NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Understanding the bifacial modeling & field research space

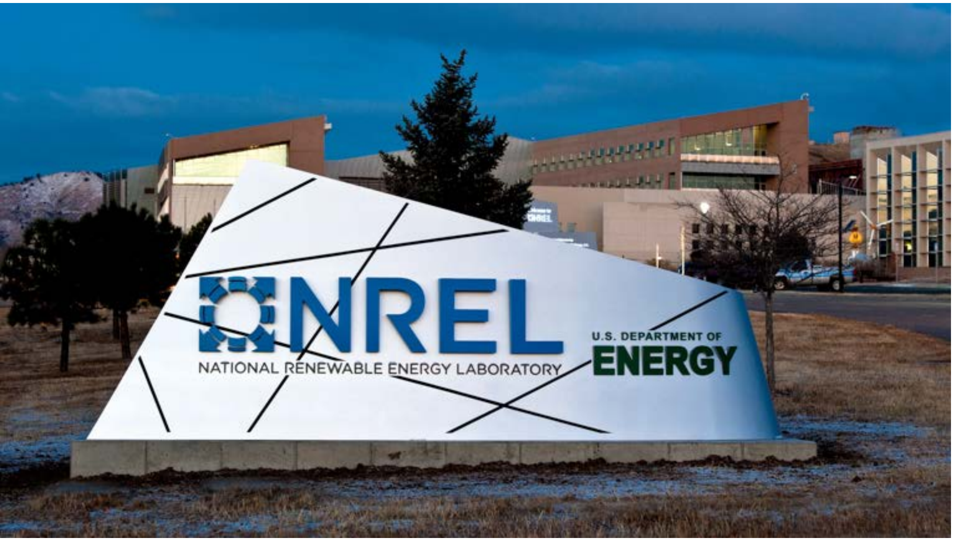
Silvana Ovaitt

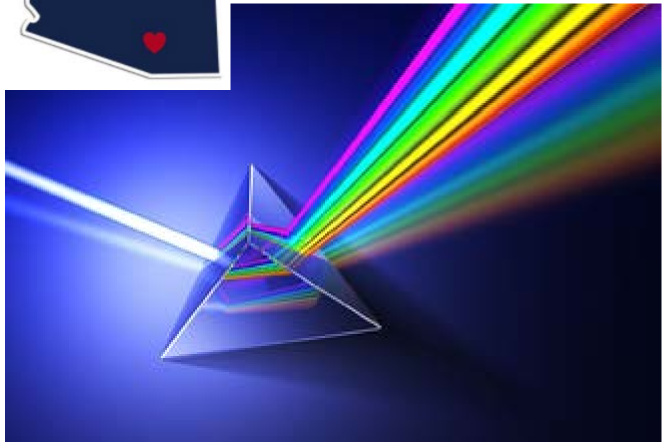
Advance in Photovoltaics: Tandems & Bifacial PV

December 7, 2022 (London / Virtual)

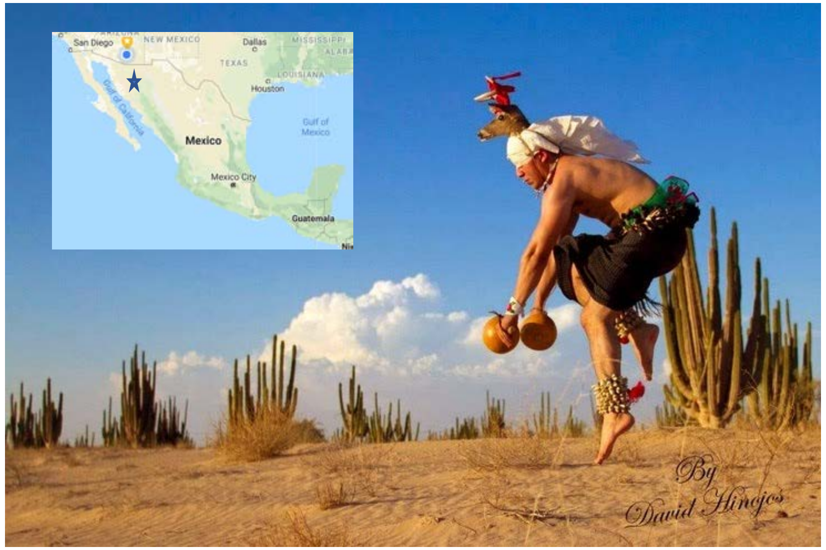
Overview

1. US Market & Market Trends
2. Lifetime and Decarbonization
3. Bifacial Reliability
4. Our field experience: how and why

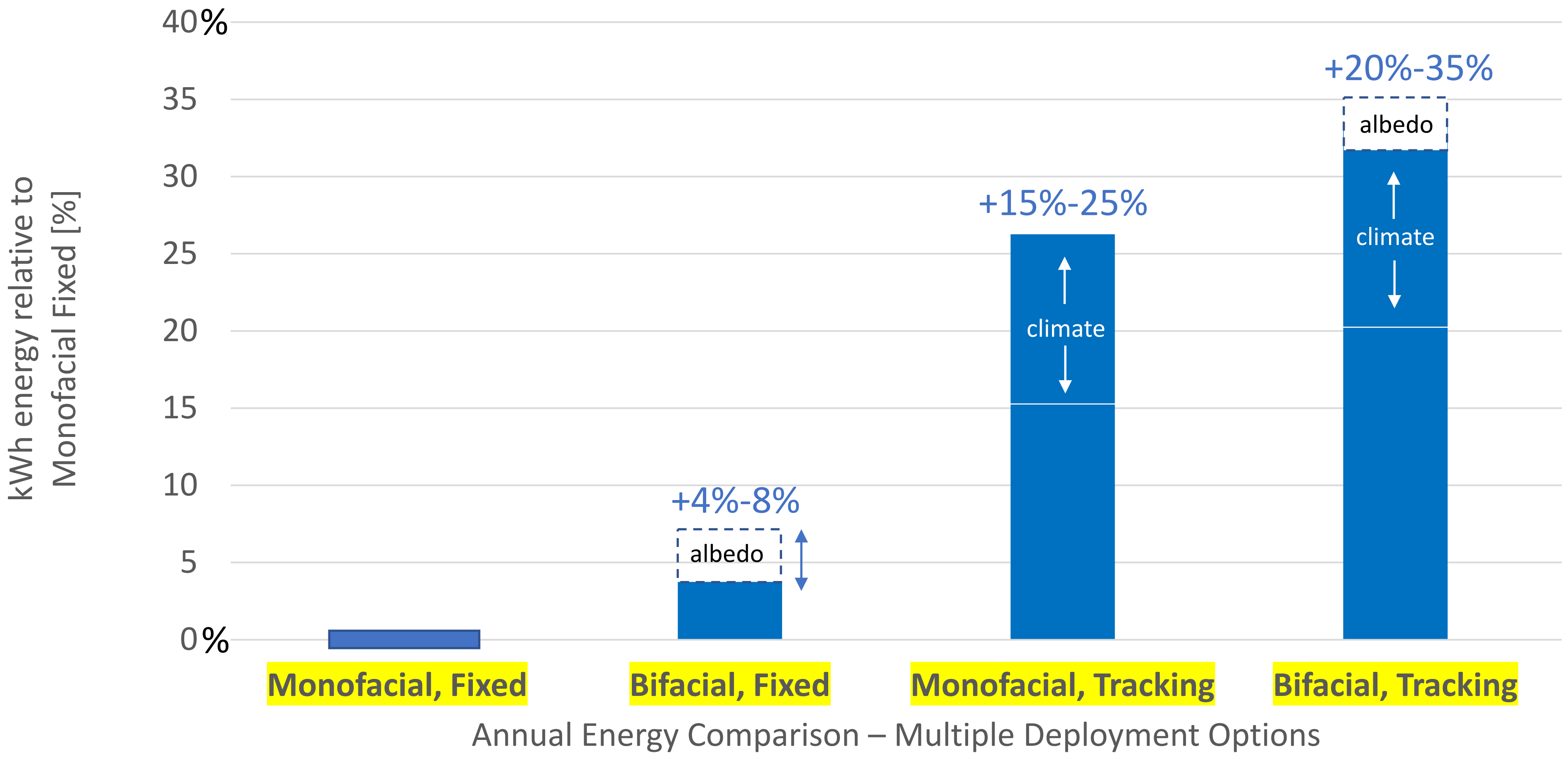


https://www.linkedin.com/in/silvana-ayala/



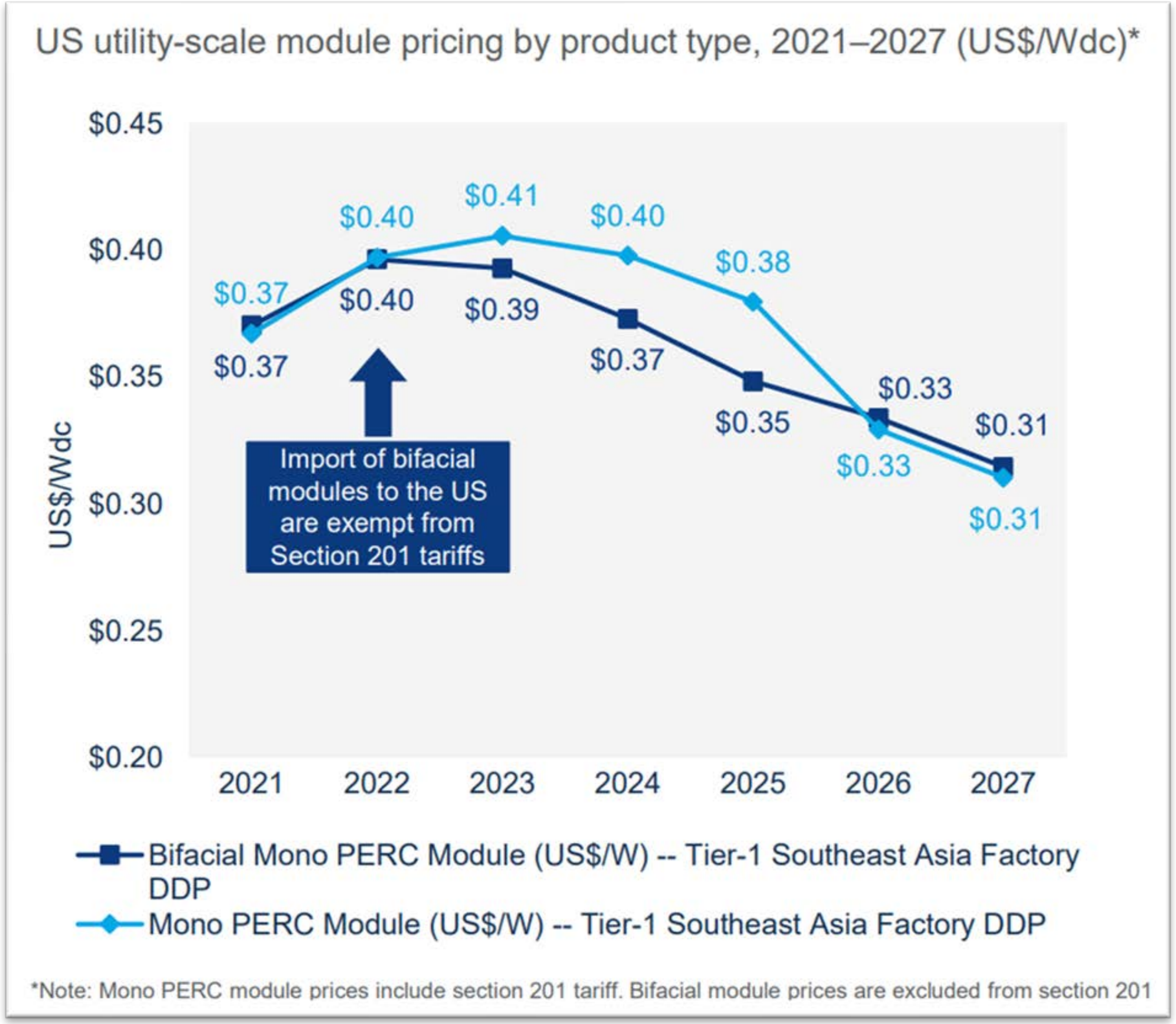

Why Bifacial: Big Levers on Energy Yield



*SAM simulation, range of scenarios

US PV Market Situation – 2022 H2

- 2021 PV deployments of 23.6 GW_{DC} (46% of new US electrical capacity)
- NREL estimates ~**50%-75%** of utility-scale installs were bifacial (~30-50% of all installs)
- Bifacial modules remain exempt from Section 201 tariffs and are forecast to be low-cost options for any utility-scale projects that can get them
  - 2022 US imports decline ~35% due to tariffs, supply chain and traceability requirements
  - Project prices increased 14% -18% year-on-year due to supply and tariff issues
- 'Inflation reduction act' sets stage for US production of poly, wafer, cell & module up to 50 GW_{dc} / yr

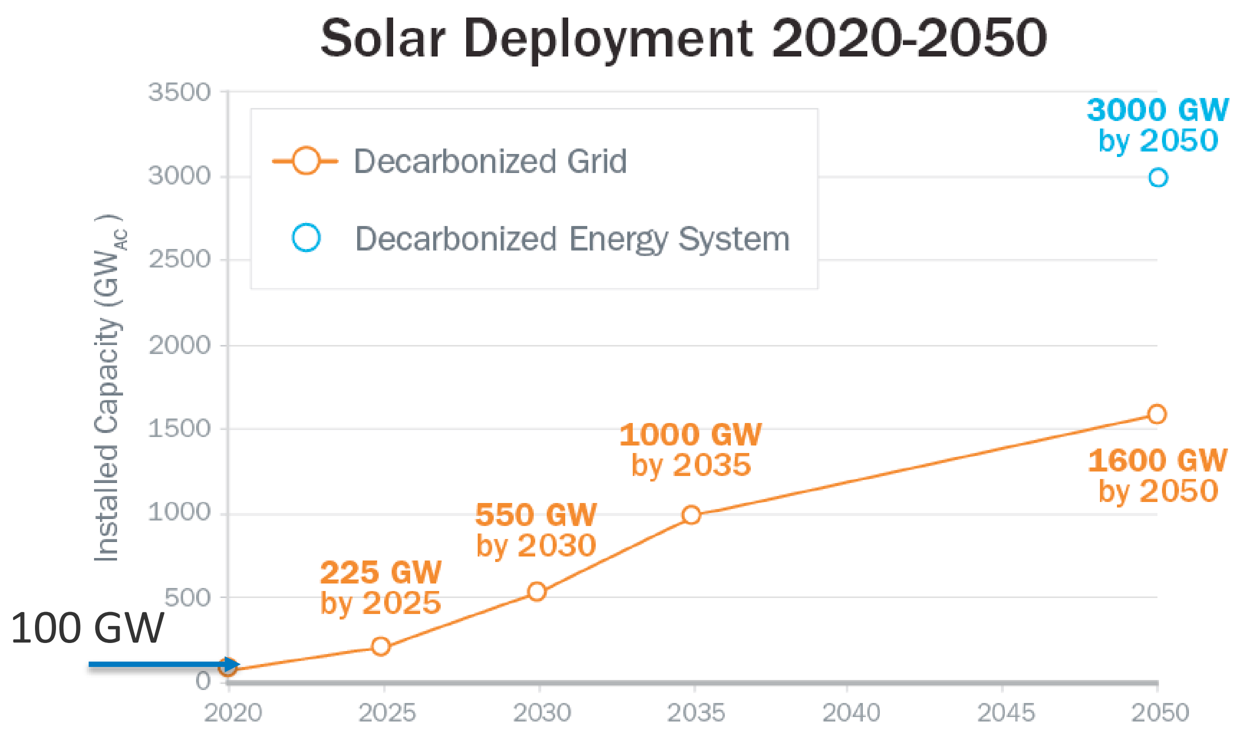


Woods Mackenzie US PV pricing forecast (March 2022)

https://www.reutersevents.com/renewables/solar-pv/us-solar-tariffs-bolster-growing-dominance-bifacial-panels

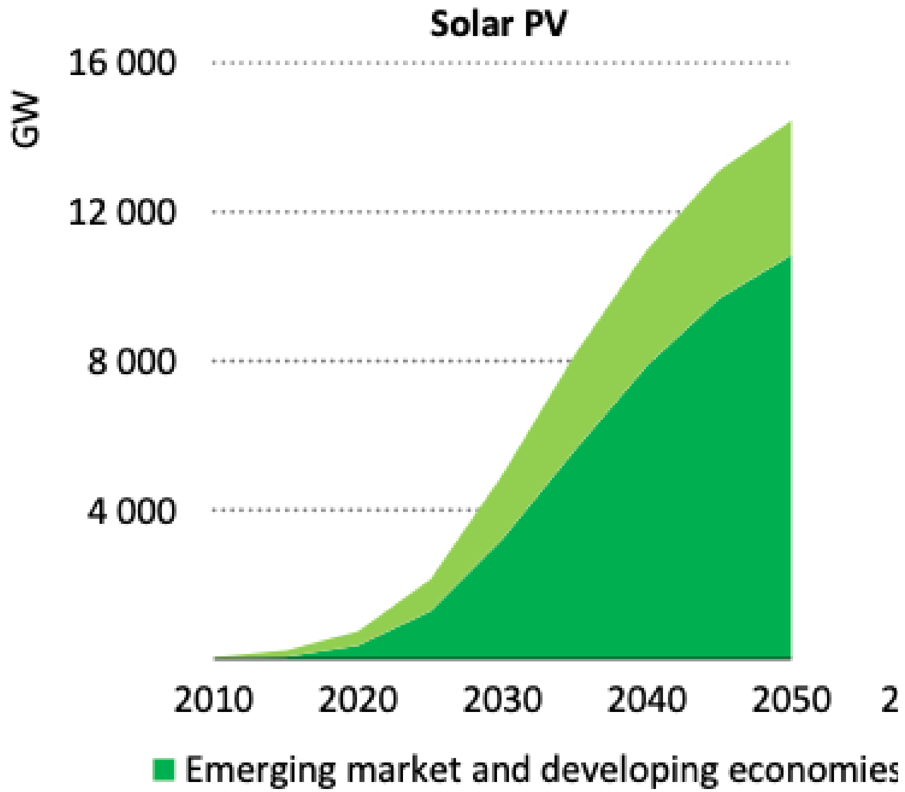
Decarbonization Goals
>90% Clean Electricity by 2035

US electrical grid Decarb + some electrification



DOE Solar Futures 2021

Global Capacity, IEA Net Zero



630 GW/Year by 2030, up from ~130 GW/yr now

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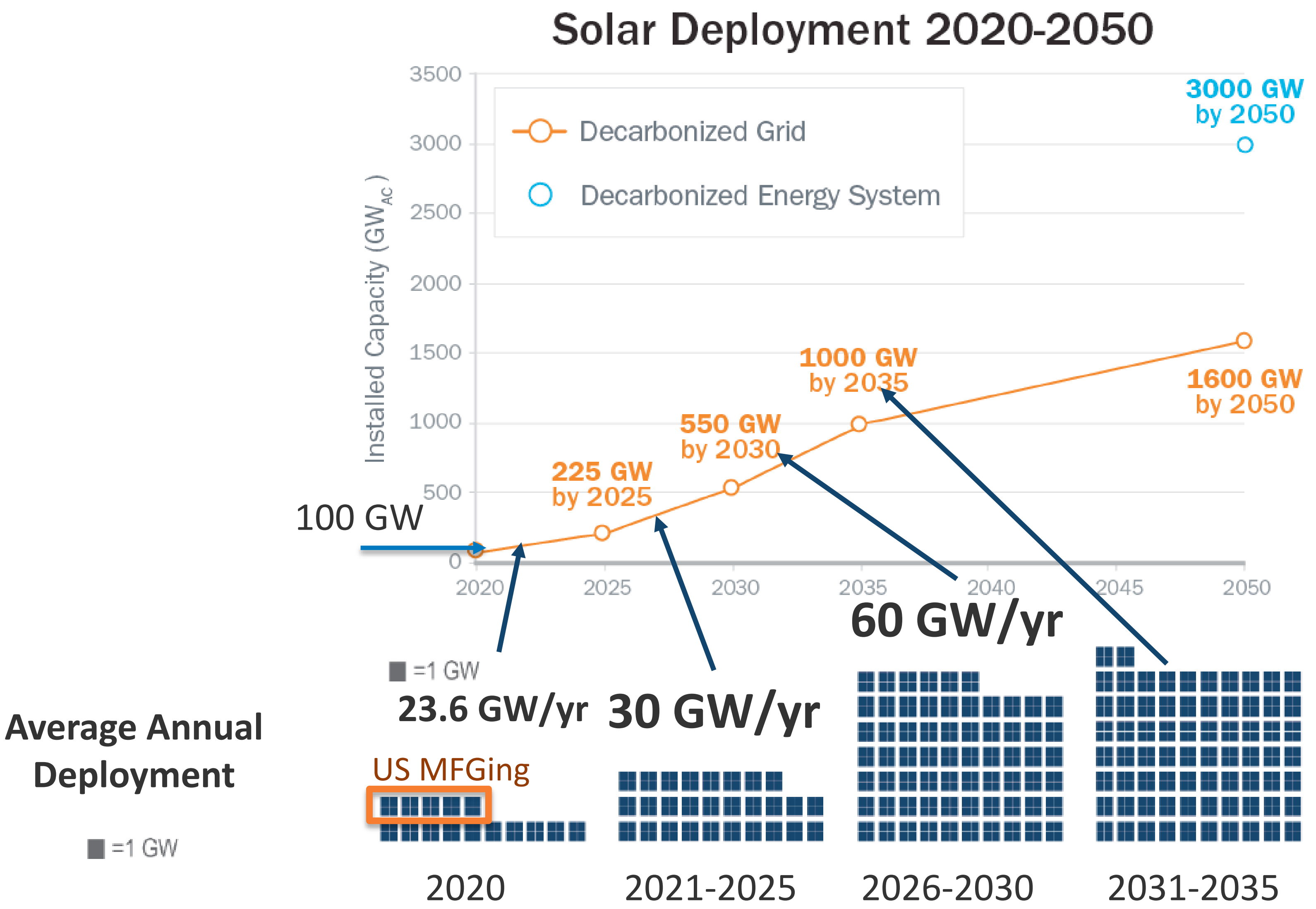
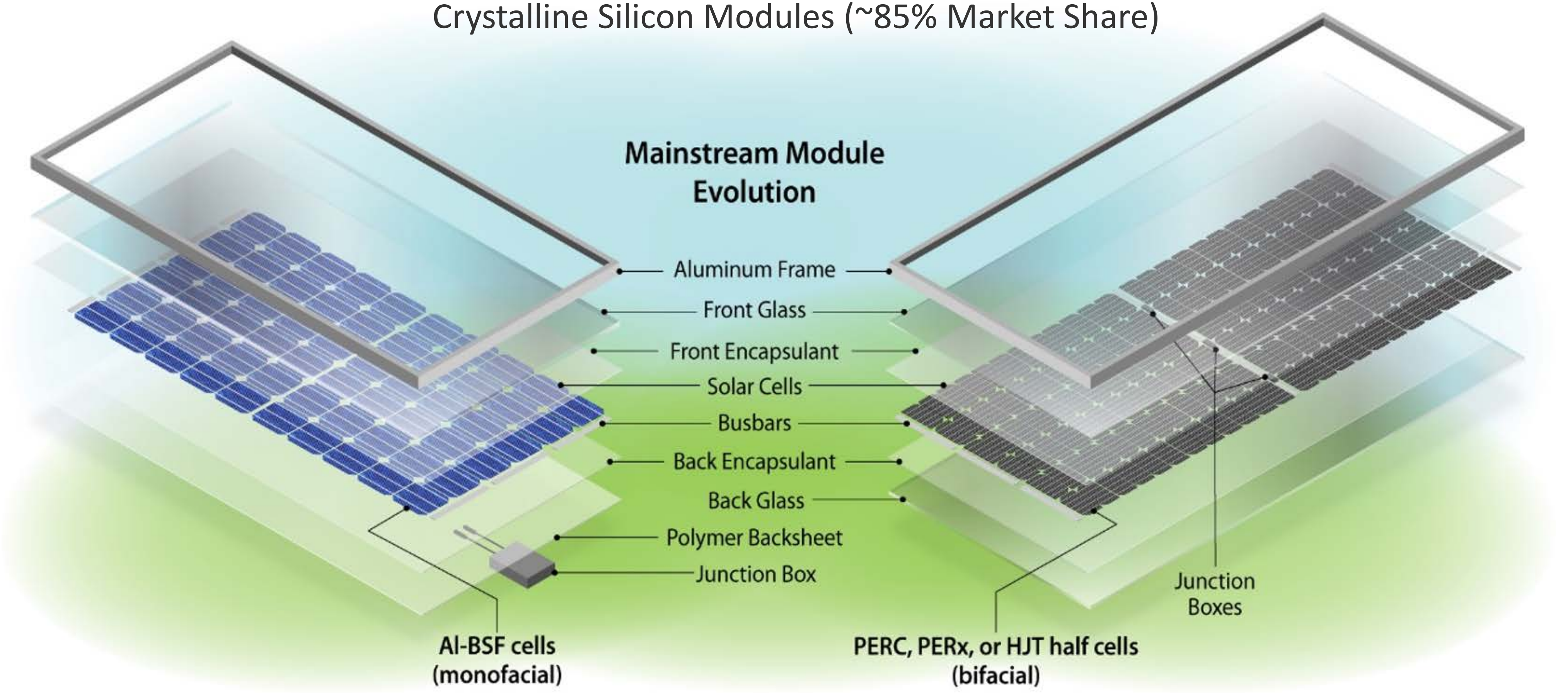


DOE, Solar Futures Study 2021

Modules Continuously Evolve

Crystalline Silicon Modules (~85% Market Share)



Pre-2015 module, 20-25 year life

2022 module, 35 year life

Ovaitt & Mirletz et al, 2022. "PV in the Circular Economy, A Dynamic Framework Analyzing Technology Evolution and Reliability Impacts." *ISCIENCE* https://doi.org/10.1016/j.isci.2021.103488.

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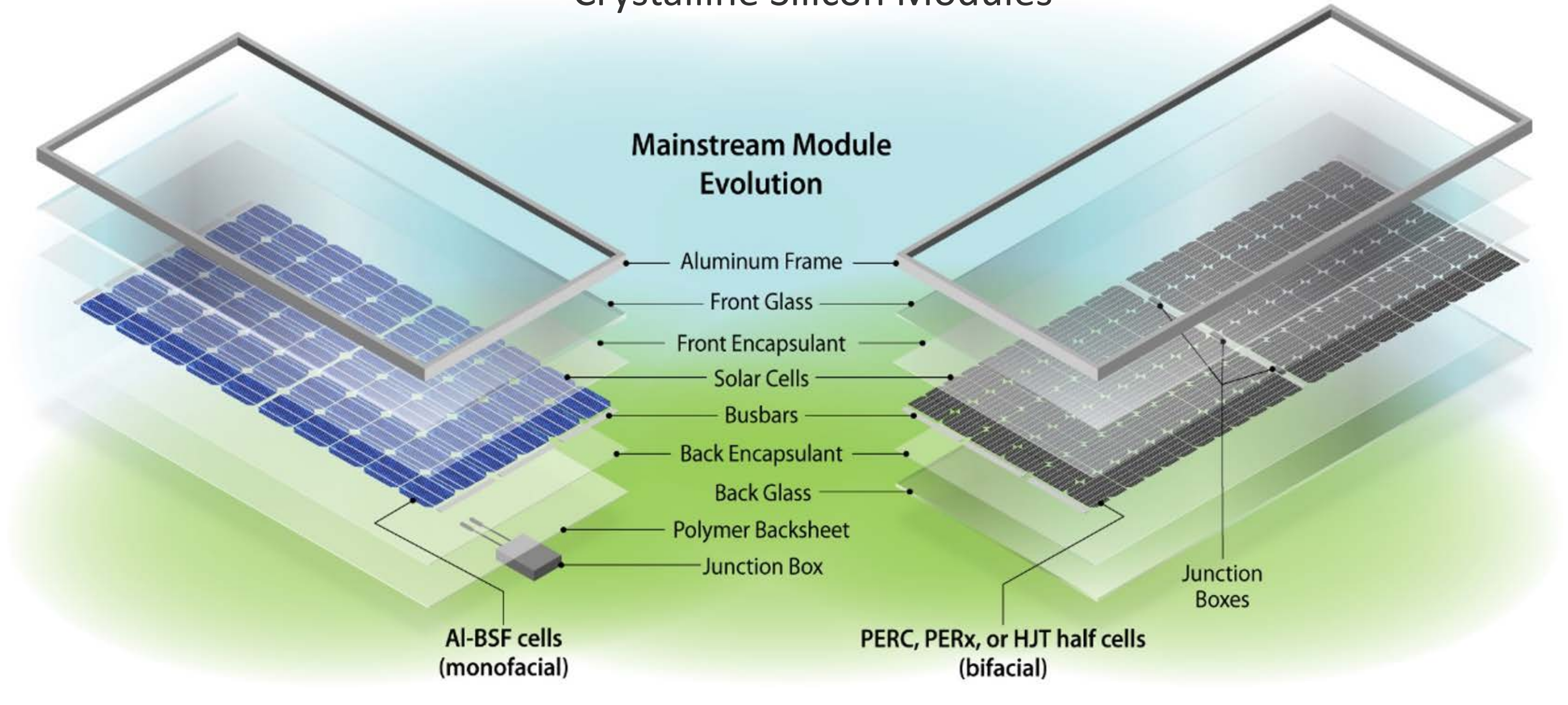

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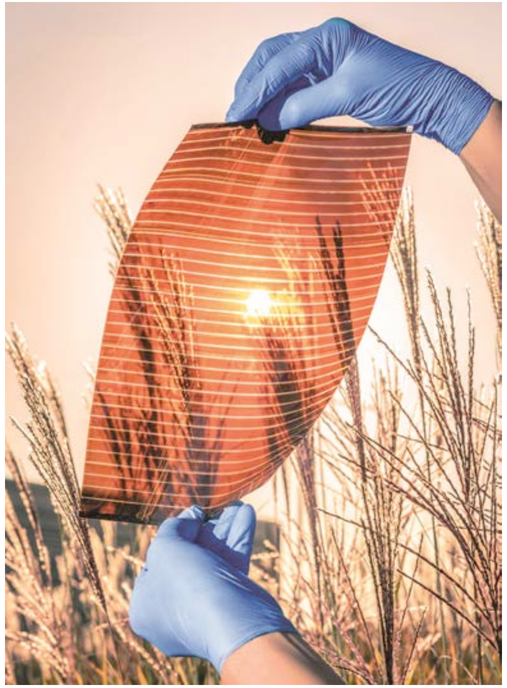
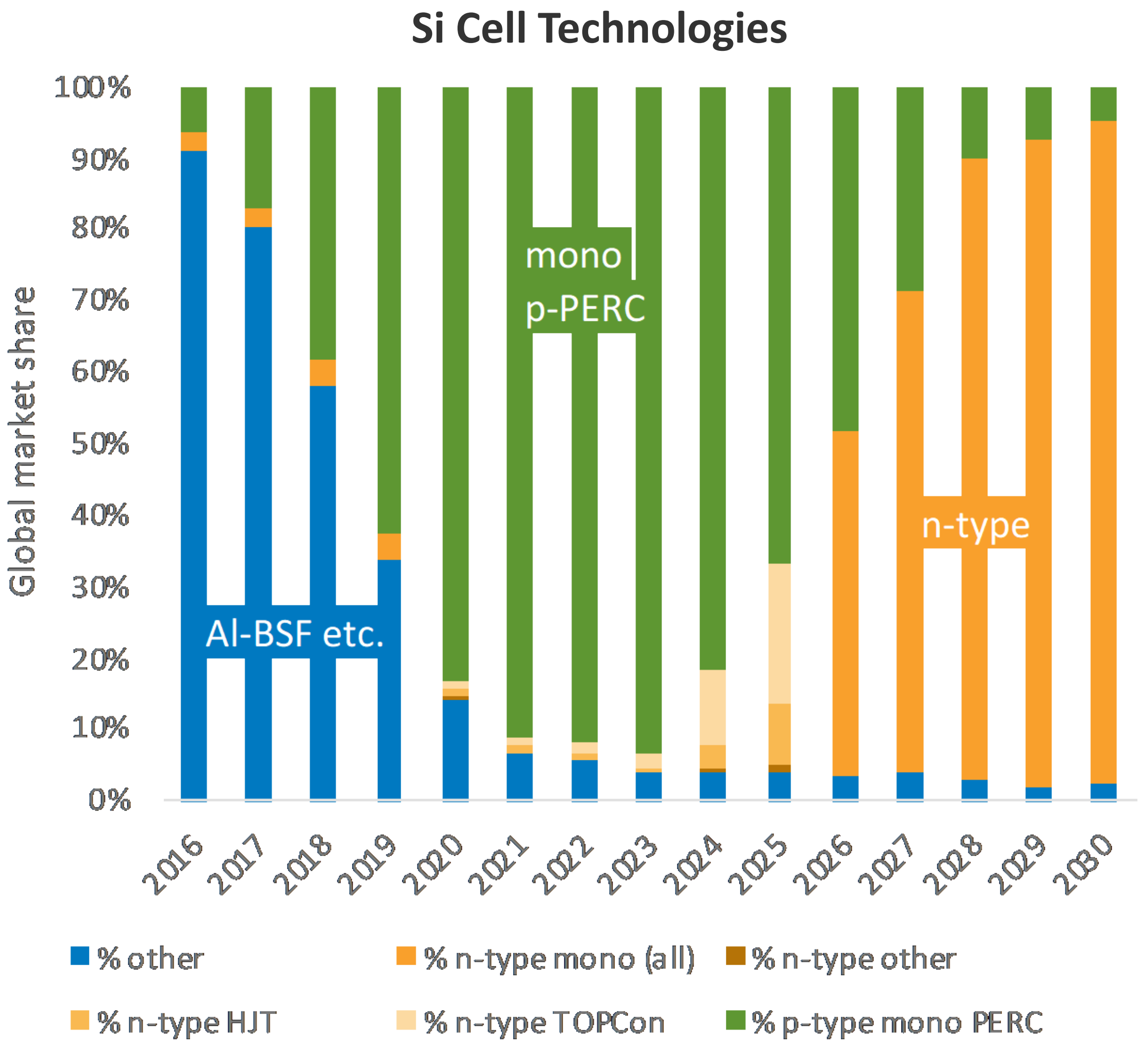


Emerging Products – flexible, non-CdTe thin film, hybrid tandems, Etc.

Ovaitt & Mirletz et al, 2022. "PV in the Circular Economy, A Dynamic Framework Analyzing Technology Evolution and Reliability Impacts." *ISCIENCE* https://doi.org/10.1016/j.isci.2021.103488.

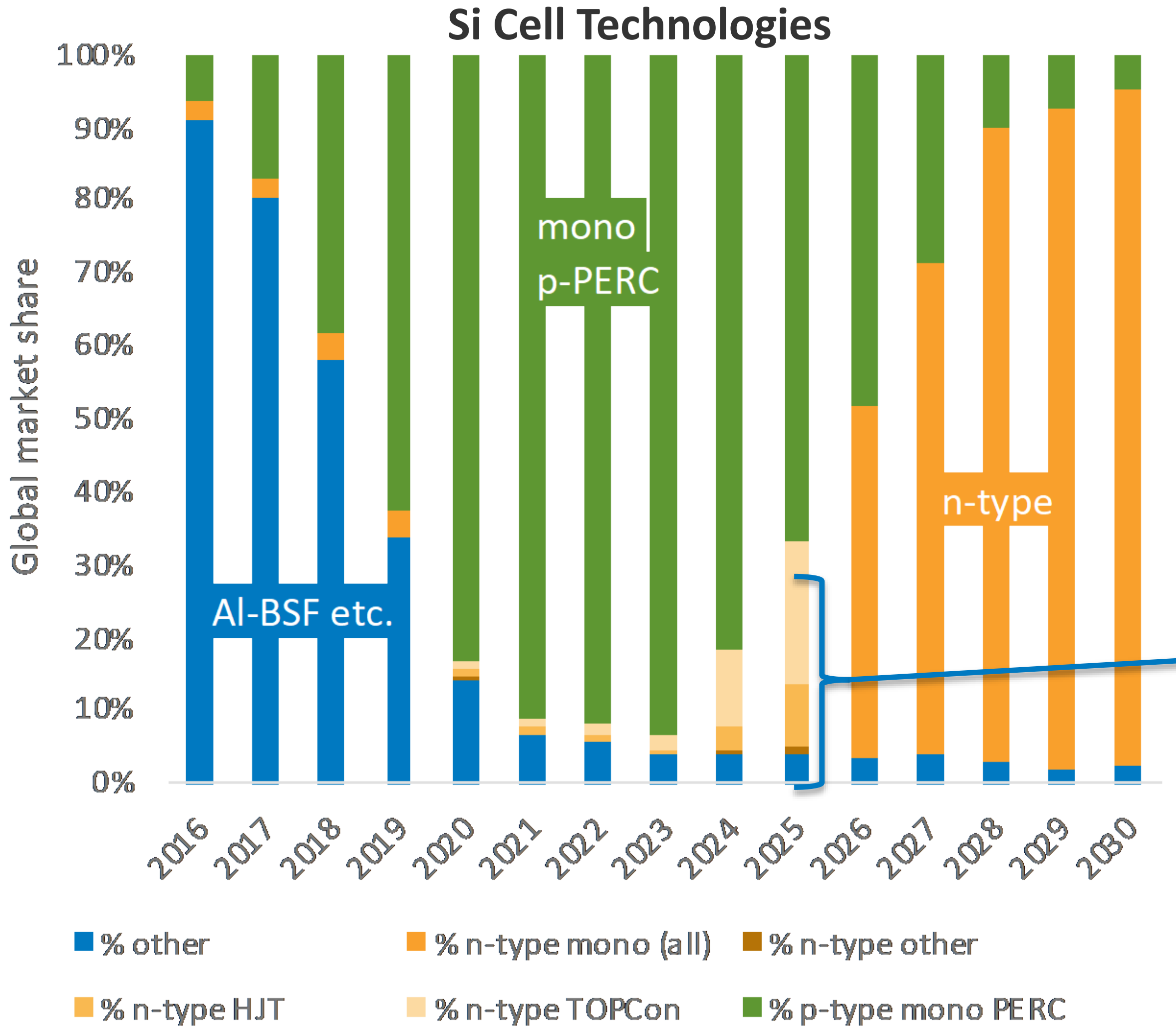
New Technology + Explosive Growth



Jarett Zuboy. DuraMAT Tech Scouting 2022

New Technology + Explosive Growth

Module bifaciality factor $\phi = \frac{P_{Rear}}{P_{Front}}$

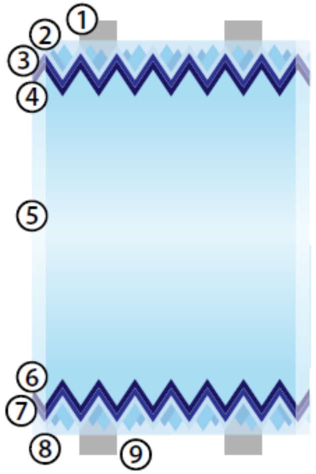


Jarett Zuboy. DuraMAT Tech Scouting 2022

HJT

23-25% cell efficiency

ϕ ~0.85 – 0.95

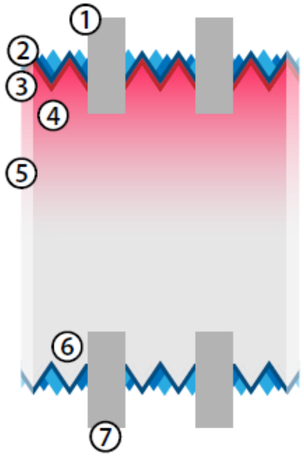


1. Frontside fingers (busbars optional) compromised of low-temperature screen-printed Ag pastes or electroplated Ni/Cu/Sn/Ag
2. TCO by PVD (typically ITO for high optical transmission and low sheet resistance)
3. p^+ doping and full-area emitter formation by PECVD of a-Si:H
4. Intrinsically doped a-Si:H by PECVD
5. High lifetime n-type base wafer
6. Intrinsically doped a-Si:H by PECVD
7. n^+ doping and full-area BSF formation by PECVD of a-Si:H
8. TCO by PVD (typically ITO for high optical transmission and low sheet resistance)
9. Backside fingers (busbars optional)

TOPCon

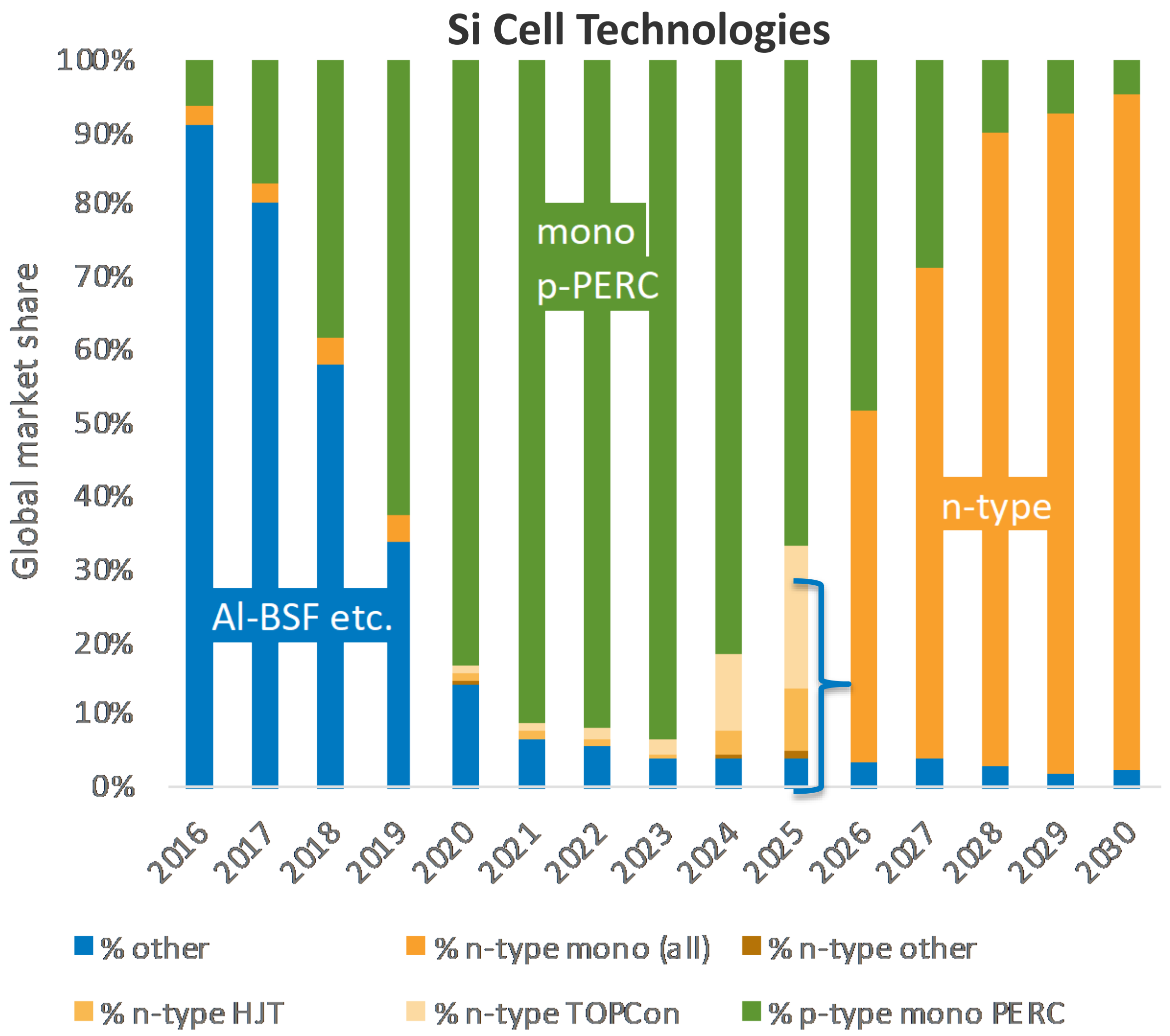
21-23% by SP, 21-26% by PVD

ϕ ~0.8



1. Ag and Al front metallization by screen-printing or PVD
2. SiN_x ARC and passivation layer by PECVD
3. PECVD or ALD of AlO_x surface passivation layer
4. p^+ doping and full-area emitter formation by ion implantation or BBr_3 diffusion
5. High lifetime n-type base wafer
6. Tunnel oxide passivated contact (TOPCon) layer formed by PECVD or LPCVD of doped a-Si or poly-Si layers
7. Ag rear metallization (sometimes full-area) by screen-printing or PVD

New Technology + Explosive Growth



Jarett Zuboy. DuraMAT Tech Scouting 2022

Expect somewhat disruptive technology changes requiring new fabs every few years

Current events illustrate benefits of increased geographic diversity for new plants, and of sustainable planning

Policies US:

- Uyghur Forced Labor Prevention Act
- Defense Production Act
- Inflation Reduction Act

Market Dynamics

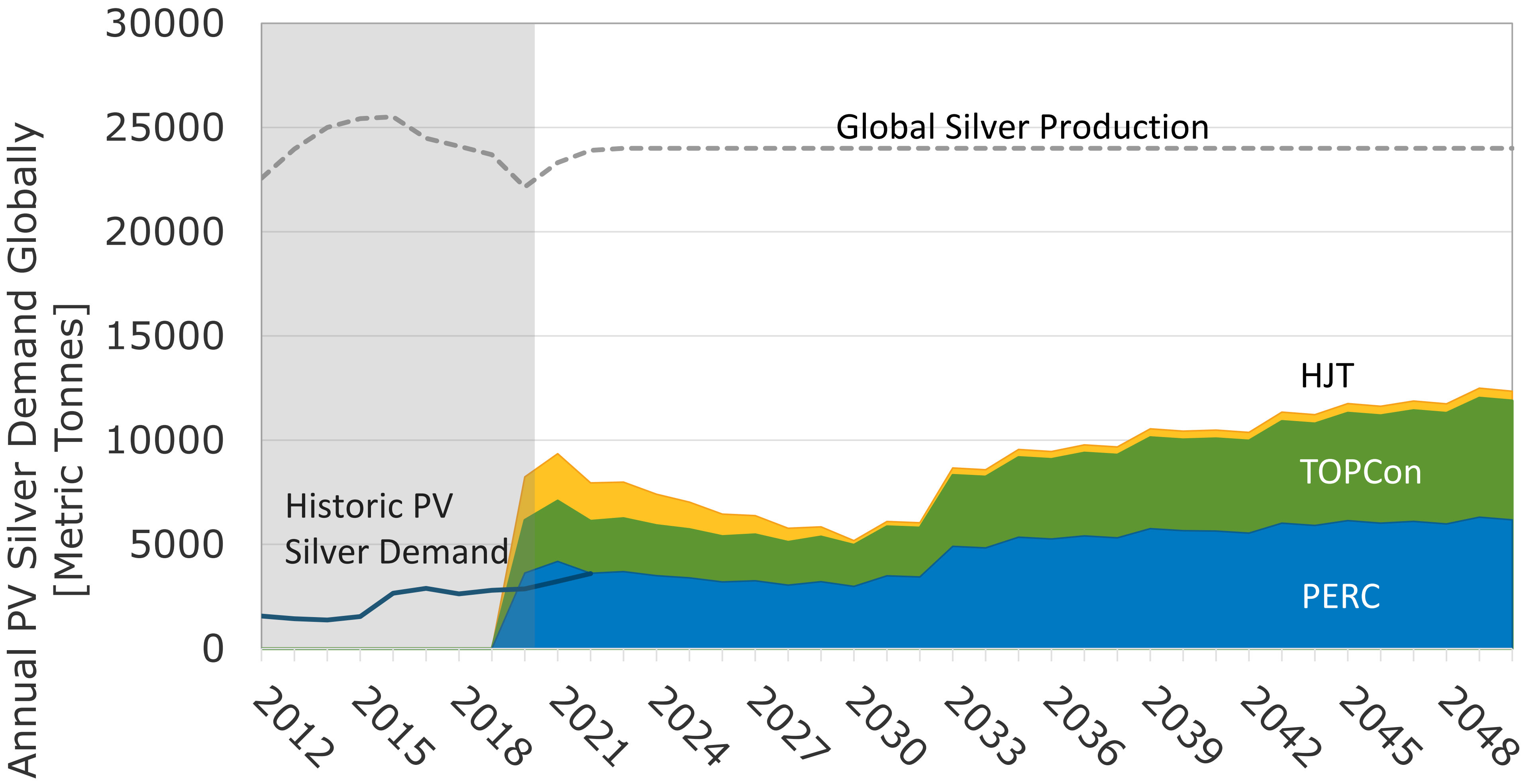
- Supply shortages, i.e. polysilicon price shocks

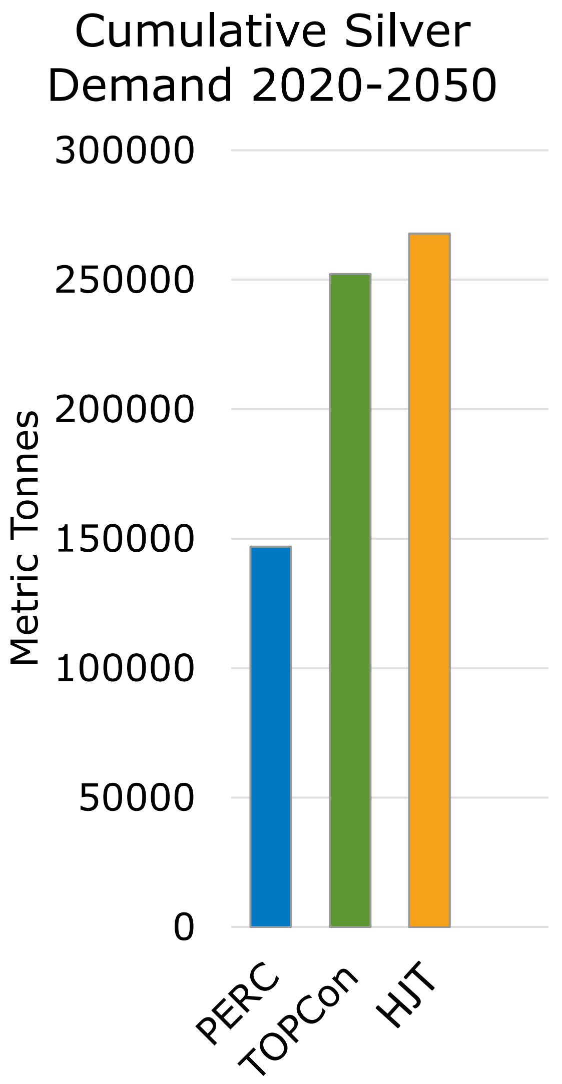
DEI & Sustainability Goals:

- Reduction of Increased negative environmental and social impacts. i.e. forced labor in polysilicon production, poorly regulated or illegal sand mining

Material - Silver

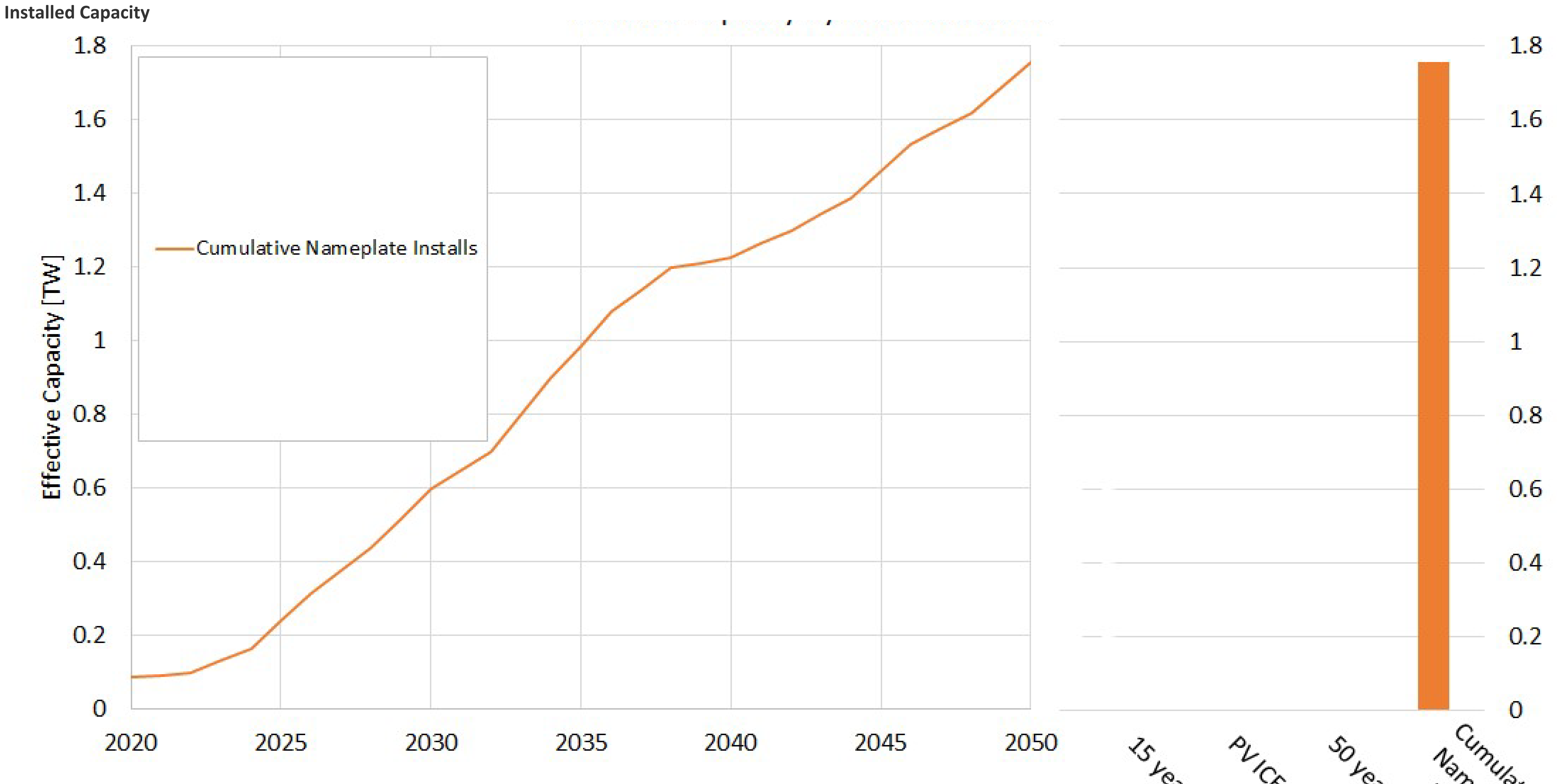
Virgin Material





Ovaitt et al MRS 2022 Proceedings

The concept of Installs vs Effective Capacity



Mirletz, Ovaitt, et al 2022. “**Circular Economy Priorities for Photovoltaics in the Energy Transition**.” https://doi.org/10.1371/journal.pone.0274351

Virgin Material
Reduce Extraction of Virgin Materials

Waste
Reduce Wastes throughout PV lifecycle

Energy Balance
Maximize Energy Return on Investment, EPBT, Net Energy

Supply Chain Security
Just and Reliable sourcing of materials

Levelized Cost of Energy
Solar PV Generation Cost

$$\frac{\text{Total Life Cycle Cost}}{\text{Total Lifetime Energy}}$$

$$LCOE = \frac{CAPEX + \sum_{n=1}^{N} \frac{OPEX - RV}{(1+r)^n}}{\sum_{n=1}^{N} \frac{Y_0(1-D)^n}{(1+r)^n}}$$

N = PV system life [years]
CAPEX = total initial investment (CAPEX) [€/kWp]
OPEX = annual operation and maintenance expenditures (OPEX) [€/kWp]
RV = residual value [€/kWp]
r = discount rate [%]
YO = initial yield [kWh]
D = system degradation rate [%]

Sensitivity of LCOE:

1. Yield
2. CAPEX
3. Lifetime or discount rate
4. OPEX
5. Degradation

C. Tjengdrawira, D. Moser, U.Jahn, M. v. Armansperg, I. Theologitis, M. Heisz,"PV Investment Technical Risk Management," Solar Bankability Consortium Deliverable D5.8, 2017

Bifacial Reliability

Module Reliability 'Laundry List'

15+ years ago:

Al-BSF

Module packaging issues:

- Encapsulant discoloration
- Delamination
- Solder bond failure
- Fractured glass
- Fractured cells
- Backsheet issues

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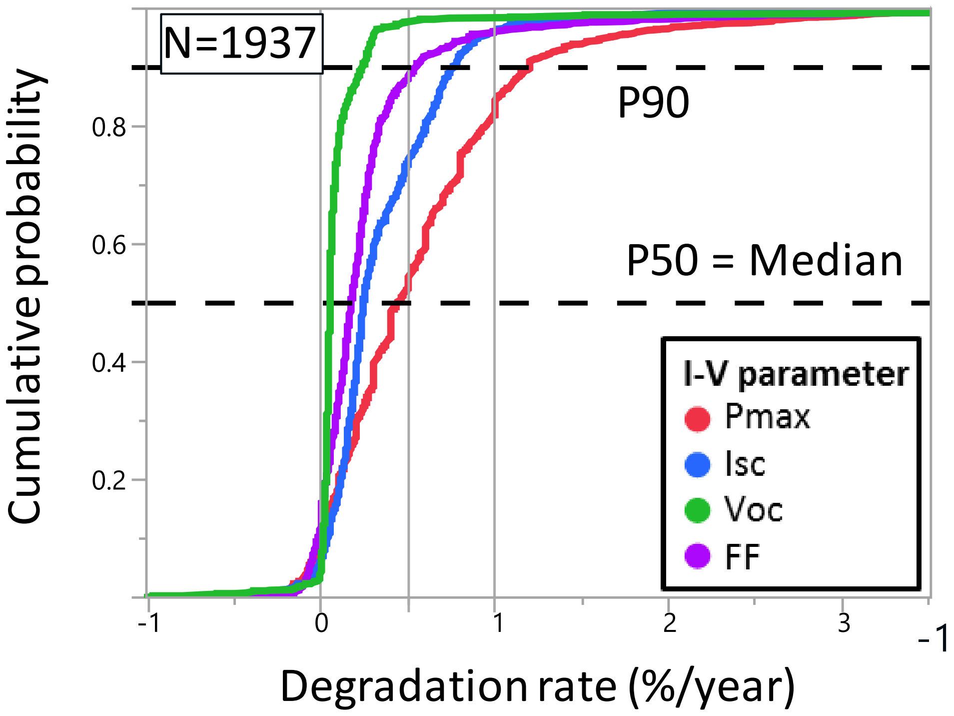

Jordan et al., JPV, 2018

Now:

Al-BSF, PERC, HIT, TOPCON, PERT

Module packaging issues:

- Encapsulant discoloration
- Delamination
- Solder bond failure
- Fractured glass
- Fractured cells
- Backsheet issues

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- **Cell related issues**

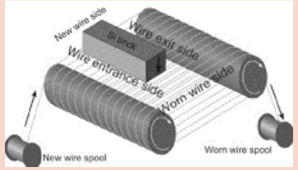
PV reliability is changing → see more cell related issues in modules & systems

D. Jordan Slide

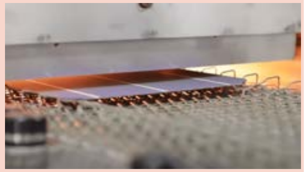
Midlife Crises for PV modules– Latent Damage and Environmental Exposure

Manufacturing

Cutting



Firing

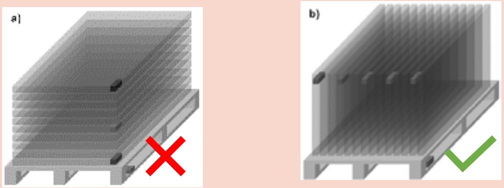


Soldering

Lamination

Installation

Transportation



Mounting

Operational loading and environmental conditions

Thermal cycles

Wind

Snow

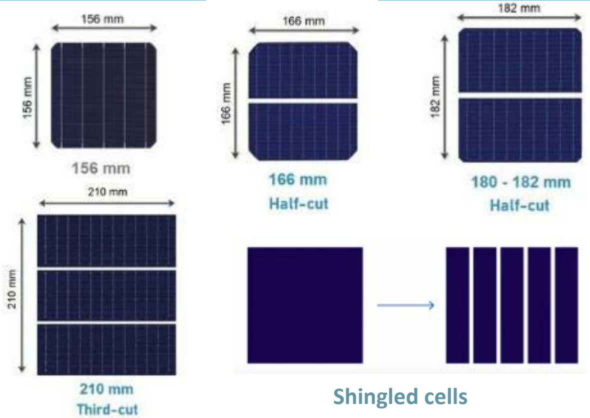
Severe weather events

Hailstorm

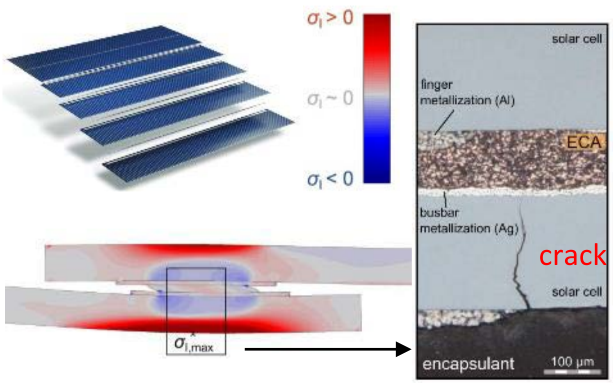
Hurricane

Tornado

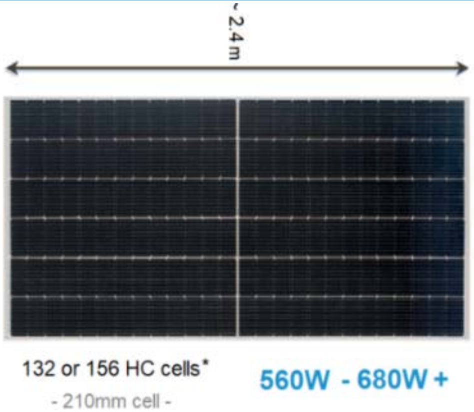
Cut Cells



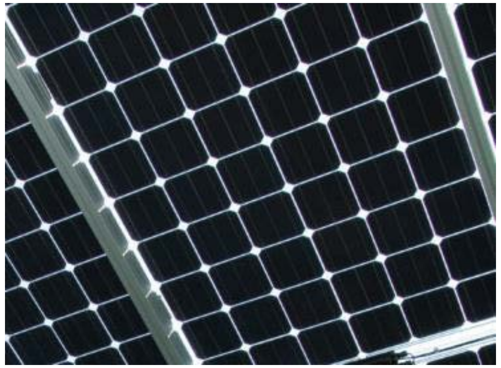
Shingled interconnection



Larger modules

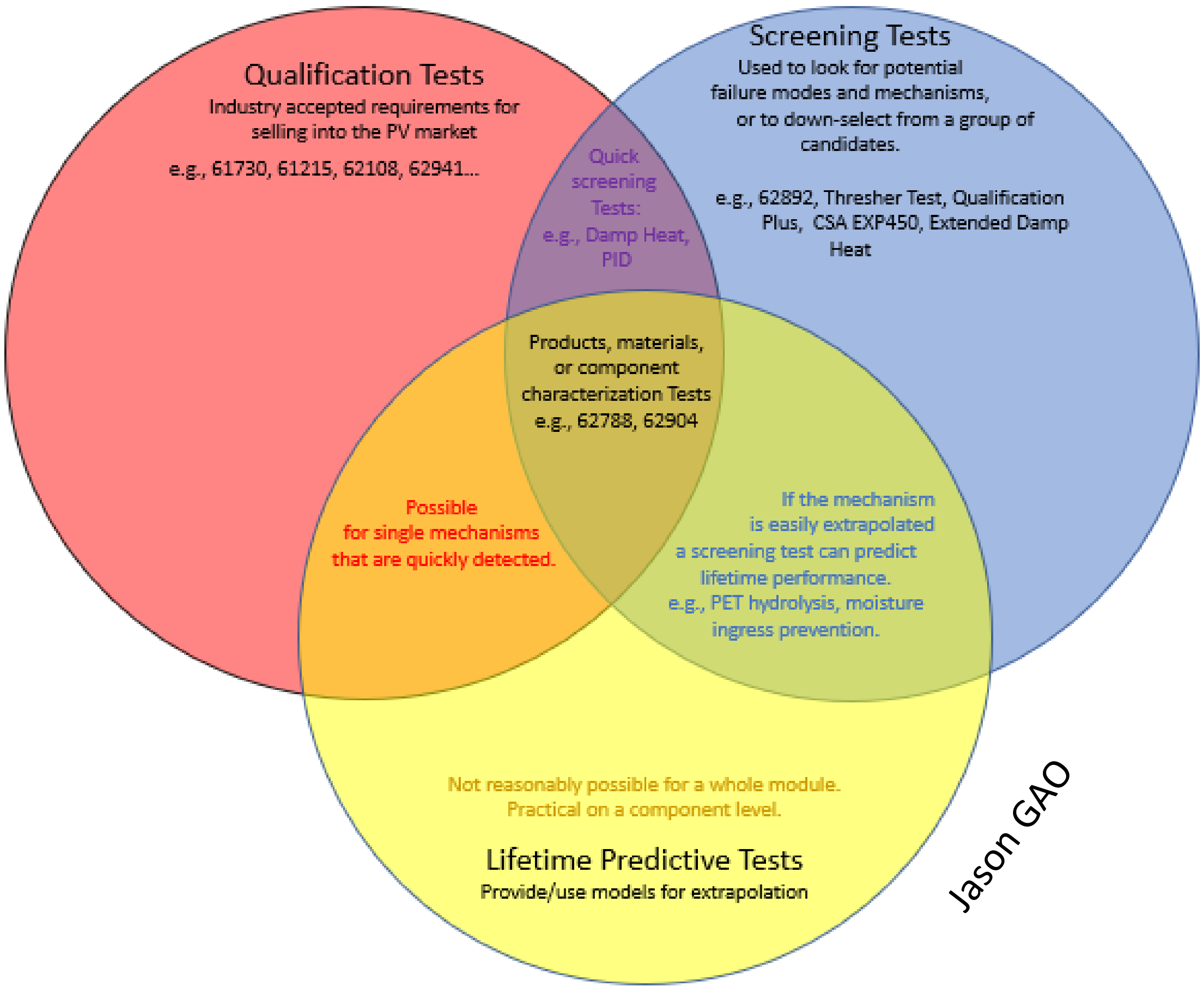


Glass/Glass modules



Bifacial Standards

- 61215 qualification test now includes 135W/m^2 rear irradiance for test conditions (BNPI)
- 1-sun STC rating includes calculation of rear efficiency ratio ϕ_{bifi} and performance at rear irradiance values of 100 & 200 W/m^2
- Capacity test, energy test, field instrumentation standards are in the works, among others



Key Differences in Bifacial Module Design

F + R

- Transparent
- Irradiance

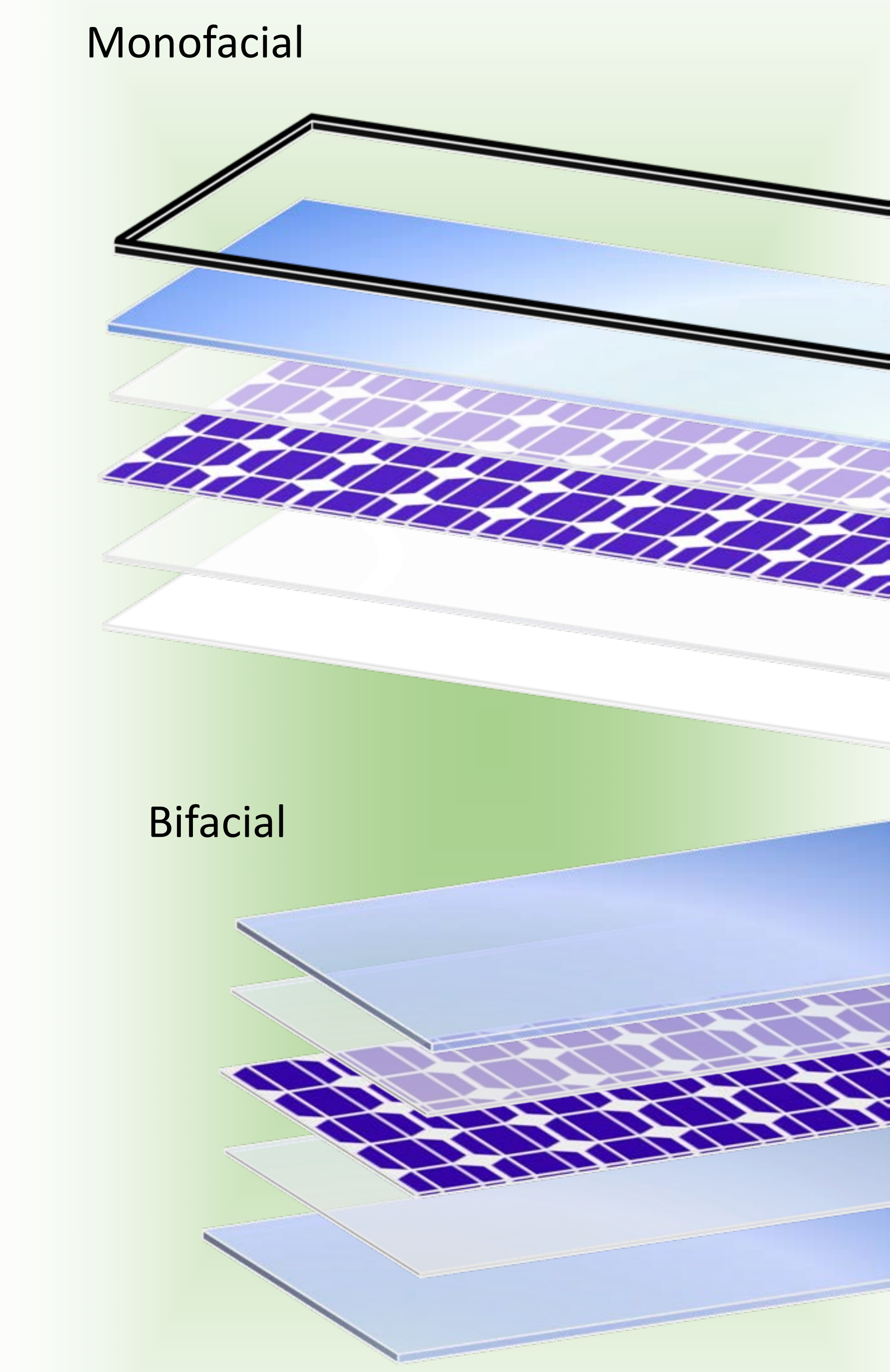
800W - >1200W

Current

- Junction Box Design
- Diode Voltage
- BOS design
- Hot Spots

Heat

- HOT Junction Box (~90^{o}C)
- NOCT is 1-5 ^{o}C higher
- Most degradation processes are thermally activated

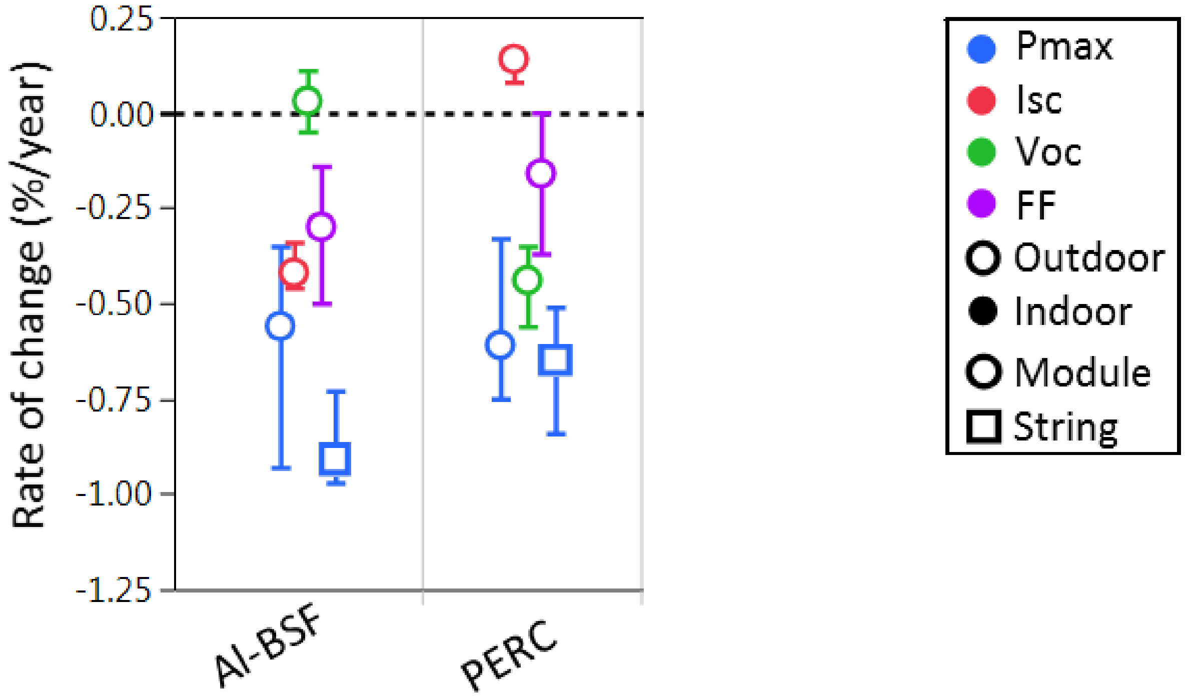


Cell degradation

Module rack

String rack

Same manufacturer, installed at the same time
Modules & 1 string with 8 modules each
All mono-Si, Al-BSF, PERC (glass-glass), Bifacial PERC (glass-glass)



Bifacial module was also measured indoors before and after 2 ½ years

- PERC & Al-BSF control module show degradation in line with historical values
- Al-BSF: typical Isc & FF ←→ PERC: Voc, Bifacial PERC: Isc, FF & Voc

D. Jordan 2020

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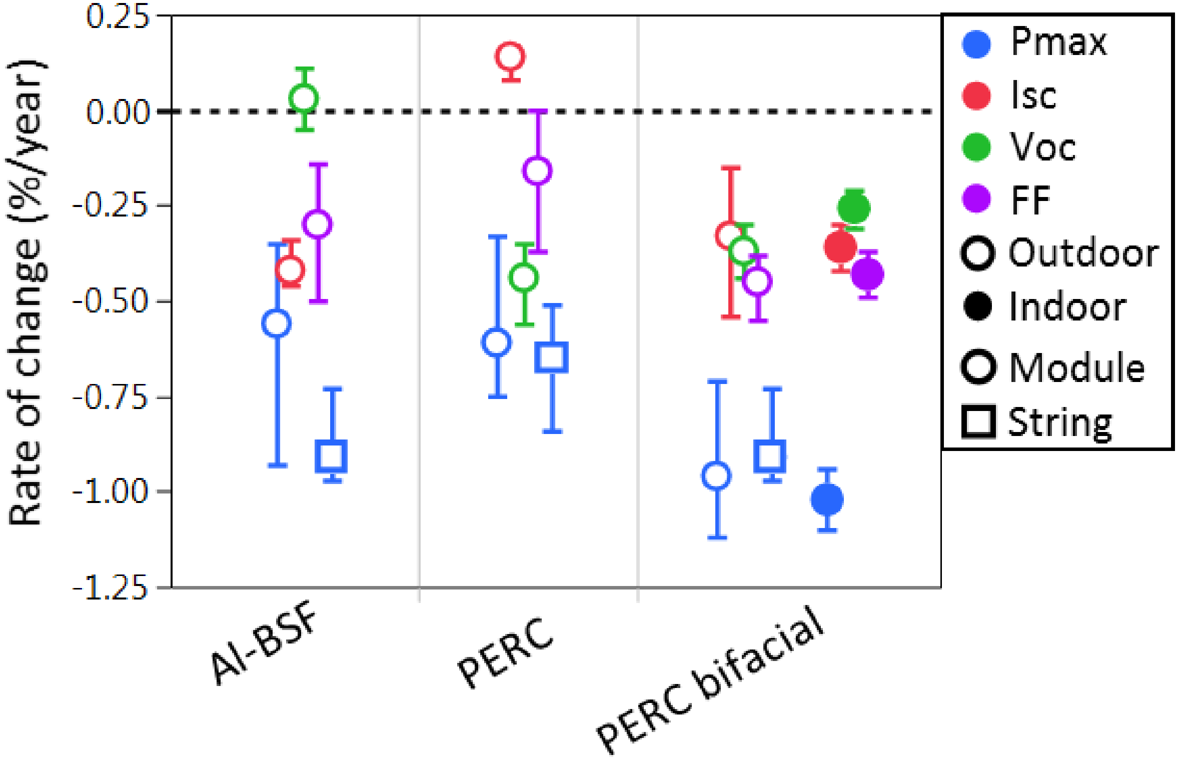

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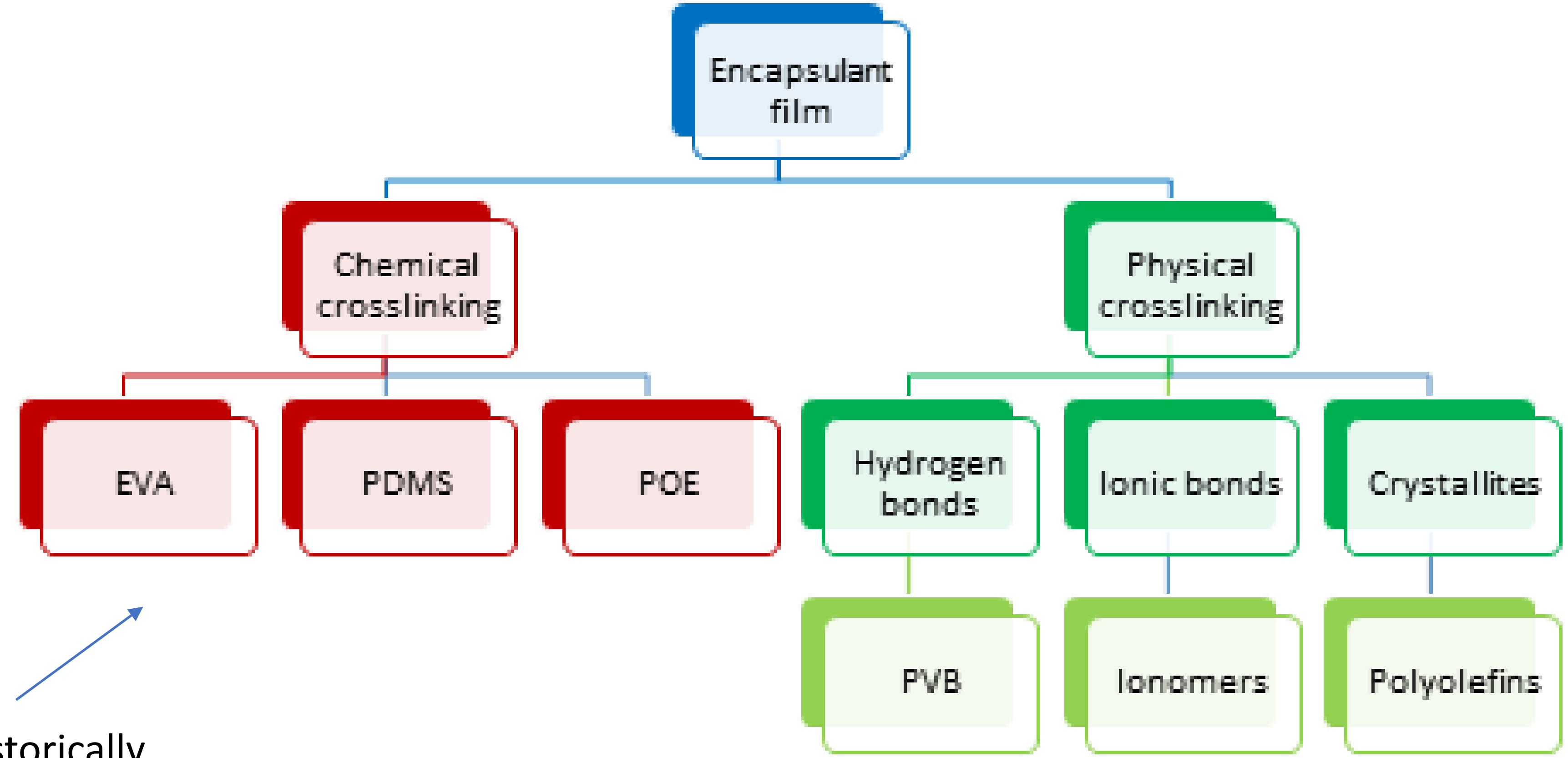
D. Jordan 2020

Encapsulant Summary



Historically common

Used in G/G modules for BiPV

lower temperature laminations (speed up manufacturing process?)

popular in certain G-G modules (i.e. First solar)

From: IEA PVPS STI 1.1 Report (tbp 2021). Arrows Silvana Summary

G/G versus G/tB

(transparent Backsheet)

CATEGORY	G/tB	G/G	+ Frameless
Industry Experience	New technology plus bifacial uncertainty added on	G/G modules in the field for a long time (not necessarily bifacial)	
Mechanical Aspects	Under evaluation	• Stronger • Less prone to scratches • Less prone to hot spot burns • Less flammable • More resistant to sand abrasion, alkali, acid, or salt mist • Less stress on cells if same thicknesses front and back ('sandwich') • Allows for Frameless Design	More uniform deformation
Permeation	• Allows diffusion and escape of H from the rear of the cell (avoids rear-delamination) • Higher moisture ingress	• Less diffusion allowed • Lower Moisture Ingress (avoids non-desirable chemical reactions in the cell and oxidation)	Might need edge seal
Encapsulant	More options	• Non-EVA encapsulants for G-G Shorter history • Increased EVA thickness to reduce risk of microcracks • EVA: risk of outgasing; acetic acid build up can lead to corrosion	
Lifetime Warranties	30 years*	30 years	
Operation Temperature		Higher than G/B	
Manufacturing	• Same manufacturing equipment as G/B	• Line requires adding glass washer, glass handling robots, and additional conveyor or handling equipment • Rework of yield loss is difficult or impossible (but glass is highly recyclable)	Less cost for manufacturer (shifts to racking company)
Cost of the back surface itself	???		
Shipping		• Special design of containers due to weight • Higher transport cost due to weight	Special transport required for frameless
Installation	Weight ~11.3kg/m2	• Weight ~15.2kg/m2 (Above OSHA1-person limit for 72 cell module)[2] • Higher installation cost • Longer Omegas to support weight	• Special Clamps needed - extra cost and extra complexity • Installation errors - learning curve. i.e. over-torqueing
Other	• Field repairable? • Less recyclability if crosslinked materials	• Not repairable • Higher module recyclability value	• Less Soiling • Less snow retention
New Failure Modes		• PID issues on mono PERC modules (possible cause doubling the NA source) • Bus wire exits -- new failure mode?	• Reduced risk of PID from the ungrounded system

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Bifacial Field at NREL

Examples of Bifacial Installations in Literature

$$BG_E[\%] = \frac{\varphi \times E_{rear}}{E_{front}} \times 100$$

$$BG[\%] = \left(\frac{Y_{bifacial}}{Y_{monofacial}} - 1\right) \times 100$$

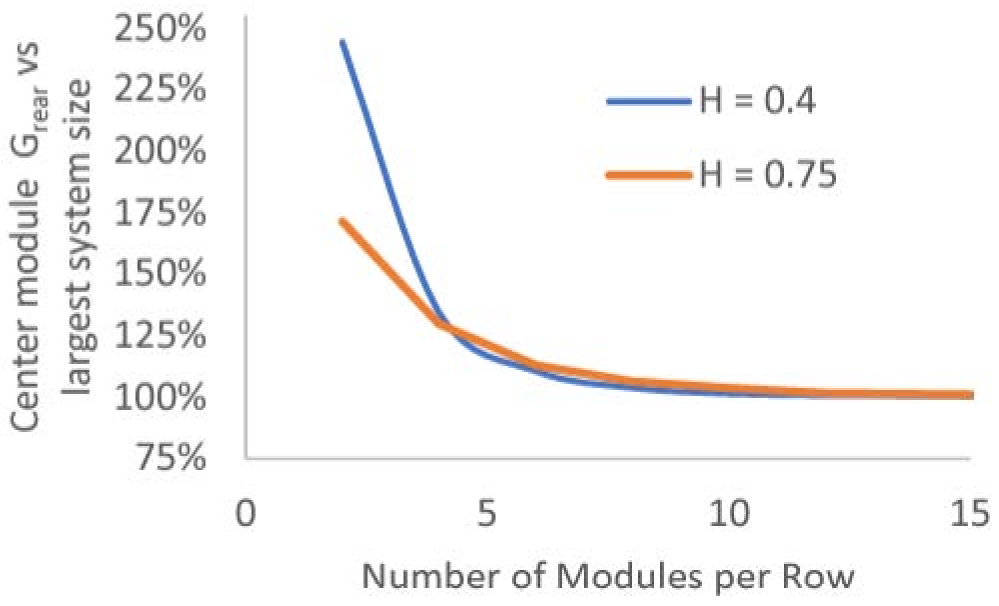
Location (Type)	Elevation / Module Height (m)	Albedo / Bifaciality	Tilt Angle / Facing	Reported Bifacial Gain (%)	Calculated Bifacial Gain (%)	Difference (%)
Cairo (Sim.) [11]	1 / 0.93	0.2 / 0.8	26° / South	11.0	11.1	-0.1
Cairo (Sim.) [11]	1 / 0.93	0.5 / 0.8	22° / South	24.8	25	-0.2
Oslo (Sim.) [11]	0.5 / 0.93	0.2 / 0.8	51° / South	10.4	13.6	-3.2
Oslo (Sim.) [11]	0.5 / 0.93	0.2 / 0.8	47° / South	16.4	22.8	-6.4
Hokkaido* (Exp.) [46]	0.5 / 1.66	0.2 / 0.95	35° / South	23.3	25.7	-2.4
Hokkaido* (Exp.) [46]	0.5 / 1.66	0.5 / 0.95	35° / South	8.6	13	-4.4
Albuquerque (Exp.) [16]	1.08 / 0.984	0.55 / 0.9	15° / South	32.5**	30.2	2.3
Albuquerque (Exp.) [16]	1.08 / 0.984	0.55 / 0.9	15° / West	39**	36.7	2.3
Albuquerque (Exp.) [16]	1.03 / 0.984	0.25 / 0.9	30° / South	19**	14.6	4.4
Albuquerque*** (Exp.) [16]	0.89 / 0.984	0.25 / 0. 9	90° / South	30.5**	32.2	-1.6
Golden (Exp.) ****	1.02 / 1.02	0.2 / 0.6	30° / South	8.3	8.6	-0.3

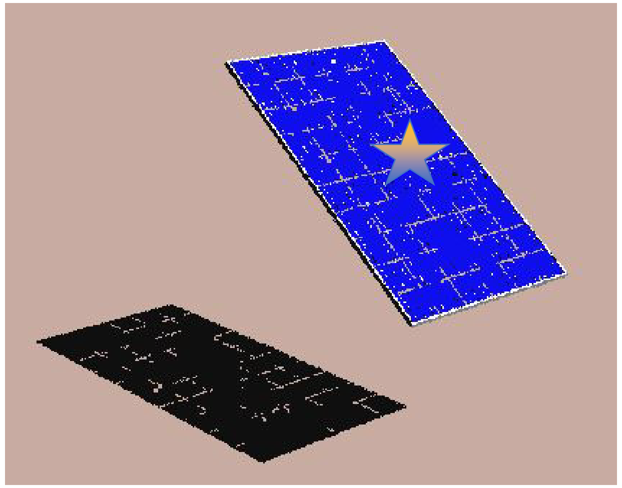
* Only data from May to August were used to eliminate snowing effects.
** Average bifacial gain of multiple test modules was used.
*** The east-west-facing vertical modules measurement in [16] shows great discrepancy between two modules; therefor, it is not included here.
**** Bifacial measurement (12/2016 to 08/2017) performed by the National Renewable Energy Laboratory.

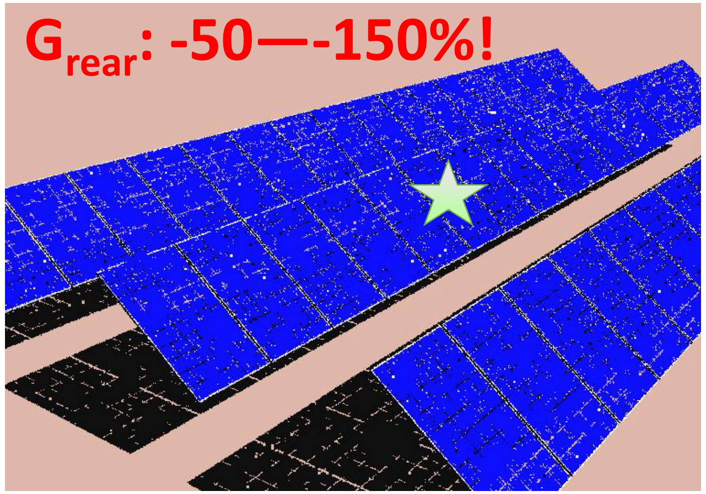
Table Source: Sun, Xingshu, Khan, Mohammad Ryyan, Deline, Chris, and Alam, Muhammad Ashraful. ***Optimization and performance of bifacial solar modules: A global perspective***. United States: N. p., 2018. Web. doi:10.1016/j.apenergy.2017.12.041.

Sistem Size for representative Self-shading

"Steady-state Rear Irradiance"







C. Deline et al., Assessment of Bifacial Photovoltaic Module Power Rating Methodologies – Inside and Out, J. Photovoltaics **7,** 2017
Ovaitt et al, Model and Validation of Single-Axis Tracking with Bifacial PV, JPV 2019. 10.1109/JPHOTOV.2019.2892872

Why bifacial vs monofacial counterpart comparison?

Overall energy gain for a bifacial system is determined by comparing Energy Yield [kWh] for both monofacial and bifacial systems

$$BG[\%] = \left(\frac{Y_{bifacial}}{Y_{monofacial}} - 1\right) \times 100$$

Silfab module photo

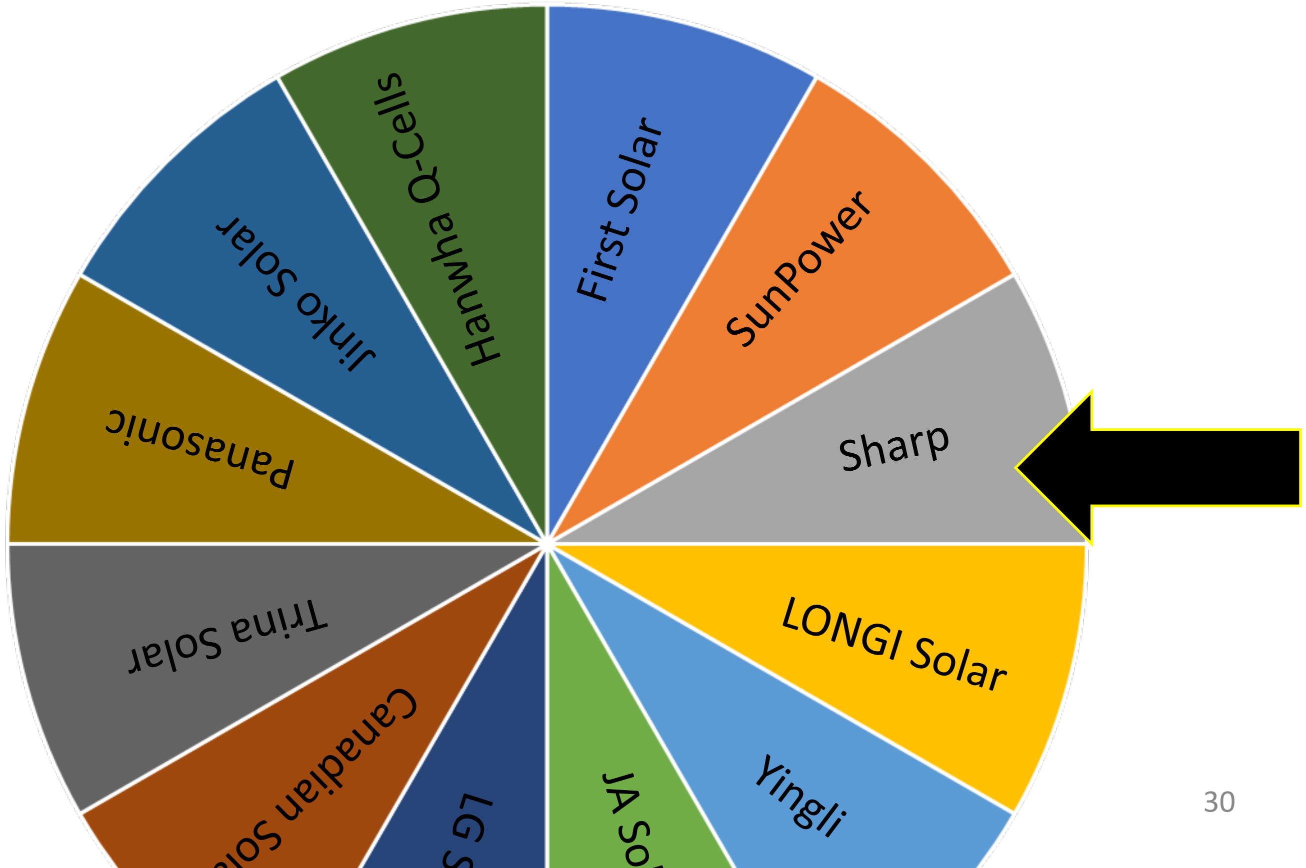
Why bifacial vs monofacial counterpart comparison?

Overall energy gain for a bifacial system is determined by comparing Performance Ratio [kWh/kW] for both monofacial and bifacial systems

$$BG_{Meas} = \left(\frac{PR_{bifi}}{PR_{mono}} - 1\right) \times 100\%$$

Silfab module photo

VS.



Why bifacial vs monofacial counterpart comparison?

$$BG_{Meas} = \left(\frac{PR_{bifi}}{PR_{mono}} - 1\right) \times 100\%$$

- Difference in module rating
- Temperature coefficient
- Low light dependence
- Mounting orientation
- Bifaciality

$$BG_{\text{Meas},bifaciality} = \left(\frac{PR_{bifi}}{PR_{mono}} \underbrace{\frac{PR_{mono,model}}{PR_{bifi,model}}}_{\text{Correction Factor}} - 1\right) \times 100\%$$

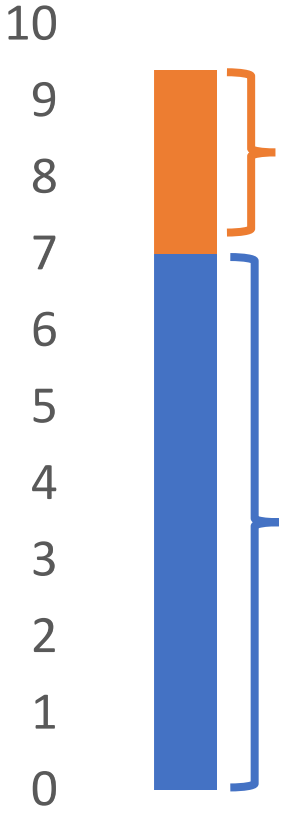
Ovaitt et al, Model and Validation of Single-Axis Tracking with Bifacial PV, JPV 2019. 10.1109/JPHOTOV.2019.2892872

Why bifacial vs monofacial counterpart comparison?

100 kW of Silfab HJT,
2-up landscape

100 kW of Trina mcSi,
1-up portrait

H = 0.75, GCR = 0.35, Albedo = 0.2 (short grass)



Expected frontside gain
(temperature coefficient, low light performance, etc...)

Bifaciality gain

$$BG_{\text{Meas},bifaciality} = \left(\frac{PR_{bifi}}{PR_{mono}} \frac{PR_{mono,model}}{PR_{bifi,model}} - 1 \right) \times 100\%$$

32

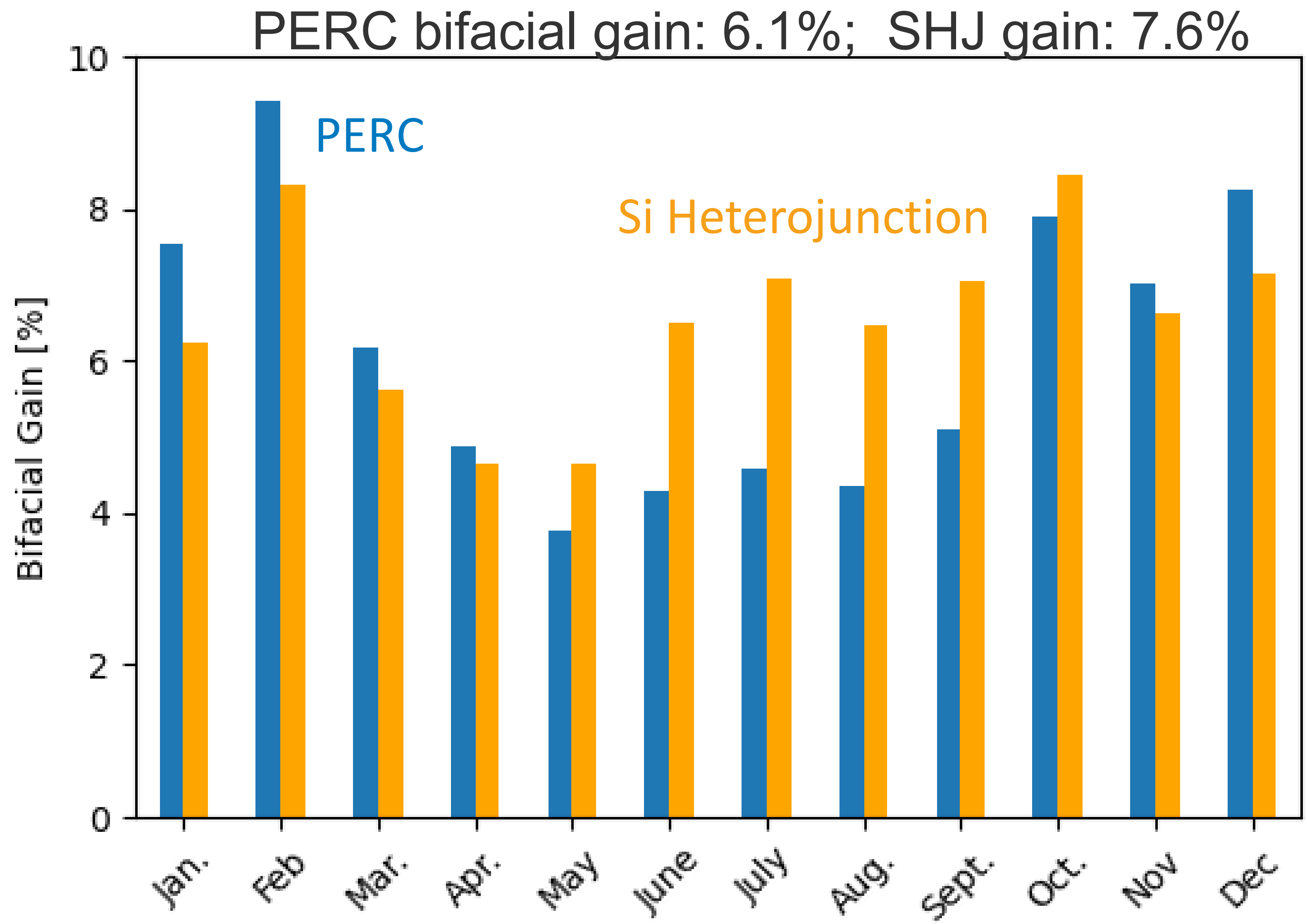
Ovaitt et al, Model and Validation of Single-Axis Tracking with Bifacial PV, JPV 2019. 10.1109/JPHOTOV.2019.2892872


75 kW bifacial HSAT
5 bifacial technologies
https://datahub.duramat.org/dataset/best-field-data

3-year Technology Performance

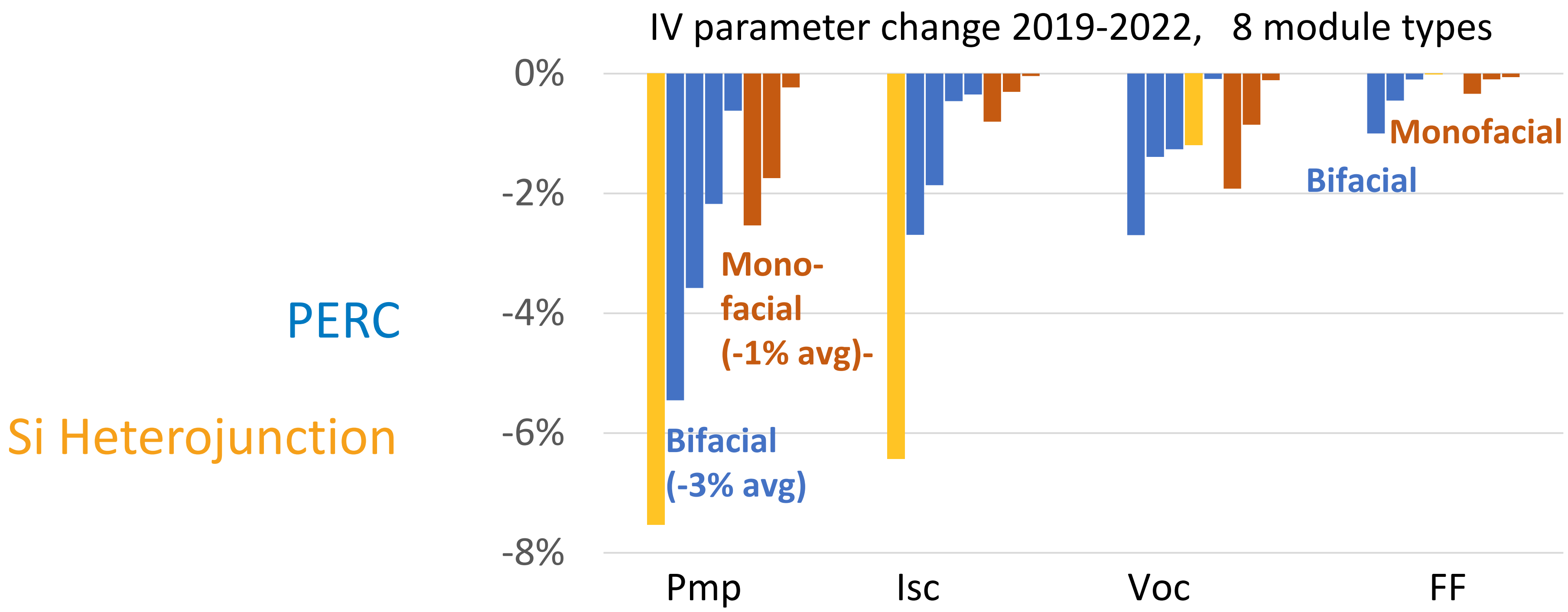
$$\frac{Energy\ bifacial}{Energy\ monofacial} - 1 \quad [\%]$$

*Grouped by Month

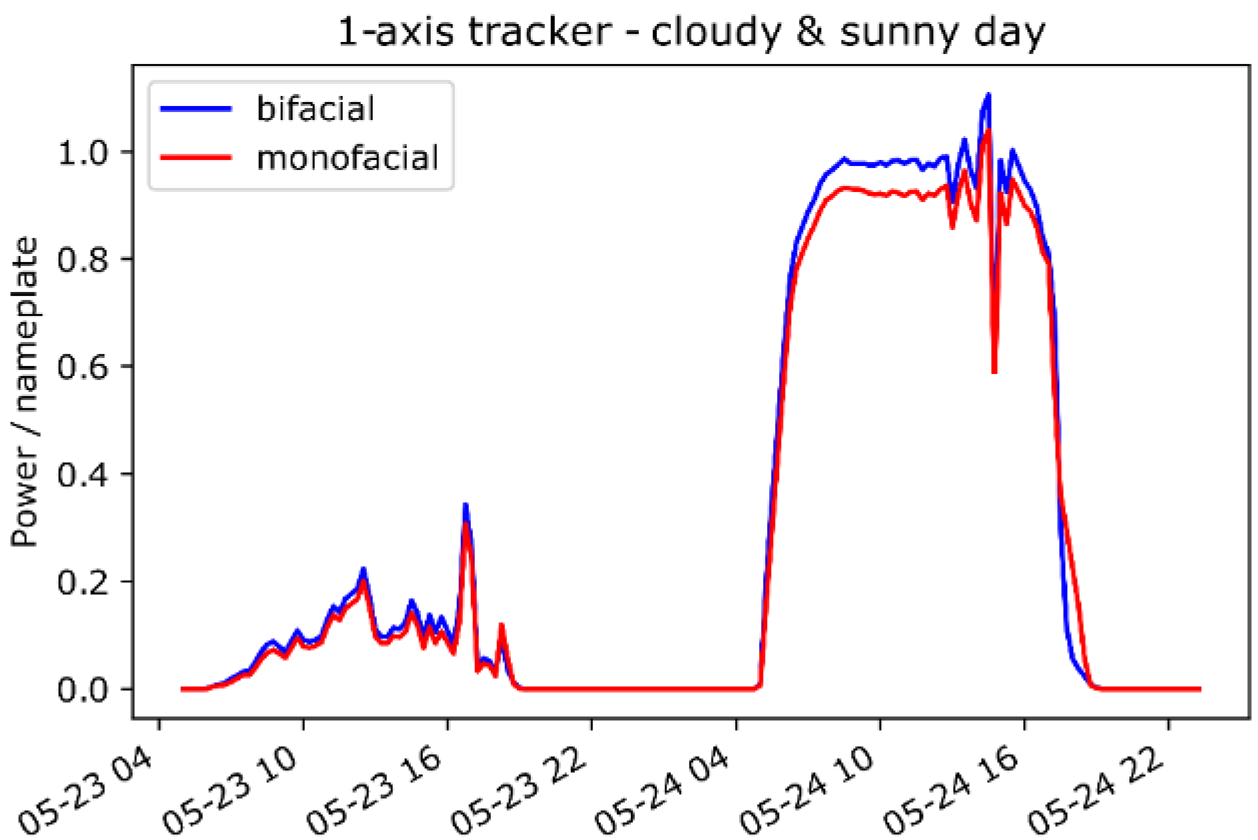


Degradation

- Initial Bifacial energy gain has a slight downward trend over 3 years.
- On average, **bifacial PERC and Si-HJT** are degrading faster than **monofacial counterpart**
- Indoor flash-test confirms performance loss; **Isc change** is the dominant difference
- Possible causes: Ga vs B doping, G/G vs G/backsheet, PID-p with high-conductivity encapsulant

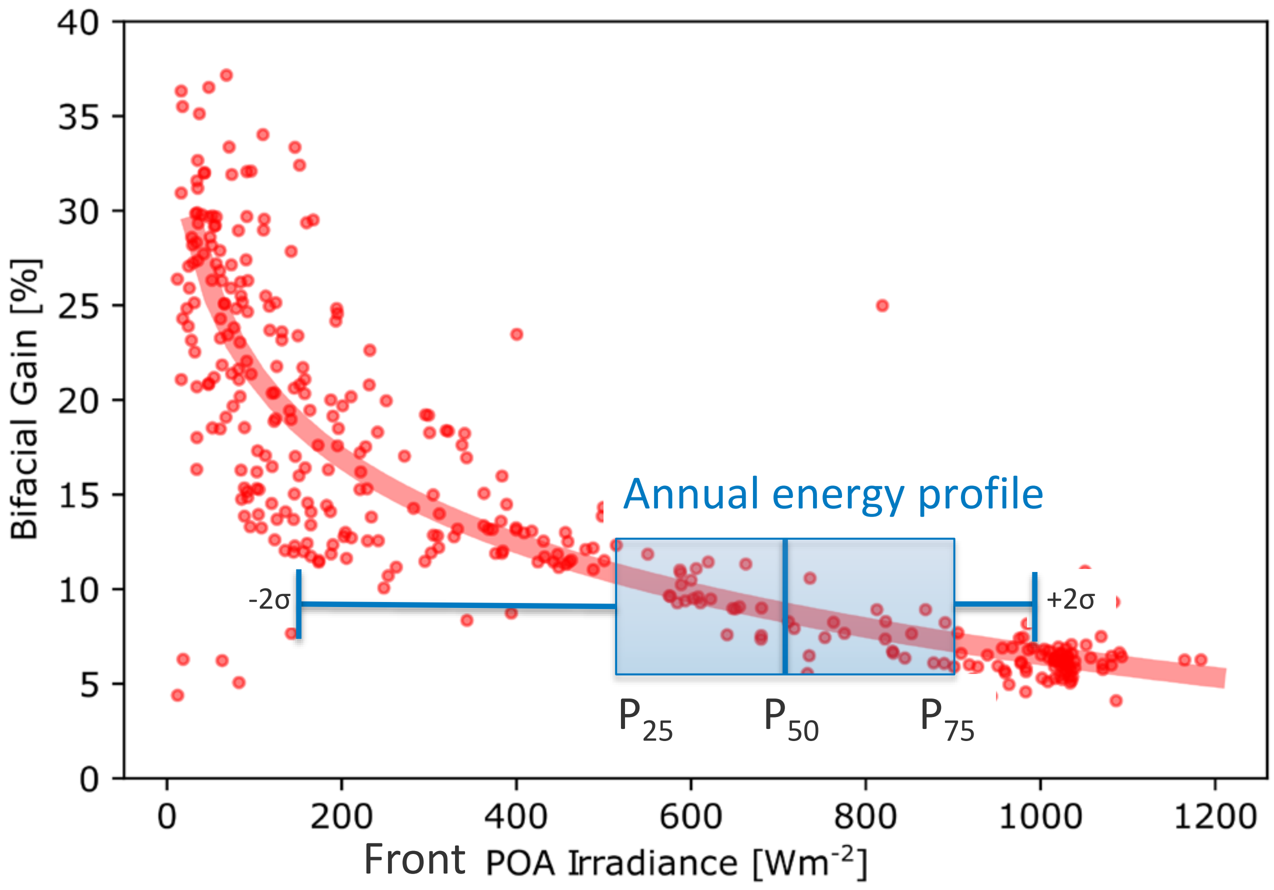


Daily Performance



$$BG_E = \frac{E_{bifacial}}{E_{mono}} - 1$$

Bifacial Gain vs Irradiance Levels



$$BG_E = \frac{E_{bifacial}}{E_{mono}} - 1$$

Bifacial Gain vs Irradiance Levels

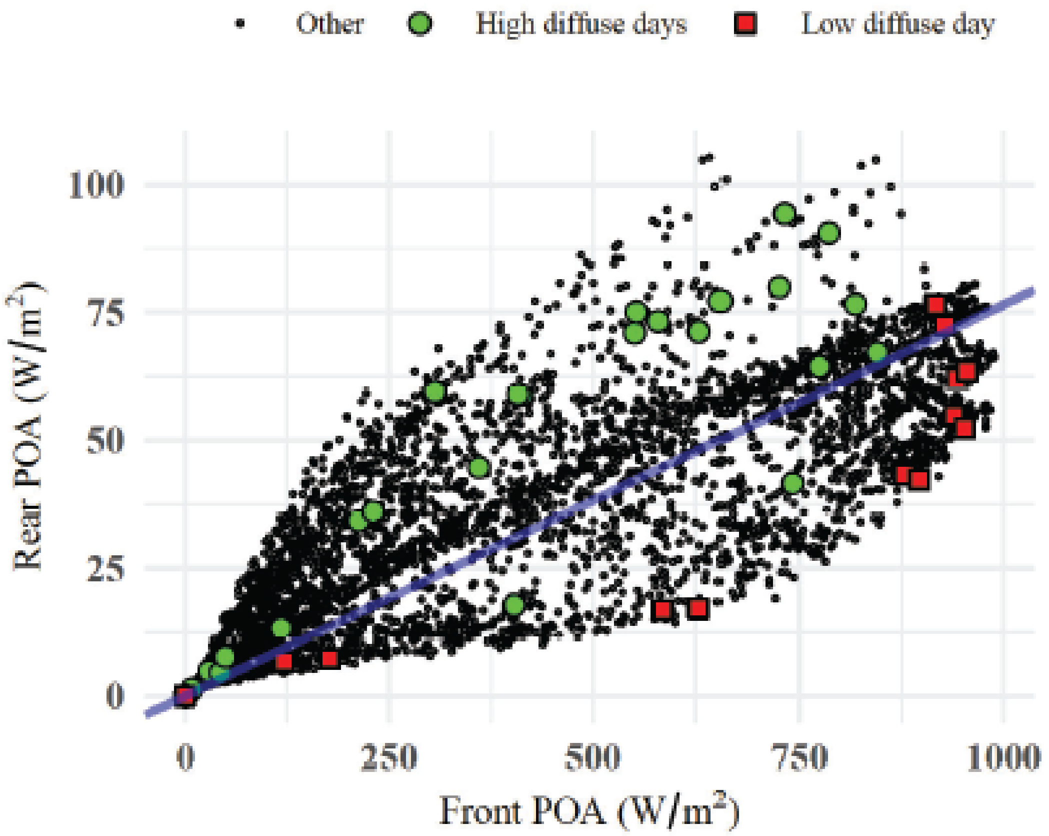
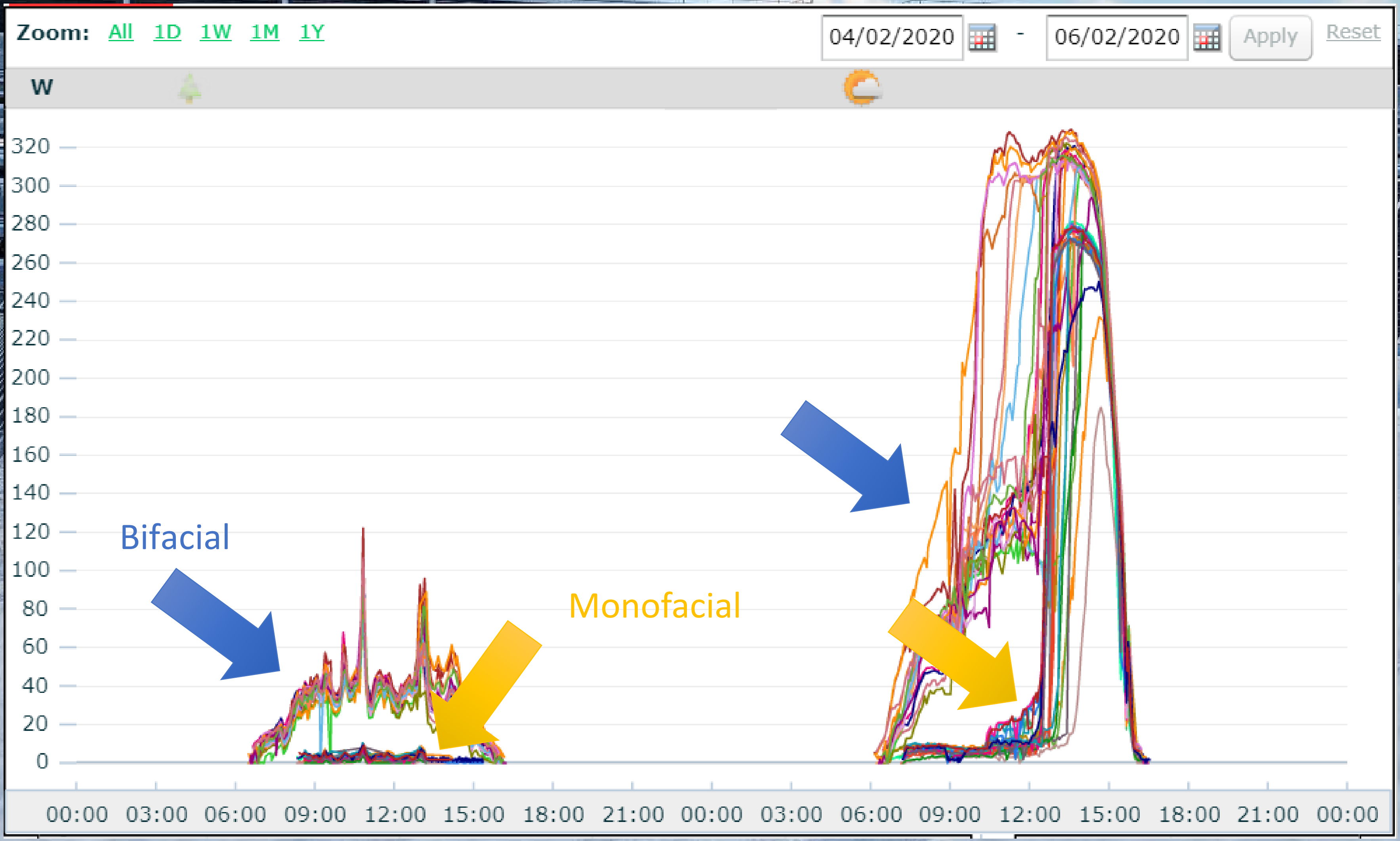


Fig. 6. Impact of different diffuse irradiance fraction conditions, showing non-proportionality of rear-side and front-side POA irradiance. Green: sample high diffuse fraction days. Red: sample low diffuse fraction days.

Gostein, Ovaitt, et al (2021). Measuring Irradiance for Bifacial PV Systems. PVSC 10.1109/PVSC43889.2021.9518601

Snow



Zoom: All 1D 1W 1M 1Y
04/02/2020 - 06/02/2020 Apply Reset
W
320
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
00:00 03:00 06:00 09:00 12:00 15:00 18:00 21:00 00:00 03:00 06:00 09:00 12:00 15:00 18:00 21:00 00:00
Bifacial
Monofacial

Instrumenting and Modeling a bifacial Field

New system design

Hourly, typical meteorological data
Due diligence software, production and even cost models
Optimizing for terrain features, weather resiliency, yield & cost
"Danger": not taking full advantage of the bifacial advantage

Comparing for capacity testing

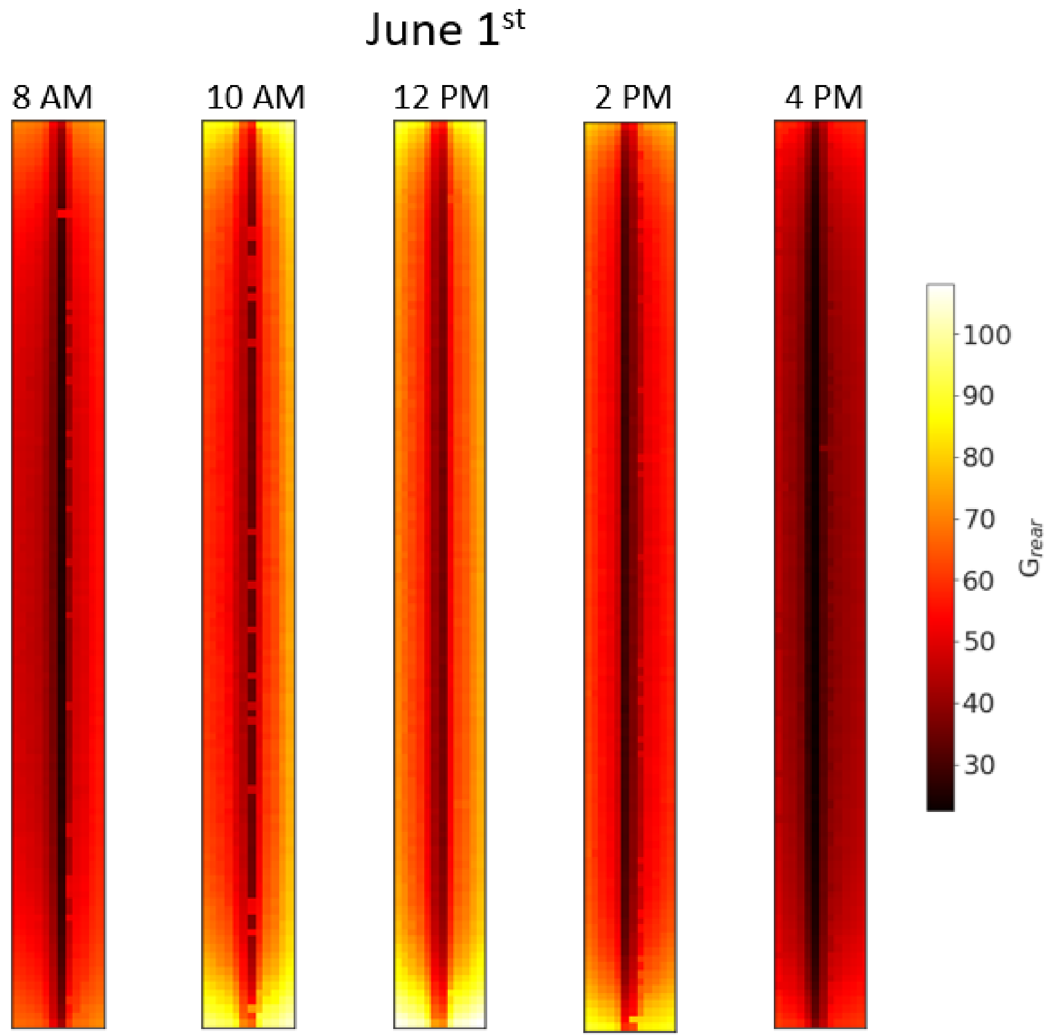
Requirement during initial powering of a system
Standards under modification IEC 61724-2 and IEC 61724-3; some options
"**Danger**": Not selecting appropriate reference conditions; measurement error due to sensor placement; edge effects, different albedo

Performance evaluation

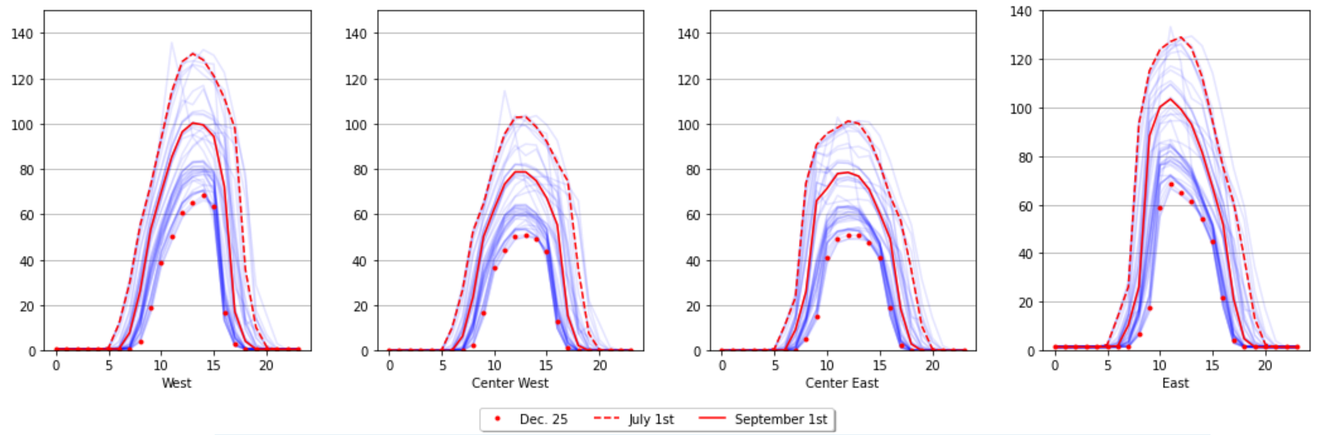
Detecting underperformance, investigate unexpected losses, planning predictive/proactive maintenance, science and knowledge gathering
"**Danger**": more than one effects causing the differences; not enough data to suss the source.

* Research

How & Where to measure rear irradiance



Clear-sky days October 2019-2021

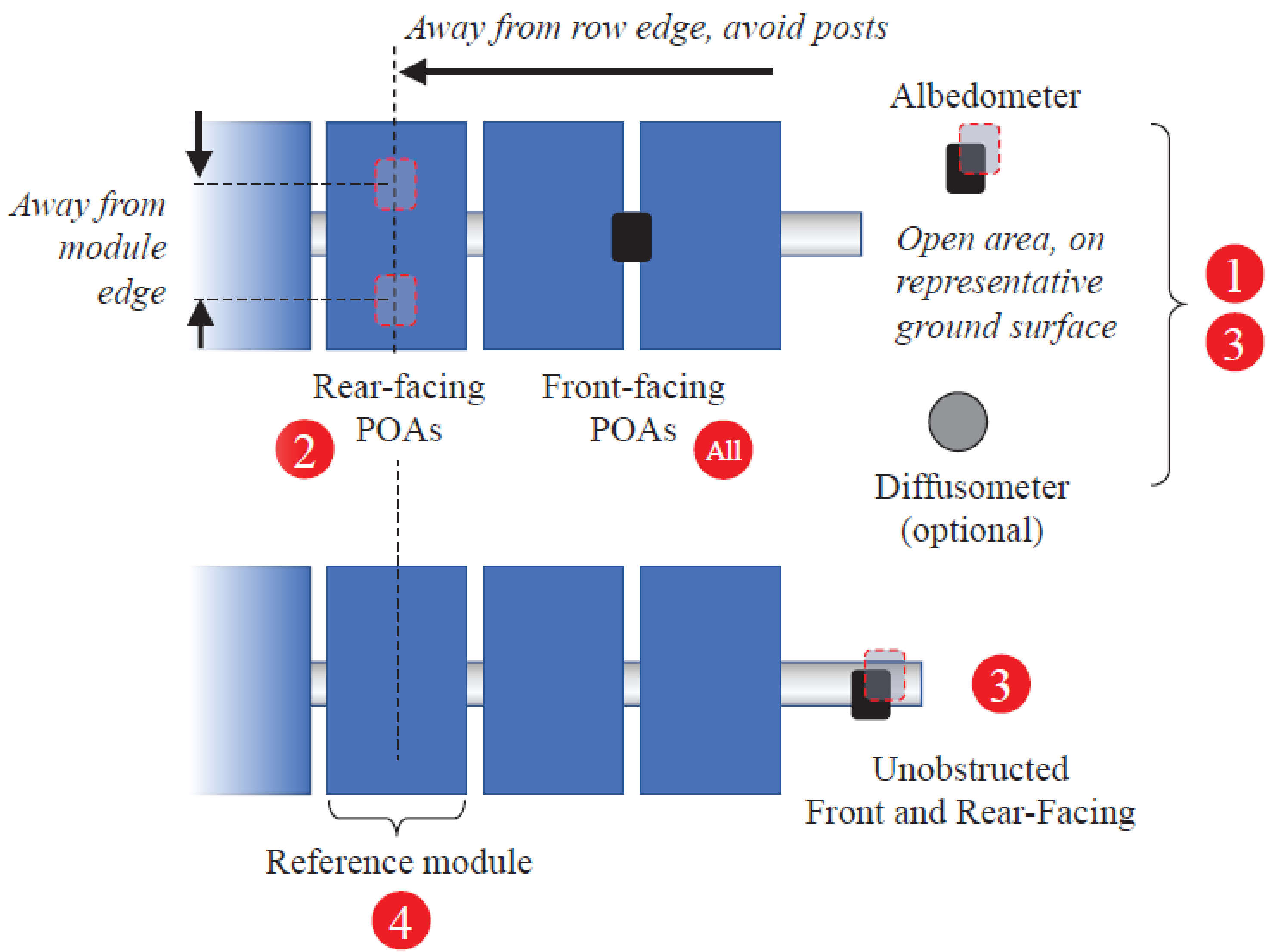


% Difference from Reference Cell Mean

Ref. Cell (WEST)	**7**	**-12**	**-8**	**13**	**Ref Cell (EAST)**
K&Z CM11	13			30%	Licor

https://www.nrel.gov/docs/fy21osti/80281.pdf PVSC 21
https://www.nrel.gov/docs/fy20osti/73203.pdf PVSC 19

How & Where to measure rear irradiance



Gostein, Ovaitt, et al (2021). Measuring Irradiance for Bifacial PV Systems. PVSC 10.1109/PVSC43889.2021.9518601

How & Where to measure rear irradiance

Using a combination of sensors across the module can help reduce standard deviation of the measurements

SENSOR A

SENSOR B

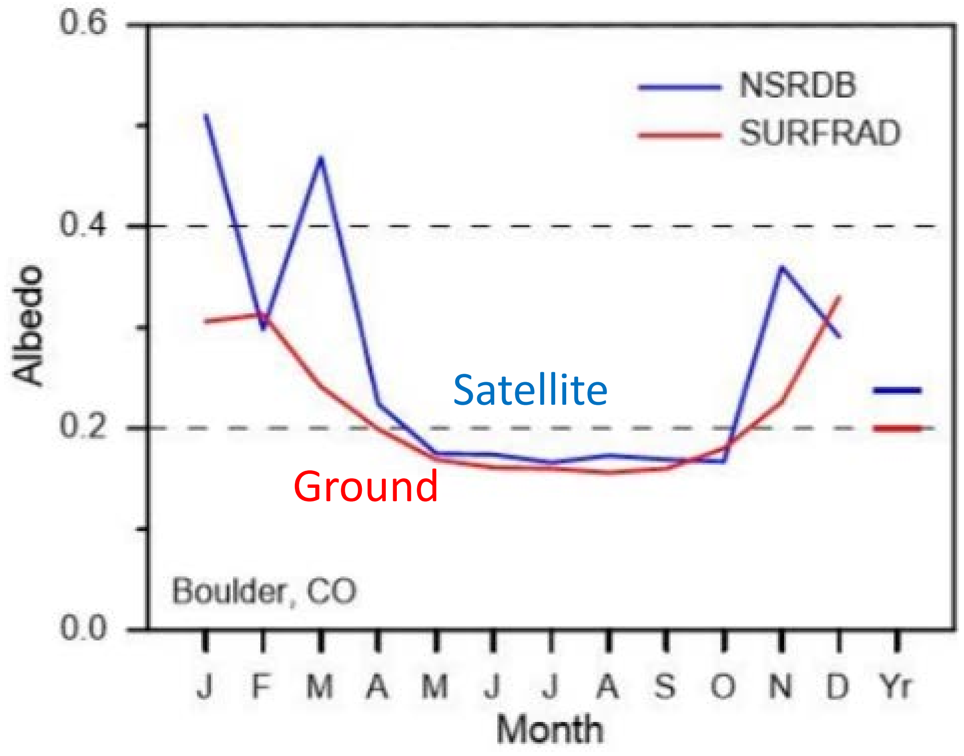
	1	2	3	4	5	6	7	8	9	10	11
2	0.10										
3	0.08	0.07									
4	0.07	0.07	0.06								
5	0.06	0.06	0.06	0.07							
6	0.05	0.05	0.05	0.06	0.08						
7	0.04	0.03	0.04	0.05	0.07	0.08					
8	0.03	0.02	0.02	0.04	0.06	0.07	0.08				
9	0.04	0.03	0.01	0.02	0.04	0.05	0.06	0.06			
10	0.05	0.04	0.02	0.01	0.03	0.04	0.05	0.05	0.06		
11	0.07	0.05	0.03	0.02	0.02	0.04	0.05	0.06	0.06	0.07	
12	0.08	0.07	0.05	0.04	0.03	0.04	0.05	0.06	0.08	0.09	0.10

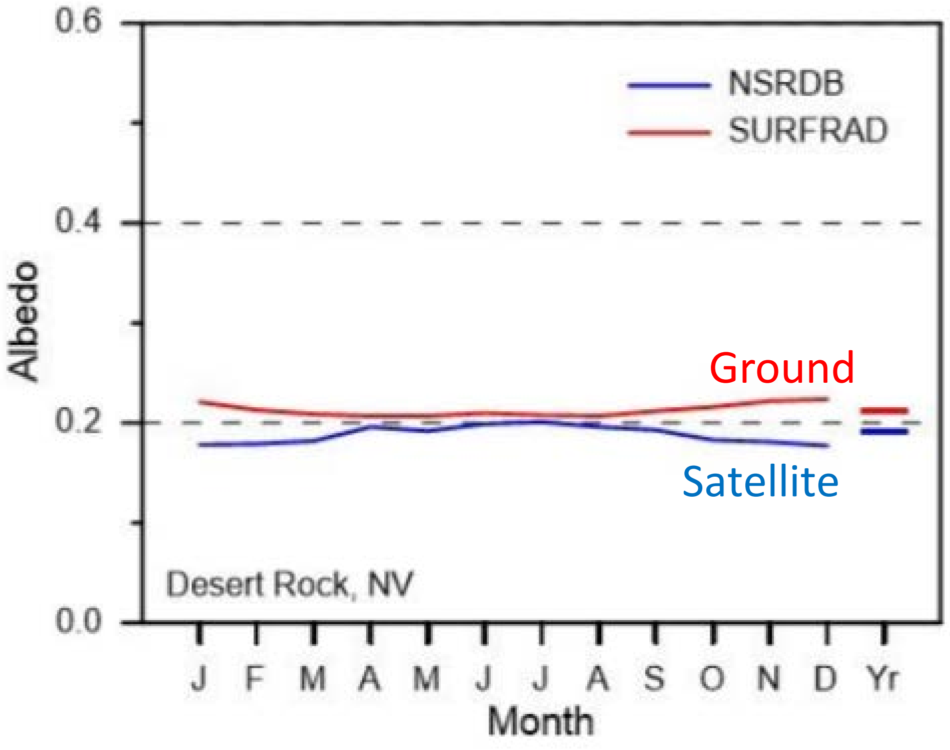
Standard Deviation from Module average

More on rear-irradiance measurement:
Gostein, Ovaitt et al PVSC 2021 https://ieeexplore.ieee.org/document/9518601

Surface vs. Satellite Albedo

Satellite albedos can be close to measured values, but snow may be problematic for the satellite data.





http://bifipv-workshop.com/fileadmin/layout/images/bifiPV/presentations2019/bifdiPV2019-NREL_Marion.pdf

Ground Modification concepts

Optimized Albedo Placement Experiment

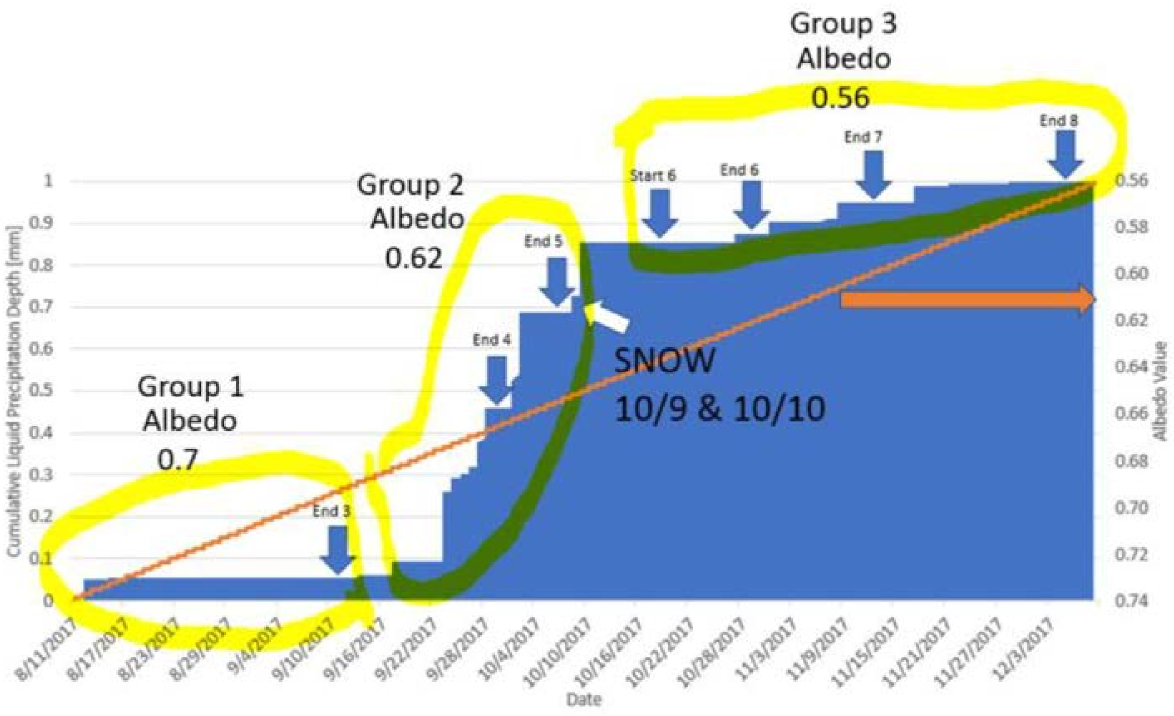
HSAT

+5% Gain in the Bifacial Performance

Optimized Albedo Placement Experiment
HSAT

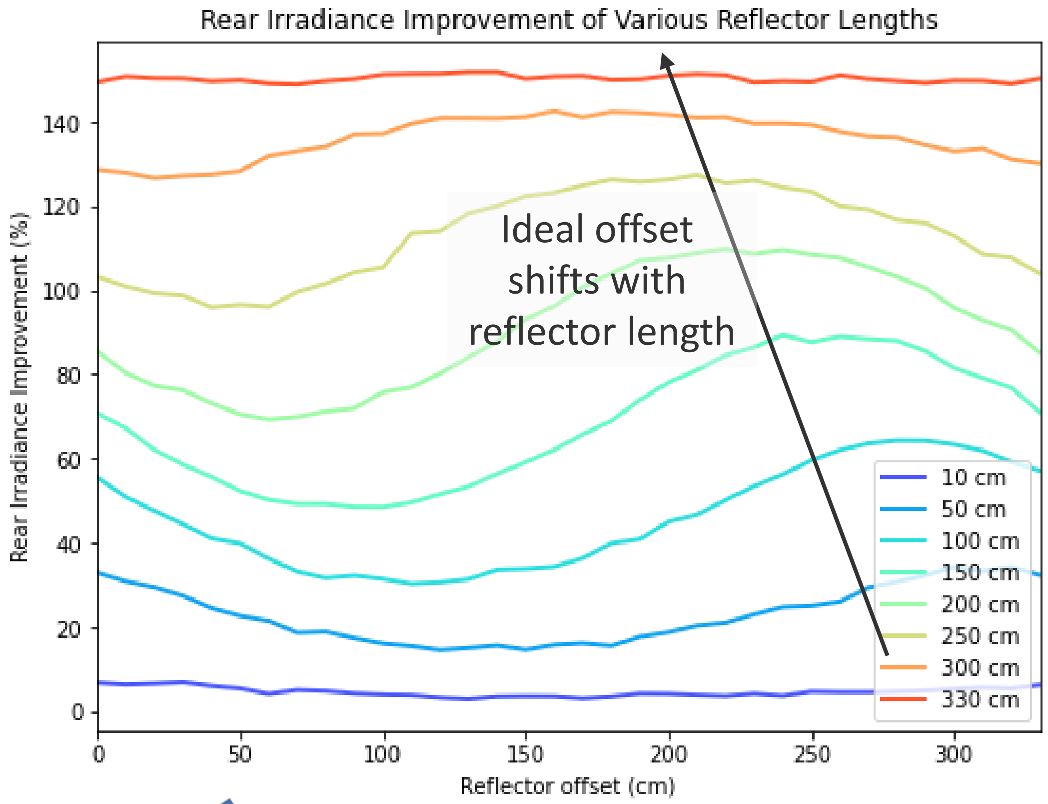
Not everything that shines… stays shiny.

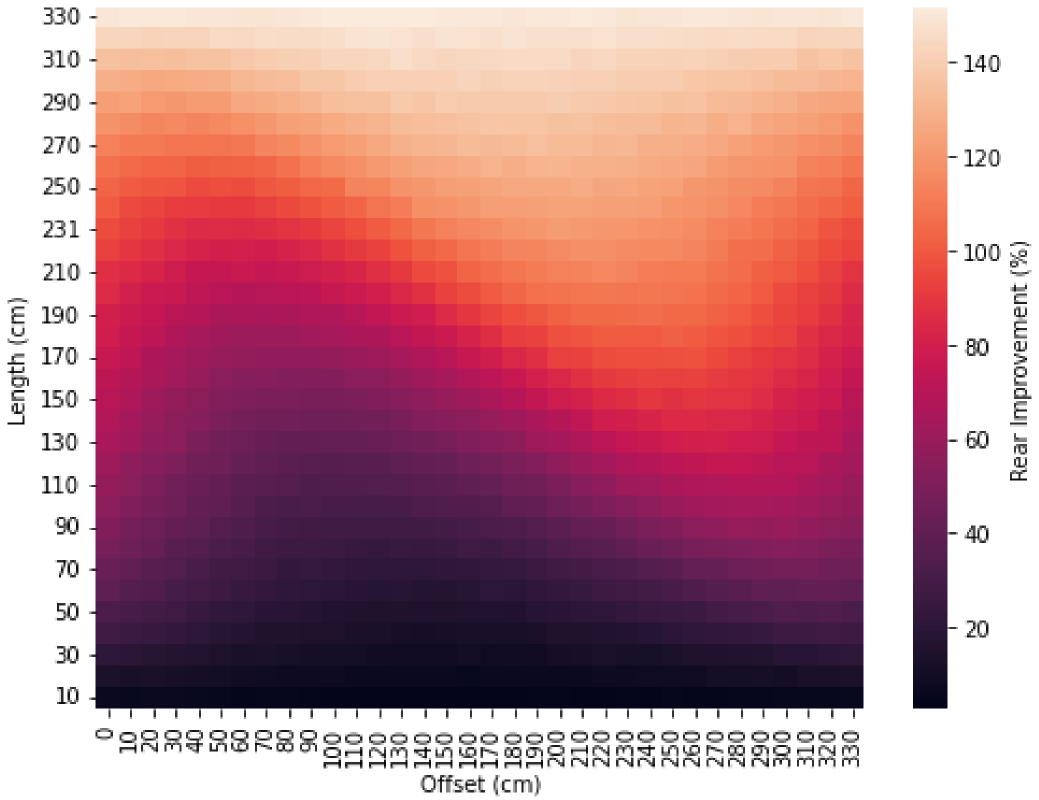
Previous ‘high reflectivity’ rooftop material reduced from 0.7 to 0.56 on 4 months

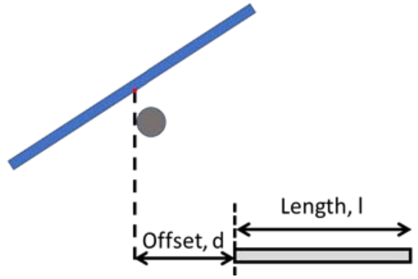


Optimized Albedo Placement

Fixed Tilt





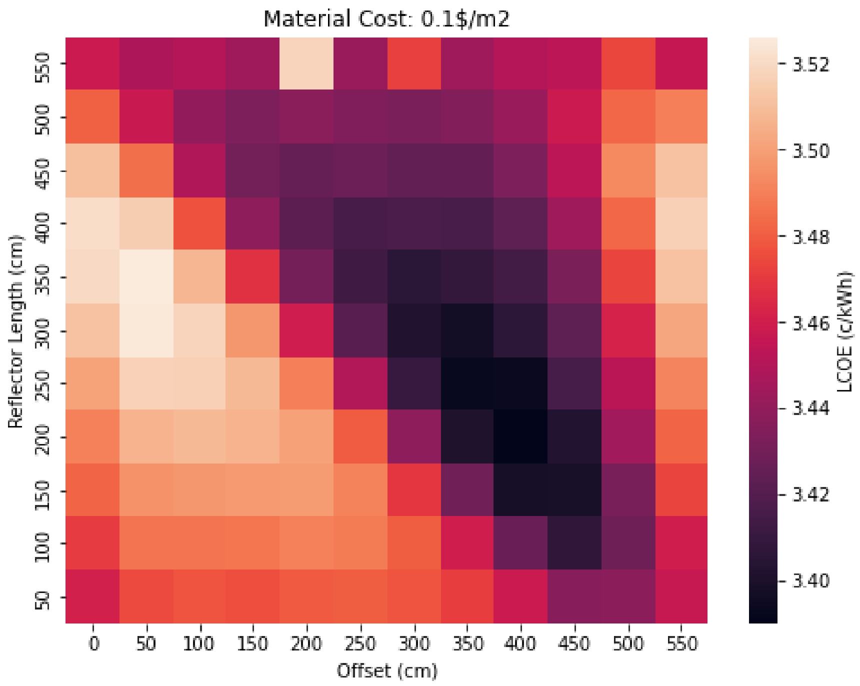


Avg. Rear Irr. (w/reflector)

$$\% \; Rear \; Irr. \; Imp. = \frac{G_{rear} - G_{ref}}{G_{ref}}$$

Avg. Rear Irr. (w/o reflector)

Next steps: LCOE Calculation



$$\text{LCOE}\ (\%) = \frac{(\text{Total CAPEX}\ (\$) * \text{CRF}) + \text{Annual O\&M}\ (\$)}{\text{CF}(\%) * 8760\ ^{\text{hrs}}/_{\text{yr}} * \text{System Size (W)}}$$

Assume: discount rate, d = 3 %
interest rate, i = 1.5%
years (CRF), n = 30

$$\text{CRF} = \frac{i * (1+1)^n}{(1+i)^n - 1}$$

Take costs from [1]:
CAPEX (SAT) = 0.89$/$W_{DC}$
O&M costs = $16.06/$kW_{DC}$/yr

- Neglecting clipping/inverters
- Neglecting inflation/taxes/extra finance factors
- O&M savings from not mowing/costs for cleaning

Break-even Analysis

$$\text{LCOE}\left(^{\text{w}}/_{\text{reflector}}\right) = \text{LCOE (reference)}$$

$$\text{Material CAPEX} = \frac{\text{LCOE}\ (\$/\text{Wh}) * \text{CF}(\%) * 8760\ ^{\text{hrs}}/_{\text{yr}} * \text{System Size (W)} - \text{Annual O\&M}\ (\$)}{\text{CRF}} - \text{PV CAPEX}$$

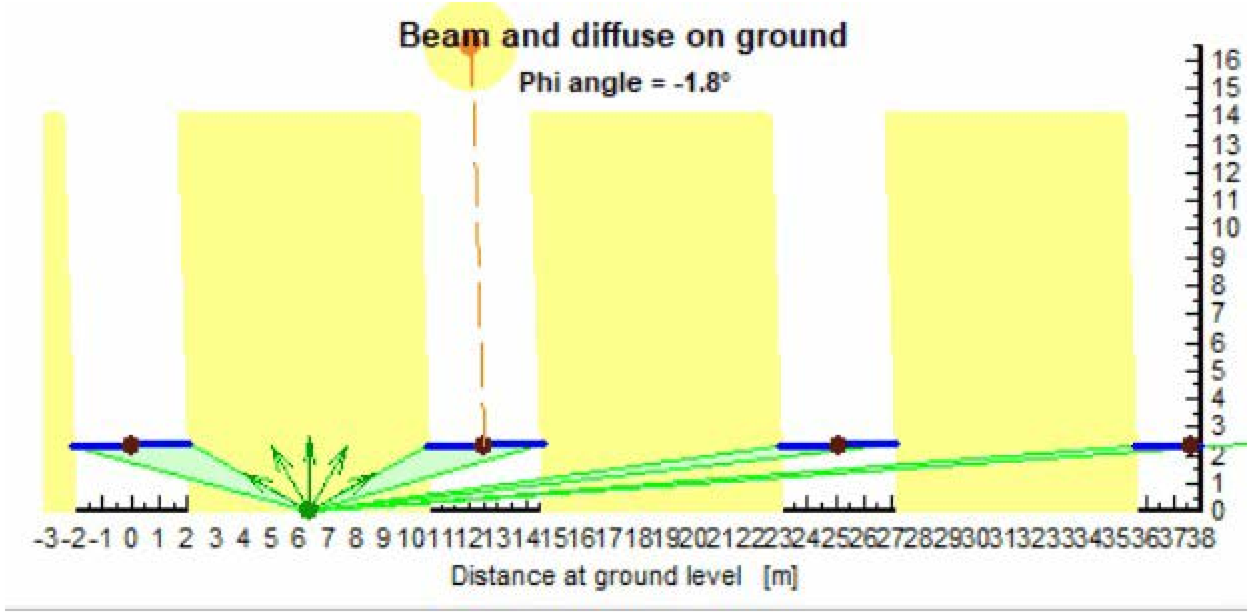
[1] Feldman, D., Ramasamy, V., Fu, R., Ramdas, A., Desai, J., & Margolis, R. (2021). *US solar photovoltaic system and energy storage cost benchmark: Q1 2020* (No. NREL/TP-6A20-77324). National Renewable Energy Lab.(NREL), Golden, CO (United States).

Modeling

Bifacial Performance

Photo credit: C. Deline

View Factor Models for Rear Irradiance



Simple

Basic
Geometry

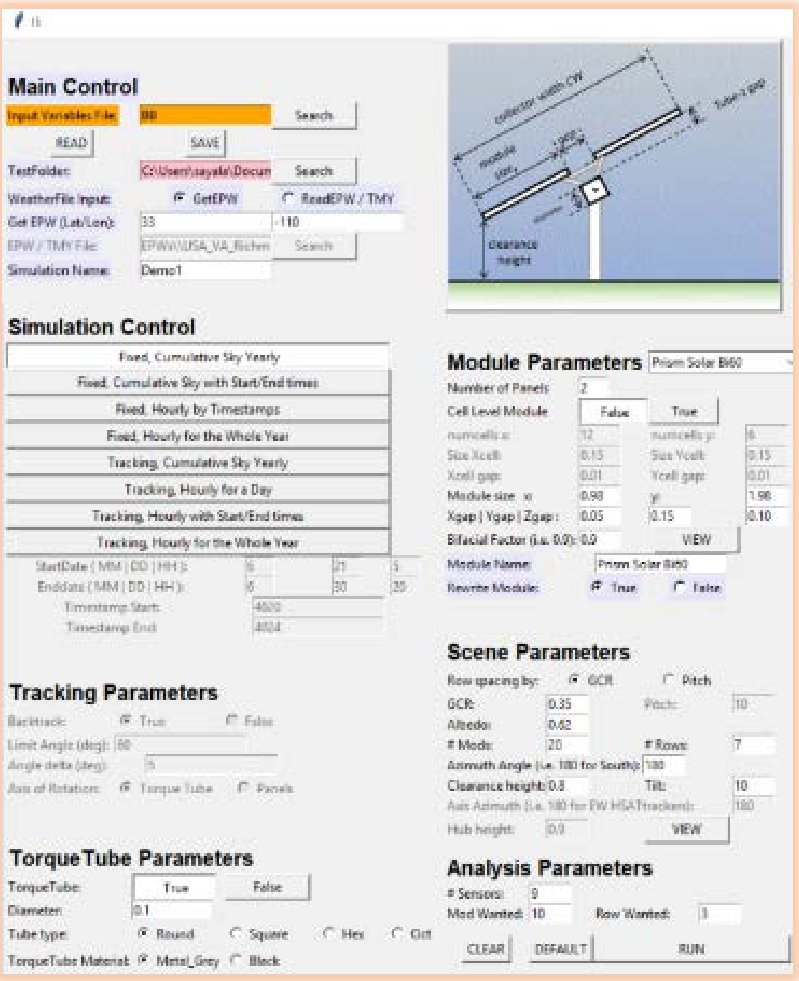
Fast

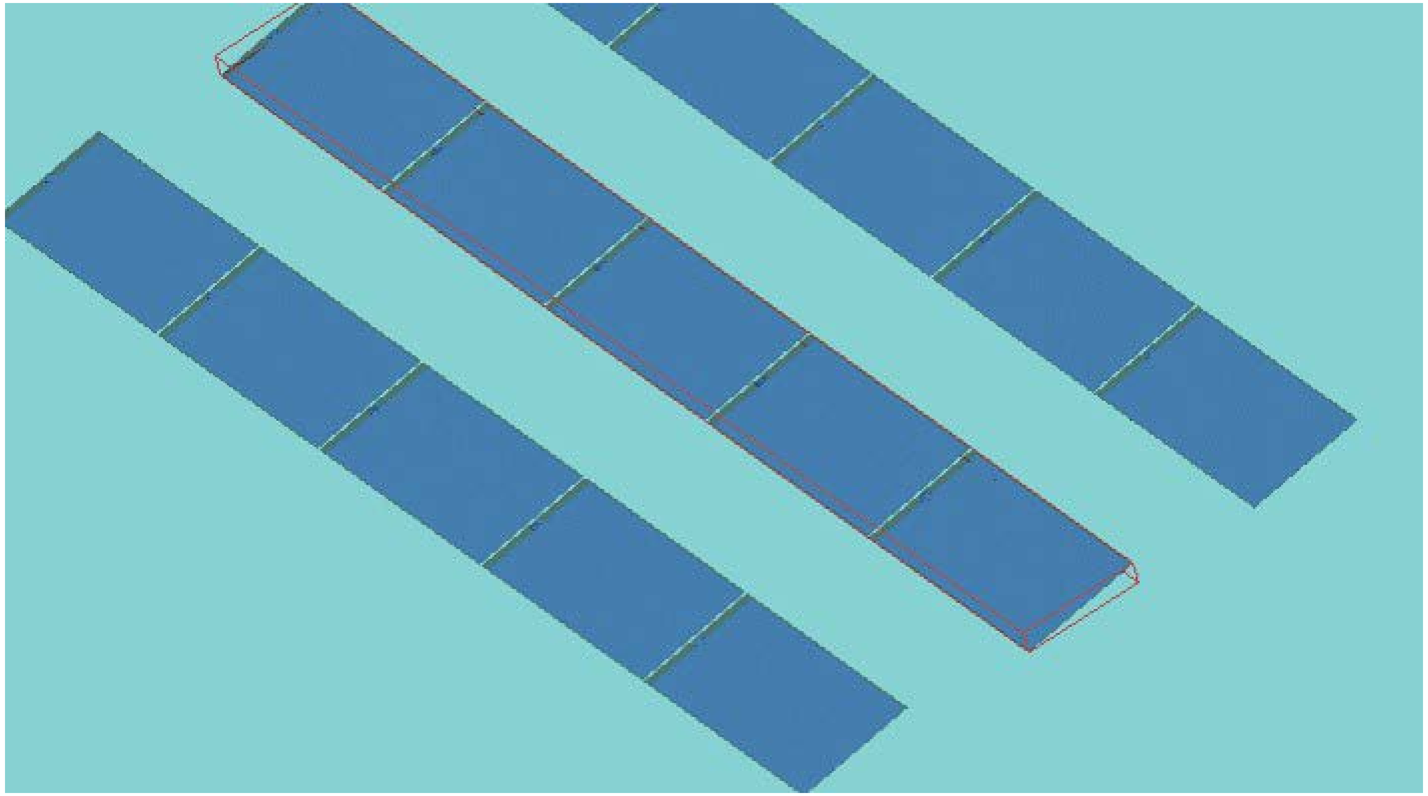
Computationally
Inexpensive

Common

Behind Due Diligence Tools
SAM, PVSyst, and others

Bifacial_Radiance Model for Rear Irradiance



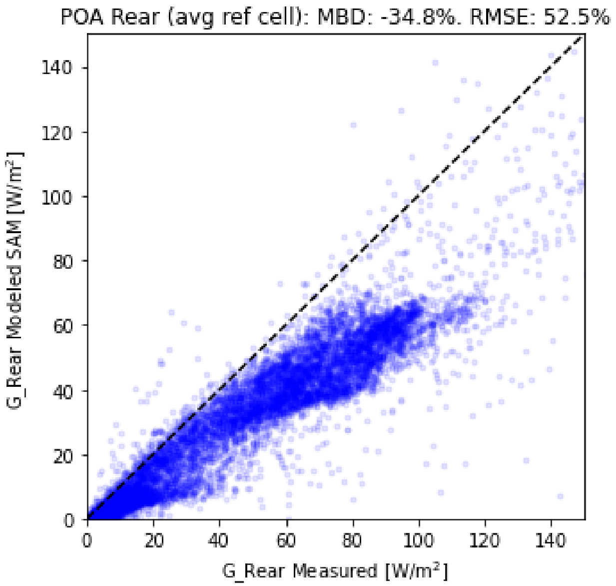


Peer Reviewed, Open-source software freely available at
http://www.github.com/NREL/bifacial_radiance

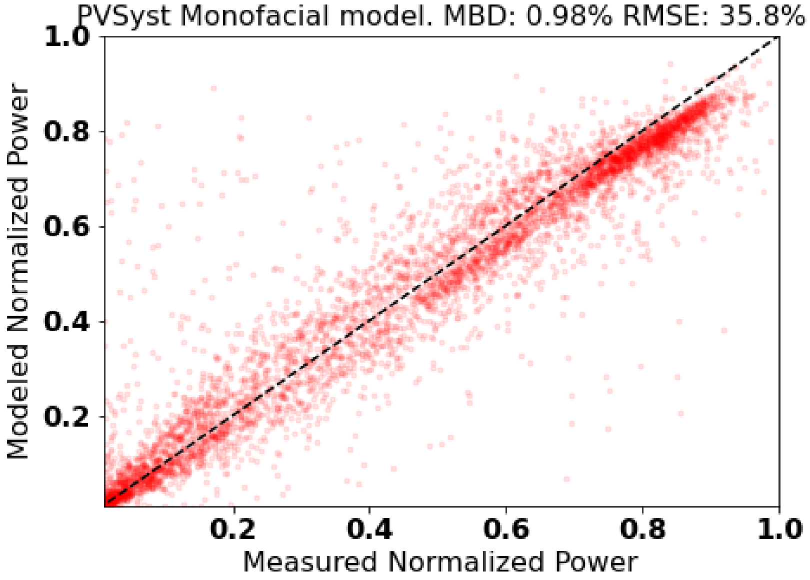
S. Ayala Pelaez, C. Deline, S. MacAlpine, B. Marion, J. Stein, R. Kostuk, "Comparison of bifacial solar irradiance model predictions with field validation," *IEEE Journal of Photovoltaics* **9**(1), 82–88 (2019).

Impact of Rear Irradiance Uncertainty on Power Modeling

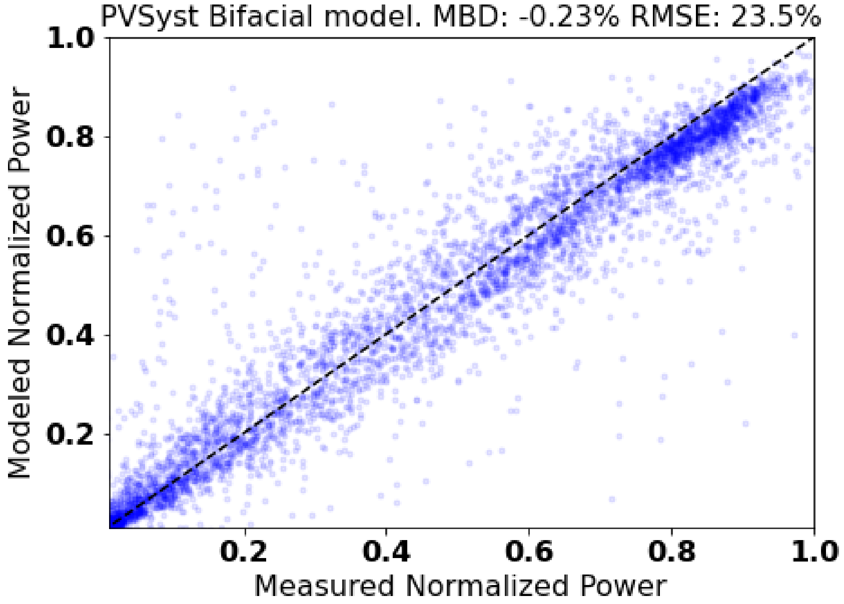
IRRADIANCE



POWER Mono



POWER BIFI



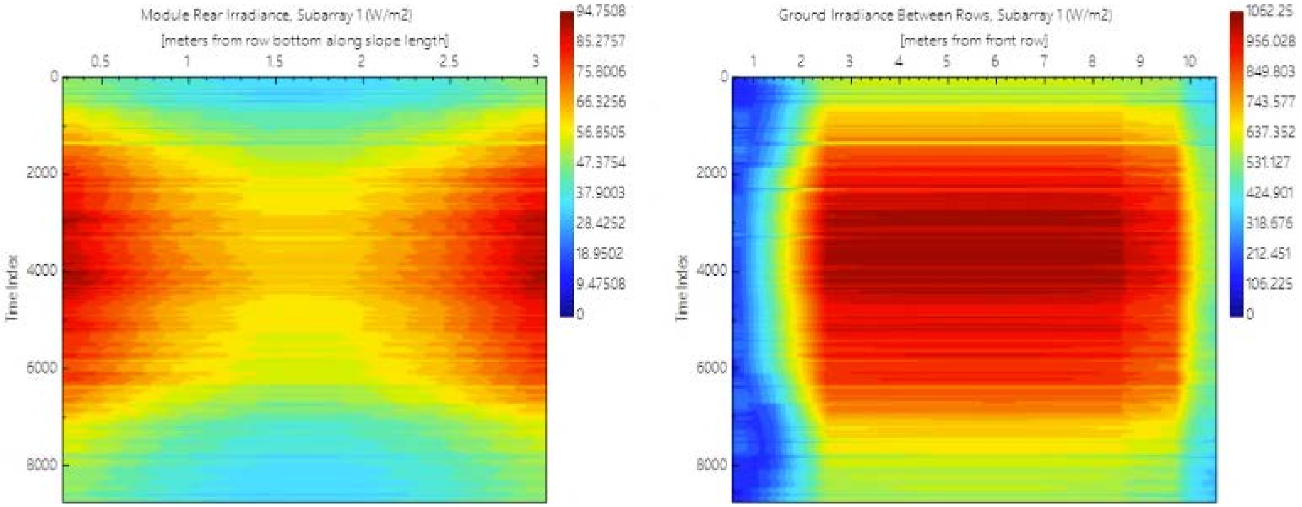
Modeling Tools Updates

bifacialVF bifacial_radiance

NREL System Advisor Model (SAM)

- SAM Release Dec. 2022!
  - GHI under the modules data for AgriPV evaluation
  - Different ground albedos
  - Shading and
  - Electrical Mismatch Bifacial loss calculated internally*

- bifacial_radiance
  - Routines from start-to-end weather to Performance with PVLib
  - Edge effects, electrical mismatch detailed calculation, shading routines
  - Complex model geometry: frames, omegas, glass
  - HPC/AWS support & tutorials



*Deline et al, 2020 https://doi.org/10.1002/pip.3259

Conclusions

- Bifacial PV is becoming mainstream with gigawatts of installed projects. As we reach for decarbonization goals, high-quality, long-lived modules offer the most sustainable choice.
- Three years of 1-axis tracker validation at NREL shows good bifacial annual energy gain of 6.1% and 7.3% for PERC and Si-HJT, respectively. The data is open-source.
- Energy gain depends on the site configuration and surface albedo. Models like SAM, PVSyst, and bifacial_radiance can assist with system design and power estimation.

Thank you

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NREL/PR-5K00-84763

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