

Bifacial Ratio (BR) – Irradiation at the backside

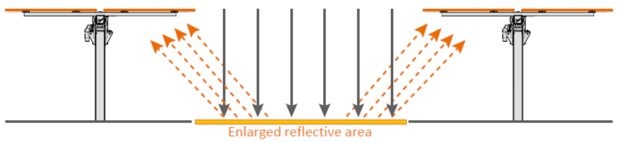
$$Bifacial\ Ratio = \frac{G_{back}}{G_{front}}$$







Wider Pitch = Longer Tracking + Better Bifacial Gain



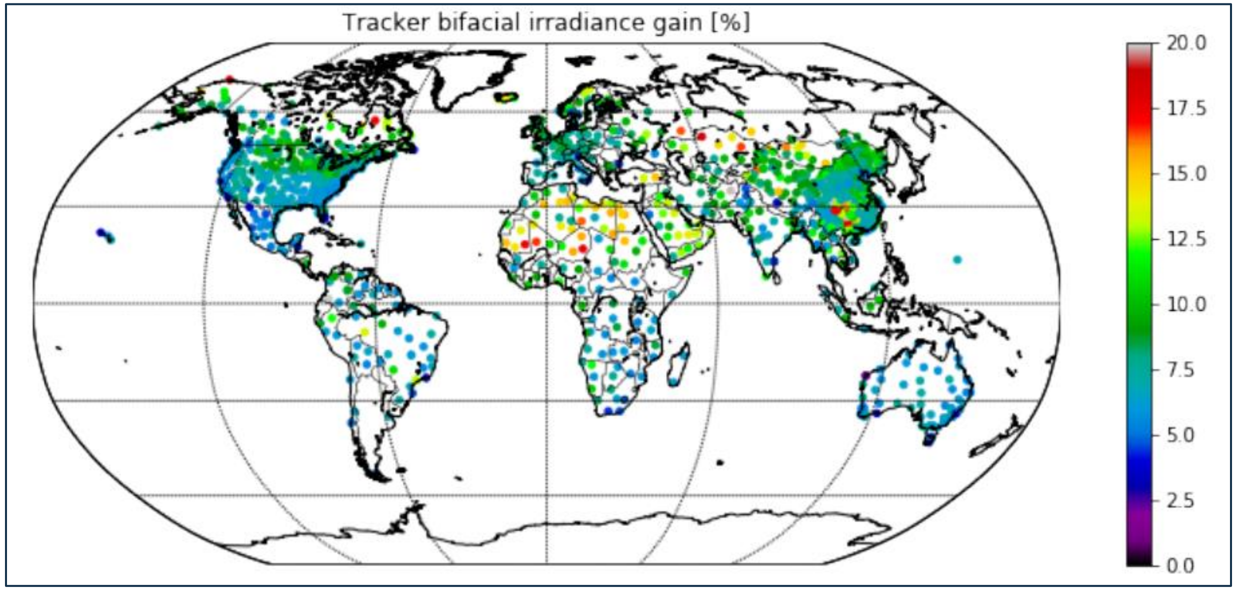
Bifacial PV Tracking: The Simulation and Optimization of Yield Gain. Soltec webinar. Apr 2018

Introduction

Bifacial Ratio (BR) – Irradiation at the backside

$$Bifacial\ Ratio = \frac{G_{back}}{G_{front}}$$

- Global expected Bifacial Ratio (Modeled Grear /Gfront)
- For 1-axis-tracked 2-up portrait systems over natural ground cover. Assumed geometry: GCR = 0.35, h = 3 m.

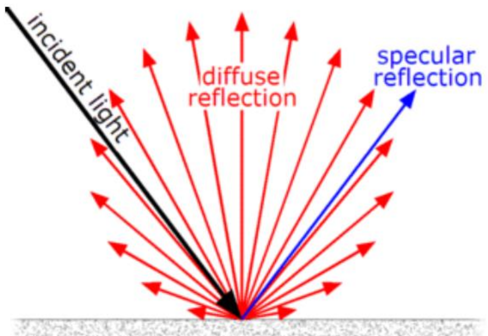


Pelaez et al. Model and Validation of Single-axis tracking with bifacial PV. IEEE Journal of Photovoltaics, vol.9, no.3, May 2019.

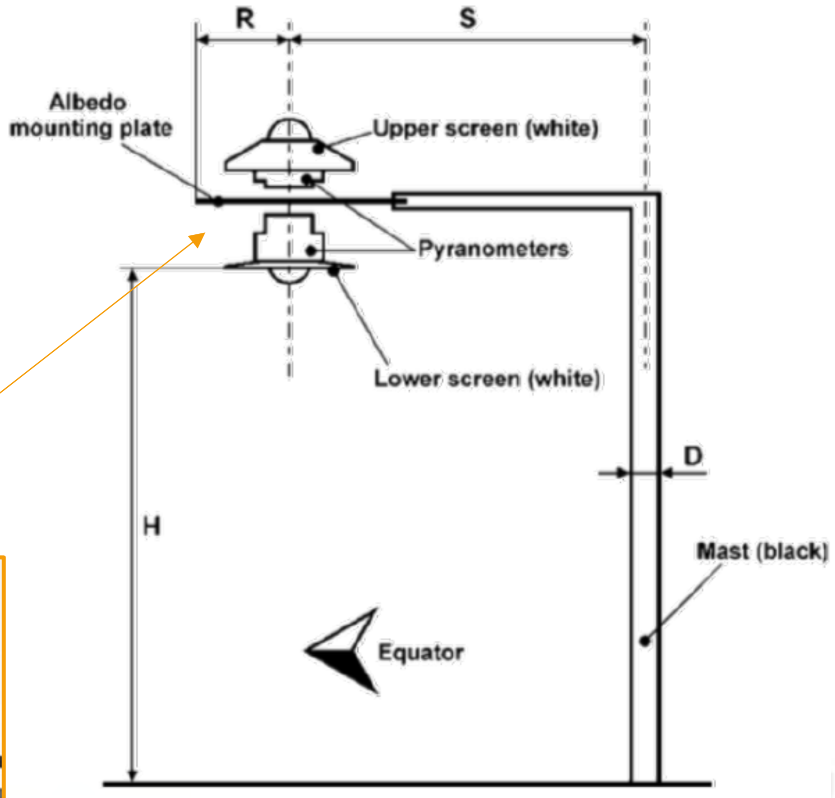
Introduction

Albedo

- The albedo of a surface is the fraction of the incident sunlight that the surface reflects.
- Important measure it. Necessary for the characterization of the results.
- Albedo may change from season to season: snow during the winter or different vegetation on the ground.
- Method for measuring albedo described in ASTM E1918-16 “Standard Test method for measuring solar reflectance of horizontal and low-sloped surfaces in the field”.
- Measurements are not even constant during the day.
- Constant values (average from measurements) are normally considered for calculations. Monthly values can be considered as well.



Source: GIS stackexchange



Albedo measurement construction

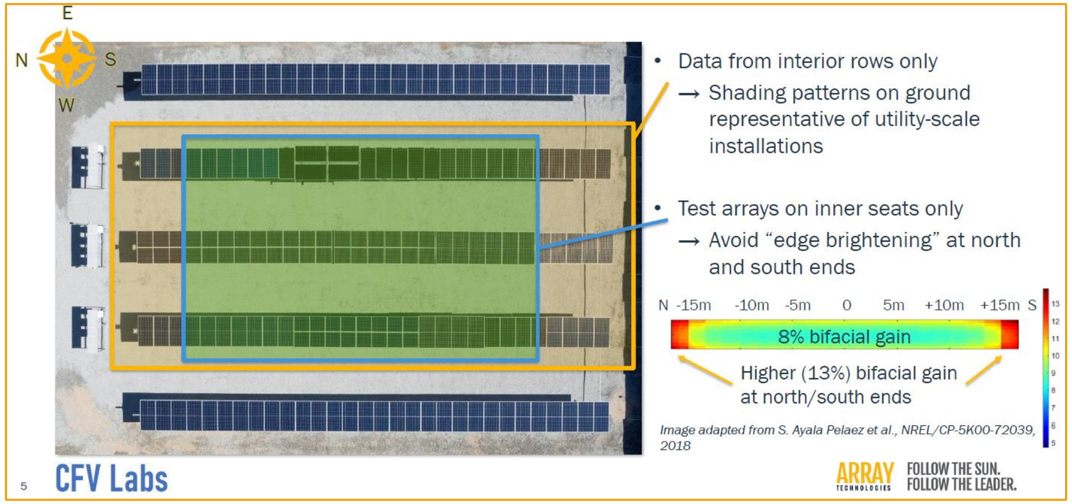
source: Kipp & Zonen

Field Testing Meets Modeling: Validated Data on Bifacial Solar Performance. Kyumin Lee, Array Technologies. BiFi July 2020.

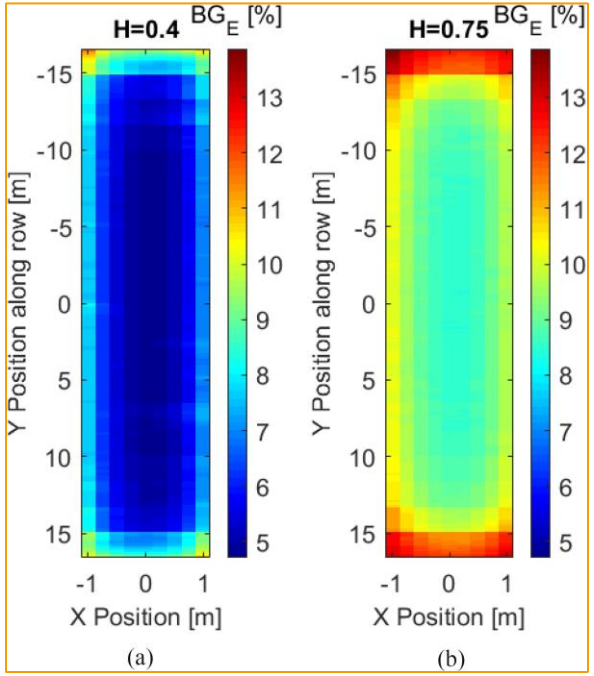
Introduction

Bifacial Ratio (BR) – Edge effects

- **Bifacial Ratio is higher near the edge of the PV panel rows** i.e. the panels close to the edge will receive more radiation at the backside.
- This will create mismatch in the electrical circuit
- Normally, due to electrical connections, the final PV production is determined by bifacial gain at the center of the row



Example of bifacial gain study where the main bifacial gain is analyzed in the center of the central rows to avoid edge effects.



Yearly cumulative distribution of BGE across the center row of a 20-module × 7-row single-axis-tracking array for (a) H = 0.4 and (b) H = 0.75. BGE is significantly higher (13.9%) at the edges of the row. Radiance simulation. GCR = 0.35, Albuquerque climate.

Pelaez et al. Model and Validation of Single-axis tracking with bifacial PV. IEEE Journal of Photovoltaics, vol.9, no.3, May 2019.

Field Testing Meets Modeling: Validated Data on Bifacial Solar Performance. Kyumin Lee, Array Technologies. BiFi July 2020.

Introduction

Module Bifaciality

$$Module\ Bifaciality = \frac{P_{mpp\ back}}{P_{mpp\ front}}$$

- **Module bifaciality is strongly related with module technology:**
- **PERC**: Most common. Monofacial manufacturing lines easy to transform to bifacial. Lower **bifaciality (70-80%).** Usually p-type cells. Probably the cheapest bifacial option.
- **PERT**: Quite common but less than PERC. Manufacturing lines transformation more complex than PERC, but still relatively easy. Good **bifaciality (80-90%).** Usually n-type cells. **Relatively cheap but more expensive than PERC**.
- **HJT/SHJ**: High efficiency, high **bifaciality (about 95%)**. Cell fabrication is very different from that of homojunction c-Si cells. Low temperature coefficient (<0.3%/ºC). Normally more expensive than PERC/PERT.
- **IBC**: promising option to obtain high-efficiency solar cells. The contacts are solely on the rear side of the solar cell. This approach requires other fabrication procedures. Still in its infancy.

Cell concept	Bifaciality factor	Si base material	Junction and BSF doping method	Contacts	(Front) Efficiency potential	Industry
Heterojunction	>0.95	n-mono	a-Si:H p- and n-type doped	TCO / Ag TCO / Cu plated	22–25%	3Sun, Hanergy, Hevel, Jinergy, Panasonic, Sunpreme, etc.
PERT	>0.90	n-mono p-mono p-multi	B and P tube diffusion n-doped poly-Si rear side possible	Ag and Ag/Al printed	21–23%	Adani, Jinko, Jolywood, LG, Linyang, REC, Trina, Yingli, etc.
PERC+	>70%	p-mono p- multi n-mono	B and P tube diffusion, local Al BSF	Ag and Al printed	21–23%	Eging, JA Solar, Jinko, Longi, NSP, SolarWorld, Trina, etc.
IBC	>70%	n-mono	B and P tube diffusion APCVD doped oxides	Ag and Ag/Al printed	22–25%	Valoe

State-of-the-art bifacial module technology. PVTech September 2018

Introduction

Bifacial Gain

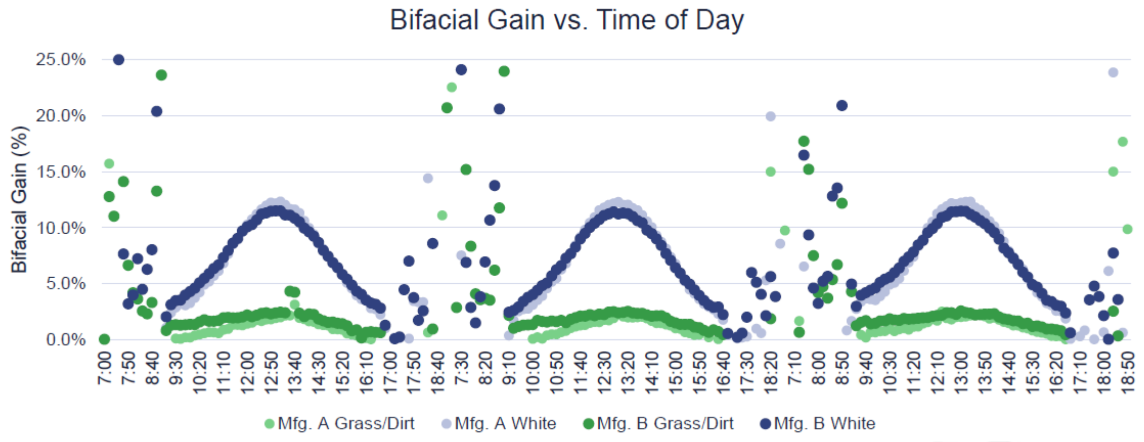
$$Bifacial\ Gain = \frac{E_{back}}{E_{front}} = Bifacial\ Ratio\ * Bifaciality$$

- Bifacial gain is the energy production increased due to backside module extra production
- **Common bifacial gains are in the range of 5% to 10% (albedo between 15-30%).** This means that bifacial systems produces between 5% to 10% more energy than equivalent monofacial installation.
- Higher bifacial gains can be obtained with small prototypes because the backside of the modules have a “better view” of the ground. However the bifacial gain decrease for real PV plants with several and long module rows.

Total bifacial gains since inception, per manufacturer

	Bifacial Gain Grass	Bifacial Gain White
Mfr. A	5.57%	8.28%
Mfr. B	6.57%	8.78%
Mfr. C	7.46%	11.44%
Mfr. D	7.23%	10.73%

Data normalized to pre-light soak flash



Example of bifacial gain using different PV modules (A, B, C, D) with two albedo conditions

Bifacial Bake-off: Comparing Technologies and Manufacturers. Jenya Meydbray, PVEL. BiFi July 2020.

Introduction

Other bifacial technical considerations

- The **extra backside radiation increase the current**, similar to an increase of radiation at the front.
- **Higher currents should be considered for bifacial** systems, specially when selecting the inverter.
- The peak power of bifacial systems will be higher, so the AC power (inverters) should be higher as well.
- The **traditional DC/AC power ratio should be close to 1 instead of 1.2**. Specific calculations of clipping losses should be performed.
- Structural systems backside shadowing should be avoided → **specific structural systems**
- **Junction boxes should be smaller** in order to avoid shadowing of backside.

PV Modules: Bifacial technology

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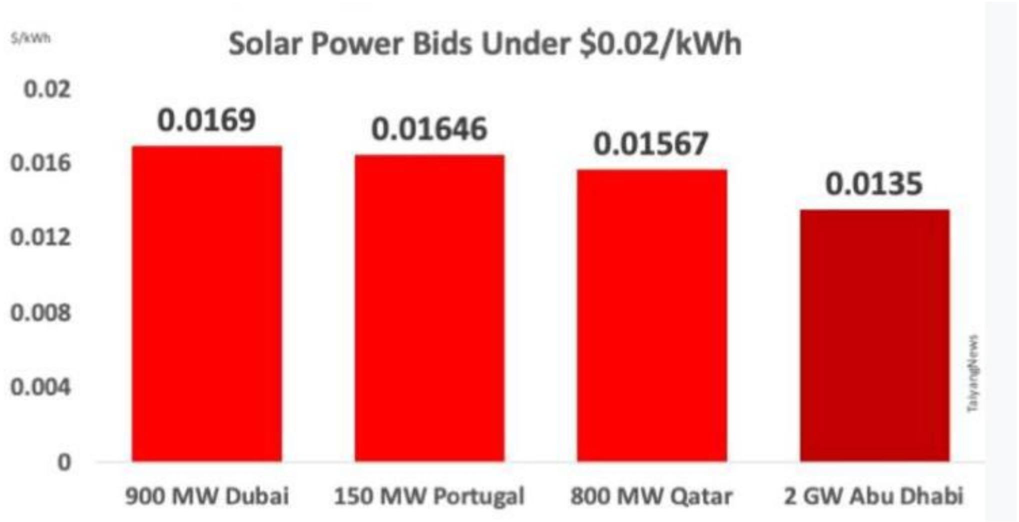
Current status

General PV status

- Total installed PV systems → 650GW
- Expected installation in 2020 are 105 GW (already reduced with COVID)
- 1TW PV to come in 2022/23 ; 30 70TW expected in 2050
- Module prices are already below 0.2 $/ Wp
- LCOEs below 2 c$/kWh possible (lowest 1.35 c$/kWh)
- Probably LCOEs at 1USct/kWh to come soon with bifacial HSAT
- Standard PERC coming to efficiency limits of below 23%
- Cost down is now realized by larger wafer sizes (M10/M12)
- N-type cell concepts are gaining importance
- “60 cells modules” are reaching 400Wp
- “72 cells modules” are exceeding 500Wp



Remarks: Bifacial PV: Chances and Challenges. Radovan Kopecek, ISC Konstanz. BiFi 2020.

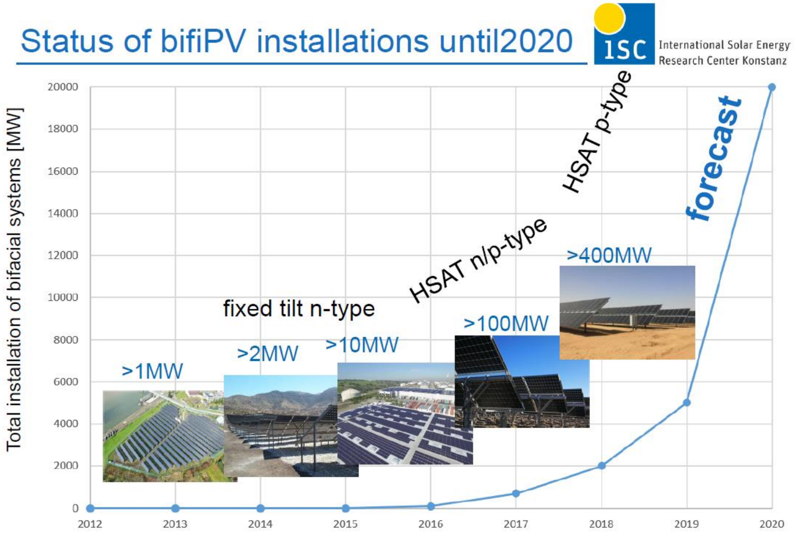
Current status

General bifacial status

- Bifacial technology offers an increase of energy yield at low additional costs
- Bifacial PERC technology is at the moment dominating the market; n-type and Ga doped PERCs are coming
- Better module testing and reliable energy yield simulations required
- With bifacial HSAT technology we will reach soon bids at and below US$0.01/kWh in MENA region and later also in e.g. in Chile and US*

First bid below $0.02/kWh was bifacial HSAT from EDF/Masdar ($0.0179/kWh) in 2017 in Saudi Arabia

>> rejected also because bifacial PV was not bankable at that time

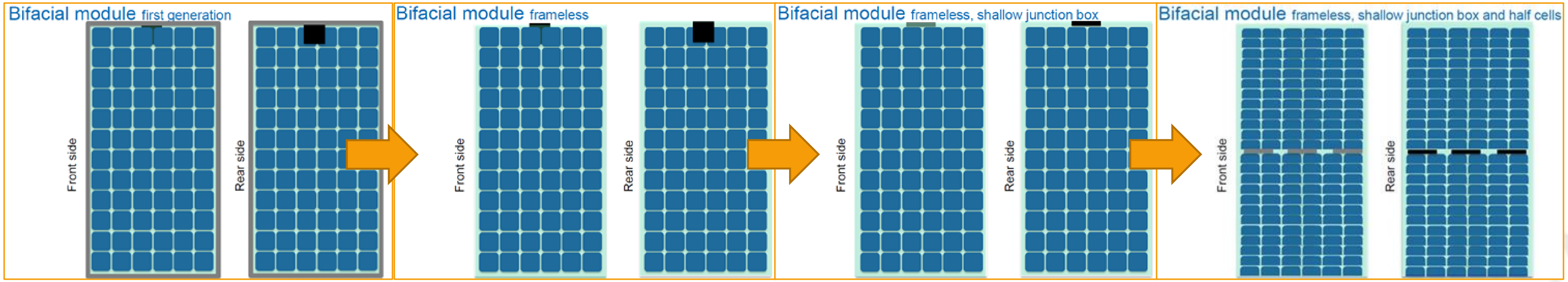


Remarks: Bifacial PV: Chances and Challenges. Radovan Kopecek, ISC Konstanz. BiFi 2020.

Current status

Module variations

- First generation was with traditional aluminium frame and tradition junction box
- Frameless: avoid shadowing at the backside of the cells close to the edges → it requires glass-glass instead of glass-backsheet
- Smaller junction box to avoid shadowing at the backside of solar cells
- Half-cells for better performance



Remarks: Bifacial PV: Chances and Challenges. Radovan Kopecek, ISC Konstanz. BiFi 2020.

Current status

Module variations: frameless glass-glass vs framed glass-backsheet

- Frameless glass-glass:
  - Better backside performance as there are no frame that may shadow cells near the edges
  - Better mechanical performance
  - Glass-glass configuration cause lower degradation rates and module guarantee can be extended
- Framed glass-backsheet:
  - Lower weight
  - Less breakages during transportation and installation
  - Installation can be made with traditional clips. Can save labor cost.
- There is not a clear winner. Some manufacturers offer both options.
- Nevertheless some manufacturers recommend glass-glass only for high mechanical loads and/or high humidity applications.
- Glass-glass + frame also possible.
- Glass-Transparent backsheet without frame not possible due to mechanical requirements.

Type	Bifacial with TB	Bifacial with dual glass
Recommended application area	1. Most on-ground PV station; 2. High labor cost area, like EU, Japan, Australia (can effective receive labor cost); 3. Commercial roof-top project	1. Most on-ground PV station; 2. In floating projects as well as super high wind speed area, bifacial with dual glass is a better choice

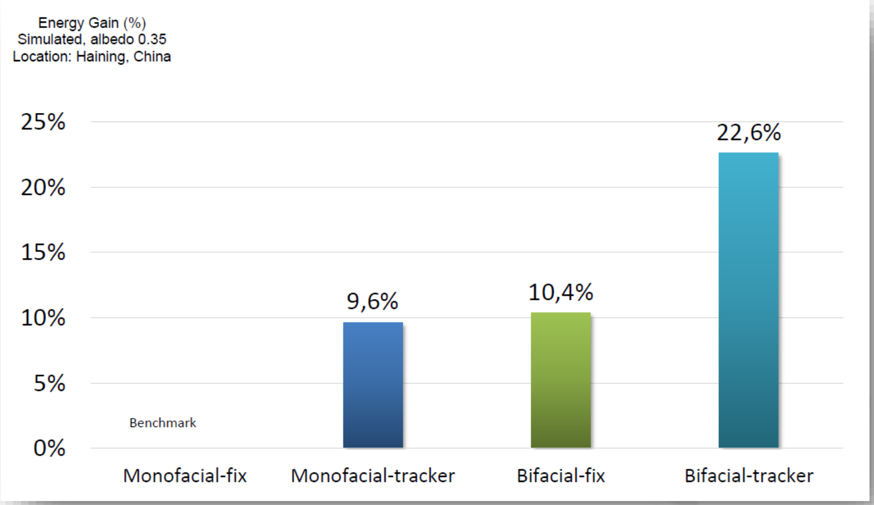
Innovation in bifacial technology for P and N-type modules to help boost efficiency and power density. Roman Giehl, Jinko Solar. BiFi July 2020.

Current status

Fixed installations vs 1-axis tracking

- First bifacial installations were fixed.
- However Single-axis tracking (aka HSAT – Horizontal Single Axis Traking) is a cost-effective deployment strategy for large-scale ground-mount photovoltaic systems in regions with high direct-normal irradiance.
- **Bifacial modules in 1-axis-tracking systems boost energy yield by 4%–15%** depending on module type and ground albedo, with a global average of 9%. This benefit is **in addition to the 15%–25% energy gain already afforded by single-axis tracking** relative to fixed-tilt deployments.
- Currently, **lower LCOE values are being obtained with bifacial+HSAT** (< 0.02 $/kWh)

Monofacial Fixed → + 10-25% → Monofacial Tracking → + 4-15% → Bifacial Tracking



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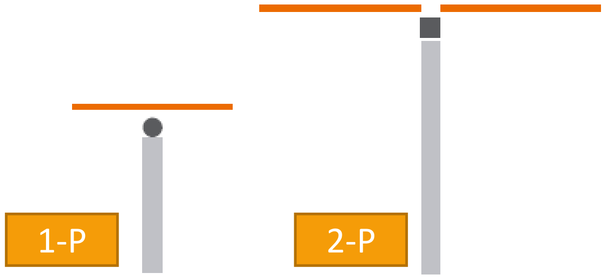
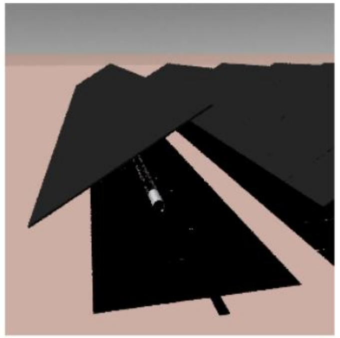
Innovation in bifacial technology for P and N-type modules to help boost efficiency and power density. Roman Giehl, Jinko Solar. BiFi July 2020.

Current status

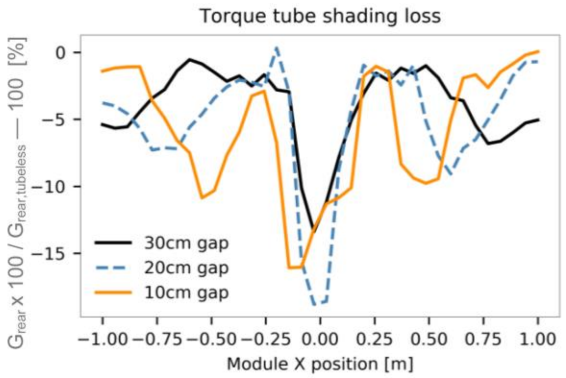
Trackers: 1P vs 2P

- Most common tracker geometries: 1 module in portrait or 2 modules in portrait (1-P or 2-P)
- Currently it is not clear which is the best option: trackers manufacturers are providing their studies
- Topics under discussion:
    - Bifacial Gain
    - Operating temperature of modules
    - Flexibility in design
    - Possible backside shadowing in 1-P due to torque-tube
    - Operation and Maintenance (O&M) differences





(a)

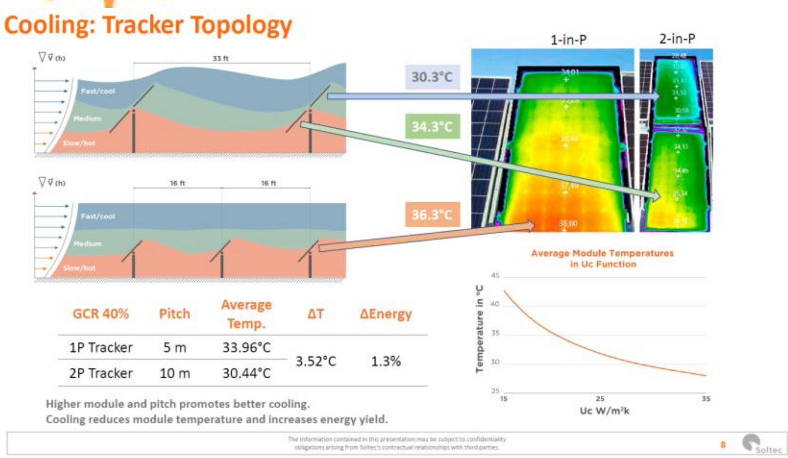


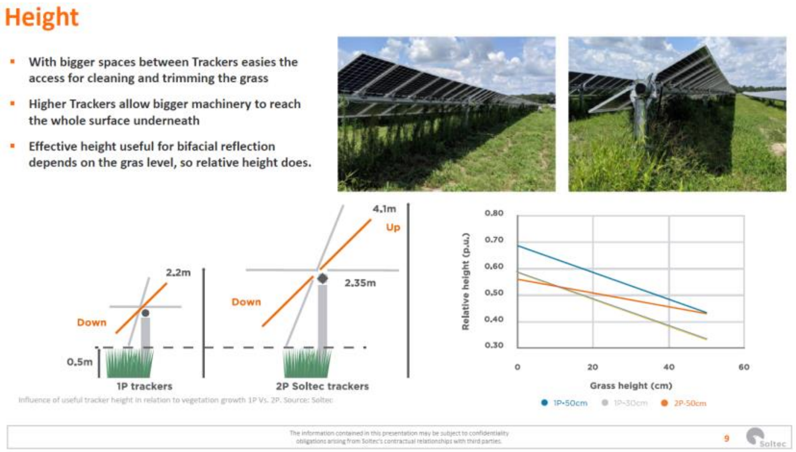
(b)

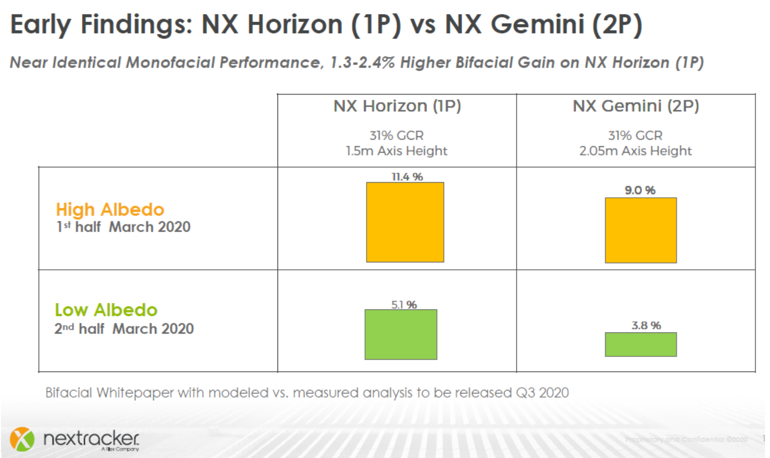
(a) RADIANCE image showing torque tube behind a module's row and
(b) (b) Grear across the module averaged over a sunny day when torque tube is present, compared to Grear for the module without torque tube (tubeless).

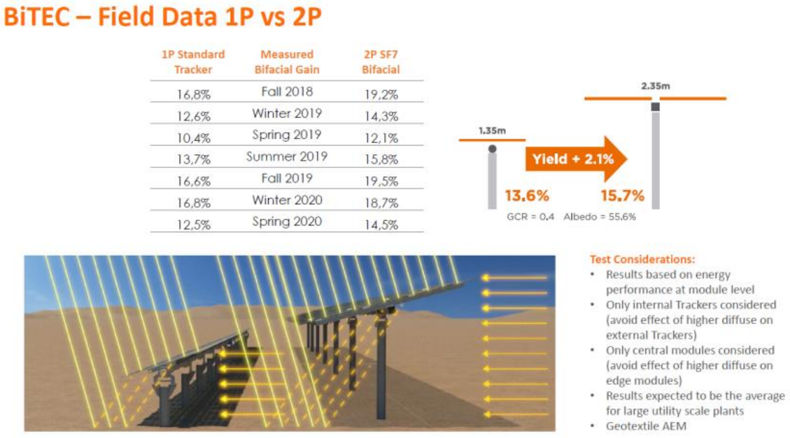
Pelaez et al. Model and Validation of Single Axis Tracking with Bifacial PV. IEEE Journal of Photovoltaics, vol. 9, no. 3, May 2019.

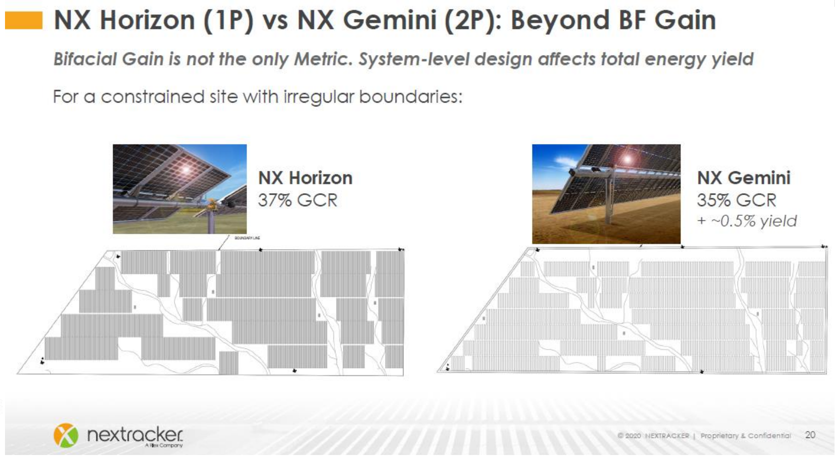
Current status











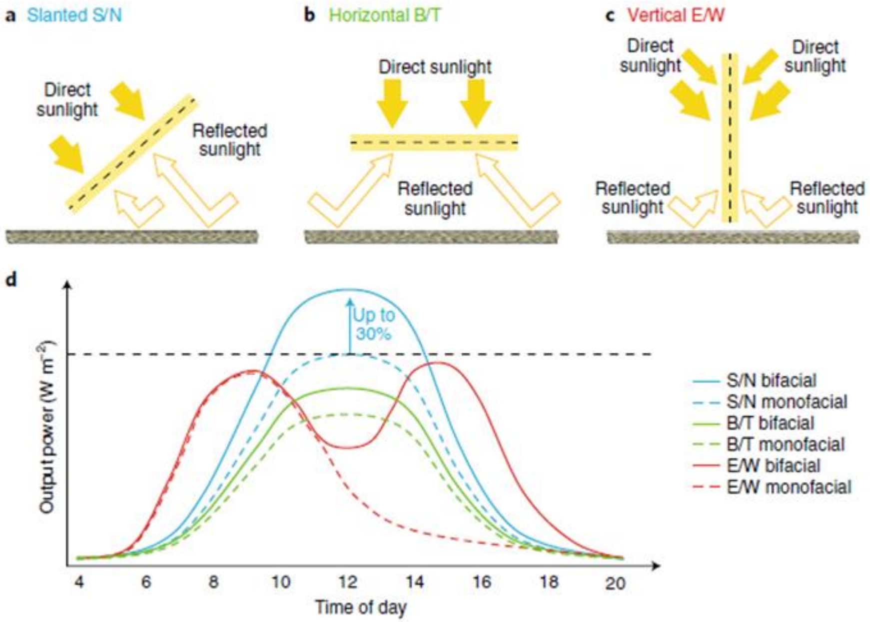
Bifacial PV Tracking: The Simulation and Optimization of Yield Gain. Soltec webinar. Apr 2018

Optimizing Plant Performance with Smart Solar Trackers & Bifacial Technology. Melissa Cooke, Nextracker. BiFi July 2020.

Current status

Vertical configuration of bifacial

- Bifacial modules open a new configuration: vertical modules facing East-West
- Normally PV production is lower than optimal configuration
- But the production profile might be interesting:
    - Peak production during the morning and in the afternoon
    - Depending on hourly energy prices, this profile production may worth
- New applications also for in Agrivoltaic (Agri-PV)



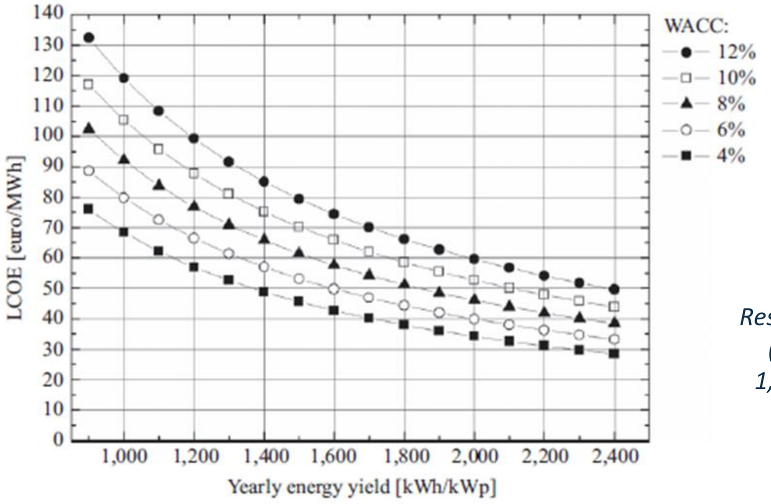
Towards large-scale deployment of bifacial photovoltaics. Nature energy vol 3 443-446, June 2018
Images from Next2Sun

Current status

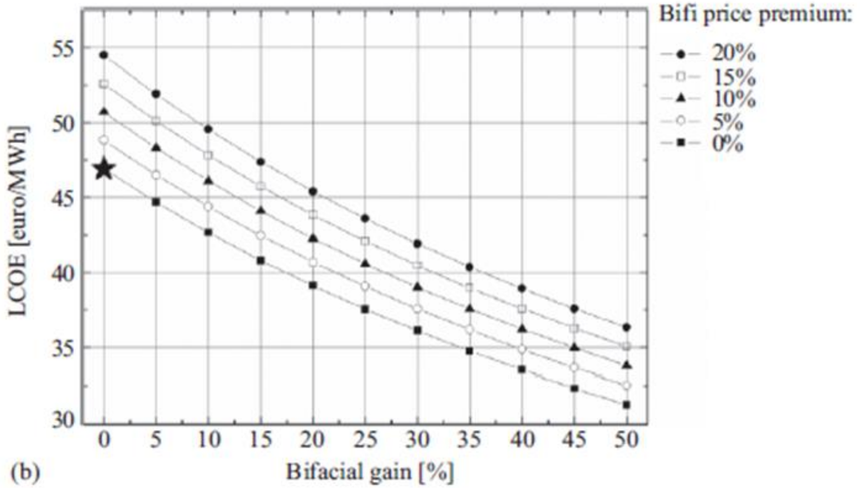
Bankability

- The uncertainty of PV production of bifacial systems means more investment risk.
- More investment risk implies higher interest rates.
- Weighted Average Capital Cost (WACC) is related to the interest rate and is crucial for PV projects development.
- The more bifacial installations, projects and studies there are, the less bifacial production uncertainty.
- **Simulation tools are a key part of the bifacial technology deployment.**

The LCOE calculations for a monofacial PV system, in dependence on the specific yield (kWh/m2) for a WACC ranging from 4% (e.g. best cases in Germany) to 12% (e.g. worst cases in Greece)



Results of LCOE calculations as in (a) but for a location featuring 1,750 kWh/kWp for monofacial systems (e.g. south of Spain).



Bifacial Photovoltaics: Technology, applications and economics. 2018

Conclusions

- **Bifacial** is a **mature technology already in the market** with reliable products. However there are **still opportunities to improve** different key aspects in the cell, modules and system level.
- The **lowest LCOE** nowadays are with bifacial modules + 1-axis tracking systems.
- The **market share** of bifacial modules is expected to **increase** significantly in the following years.
- **New parameters** should be understood and considered **for bifacial systems design**.
- **Every utility PV project should**, at least, **evaluate the bifacial PV option**.
- **Bifacial Ratio (i.e. irradiation at backside) is difficult to foreseen**. Specific software tools have been developed.
- **Interest rates** are directly related with **bifacial performance uncertainty**. It is **decreasing due to several published studies** focused on software validation and real measurements.

GLOBAL OPTIMIZATION OF INTEGRATED PHOTOVOLTAIC SYSTEM FOR LOW ELECTRICITY COST

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 792059

Thank you for your attention!

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PV Modules: Bifacial technology

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- 14:30 – Introduction to bifacial technology [D. Valencia - TECNALIA]
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- **15:05 – Bifacial modules developed in GOPV project: beyond the market status [Paul Berthelemy - CEA]**
- 15:40 – 15 min BREAK
- 15:55 – Bifacial PV production software options [D.Valencia – TECNALIA]
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PV Modules: Bifacial technology

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Bifacial PV production

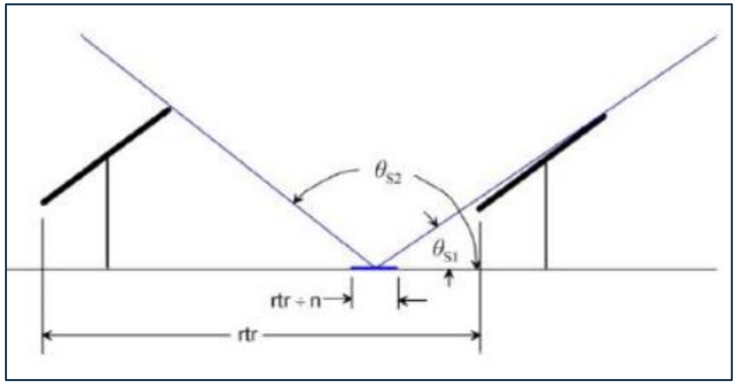
Model approaches

- Objective: **calculate the radiation received at the module backside (i.e. Bifacial Ratio)**

$$Bifacial\ Ratio = \frac{G_{back}}{G_{front}}$$

- State-of-the-Art: View factor models vs Ray tracing models

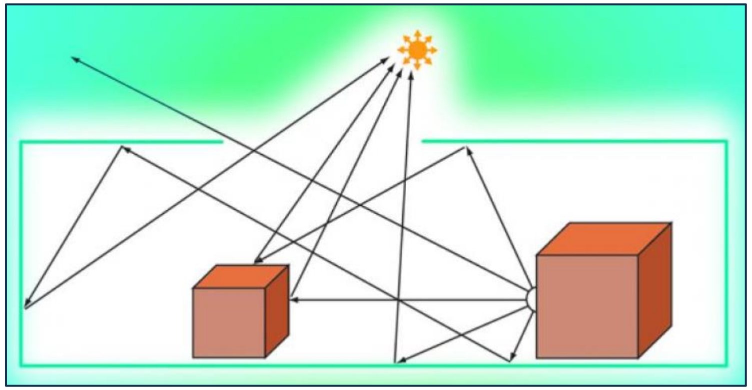
VIEW FACTOR



A Practical Irradiance Model for Bifacial PV Modules, Marion et al.

- 2D model. Geometrical/analytical description
- No differences between modules in the middle and on the edge of a row
- No details can be included like trackers torque-tube or transparency between cells
- Fast computation
- Available in commercial software (e.g. PVSyst and SAM)

RAY TRACING



Chaudhuri, A. (2019). Shape Deformation Models. https://doi.org/10.1007/978-3-319-08234-9_358-1

- 3D model. The reflections of a set of rays are calculated
- More detailed analysis, with differences between all the modules and cells
- Slow/ Very slow computation (depending on detail and PV installation size)
- Not available in most common commercial SWs

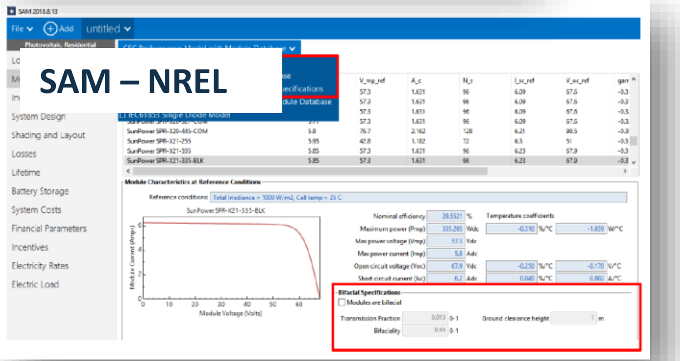
Bifacial PV production

Simulation tools – View Factor

View factor – Already implemented in commercial software

PVSyst

SAM – NREL



- Examples of software using view factor: PVSysts, SAM, bifacialvf, MoBiDiG, pvfactors, …
- Commercial software with an easy interface
- There might be doubts regarding the value of some inputs like *shading loss factor* or *backside mismatch loss factor.*
- These input values are being studied with ray-tracing tools.
- According to recent studies, current VF software (SAM, PVSyst) appears to be conservative relative to measured rear irradiance[1]. However, other studies shows that 2D VF models are enough accurate[2,3].
- Probably they are the mostly used due to its "historical reliability" and because they are widely used and known in the sector.

[1] Ultimate Bifacial Showdown: 75kW Field Results. Silvana Ayala Peláez, NREL. BiFi July 2020.

[2] Field Testing Meets Modeling: Validated Data on Bifacial Solar Performance. Kyumin Lee, Array Technologies. BiFi July 2020.

[3] Amir Asgharzadeh et al. A Benchmark and Validation of Bifacial PV Irradiance Models.

Bifacial PV production

Simulation tools – View Factor

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View factor – References of inputs for PVSyst related to the trackers

How to simulate bifacial projects in PVsyst®

Structure Shading Factor: since a negative Structure Shading Factor cannot be entered in PVsyst®, the best option is to set it up at 0% and increase the Shed Transparent Fraction.

Figure 8: Structure Shading Factor PVsyst® location

Shed Transparent Fraction: to optimize software simulation, it is necessary to aggregate a Shed Transparent Fraction value of 3.75%. Additionally, this parameter should be multiplied by 1.017 in order to consider the irradiation gain.

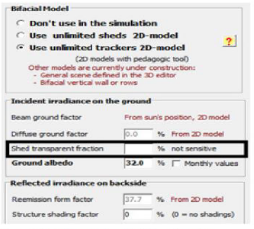
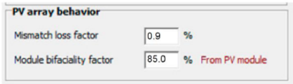


Figure 9: Shed Transparent Fraction PVsyst® location

Thermal Loss Factors (Uc & Uv): PVsyst® can consider the structure's cooling capacity by including two thermal heat transfer coefficients: constant factor (Uc) and convective factor (Uv). based on result evaluation at BiTEC, Soltec recommends the following SF7 Bifacial tracker values: Uc= 31 W/m2 K and Uv= 1.6 W/m2 K /m/s. With such values, it is possible to simulate power losses caused by temperature as measured in BiTEC modules

Figure 7: Thermal factors PVsyst® location

Mismatching Loss Factor: PV designers should use a Mismatch loss factor in PVsyst® of 0.9% for SF7 Bifacial solar tracker.



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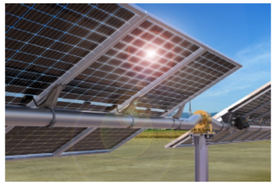
Soltec

NX Horizon PVSyst Bifacial Parameters

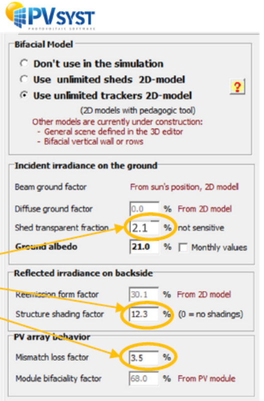
Reviewed by PVEL



- 90mm vertical separation from torque tube to PV cells
- 125mm round torque tube
- No piers, bearings or drive components underneath modules
- 400mm long mounting rails

PVSyst Bifacial Parameters	NX Horizon Tracker Related Inputs
Shed Transparent Fraction	MT* + 2.1%
Backside Structure Shading Factor	12.3%
Backside Mismatch Loss Factor	3.5%
Uc (W/m2k)	25
Uv (W/m2k/m/s)	1.2
Module Height (m)	1.35 - 1.50 m**

*MT: Module Transparency Factor (%)
**Specific value depends on module size and site conditions



nextracker

13

PVsyst Loss Factors for 1MIP and 2MIP Bifacial Trackers

	Array 1MIP Tracker	Generic 2MIP Tracker
System Inputs		
Row Spacing	5.9 m	11.8 m
Table Width	2.06 m	4.13 m (zero E-W gap)
Torque Tube	Circular, 12 cm diameter	Square, 16 cm x 16 cm
Torque Tube Height Above Ground	1.6 m	2.0 m
PVsyst Loss Factors from SunSolve		
Structural Shading Loss Factor	7.8 %	6.5 %
Backside Mismatch Loss Factor	2.5 %	2.5 %

These loss factors are also recommended for other softwares that implement the 2D view factor model, such as NREL SAM and PlantPredict.

PV LIGHTHOUSE
ARRAY TECHNOLOGIES FOLLOW THE SUN. FOLLOW THE LEADER.

Bifacial tracker and simulations on PV Plants. Mireia Jiménez, Soltec. BiFi July 2020.
Optimizing Plant Performance with Smart Solar Trackers & Bifacial Technology. Melissa Cooke, Nextracker. BiFi 2020.
Field Testing Meets Modeling: Validated Data on Bifacial Solar Performance. Kyumin Lee, Array Technologies. BiFi July 2020.

Bifacial PV production

Simulation tools – Ray Tracing

Ray tracing – Implemented in a few “advanced” software tools

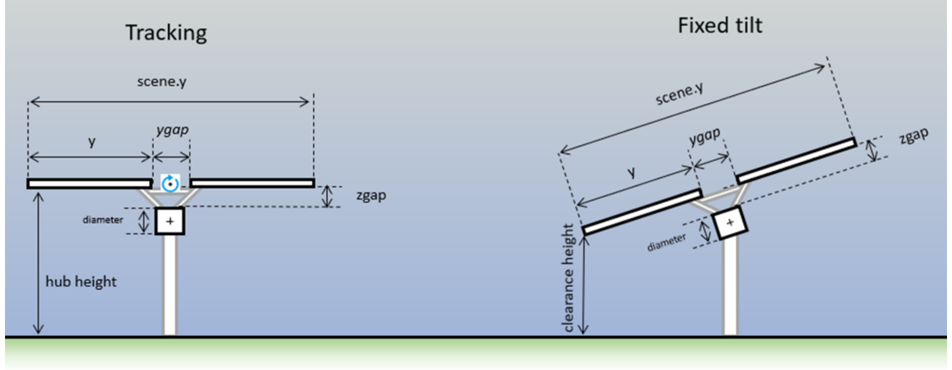
Irradiance level on modules backside

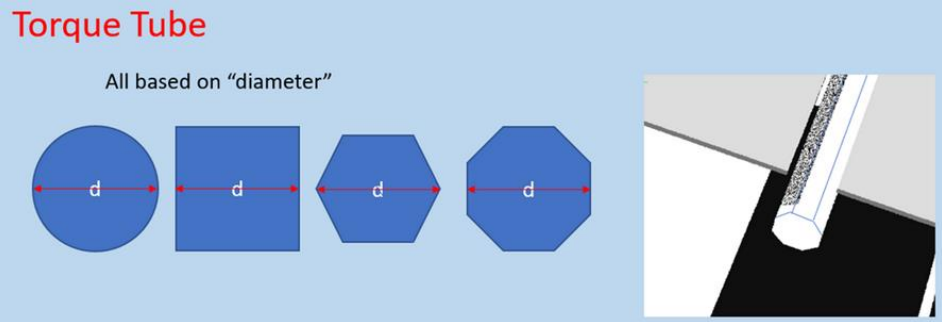
- Examples of software using ray-tracing:
  - bifacial_radiance: opensource Python code developed by NREL.
  - SunSolve: developed by PVLightHouse
- Bifacial_radiance:
  - Not easy interface. GUI (graphic user interface) has been developed but highly recommended to understand Python code.
  - Additional geometries like tracker-torque tube can be considered
  - Optical properties of materials can be customized
  - The irradiance at different module position can be analyzed
  - 3D ray-tracing calcultaions require time!
    - Simulation of 8760 yeary hours: very long process. Requires HPC.
    - **Cumulative sky approach**: build one sky with the radiation of one year, or several skies for 1-axis trackers

Bifacial PV production

Simulation tools – Ray Tracing

Ray tracing – Implemented in a few "advanced" software tools





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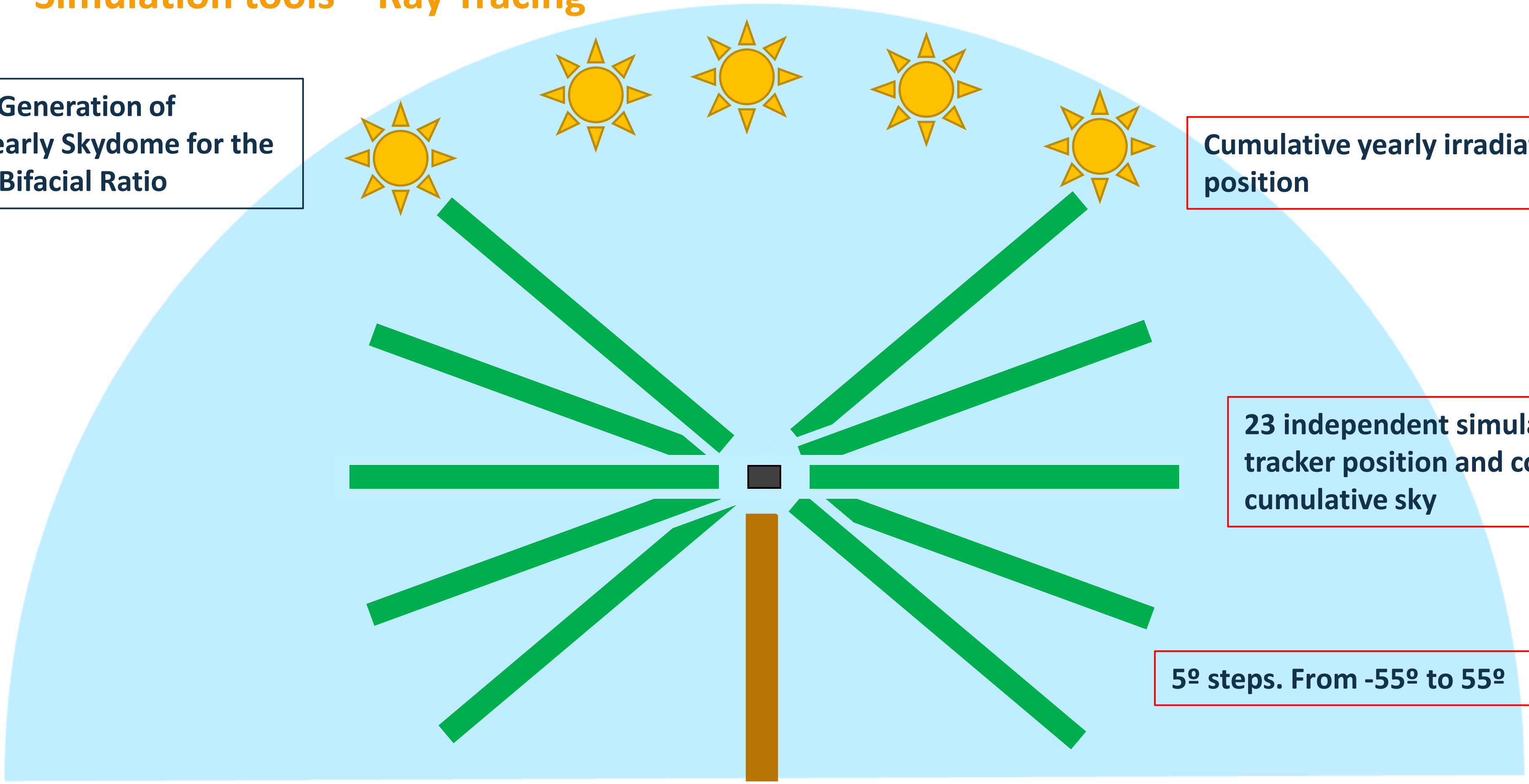
Bifacial Radiance Tutorial. Silvana Ayala Peláez, NREL.

Bifacial PV production

Simulation tools – Ray Tracing

Ray Tracing – Generation of Cumulative yearly Skydome for the evaluation of Bifacial Ratio



Cumulative yearly irradiation in this position

23 independent simulations for each tracker position and corresponding cumulative sky

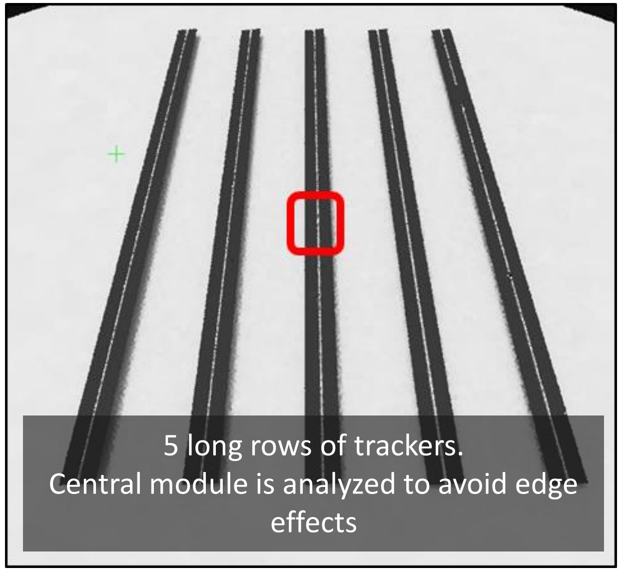
5º steps. From -55º to 55º

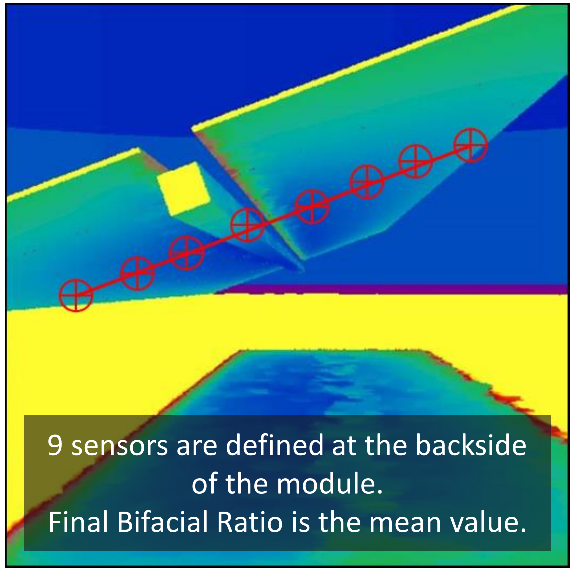
Specific simulations for one specific moment are also possible

Bifacial PV production

Simulation tools – Example of bifacial_radiance simulation

Inputs	Base-case scenario
Weather data (EPW or TMY)	Totana file (37.758,-1.429)
Albedo	0,2
Sky model	Cumulative Sky (yearly)
Module dimensions: width & height	1 x 1,98 m Frameless
Orientation: portrait / landscape	Portrait
GCR (ground overage ratio)	0,3
Tilt of modules	0
Azimuth	180º (tracker in N-S axis)
Height of rotation axis	2 m
Gap between 2-portrait modules	400 mm
Modules per row	2-portrait x **118** (**236 modules/tracker**)
Number of rows	5
Tracker torque-tube?	Yes
Torque-tube section	Squared
Distance tube_edge -module	-10 cm (above module)
Tracker limit angle and backtracking	55º. Backtracking = Yes





Bifacial Ratio = 6,24%

With viewfactor (SAM) model is 5,65%

- Albedo 20%, bifacial ratio is 6.24%
- Albedo 30%, bifacial ratio is 8.5%
- Albedo 40%, bifacial ratio is 10.7%

PV Modules: Bifacial technology

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https://www.cetcsolarpv.com/es/index.php?c=content&a=show&id=564

Bifacial PV production: Practical Case

Bifacial_radiance – How to start

- Bifacial_radiance is the most complete and advanced software for the calculation of bifacial ratio i.e. the radiation at the module backside compared to the radiation at the frontside.

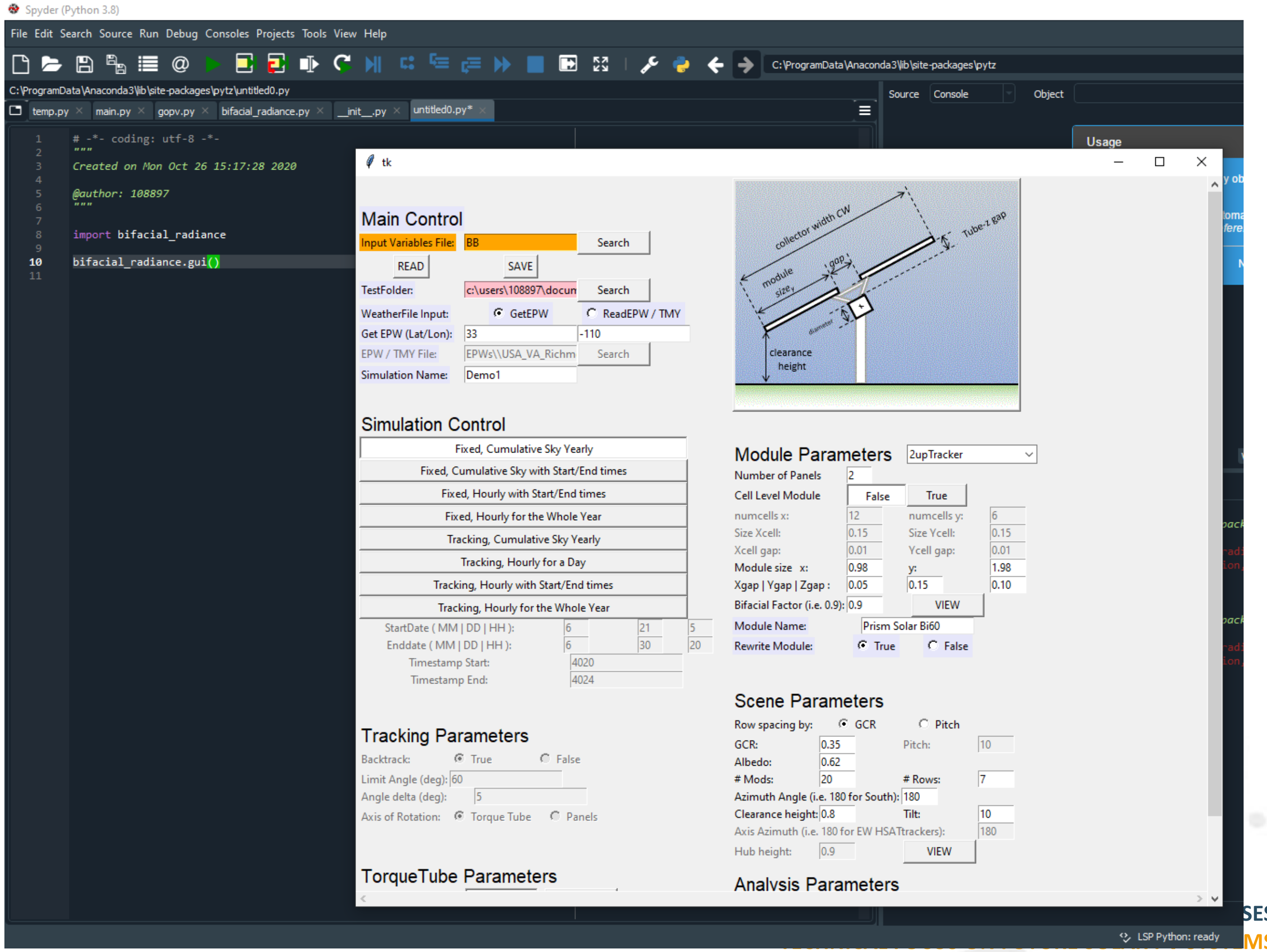
$$Bifacial\ Ratio = \frac{G_{back}}{G_{front}}$$

- It can give estimated PV production introducing the module bifaciality, but not accurate thermal and electrical models are implemented.
- Main software webpage: https://github.com/NREL/bifacial_radiance
- Installation requirements: Anaconda with Python v3, Radiance, Radiance executables (jaloxa), PVLib, bifacial_radiance package, gencumulativesky.exe
- Installation described in Youtube video: *Bifacial_Radiance, guía de instalación* → https://www.youtube.com/watch?v=4A9GocfHKyM&feature=youtu.be
- The file containing the most important code that describe the functions is ***main.py***, probably located in C:\Users\...\Documents\bifacial_radiance-master\bifacial_radiance

Bifacial PV production: Practical Case

Bifacial_radiance – Simulation example with GUI

- Open Spyder program (installed with Anaconda package)
    - Type: *import bifacial_radiance* (this will import the bifacial_radiance package and all its functions)
    - Type: *bifacial_radiance.gui()* (function to open the graphic user interface)
    - Click on  and GUI will be displayed.



Bifacial PV production: Practical Case

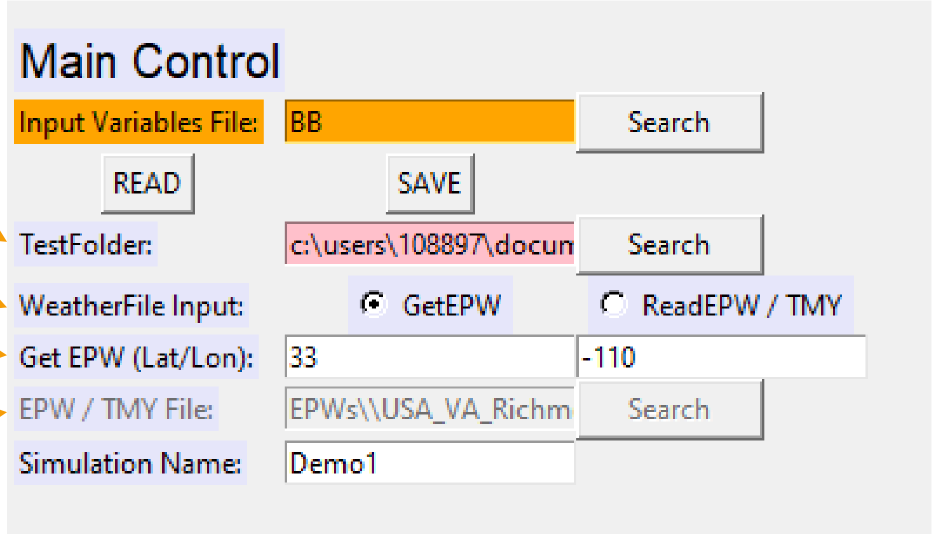
Bifacial_radiance – Simulation example with GUI

Choose a folder to sabe all the generated files from the simulation

Here the weather file should be indicated. It could be in EPW or TMY format.

You select *GetEPW* and indicate coordenates or

You can select *ReadEPW/TMY* and load your own weather file.



Two sources of weather data:

In Europe, you can download weather files for an specific location from PVGIS https://re.jrc.ec.europa.eu/pvg_tools/es/#TMY

Global weather files can be found in EnergyPlus https://energyplus.net/weather

Main functions within *main.py* code:
getEPW
readEPW

Bifacial PV production: Practical Case

Bifacial_radiance – Simulation example with GUI

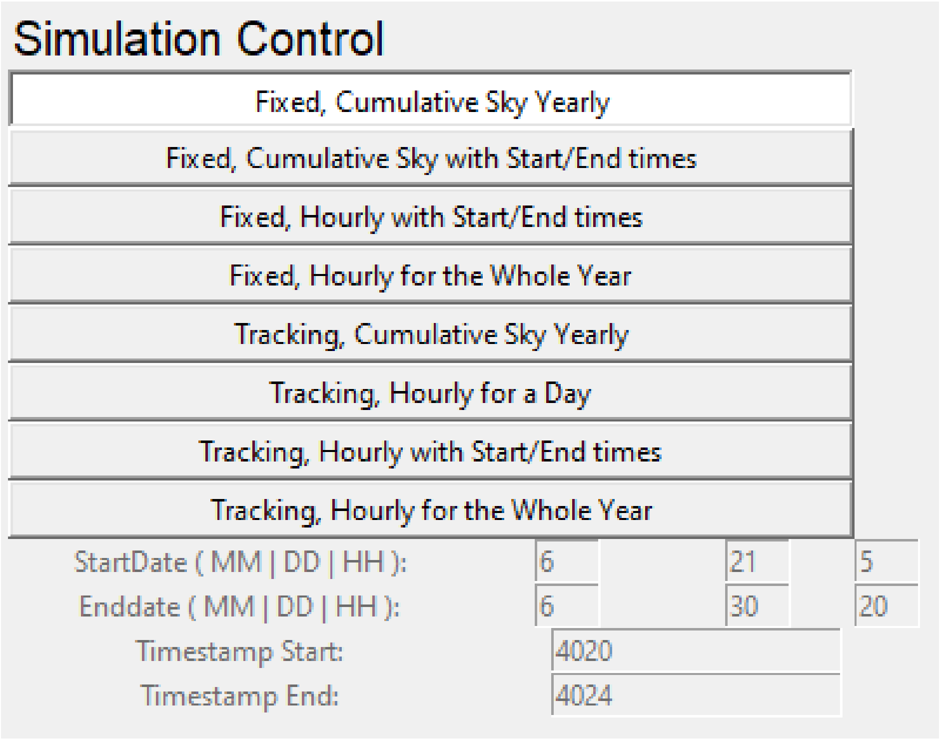
Choose Fixed or Tracking depending on your installation.

Fixed: It will require a clearance height and tilt angle.

- With cumulative sky will take a few minutes
- Hourly for the whole year will take too much time. Not recommended.
- Hourly analysis only recomended for short periods (f.i. 1 day)

Tracking: It will require tracker geometry description.

- With cumulative sky: angular step should be defined. An analysis will be performed for each angular step, with its corresponding cumulative skydome. Simulation of big enought systems (to avoid Edge effects) may take 1-3 hours.
- Hourly for the whole year will take too much time. Not recommended.
- Hourly analysis only recomended for short periods (f.i. 1 day)



Main functions within *main.py* code:
genCumSky
gendaylit
genCumSky1axis
gendaylit1axis

Bifacial PV production: Practical Case

Bifacial_radiance – Simulation example with GUI

Just if a *Tracking* option has been selected

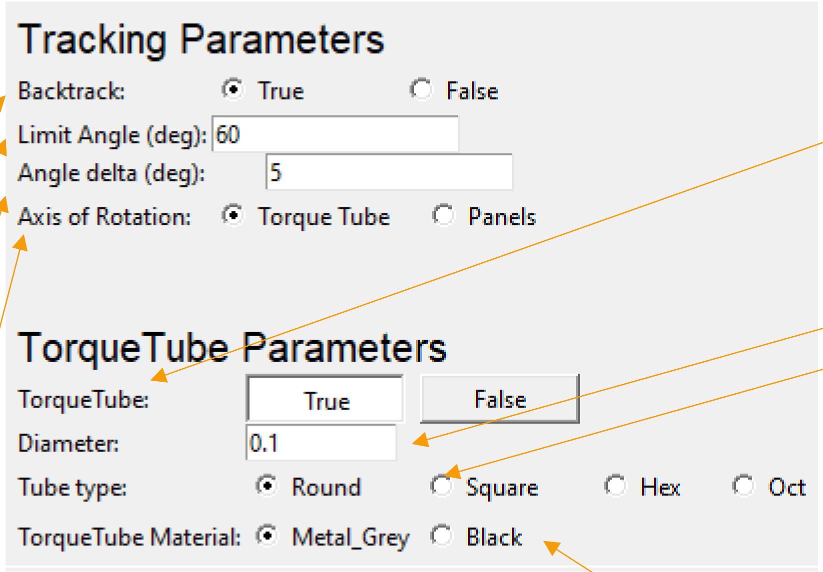
Backtracking is an algorithm that trackers may have to avoid shadowing from one tracker to another during the sunrise and sunset. Most of the comercial trackers have this property.

The software do not have a specific algorithm but it take the code from PVLib.

Indicate the limit angle of the trackers. Normally the trackers are able to move from -60º to 60º from East to West.

Indicate the angular step you want to divide the analysis. An Radiance scene and a skydome will be created for each step. Lower angular step means higher accuracy but more simulation time. Normally 5º is enought.

Axis of rotation normally will be the torque tuve of the tracker. However you may prefer the center of the panels

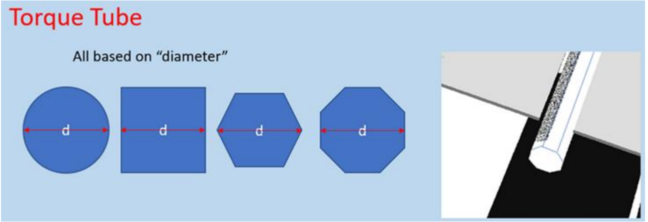


Main functions within *main.py* code:
makeModule
set1axis

All dimensions should be in meters

Do you want to consider the optical reflections/shadows of the tracker torque-tube? If you want to do a good analysis, you should.

Introduce the diameter of the torque-tube and the shape.



Introduce the torque-tube material from an optical viewpoint. Additional customized materials can be defined but not in the GUI module.

Bifacial PV production: Practical Case

Bifacial_radiance – Simulation example with GUI

Menu to load parameters of example cases

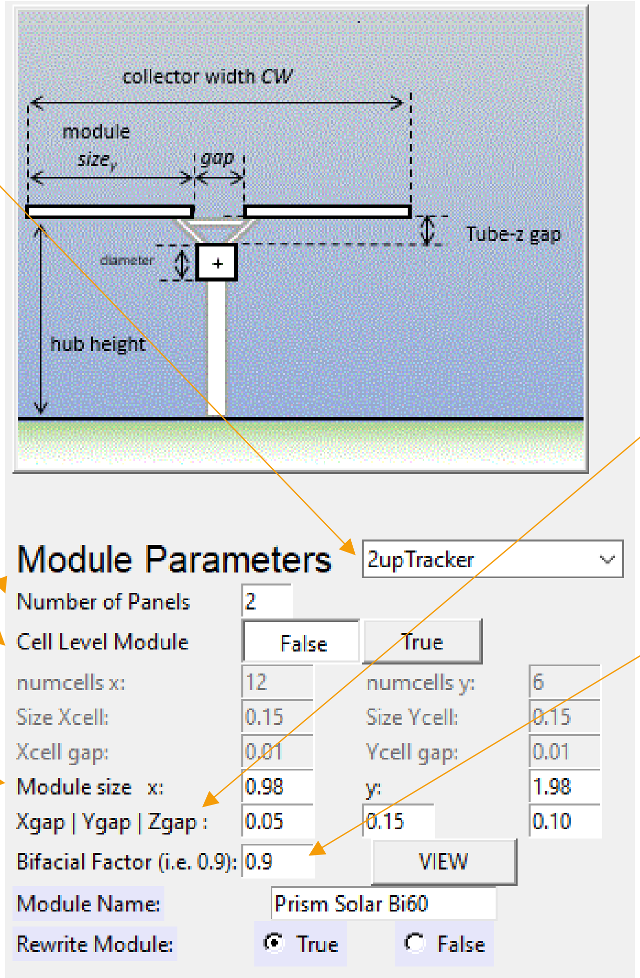
Indicate if the tracker is for 1 or 2 modules in portrait (1-P or 2-P). In the sketch, the system is 2-P.

If system is fixed, you have to indicate the number of modules as well.

If cell level is true, thus you will describe your module as a set of cells, so you need to indicate cell size, number of cells and cell gaps. If cell level is false, your module will be a black box. Other materials can be defined but not in GUI.

Dimensions of module in Y axis (normally East-West axis) and X axis (normally North-South axis).

If Y>X thus the module is in portrait, if Y<X the module is in landscape.



Xgap: Gap between modules in X axis

Ygap: Gap between modules in Y axis (*gap* in the sketch)

Zgap: distance from torque-tube to module (*Tube-z gap* in the sketch)

Module bifaciality. Set to 1 to obtain Bifacial Ratio. Set another module bifaciality (normally between 0.6-0.95) to obtain estimated Bifacial Gain

Main functions within *main.py* code: *makeModule*

All dimensions should be in meters

Bifacial PV production: Practical Case

Bifacial_radiance – Simulation example with GUI

Definition of distance between trackers or module rows.
- Pitch is the distance between rows
- Ground Coverage Ratio (GCR) is the collector width (CW in previous slide) divided by Pitch.

Albedo is the irradiation reflection of the ground. If not known, it can be estimated from available data for different grounds. General values are about 0.1 and 0.3.

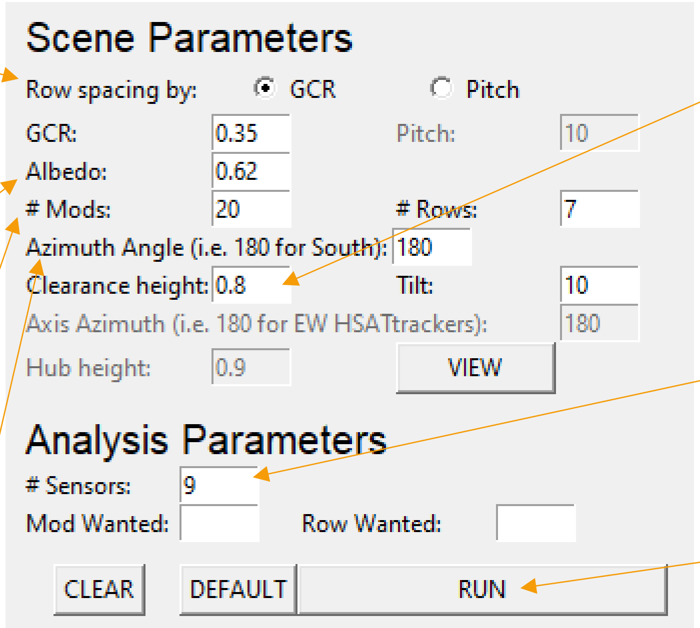
Number of modules and rows in the scene.

If 20 modules are set in this box, and we have 2 modules up defined in previous step, thus we will have 40 modules in the scene.

At least 3 rows are recommended to calculate properly the bifacial ratio for a real utility system. 5 would be better but will take more simulation time.

Azimuth should be 180º if modules are facing South (fixed systems). If tracker is in North-South axis and the modules move from East to West.

Tilt will be determined by ground tilting. 0º if ground is flat.



Clearance height (fixed installations) is the distance from the bottom of the module to the ground.

Hub height (1-axis tracking systems) is the distance from the torque-tube to the ground.

Number of sensors at the back of modules. In 2-up trackers, if odd number, one of the sensors will be between the 2 modules and its result should not be considered.

Default results are from the central module in the central row. If other are desired, it can be specified.

Click on RUN and wait for the results

Main functions within *main.py* code:
sceneDict in makeScene1axis
Analysis1axis
makeCustomObject to include additional objects

All dimensions should be in meters

Bifacial PV production: Practical Case

Bifacial_radiance – Simulation example with GUI

- Finally go to the simulation folder
- Your results will be in cumulative_results_.csv
- But take care!!
- If a sensor is in the gap between modules its contribution should be removed!

cumulative_results_.csv

x	y	z	rearZ	mattype	rearMat	Wm2Front	Wm2Back	Back/FrontRatio
1,644	1,01E-16	1,121	1,099	a9.1.a0.Prism_Sol	a9.1.a0.Prism_Sol	2350442,727	299193,2954	0,127292315
1,233	7,55E-17	1,121	1,099	a9.1.a0.Prism_Sol	a9.1.a0.Prism_Sol	2796593,741	270997,0998	0,096902562
0,822	5,03E-17	1,121	1,099	a9.1.a0.Prism_Sol	a9.1.a0.Prism_Sol	2796289,398	261280,1845	0,093438177
0,411	2,52E-17	1,121	1,099	a9.1.a0.Prism_Sol	a9.1.a0.Prism_Sol	2769844,282	257001,136	0,092785409
0	0	1,121	1,099	a9.1.tube1.17	sky	2273198,611	5209880,58	2,291872145
-0,411	-2,52E-17	1,121	1,099	a9.1.a1.Prism_Sol	a9.1.a1.Prism_Sol	2750100,695	269587,6971	0,0980283
-0,822	-5,03E-17	1,121	1,099	a9.1.a1.Prism_Sol	a9.1.a1.Prism_Sol	2731416,285	286607,4283	0,10492997
-1,233	-7,55E-17	1,121	1,099	a9.1.a1.Prism_Sol	a9.1.a1.Prism_Sol	2664213,236	324483,3295	0,121793303
-1,644	-1,01E-16	1,121	1,099	a9.1.a1.Prism_Sol	a9.1.a1.Prism_Sol	2046597,678	377250,5599	0,184330591
						23178696,65	**7556281,31**	**0,32600113**

Console 1/A

```
Linescan in process: 1axis_50.0_Back
Saved: results\irr_1axis_50.0.csv
Index: 50.0. Wm2Front: 109335.74213777778. Wm2Back: 8487.321424814814
Linescan in process: 1axis_55.0_Front
Linescan in process: 1axis_55.0_Back
Saved: results\irr_1axis_55.0.csv
Index: 55.0. Wm2Front: 356862.19001633336. Wm2Back: 47550.368999259255
Saving a cumulative-results file in the main simulation folder.This adds up by sensor location the irradiance over all hours or
configurations considered.
Warning: This file saving routine does not clean results, so if your setup has ygaps, or 2+modules or torque tubes, doing a deeper
cleaning and working with the individual results files in the results folder is highly suggested.

Saving Cumulative results
Saved: cumulative_results_.csv
Annual RADIANCE bifacial ratio for 1-axis tracking: 0.326
```

GLOBAL OPTIMIZATION OF INTEGRATED PHOTOVOLTAIC SYSTEM FOR LOW ELECTRICITY COST

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 792059

Thank you for your attention!

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