NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Bifacial PV System Performance:
Separating Fact from Fiction

Chris Deline, Silvana Ayala Peláez,
Bill Marion, Bill Sekulic, Michael Woodhouse,
and Josh Stein (Sandia National Labs)

PVSC-46, Chicago, IL 2019

NREL/PR-5K00-74090

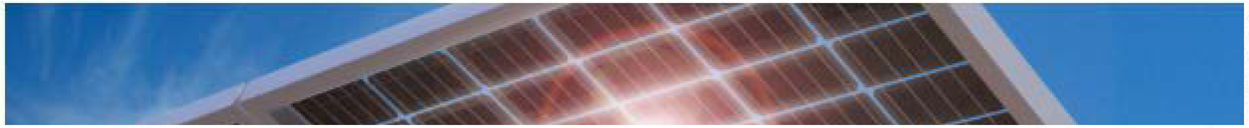
Bifacial PV in the news

Bifacial beats Trump's tariffs

Federal trade authorities have ruled that bifacial solar modules are no longer sub
the Section 201 ruling, which currently apply a 25% tariff to most solar modules i
to the United States.

JUNE 12, 2019 JOHN WEAVER

BUSINESS | COST AND PRICES | MARKETS | MODULES & UPSTREAM MANUFACTURING | POLICY | UNITED STATES



Georgia will be home to largest solar PV project in th
to use bifacial modules and tracking

February 25, 2019

By Renewable Energy World Editors

Canadian Solar Secures Its Largest Order as Bifacial Modules Gain Traction

EDF Renewable Energy will buy 1.8 gigawatts of modules from Canadian Solar as the Investment Tax Credit phases down, in a sign that developers are growing more comfortable with two-sided solar technology.

KARL-ERIK STROMSTA | MAY 29, 2019

2

Scatec Solar's first bifacial project goes live in Egypt

By José Rojo Martín | Apr 12, 2019 10:44 AM BST | 0 | Share

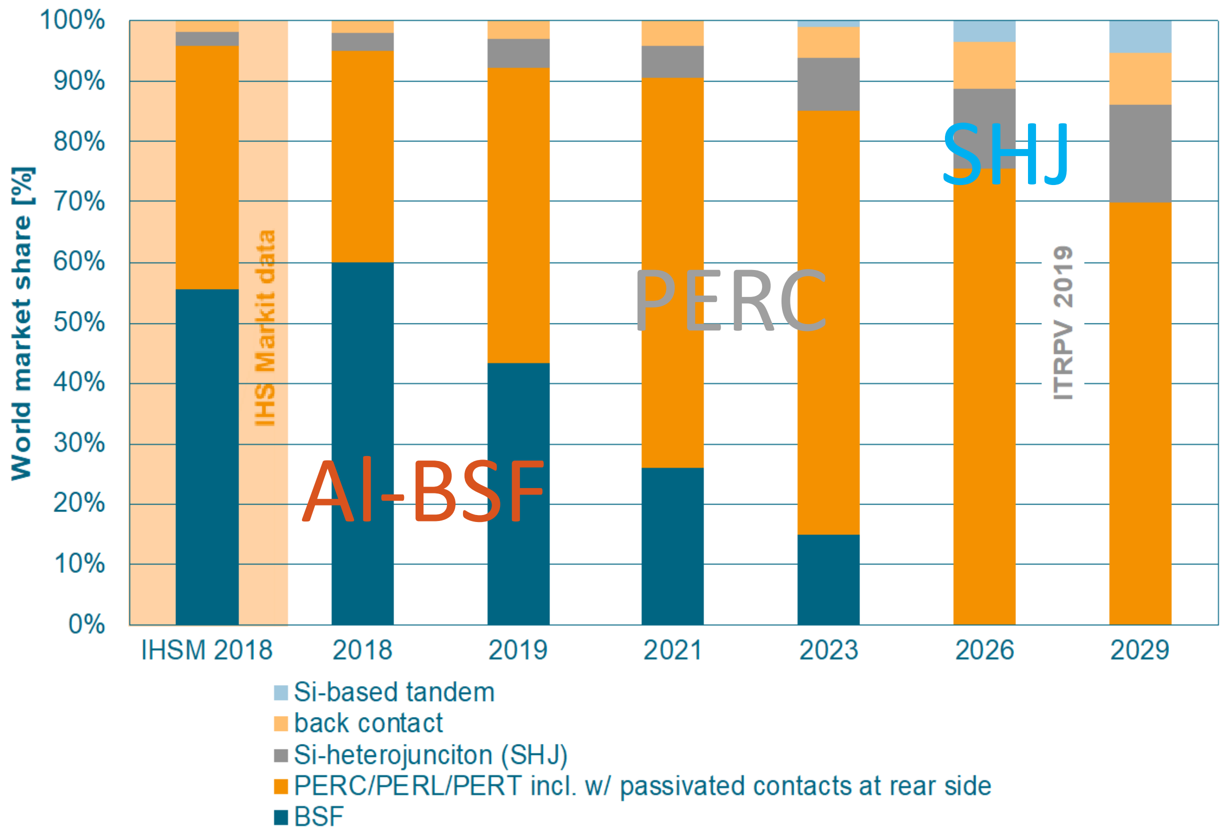
Status of Bifacial Installations 2019

International Solar Energy Research Center Konstanz

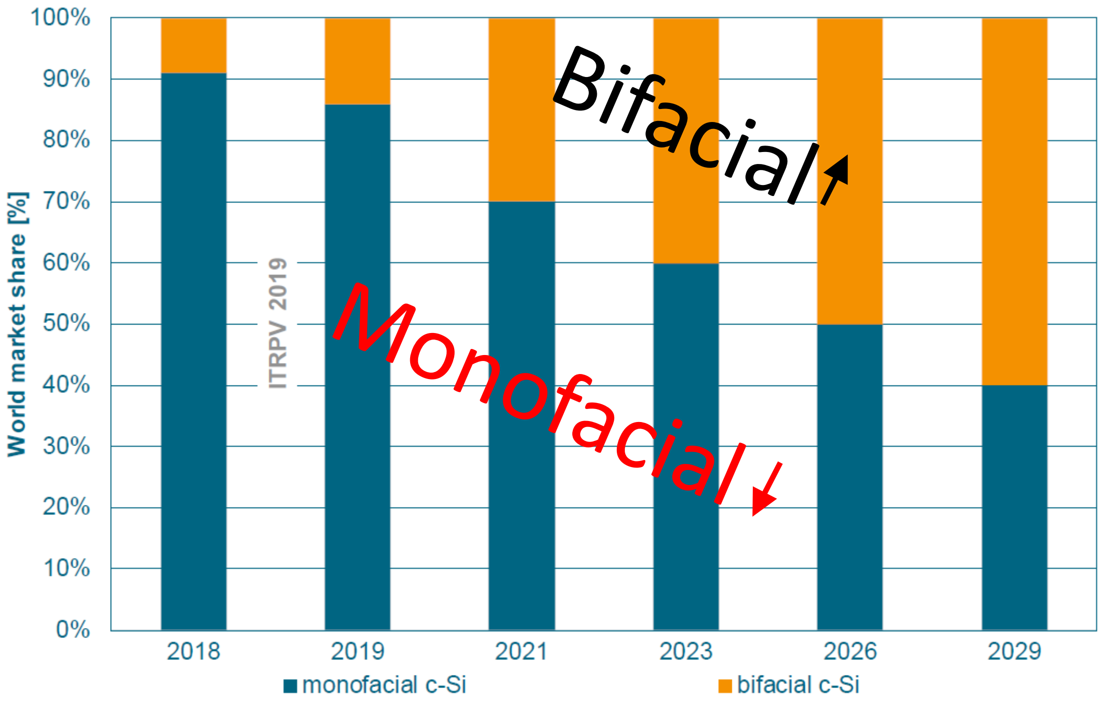
R. Kopecek, Photonics North 2019, May 22nd Quebec

Historic & projected PV market

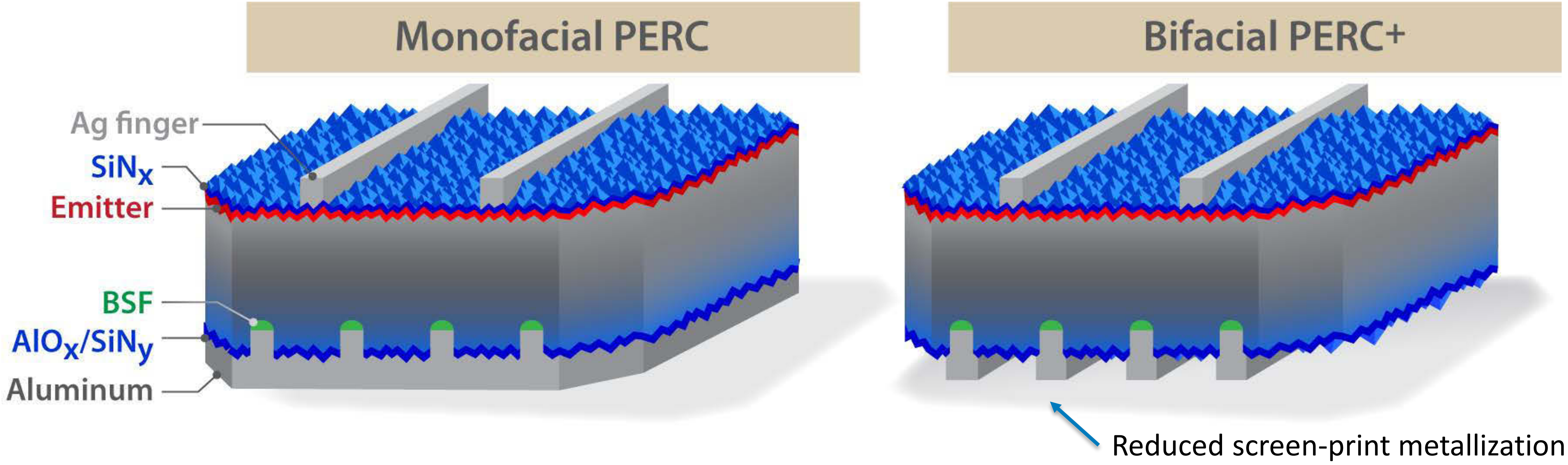
Different cell technology



Bifacial cell in world market



PERC cell technology – easily bifacial

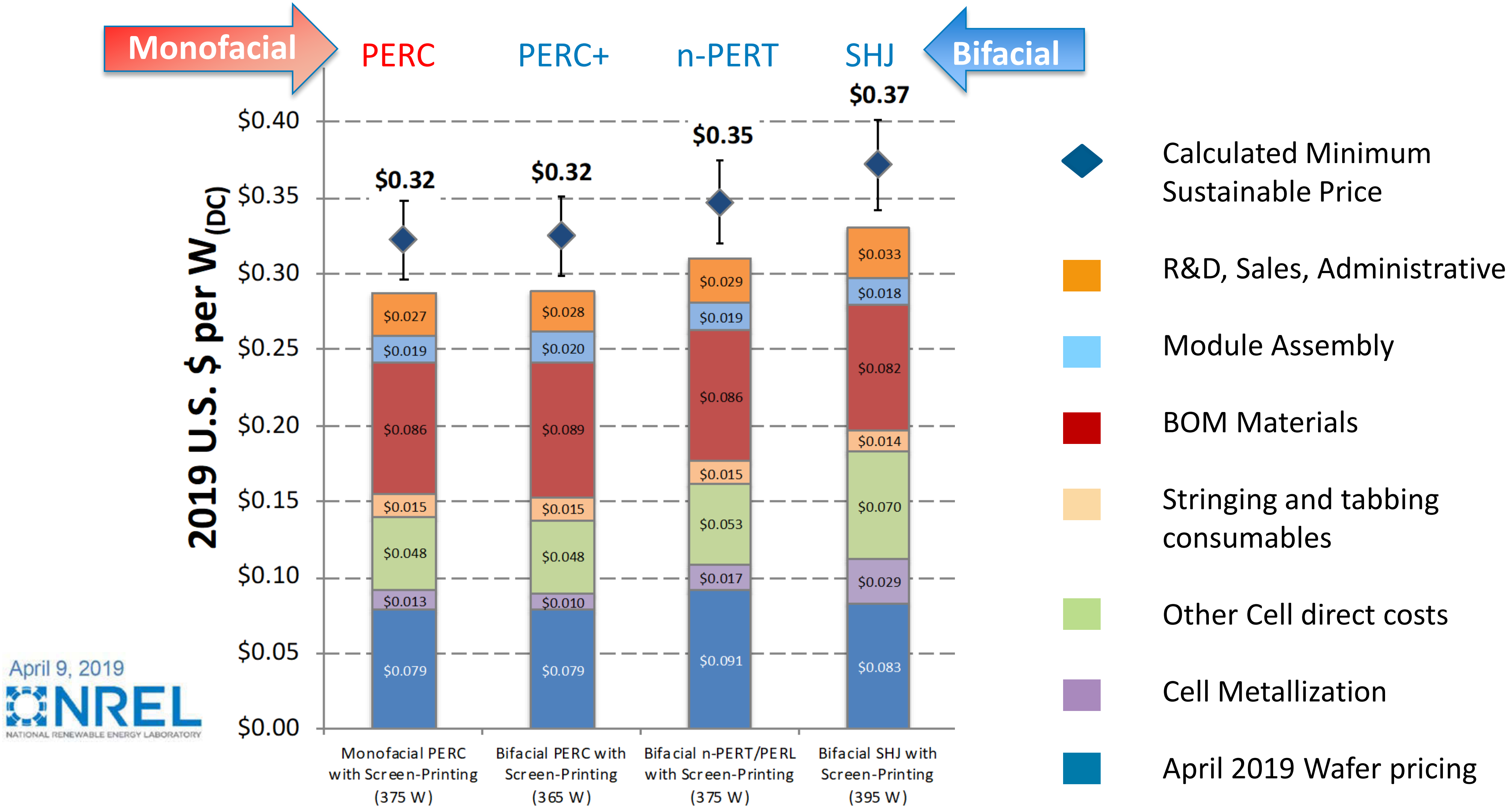


Module bifaciality $\phi = \frac{P_{Rear}}{P_{Front}} =$

0.65-0.80 (p-PERC)	**0.75-0.90 (n-PERT)**	**0.85 – 0.95 (Si Heterojunction)**

Thorsten Dullweber et al. PERC+: industrial PERC solar cells with rear Al grid enabling bifaciality and reduced Al paste consumption, Prog. Photovolt: Res. Appl. (2015)

Monofacial vs Bifacial module manuf. cost



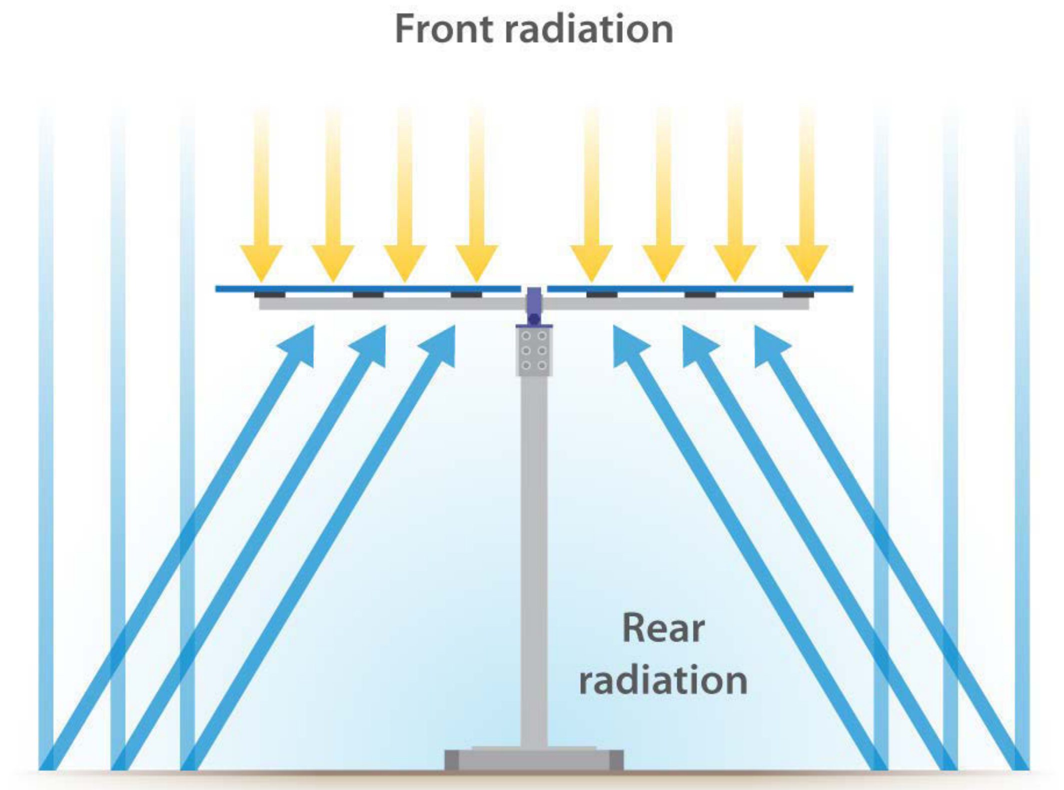
Additional details given in: (1) M Woodhouse, B Smith, A Ramdas, and R Margolis "Economic Factors of Production Affecting Current and Future Crystalline Silicon Photovoltaic Module Manufacturing Costs and Sustainable Pricing", *In preparation.* (2) A Faes, C Ballif, M Despeisse, et al, "Metallization and interconnection for high efficiency bifacial silicon heterojunction solar cells and modules", *Photovoltaics International,* 3, 1—12 (2018) (3) A Louwen, W van Sark, R Schropp, and A Faaij, "A Cost Roadmap for silicon heterojunction solar cells", Solar Energy Materials and Solar Cells, 147, 295—314 (2016)

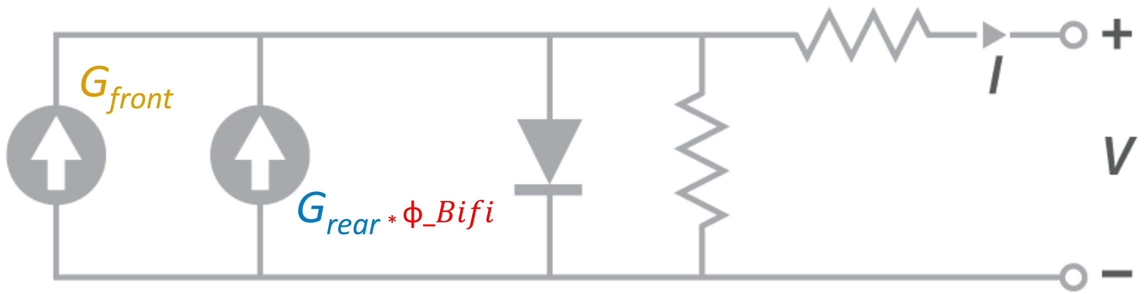
Bifacial Performance
Modeling

Photo credit: Prism Solar

Bifacial total irradiance

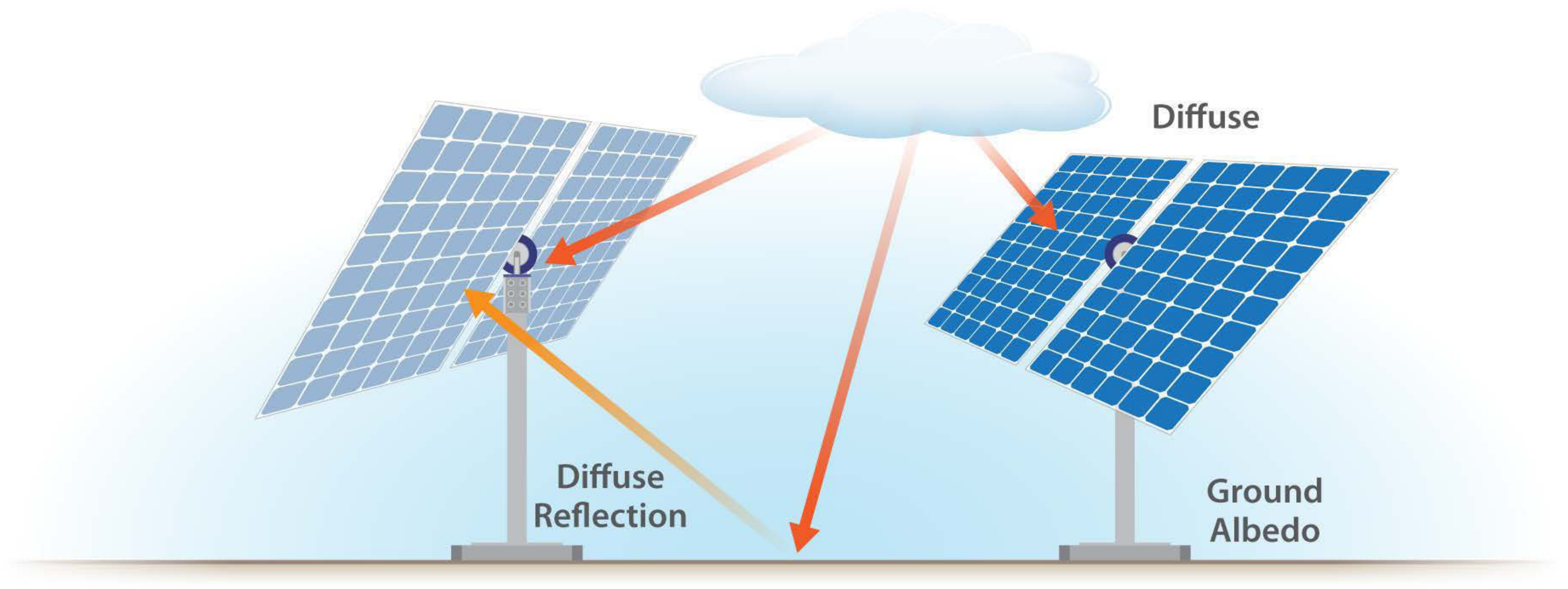
$$G_{Total} = G_{Front} + (G_{Rear}) \times (bifaciality) \times (1 - \eta_{Loss})$$





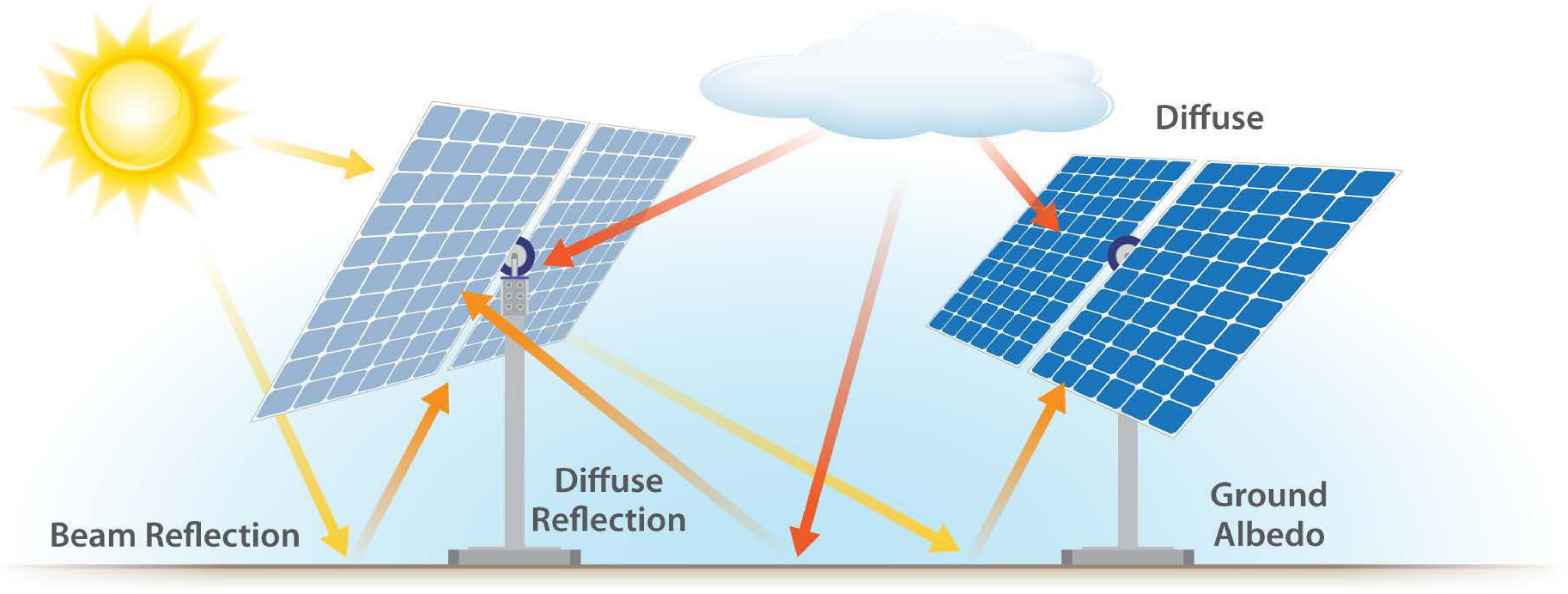
Module bifaciality $\boldsymbol{\phi\_Bifi} = \frac{Pmp_0\ rear}{Pmp_0\ front}$

Modeling Rear Irradiance



$G_{rear} = G_{diffuse,r} + G_{reflected,r} + G_{beam,r}$

Modeling Rear Irradiance



$$G_{rear} = G_{diffuse,r} + G_{reflected,r} + G_{beam,r}$$

What bifacial gain can be expected?

Bifacial Plus Tracking Boosts Solar Energy Yield by 27 Percent

Recent testing shows bifacial PERC modules can significantly increase energy yields.

GTM CREATIVE STRATEGIES | APRIL 18, 2018

Technology and innovation drive the next generation of PV solutions.

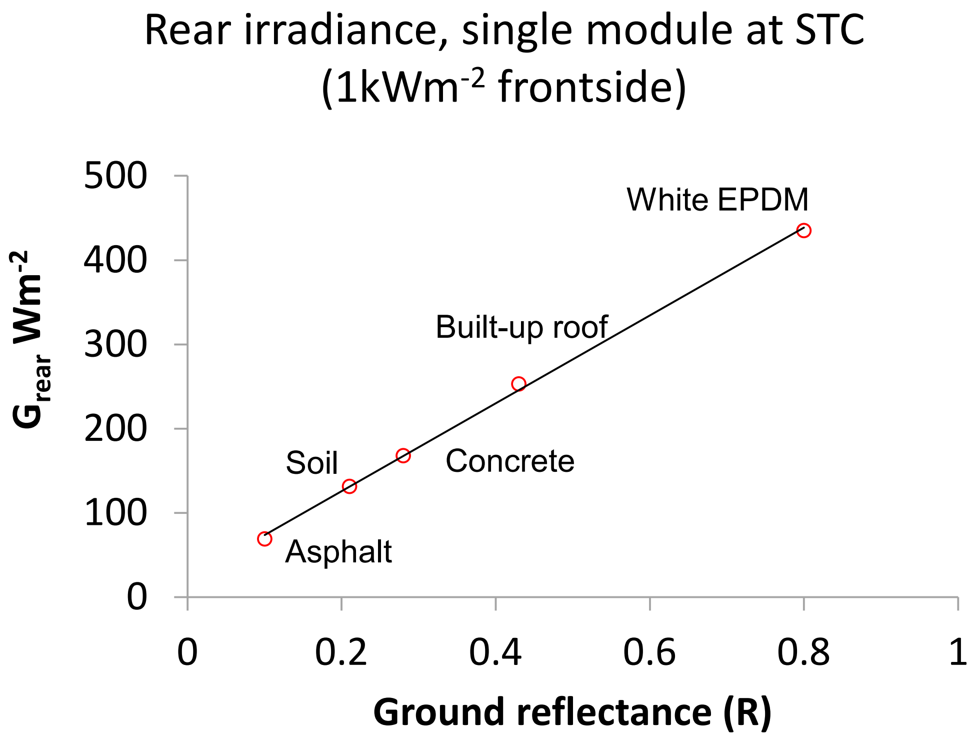
Photo Credit: LONGi

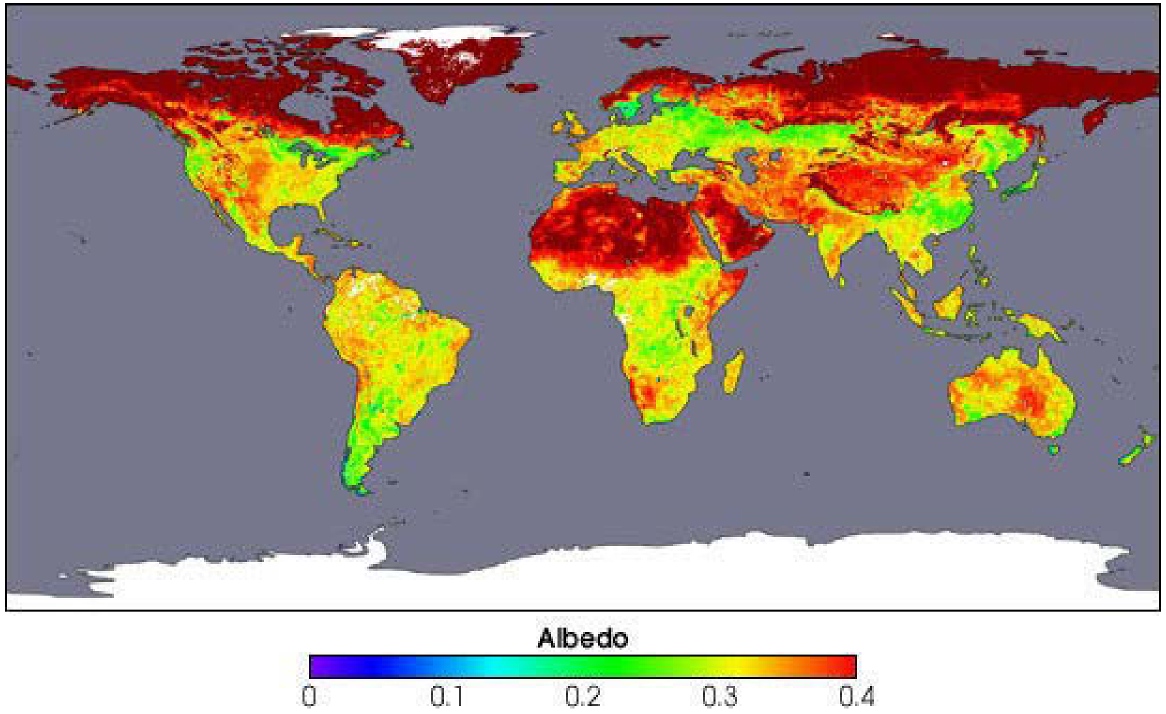
Bifacial energy gain BG_E

$$= E_{Bifacial}/E_{Mono} - 1$$

$$= ??$$

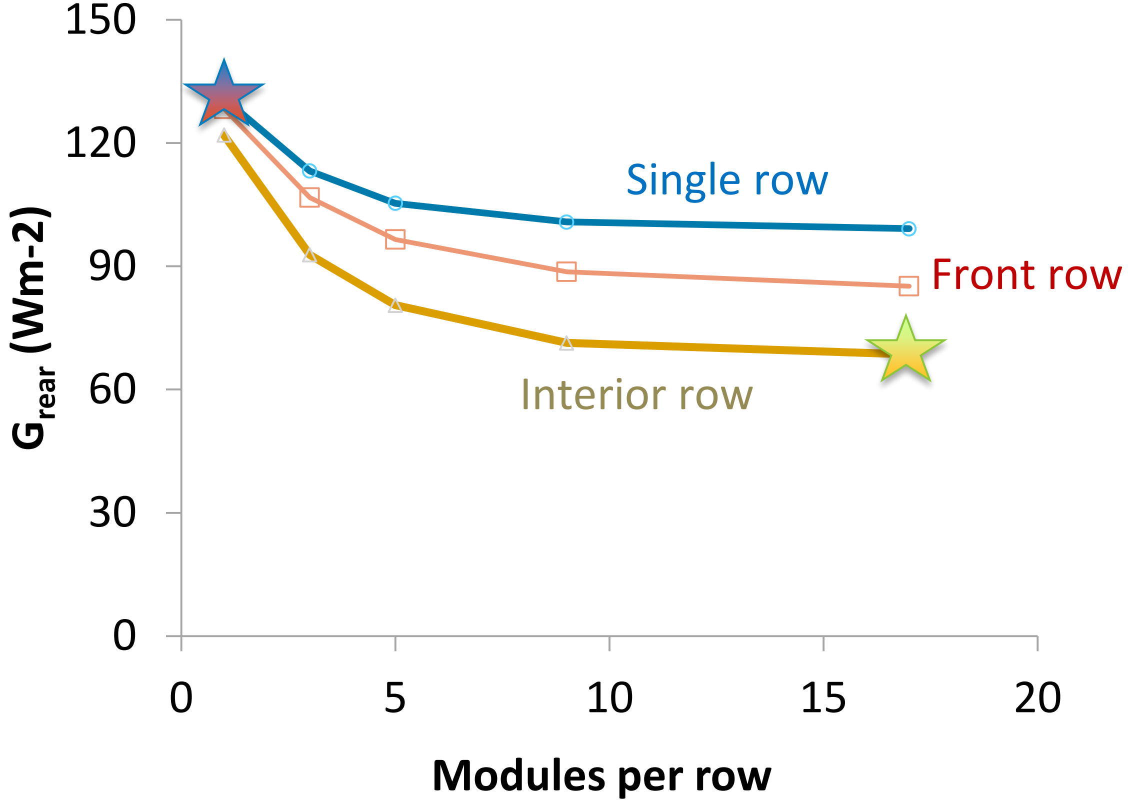
Surface Albedo has a big effect

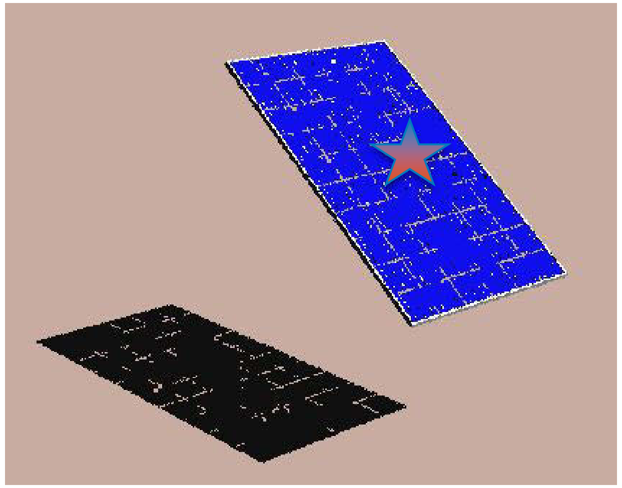


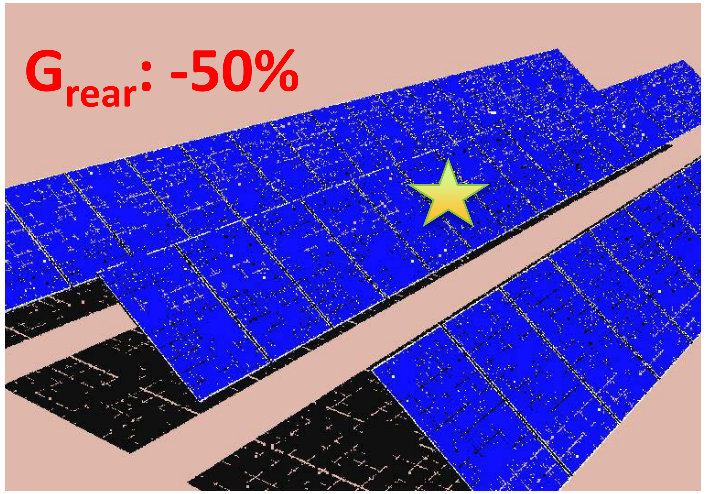


NASA Earth Observations, https://neo.sci.gsfc.nasa.gov/view.php?datasetId=MCD43C3_M_BSA
R. Kopecek and J. Libal, Bifacial Photovoltaics: Technology, applications and economics, IET publishing, 2019

System G_{Rear} experiences self-shading







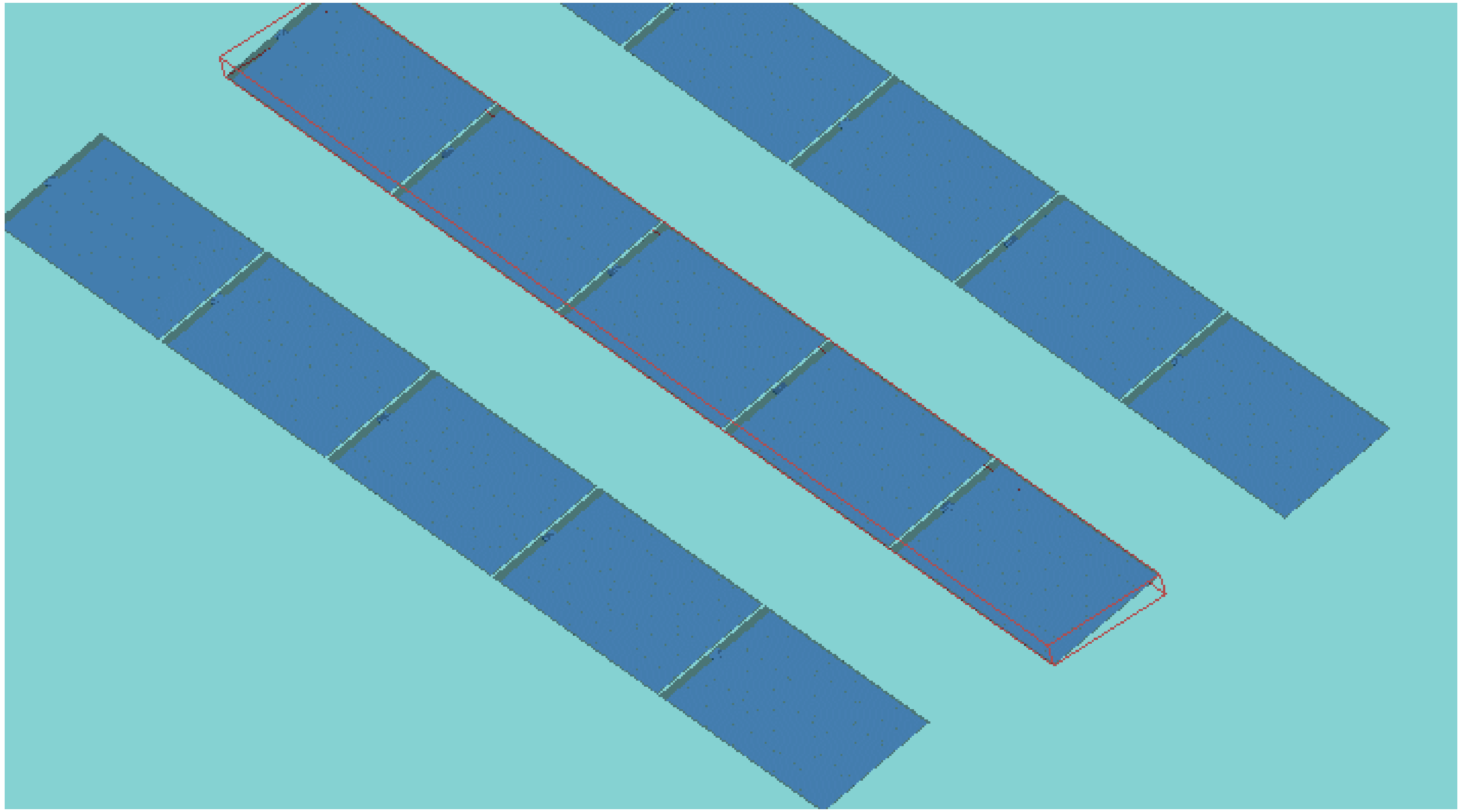
C. Deline et al., Assessment of Bifacial Photovoltaic Module Power Rating Methodologies – Inside and Out, J. Photovoltaics **7,** 2017

Bifacial Performance

Models

Photo credit: C.Deline

Bifacial_Radiance Model for Rear Irradiance

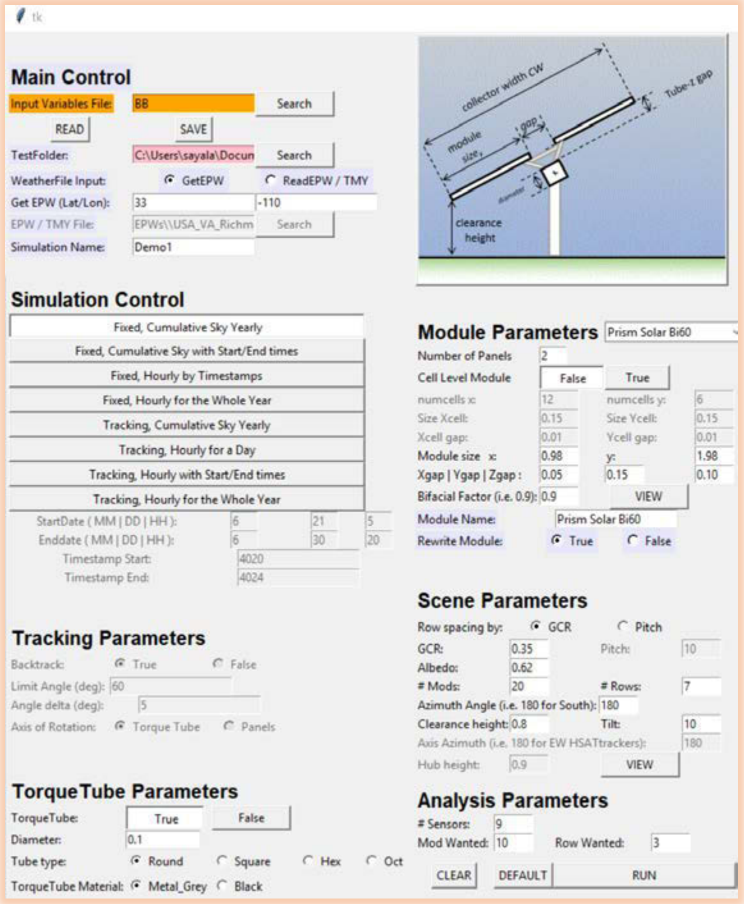


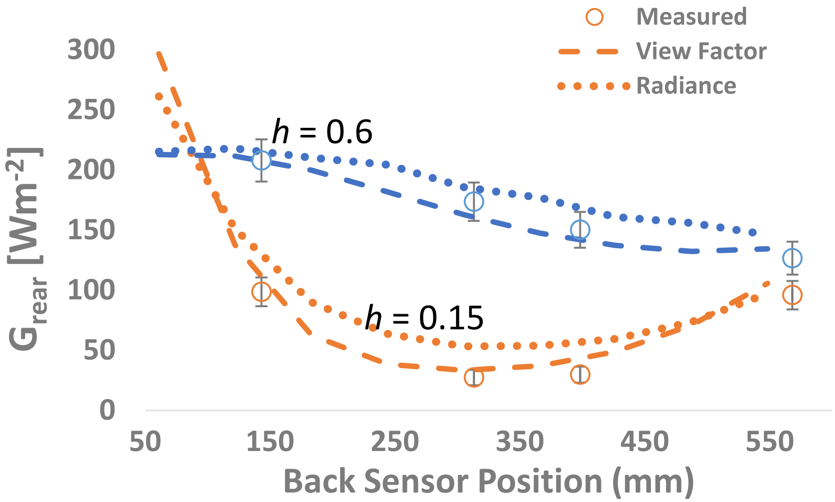
Complicated geometries possible, including racking and terrain.

Radiance uses backward ray-trace to evaluate the irradiance (W/m^2) at the modules

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

Bifacial_Radiance Model for Rear Irradiance



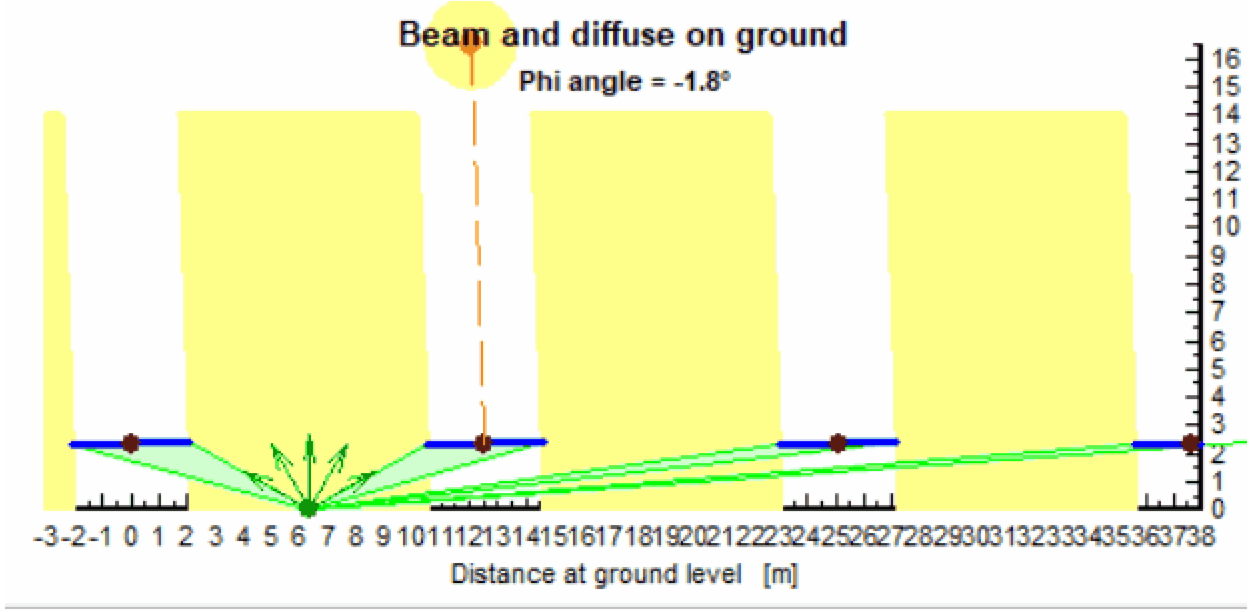


Open-source software freely available at http://www.github.com/NREL/bifacial_radiance

Field validation shows good agreement with close-mount rooftop mockup

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, 2019, vol 9 no. 1, pp. 82-88.

View Factor Model for Rear Irradiance



PVSyst v6.75

Simple

basic
geometry

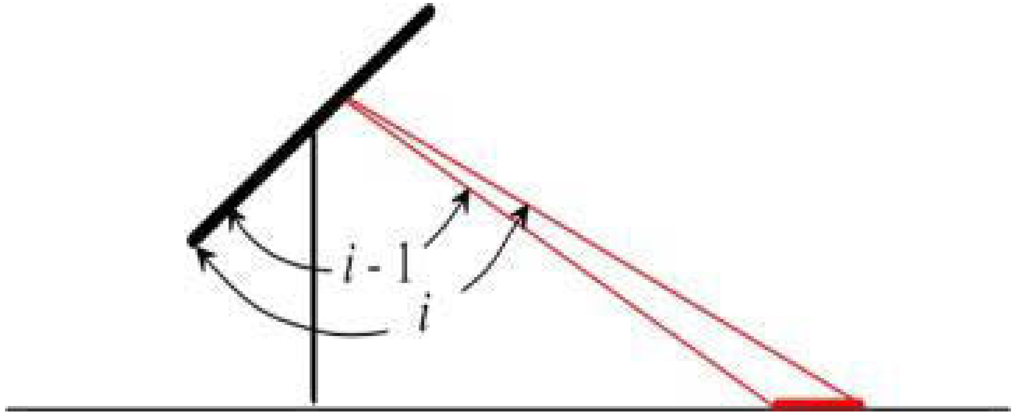
Fast

computationally
inexpensive

Common

Behind
SAM, Pvsyst, and others

View Factor Model for Rear Irradiance



G_{rear} is summed over 180° field-of-view:

$$\mathrm{G_{rear}} = G_{DNI,rear} + \sum_{i=1°}^{180°} VF_i \cdot F_i \cdot G_i \ ;$$

$$VF_i = \frac{1}{2} \cdot [\cos(i-1) - \cos(i)] \ ;$$

$$F_i = Incidence\ angle\ modifier(\Theta)$$

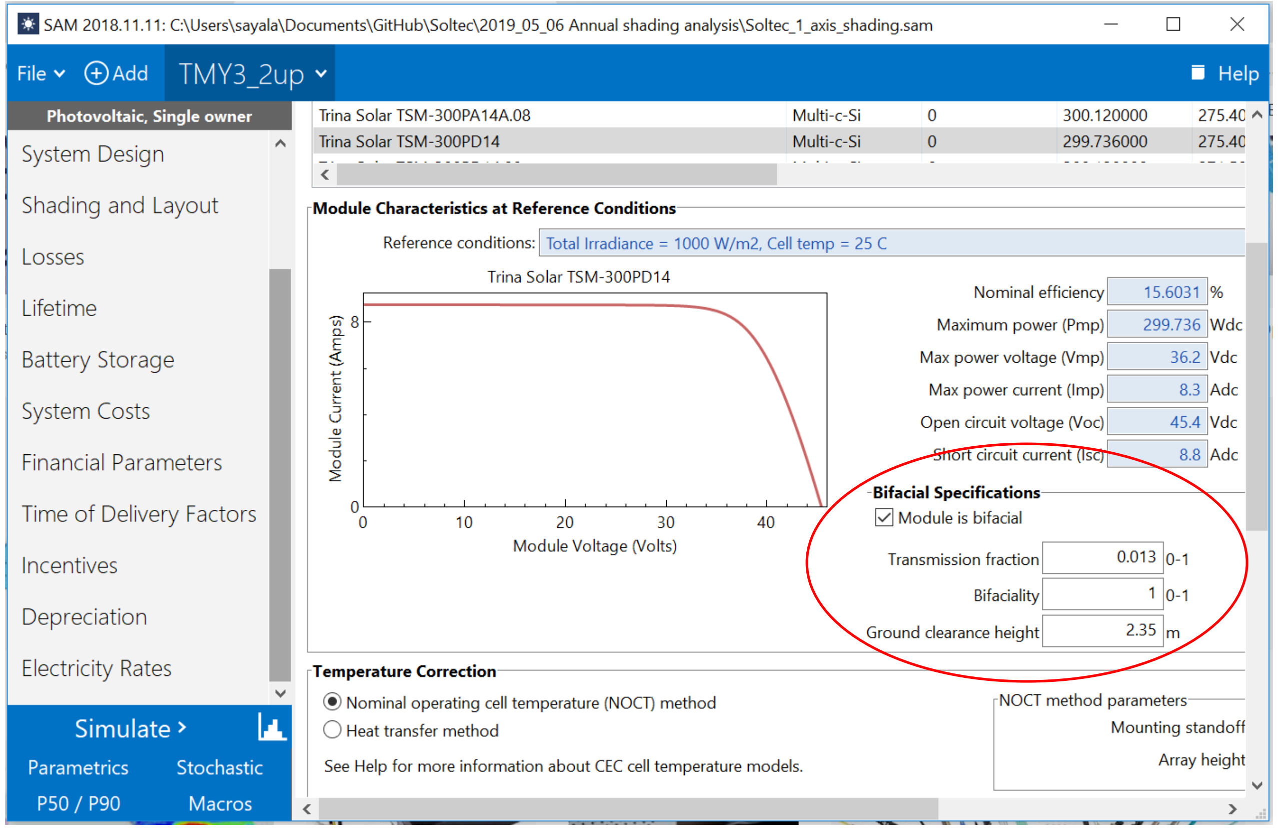
$$G_i = Irradiance\ [G_{sky}, G_{hor}, \rho \cdot G_{ground}] \ ;$$

Irradiance sources: sky, ground (shaded or unshaded)

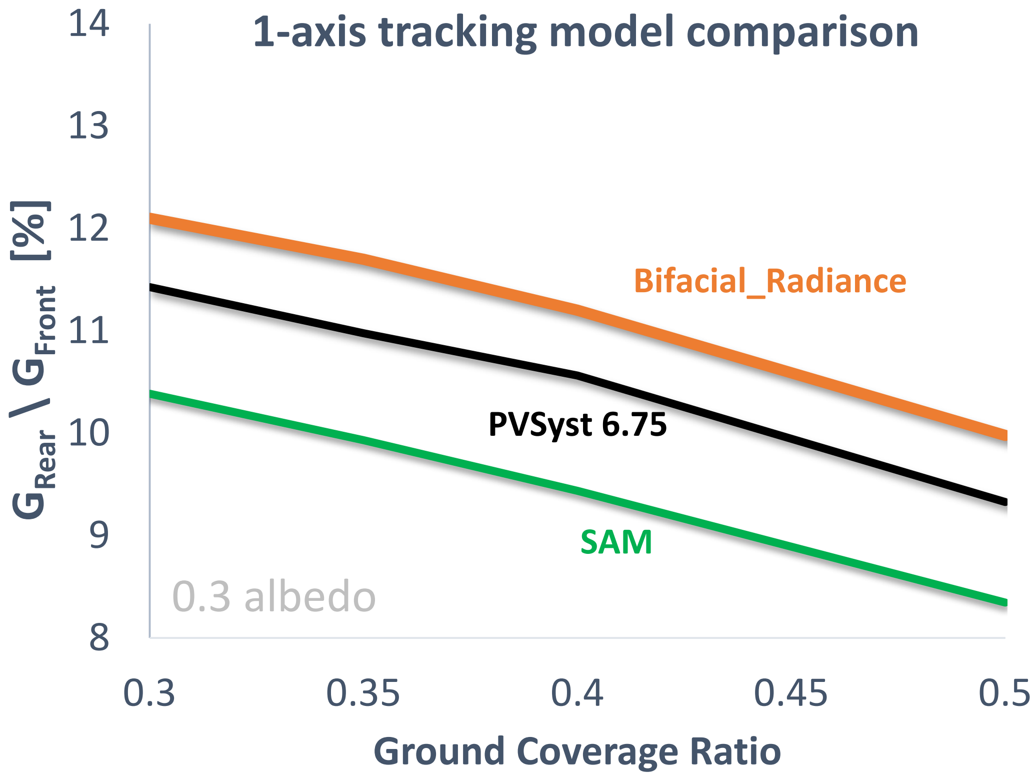
B. Marion et al., A Practical Irradiance Model for Bifacial PV Modules, 2017

B. Marion, Numerical method for angle-of-incidence correction factors for diffuse radiation incident photovoltaic modules, 2017

NREL SAM Model



SAM v2018.11



N. DiOrio, C. Deline, “Bifacial simulation in SAM”, presented at 5th BifiPV in Denver, CO 2018.
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, 2019, vol 9 no. 1, pp. 82-88.


Transforming
Bifacial trackers, 75 kW
5 bifacial technologies

Bifacial system configuration

20 modules (7.5 kW) / row

4 PERC, 1 SHJ Bifacial strings

3 PERC monofacial strings

Module electronics / monitoring

String kWh_{DC} monitoring

Front, rear POA irradiance

Bifacial system configuration

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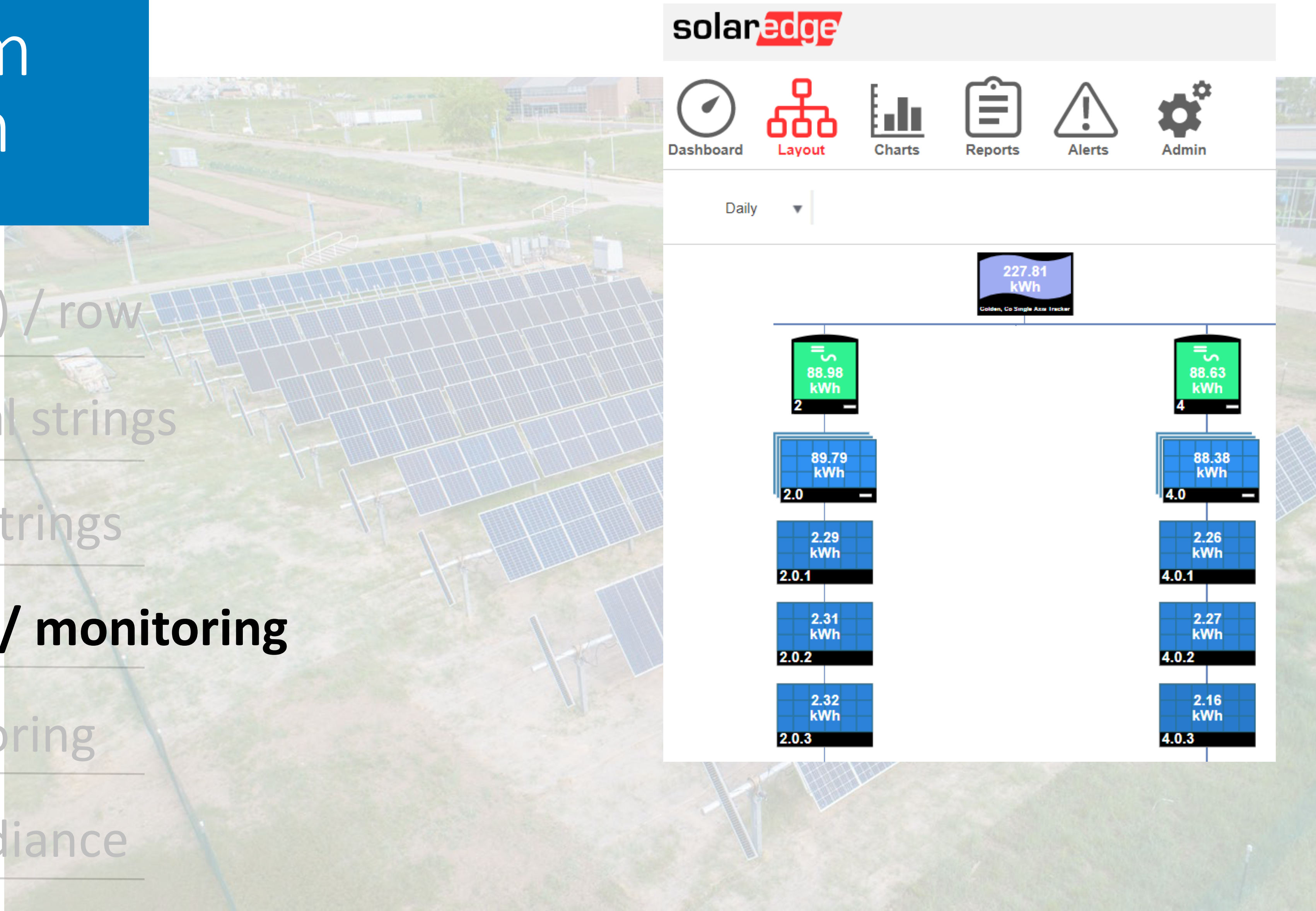

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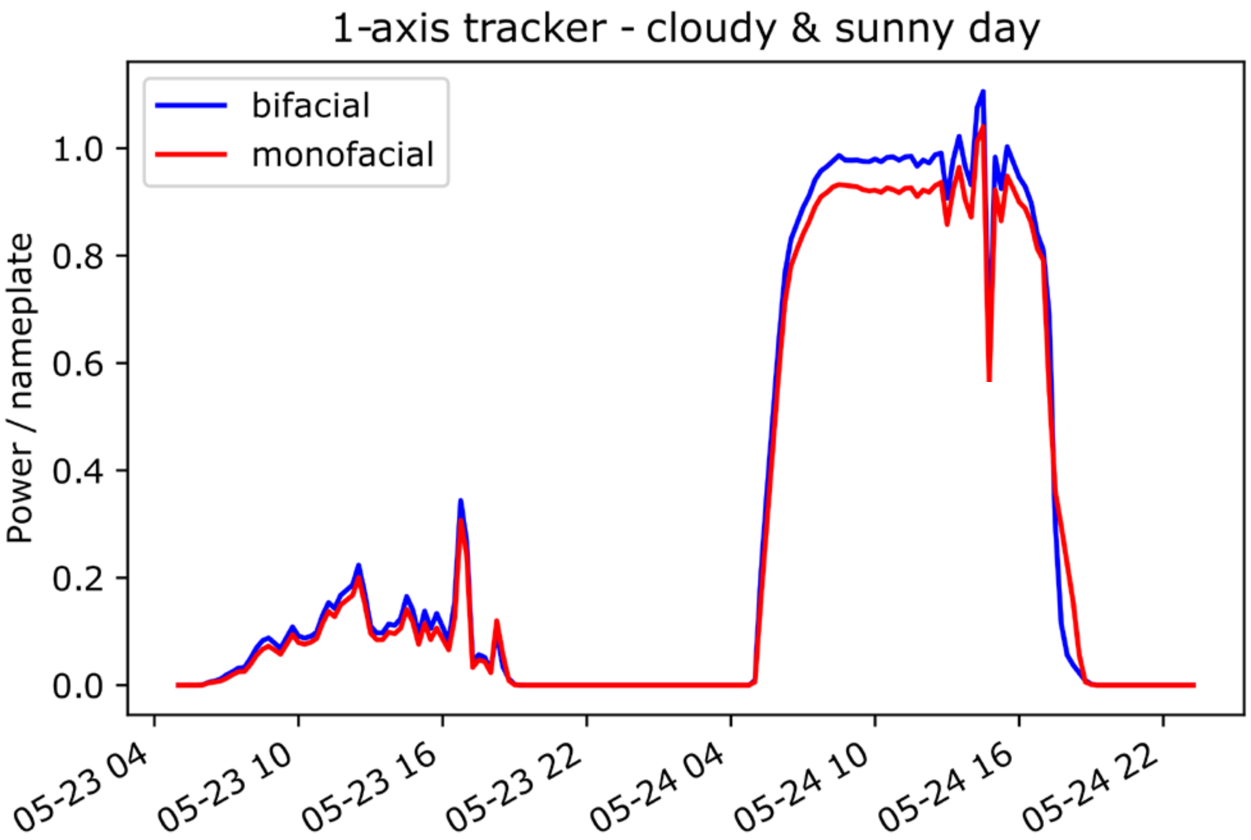
- String kWh_{DC} monitoring
- **Front, rear POA irradiance**

= Front POA

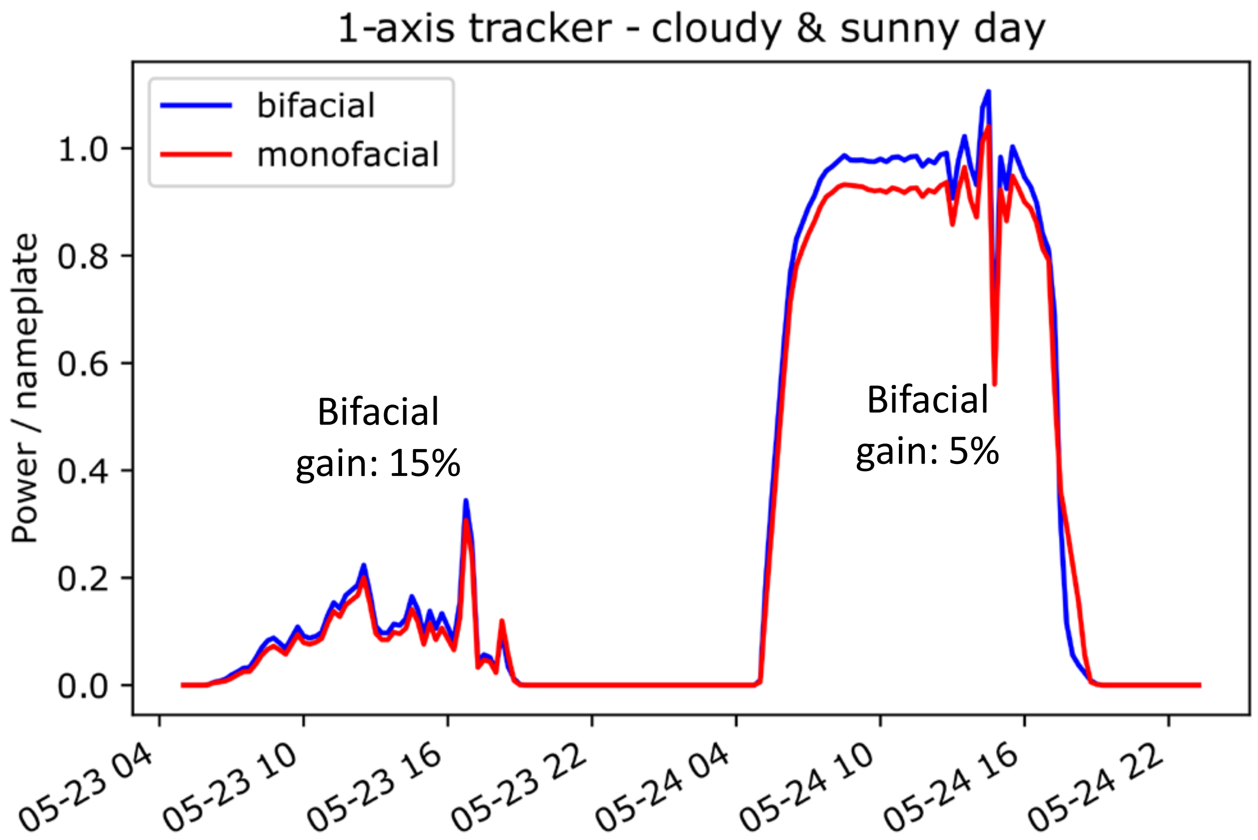
= Rear POA

Initial field results – bifacial trackers



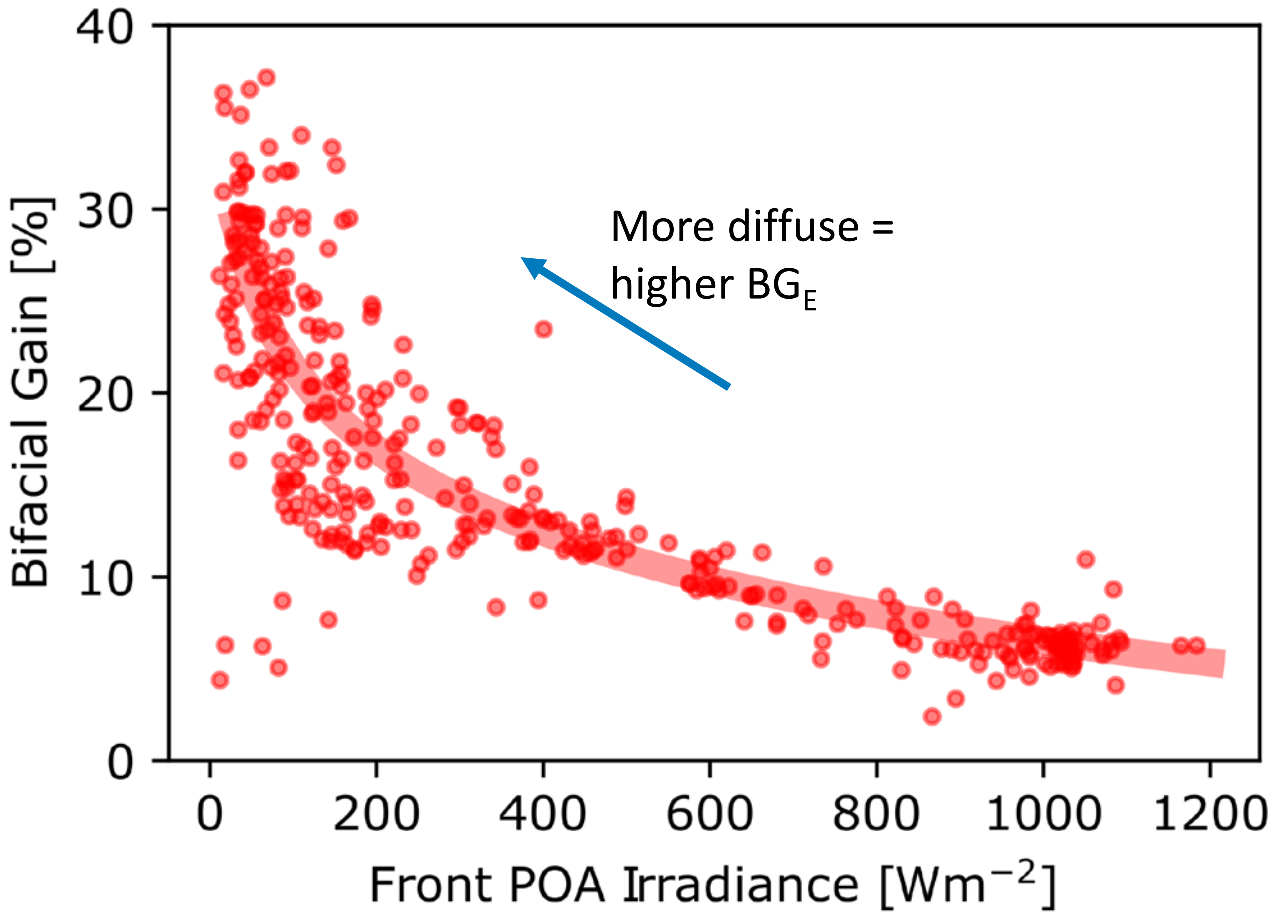
$$BG_E = \frac{E_{bifacial}}{E_{mono}} - 1$$

Initial field results – bifacial trackers



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

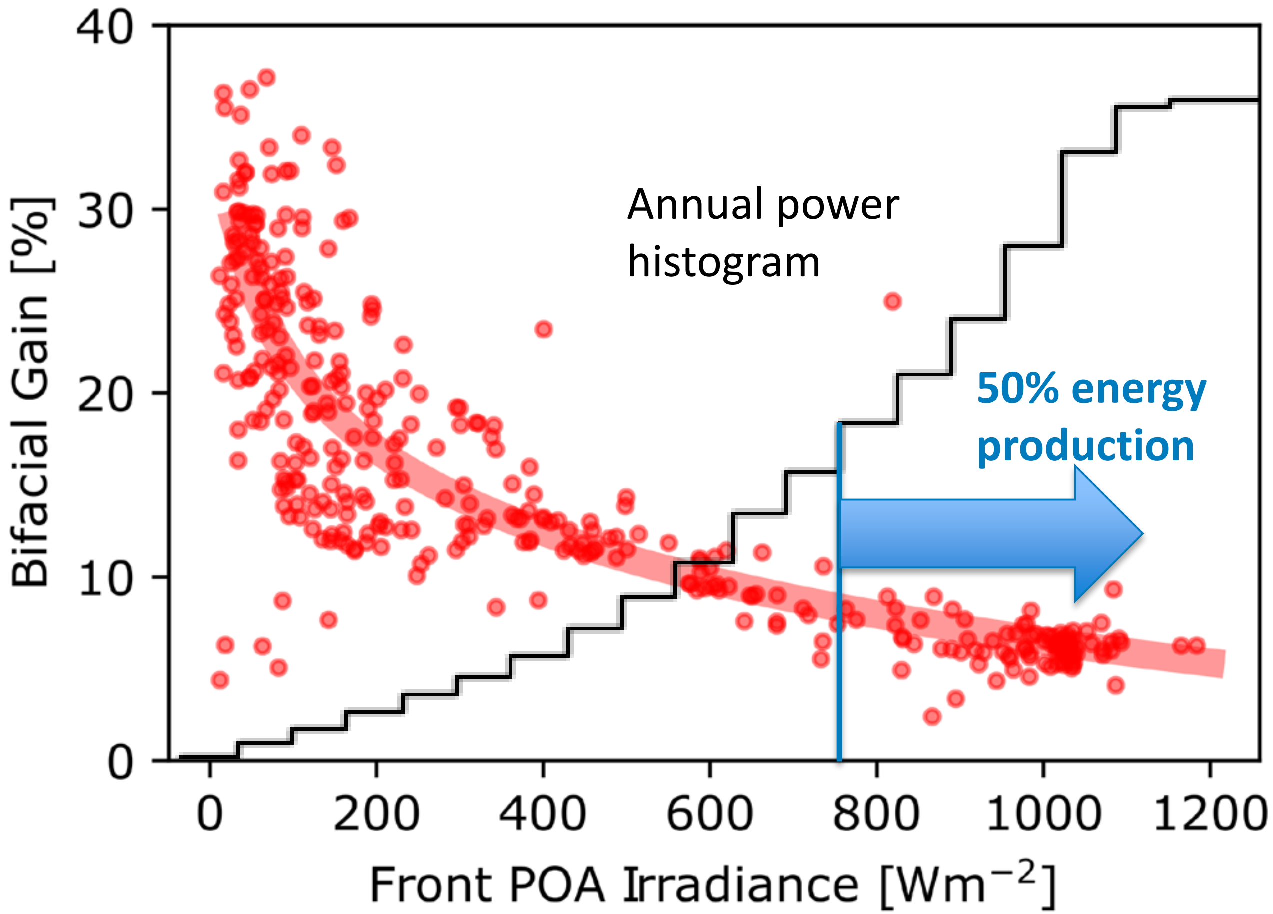
Initial field results – bifacial trackers



More diffuse = higher BG_E

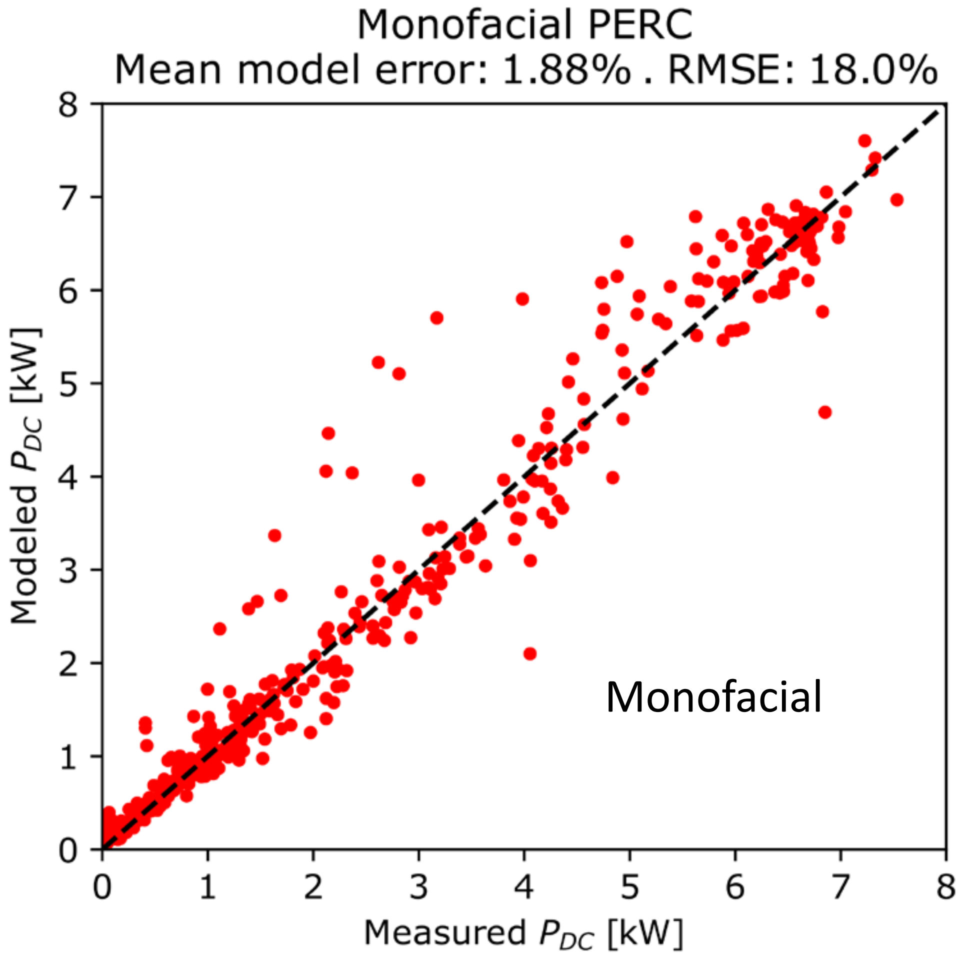
$$BG_E = \frac{E_{bifacial}}{E_{mono}} - 1$$

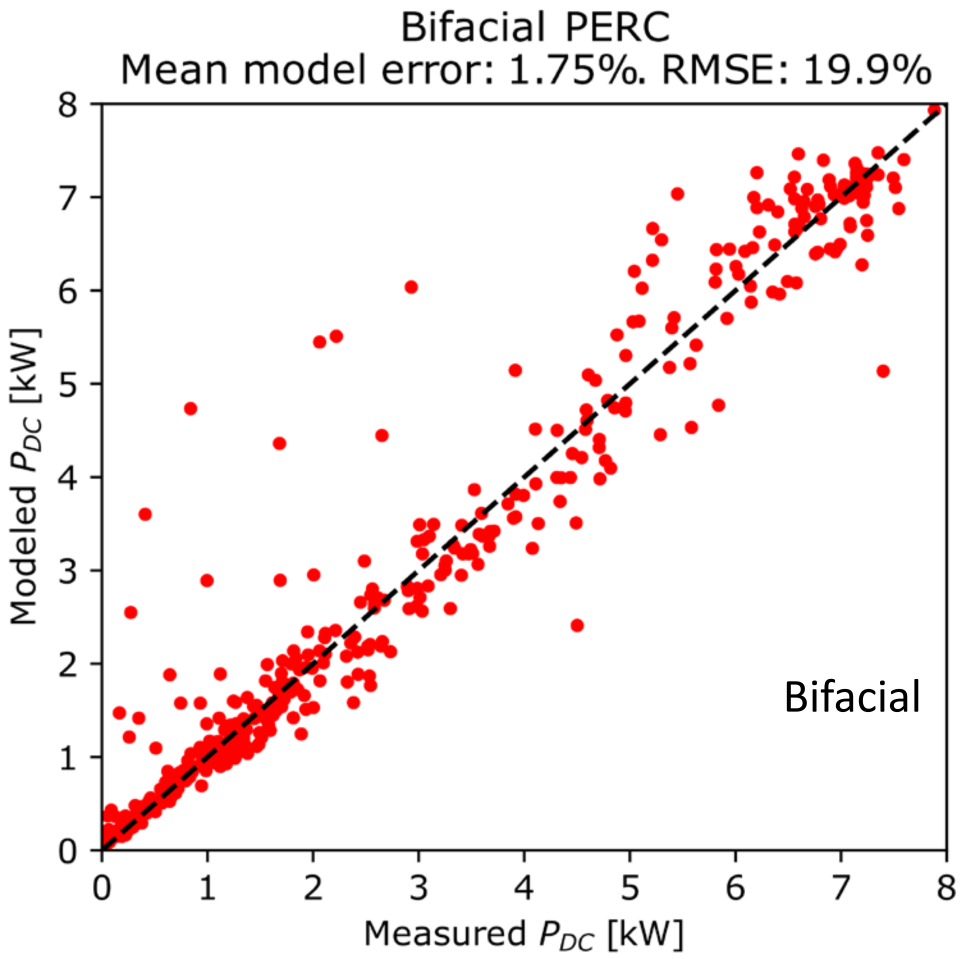
Initial field results – bifacial trackers



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

Modeled vs Measured kW_{DC} Power



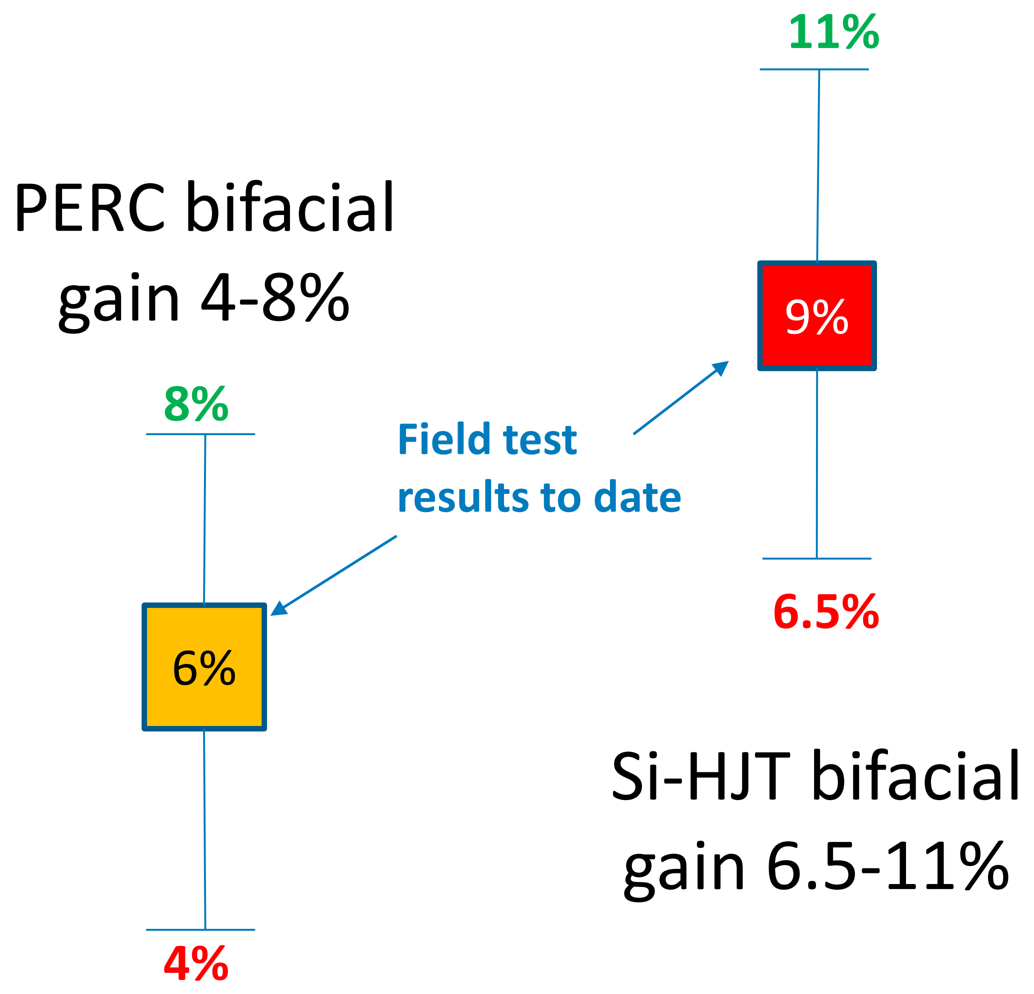


*SAM v2018.11 using 15-minute measured DNI, DHI, albedo from SRRL BMS. Andreas, A.; Stoffel, T.; (1981). NREL Solar Radiation Research Laboratory (SRRL): Baseline Measurement System (BMS); Golden, Colorado (Data); NREL Report No. DA-5500-56488. Bifacial systems assume 5% shading loss, 5% mismatch loss, 0% transmission factor

Bifacial modeling sensitivity

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

3 sensitivity cases:	Ground albedo	PERC ϕ_{Bifi}	Si-HJT ϕ_{Bifi}
High case	0.30	0.75	0.95
Average case	0.20	0.7	0.90
Low case	0.15	0.65	0.85



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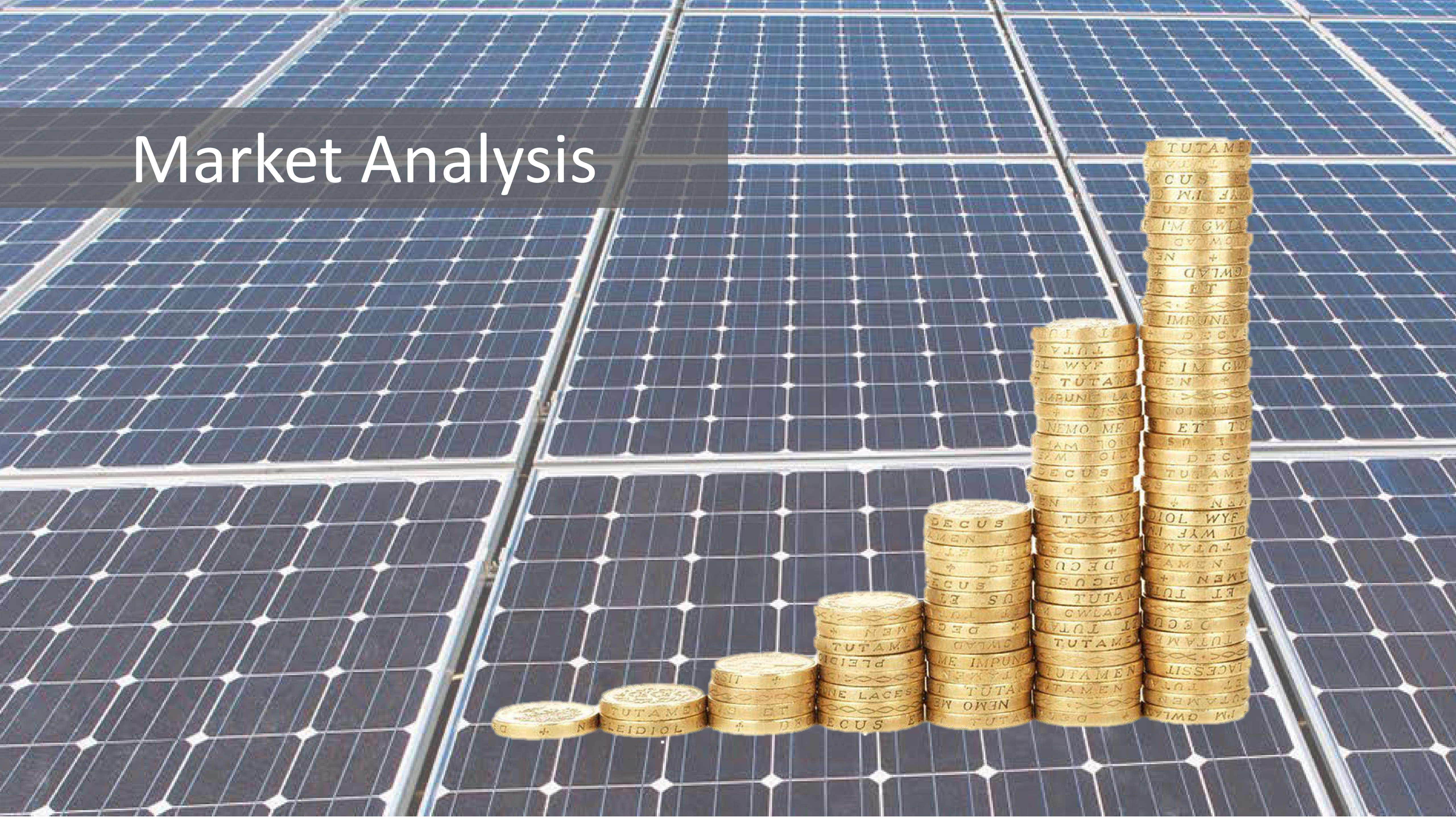
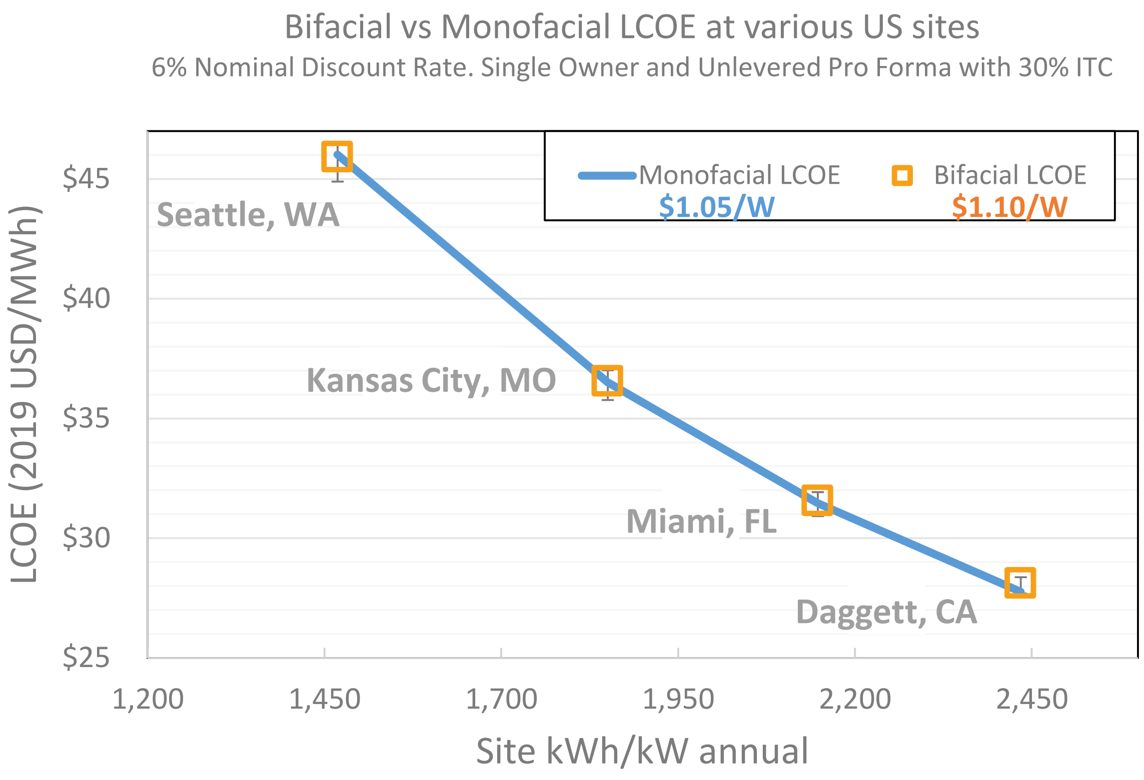
Market Analysis



LCOE Analysis for Monofacial and Bifacial PV Systems



Pre-Tariff situation illustration based on R. Fu, D. Feldman, R. Margolis, M. Woodhouse, K. Ardani, "U.S. Solar Photovoltaic System Cost Benchmark: Q1 2017" NREL/TP-6A20-68925, 2017 And Solar Energy Industries Association. US Solar Market Insight: 2018 Year in Review. Washington, DC March. 2019.
Assumptions: 100MW system, 1.2 DC-AC ratio, 0.35 GCR

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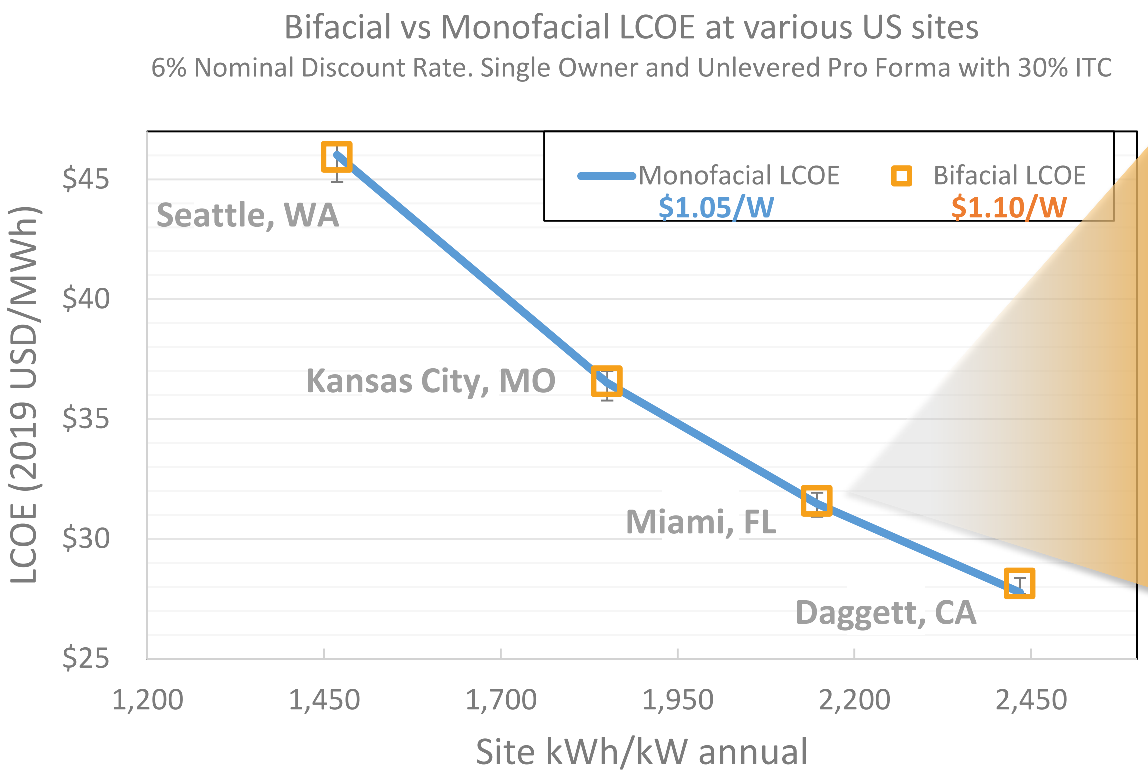

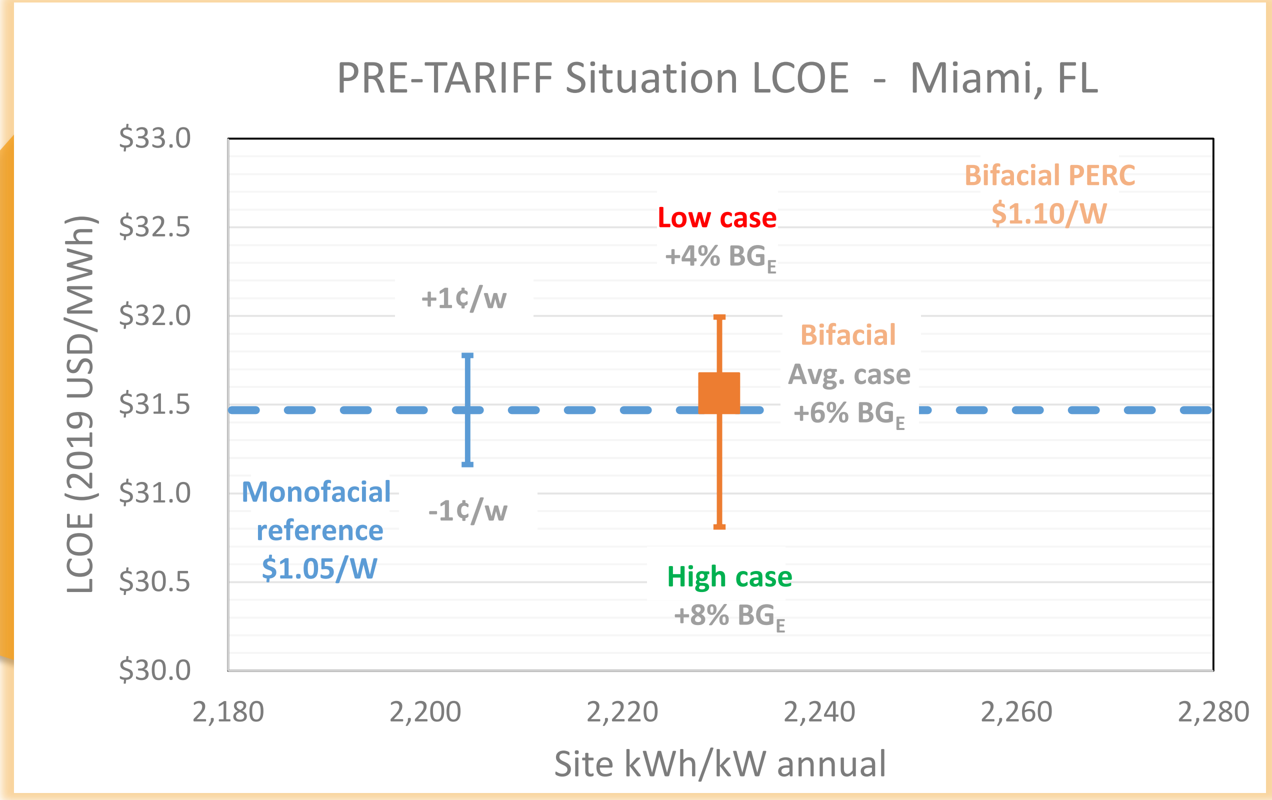

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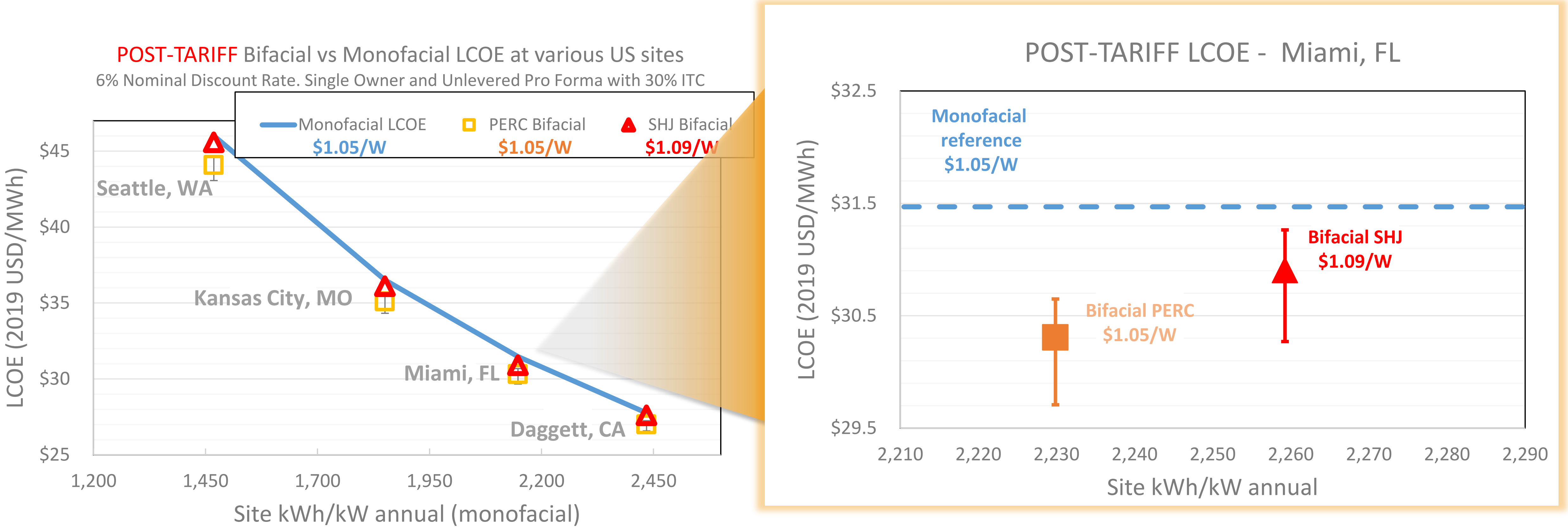


Post-Tariff illustration: -5¢/W bifacial based on R. Fu, D. Feldman, R. Margolis, M. Woodhouse, K. Ardani, "U.S. Solar Photovoltaic System Cost Benchmark: Q1 2017" NREL/TP-6A20-68925, 2017 And Solar Energy Industries Association. US Solar Market Insight: 2018 Year in Review. Washington, DC March. 2019.
Assumptions: 100MW system, 1.2 DC-AC ratio, 0.35 GCR

Conclusions:

- Bifacial PV is becoming mainstream with GW's of installed projects
- 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.
- 1-axis tracker validation is underway at NREL, showing good initial match with model, and energy gain of 6% and 9% annually for PERC and Si-HJT.
- LCOE of bifacial systems is competitive with monofacial systems now, even with initial cost adder of 5-6 ¢/W. Post-tariff, bifacial is a clear winner.

Look for more

June 19

WEDNESDAY, 10:30A: (Sheraton 4-5)

- B. Lee, J. Wu: Bifacial PERC cells. 11A & 11:30A

June 20

THURSDAY, 8:30A: *(Chicago 8)*

- A. Asgharzadeh: Benchmarking models. 8:30A
- M. Waters: Bifacial Capacity Testing. 8:45A
- K. McIntosh: Bifacial mismatch loss 9:00A

THURSDAY 10:30A: *(Sheraton 1)*

- M. Patel, R. Bailey: Albedo. 10:30 & 10:45A
- S. Ayala: Shading effects on bifacial trackers. 11A

Sept 12-17

36th EU PVSEC (Marseille)

6th Bifi PV Workshop (Amsterdam)

- S. Ayala: Electrical mismatch and shading
- B. Marion: Ground albedo measurements
- J. Stein: HPC Optimization of Bifacial Systems

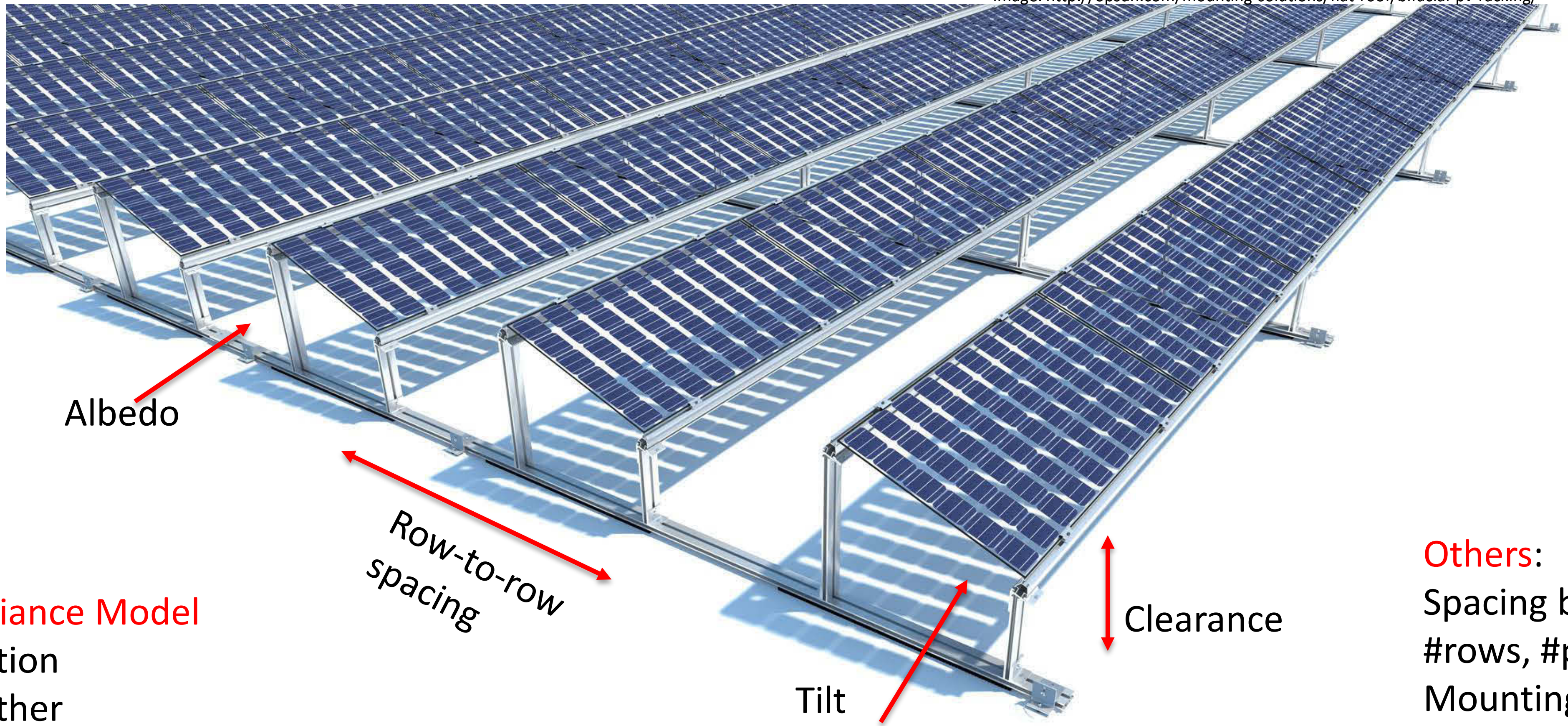
Acknowledg-ments

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory (NREL). Funding provided by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under Solar Energy Technologies Office (SETO) Agreement Number 34910. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government.

Backup Slides

Modeling Rear Irradiance

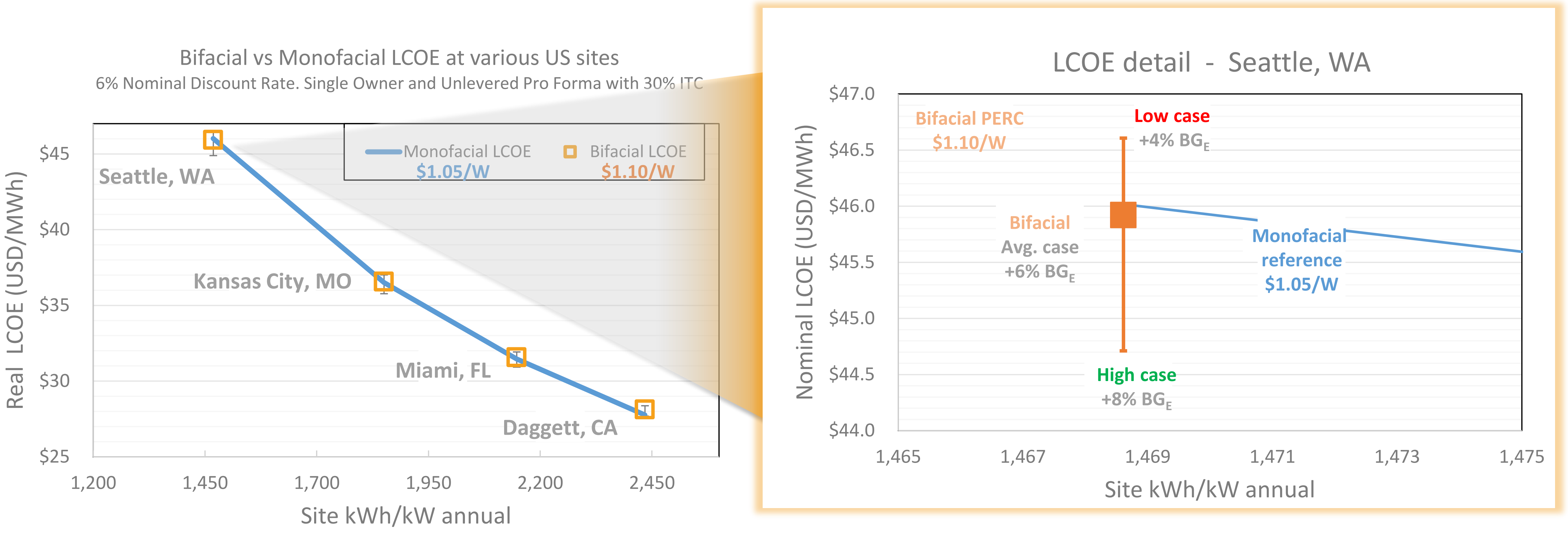
Image: http://opsun.com/mounting-solutions/flat-roof/bifacial-pv-racking/



Irradiance Model
Location
Weather
Sky Diffuse Model

Others:
Spacing between cells
#rows, #panels
Mounting Structure
Other scene elements

LCOE Analysis for Monofacial and Bifacial PV Systems



Illustrative example based on R. Fu, D. Feldman, R. Margolis, M. Woodhouse, K. Ardani, "U.S. Solar Photovoltaic System Cost Benchmark: Q1 2017" NREL/TP-6A20-68925, 2017
And Solar Energy Industries Association. US Solar Market Insight: 2018 Year in Review. Washington, DC March. 2019.
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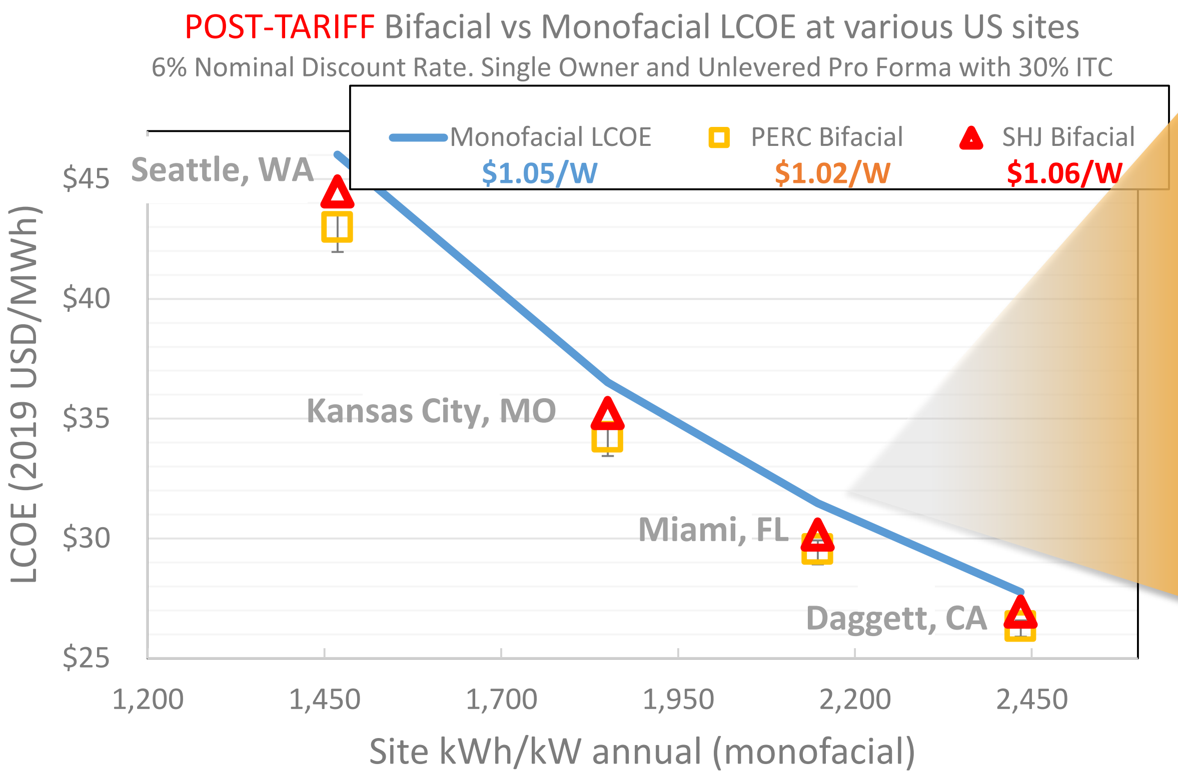

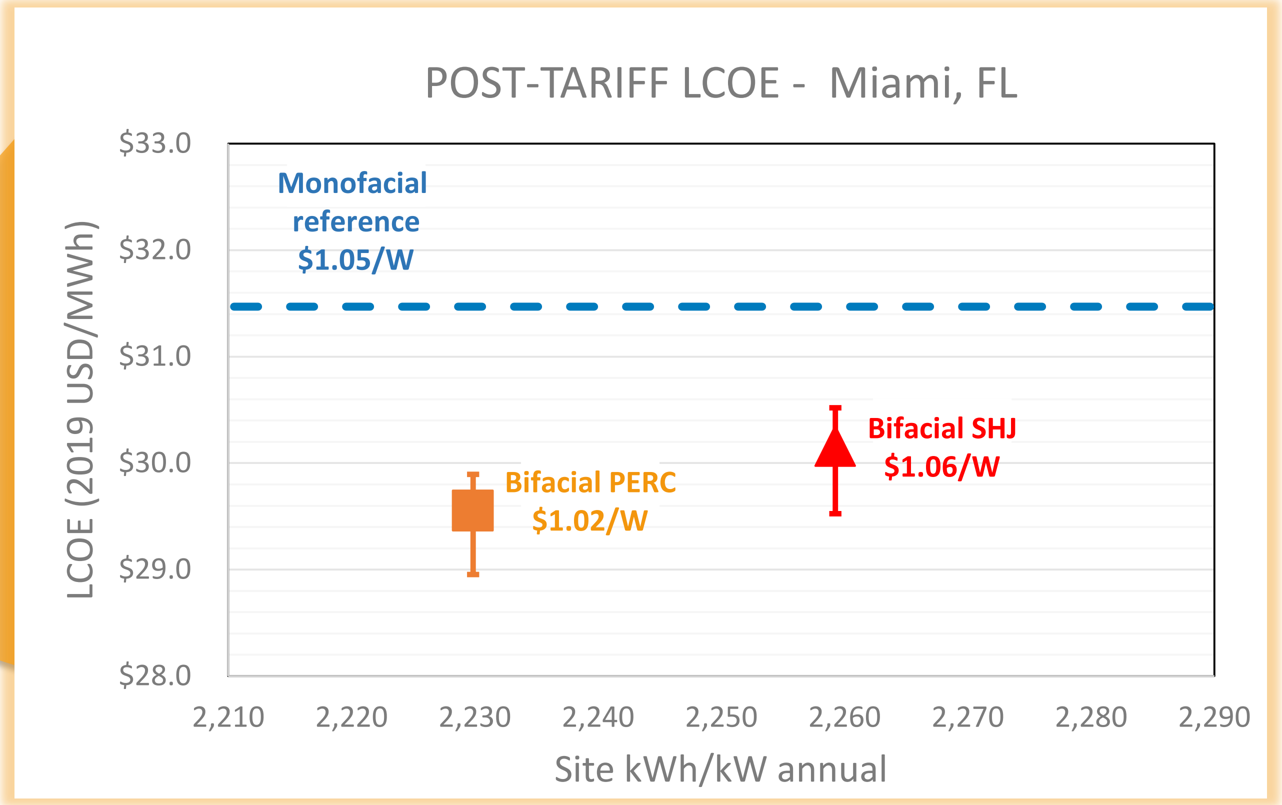

Post-Tariff illustration: -8¢/W bifacial based on R. Fu, D. Feldman, R. Margolis, M. Woodhouse, K. Ardani, "U.S. Solar Photovoltaic System Cost Benchmark: Q1 2017" NREL/TP-6A20-68925, 2017 And Solar Energy Industries Association. US Solar Market Insight: 2018 Year in Review. Washington, DC March. 2019.

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