NREL
NATIONAL RENEWABLE ENERGY LABORATORY

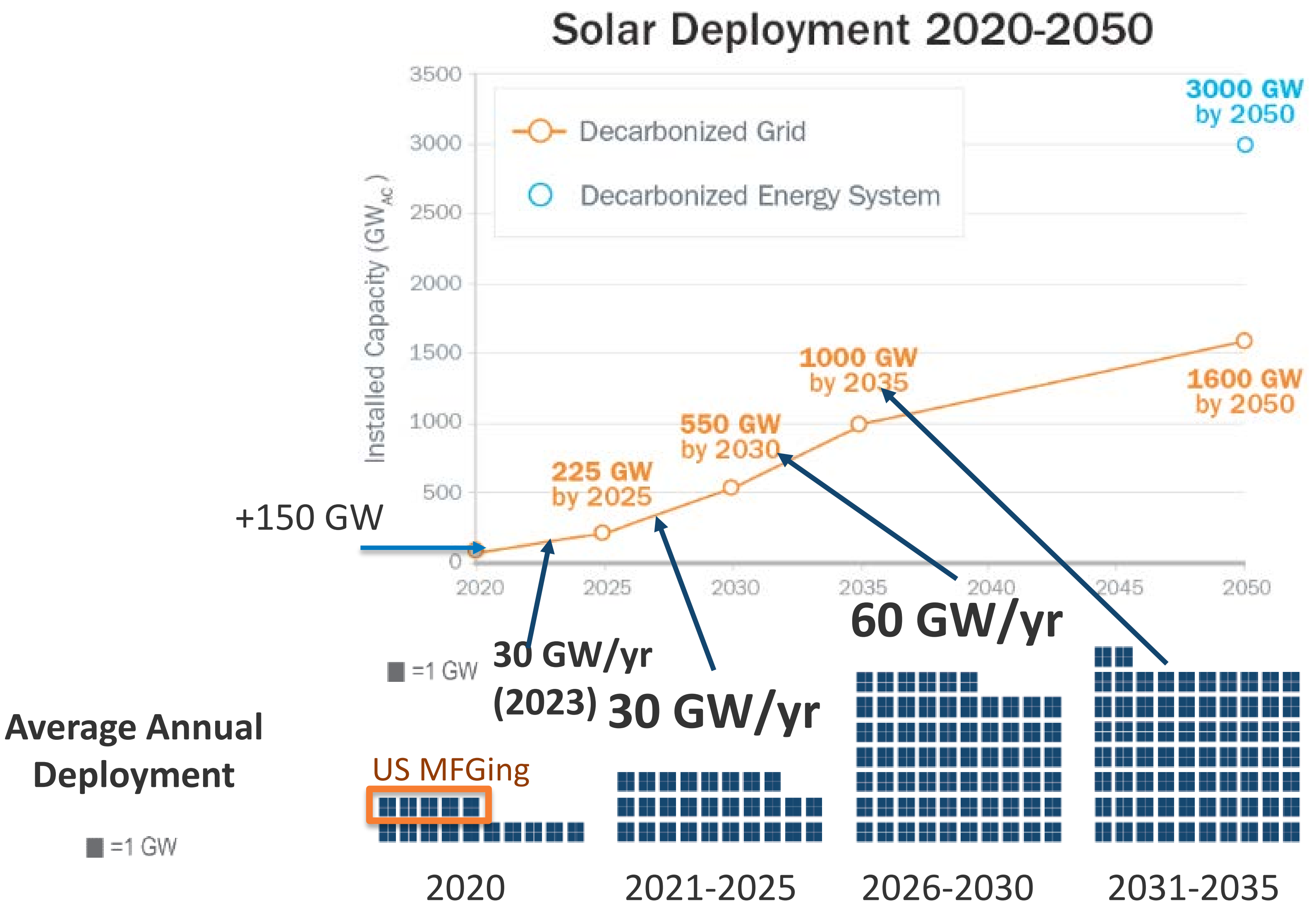
Catching Rays: How bifacial_radiance Sheds Light on the Future of Solar PV

Silvana Ovaitt, Chris Deline

Radiance Workhshop 2024, SLC

Contents

US Decarbonization Goals
>90% Clean Electricity by 2035

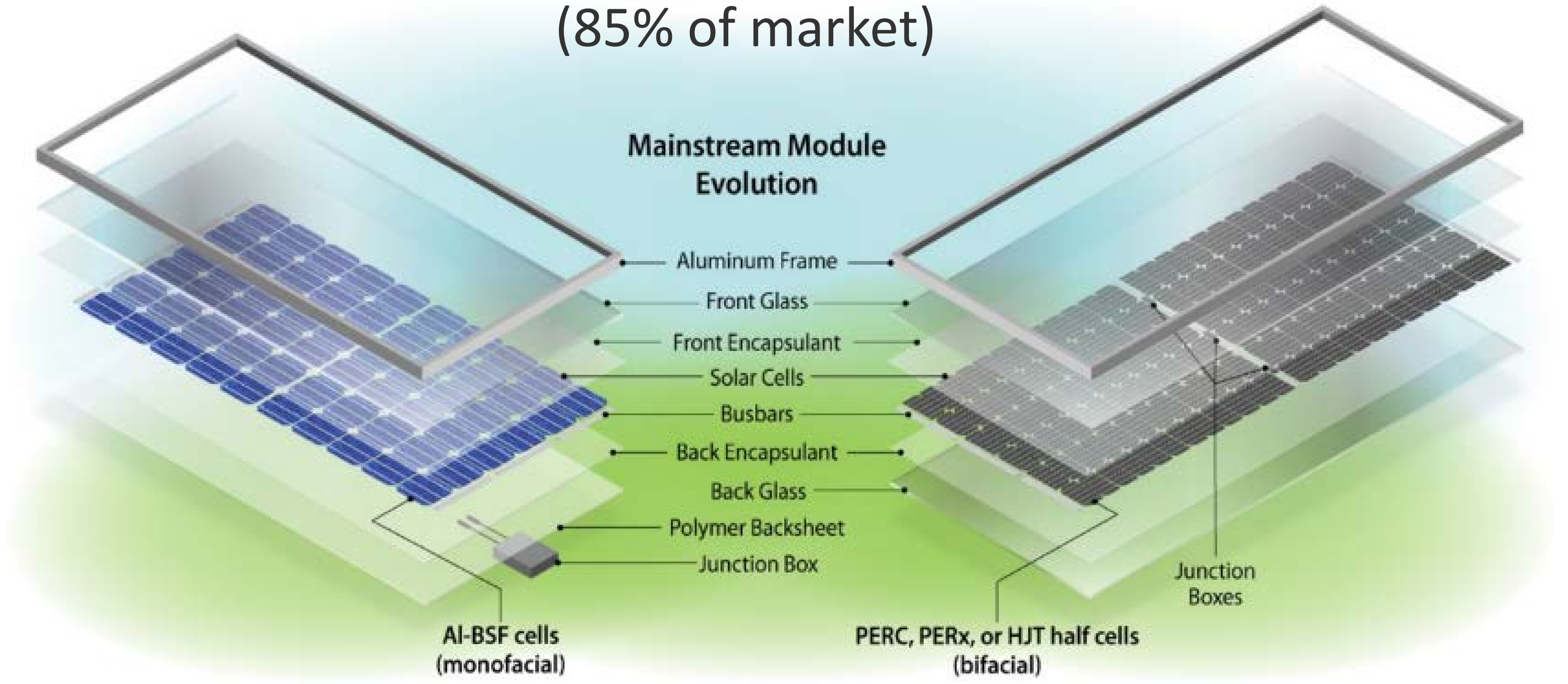


DOE, Solar Futures Study 2021

[1]IRENA, IEA, Feldman et al 2023, Wood Mackenzie

Modules Continuously Evolve

Silicon Modules
(85% of market)



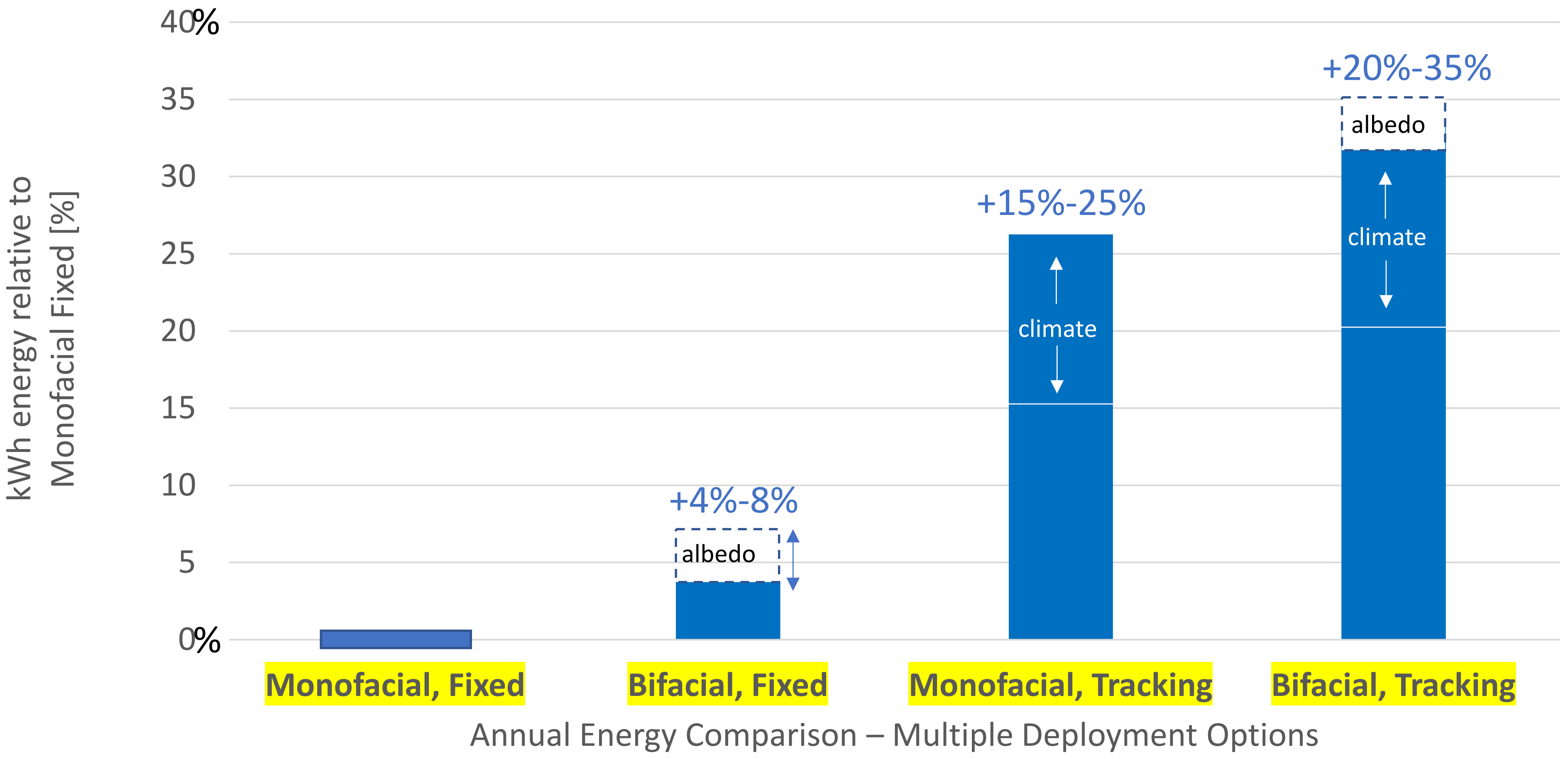
Pre-2015 module, 20-25 year life

2024 module, 35 year life

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

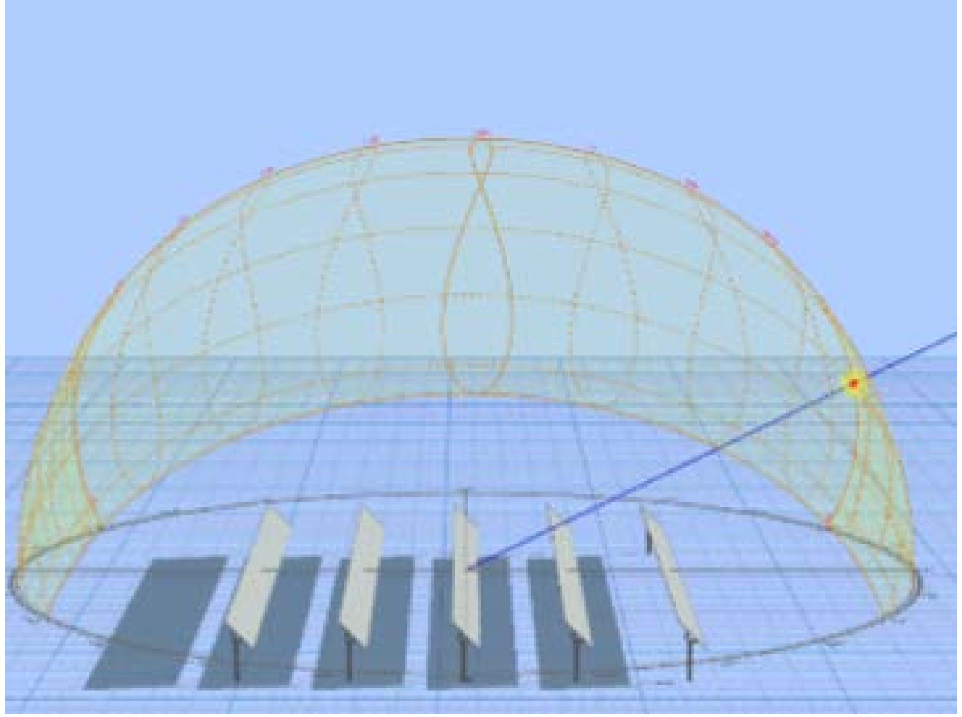
Ovaitt & Mirletz et al, 2022. "PV in the Circular Economy, A Dynamic Framework Analyzing Technology Evolution and Reliability Impacts." *ISCIENCE* https://doi.org/10.1016/j.isci.2021.103488.

Why 50% of modules are bifacial now and growing?
Big Lever on Energy Yield



*2024 Market Share: ITRPV 2024
*SAM simulation, range of scenarios

Modeling PV



Sky models	Irradiance Input
Isotropic	DNI & DHI
HDKR	DNI & GHI
Perez	GHI & DHI
	GHI

Wind, Temperature, Albedo

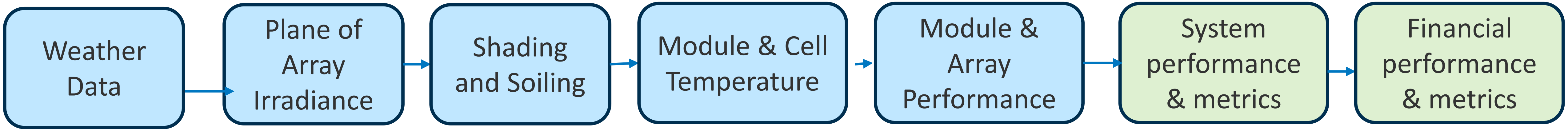
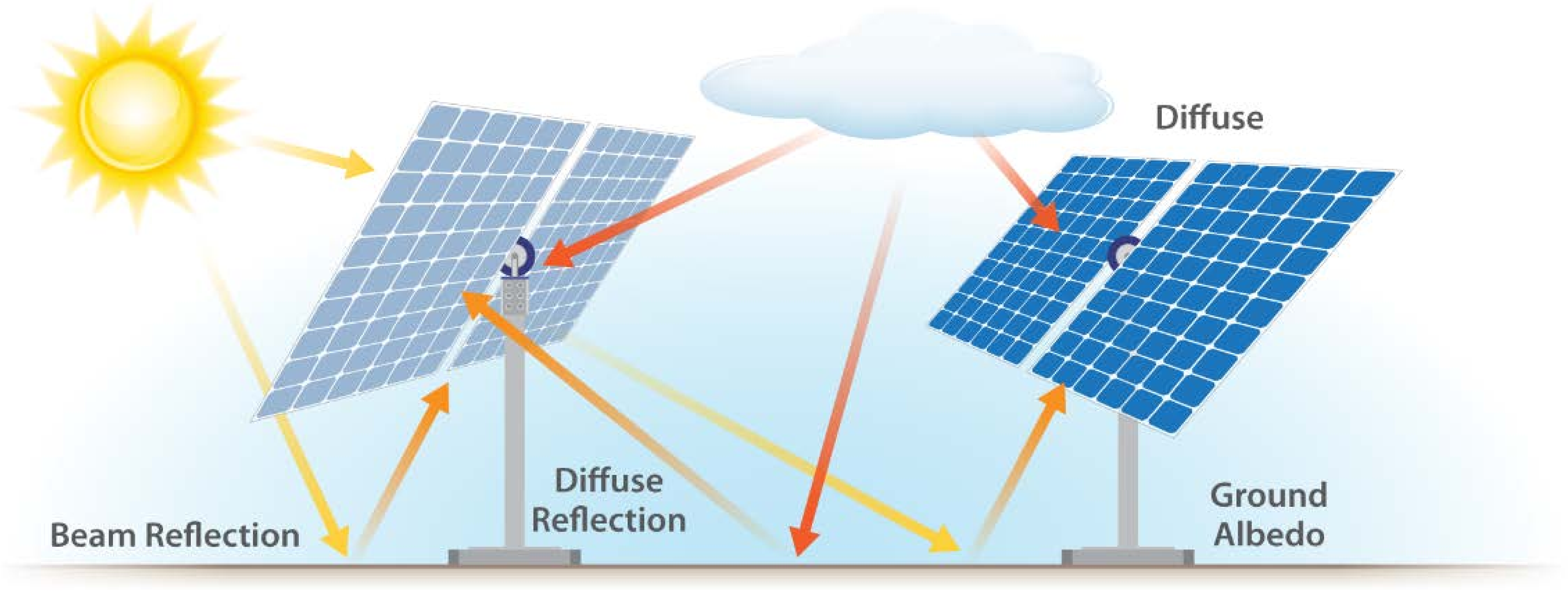


Diagram by S. Ovaitt, included in IEA Task 13 AgriPV Report, 2024

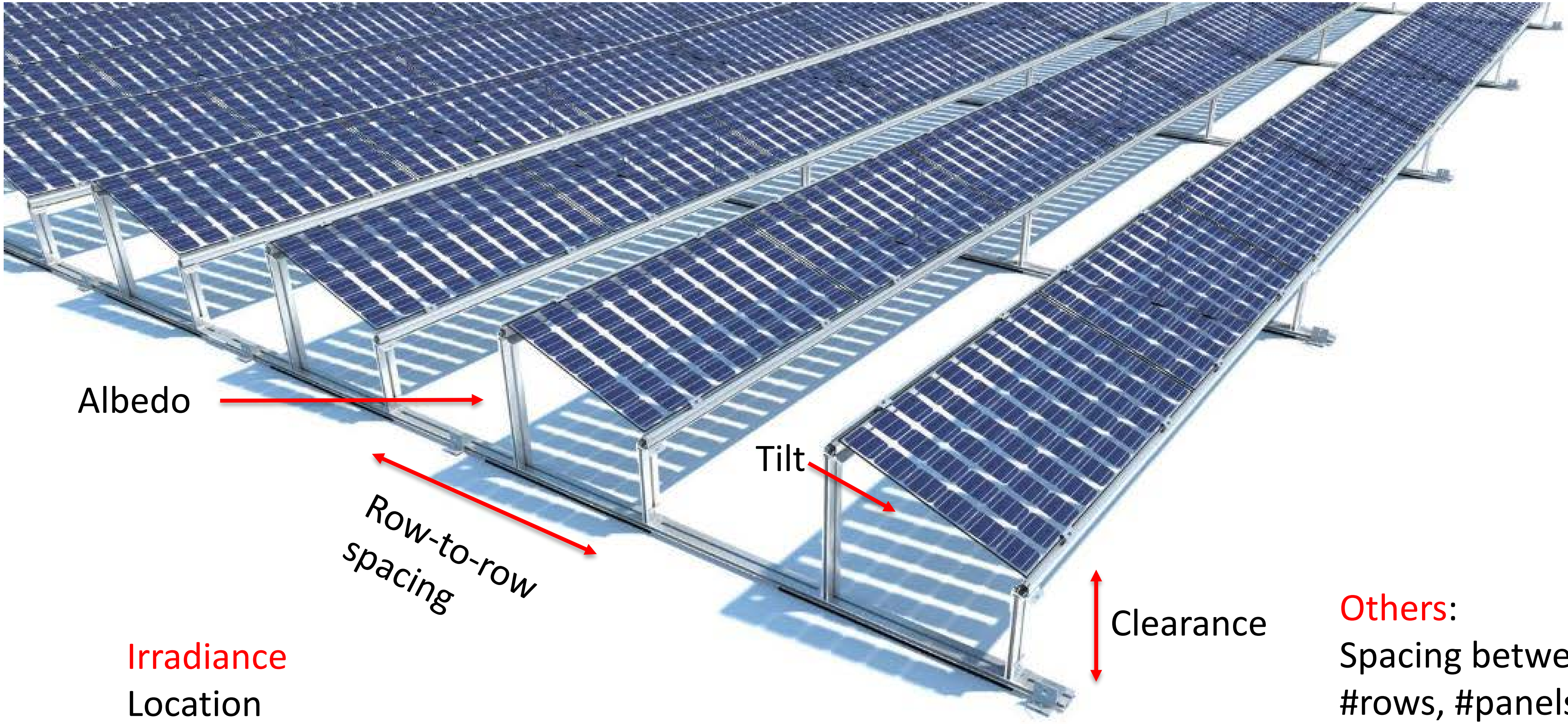
Modeling Rear Irradiance



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

Parameters that affect rear Irradiance

Image courtesy of Opsun trackers, via Francois Gilles-Gagnon



Irradiance
Location
Weather
Sky Diffuse

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

8

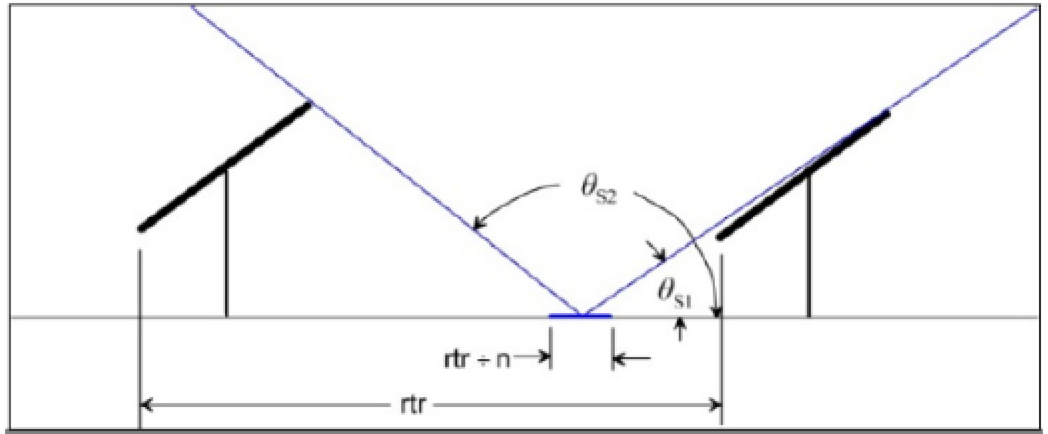
Modeling Rear Irradiance

Less complexity → **More complexity**

View Factor Models

Due-diligence Software
(PVSyst, NREL's System Advisor Model)

NREL's bifacialVF
gitub.com/NREL/bifacialvf



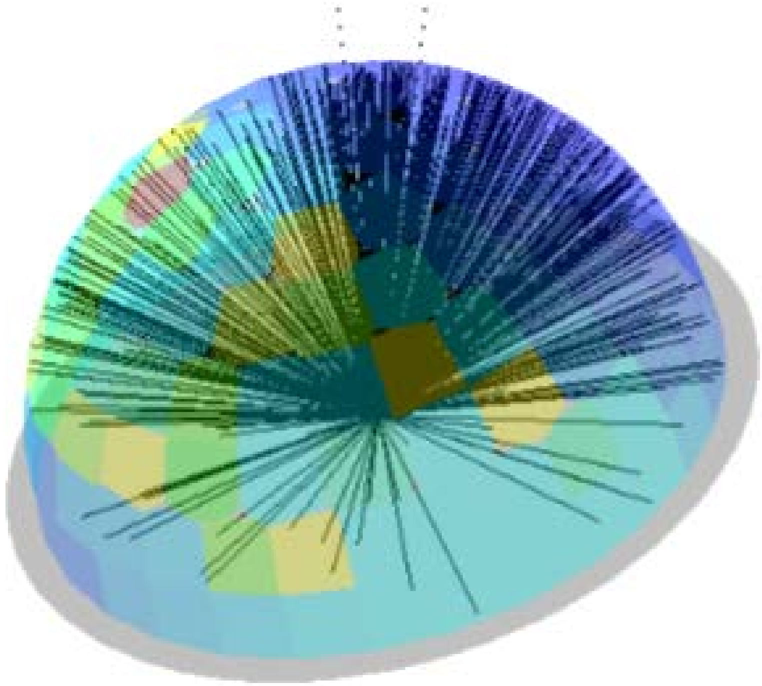
View Factor ground reflection geometry

Marion, B., MacAlpine, S., Deline, C., Asgharzadeh, A., Toor, F., Riley, D., ... & Hansen, C. (2017). A Practical Irradiance Model for Bifacial PV Modules: Preprint (No. NREL/CP-5J00-67847). National Renewable Energy Laboratory (NREL), Golden, CO (United States).

Raytrace Model

Commercial: PVLighthouse, PVCase, etc..

Open-source: NREL Bifacial Radiance
github.com/NREL/bifacial_radiance



View Factor

EXAMPLE 5-3 Consider an infinitely long wedge-shaped groove as shown in cross section in Fig. 5-4. Determine the configuration factor between the differential strips dx and $d\xi$ in terms of x, ξ, and α.

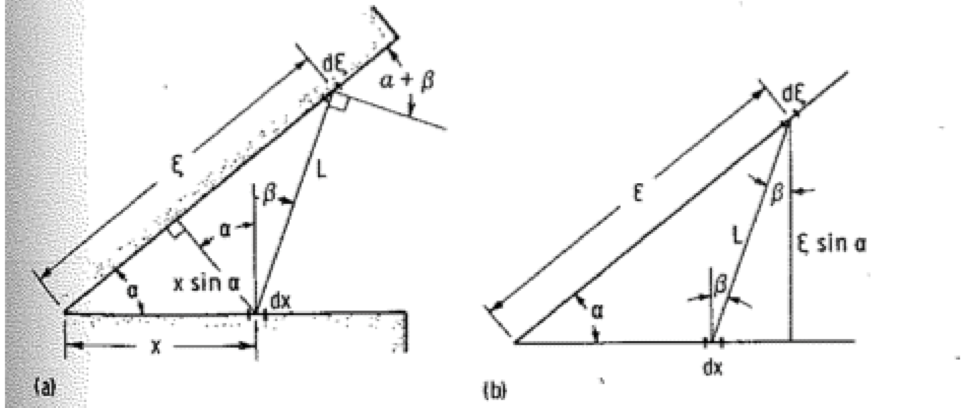


FIGURE 5-4 Configuration factor between two strips on sides of wedge groove. (*a*) Wedge-shaped groove geometry; (*b*) auxiliary construction.

From Example 5-2, the configuration factor is

$$dF_{dx-d\xi} = \tfrac{1}{2}d(\sin\beta) = \tfrac{1}{2}\cos\beta\, d\beta$$

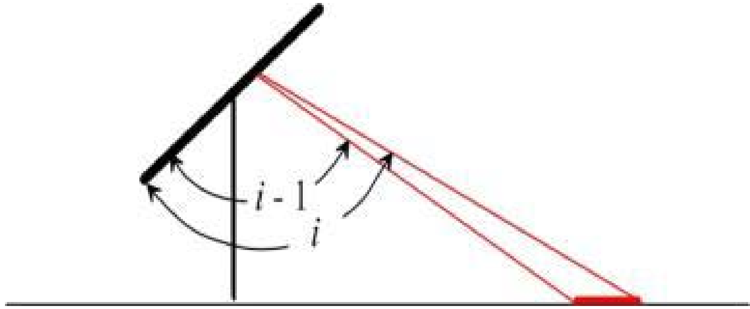
From the construction in Fig. 5-4*b*, $\cos\beta = (\xi\sin\alpha)/L$. The $d\beta$ is the angle subtended by the projection of $d\xi$ normal to L, that is,

$$d\beta = \frac{d\xi\cos(\alpha+\beta)}{L} = \frac{d\xi}{L}\frac{x\sin\alpha}{L}$$

From the law of cosines, $L^2 = x^2 + \xi^2 - 2x\xi\cos\alpha$. Then

$$dF_{dx-d\xi} = \tfrac{1}{2}\cos\beta\, d\beta = \frac{1}{2}\frac{x\xi\sin^2\alpha}{L^3}d\xi = \frac{1}{2}\frac{x\xi\sin^2\alpha}{(x^2+\xi^2-2x\xi\cos\alpha)^{3/2}}d\xi$$

Book Thermal Radiation Heat Transfer– Robert Siegel & John Howell



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

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

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

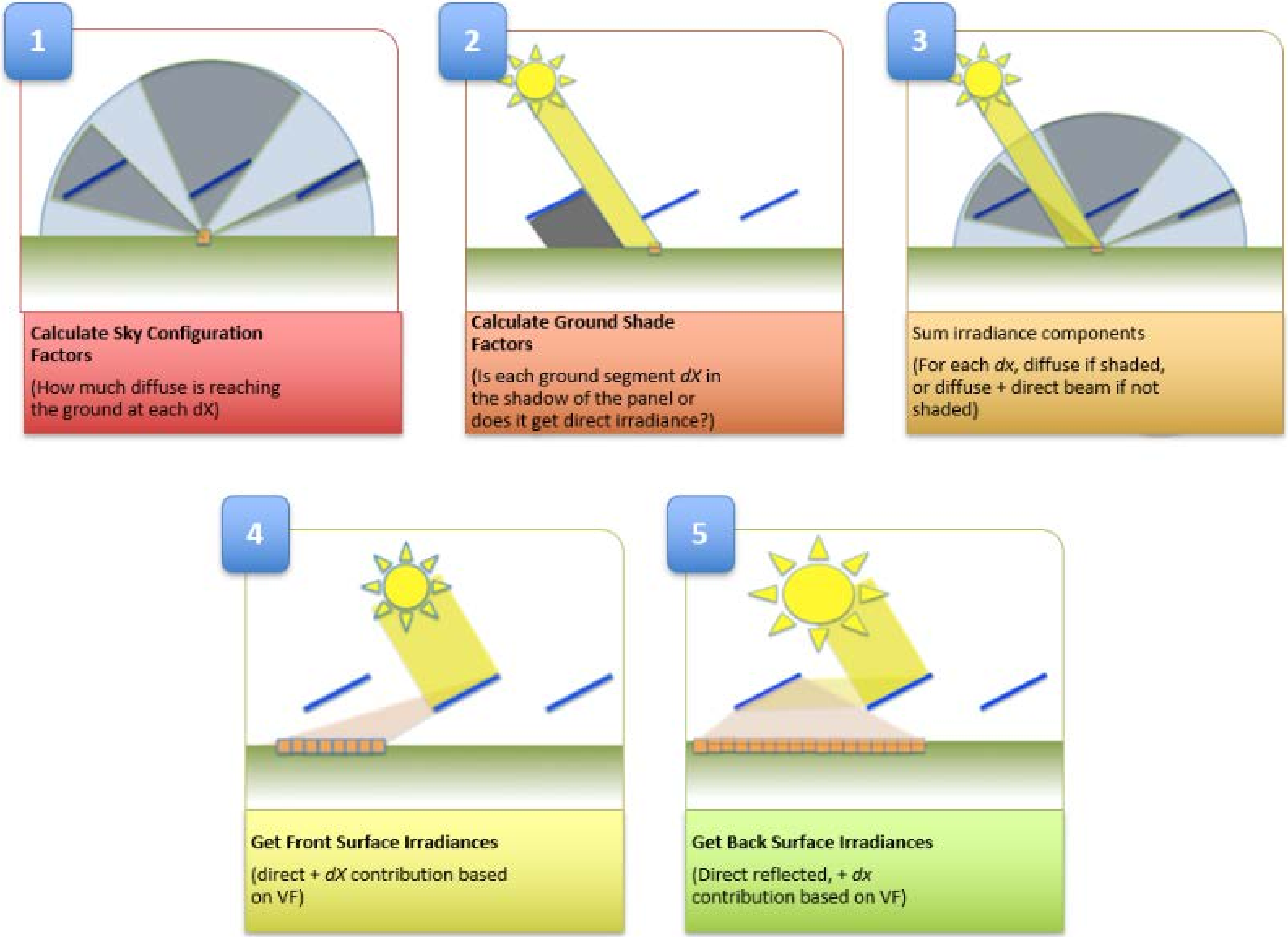
$$F_i = Incidence\ angle\ modifier(\Theta)$$

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

Irradiance sources:
sky, ground (shaded or unshaded)

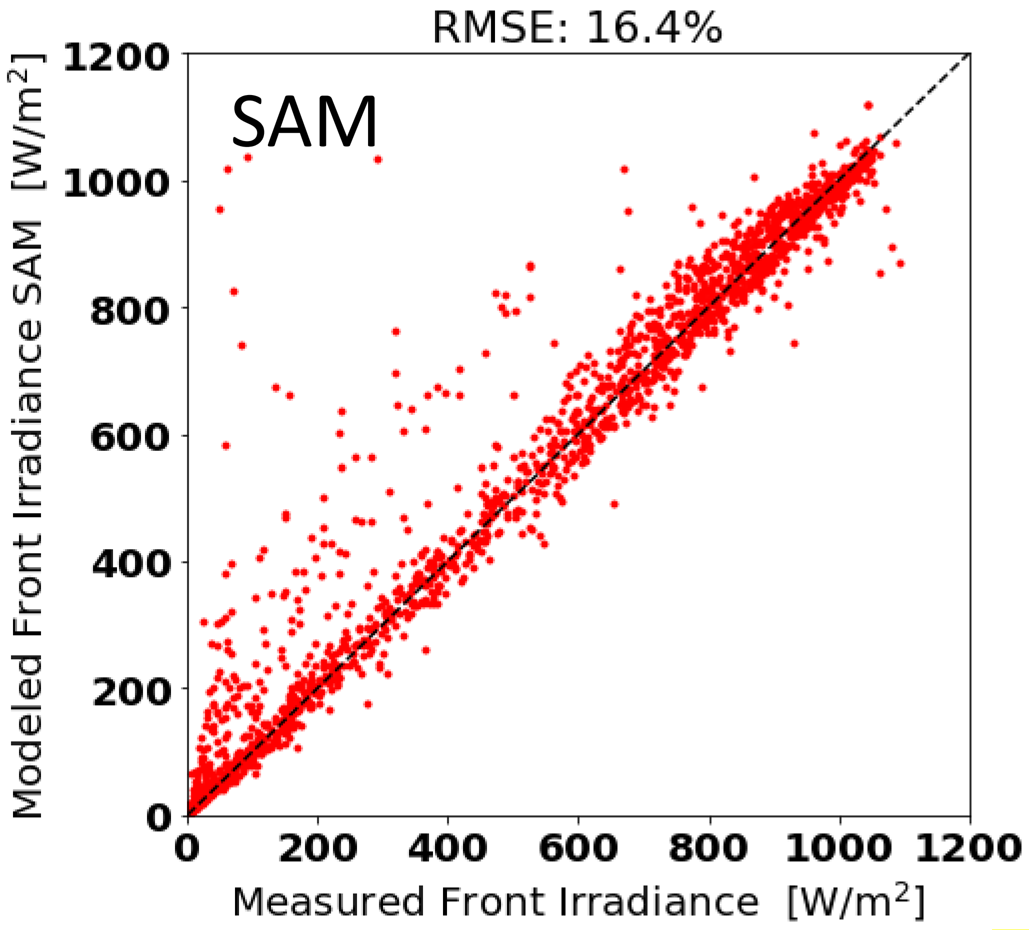
B. Marion et al., A Practical Irradiance Model for Bifacial PV Modules, 2017
B. Marion, Numerical method for angle-of-incidence correction factors for diffuse radiation incident photovoltaic modules, 2017

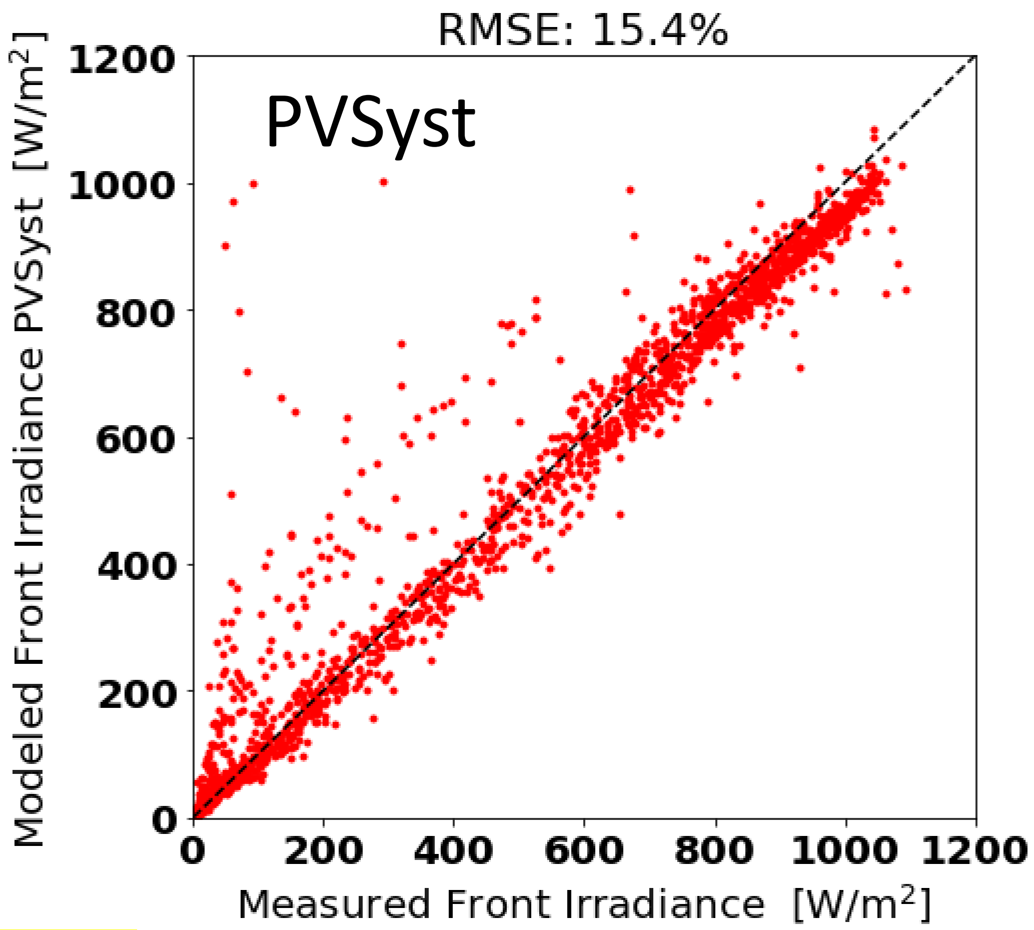
View Factor: Step by Step



Measured vs Modeled Irradiance

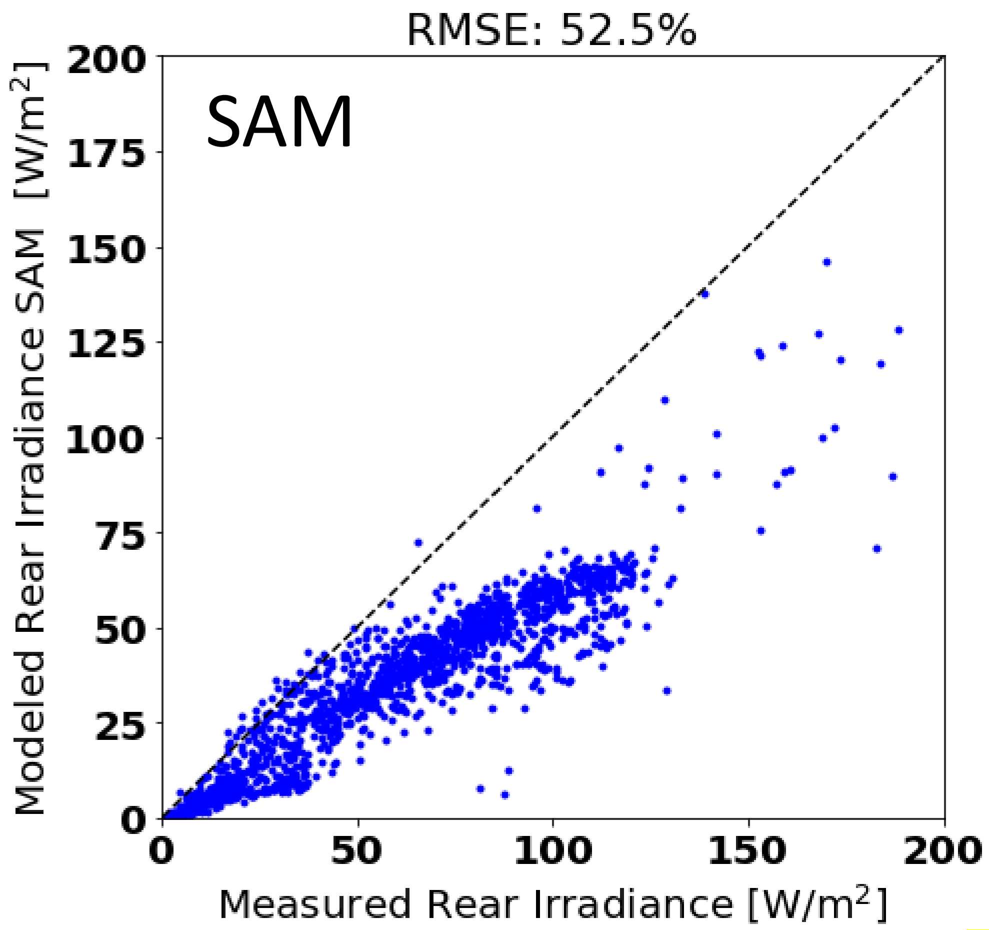
July to November 21st

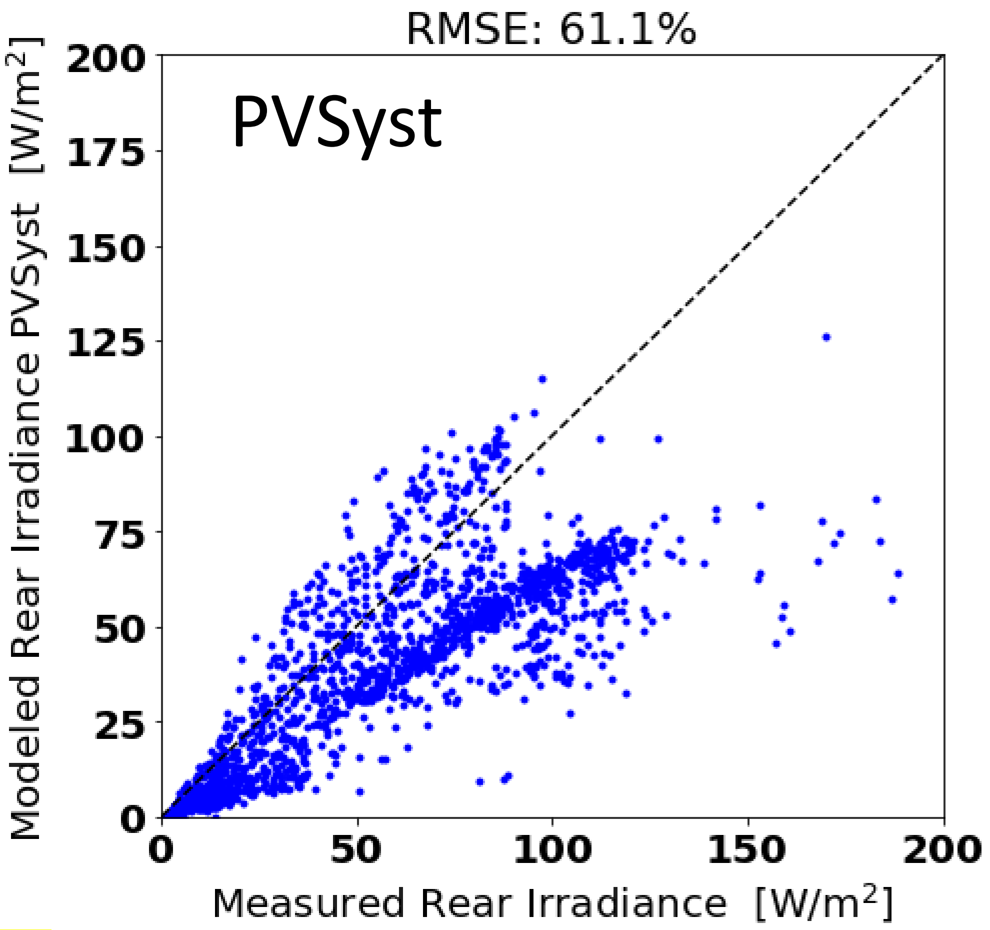




FRONT

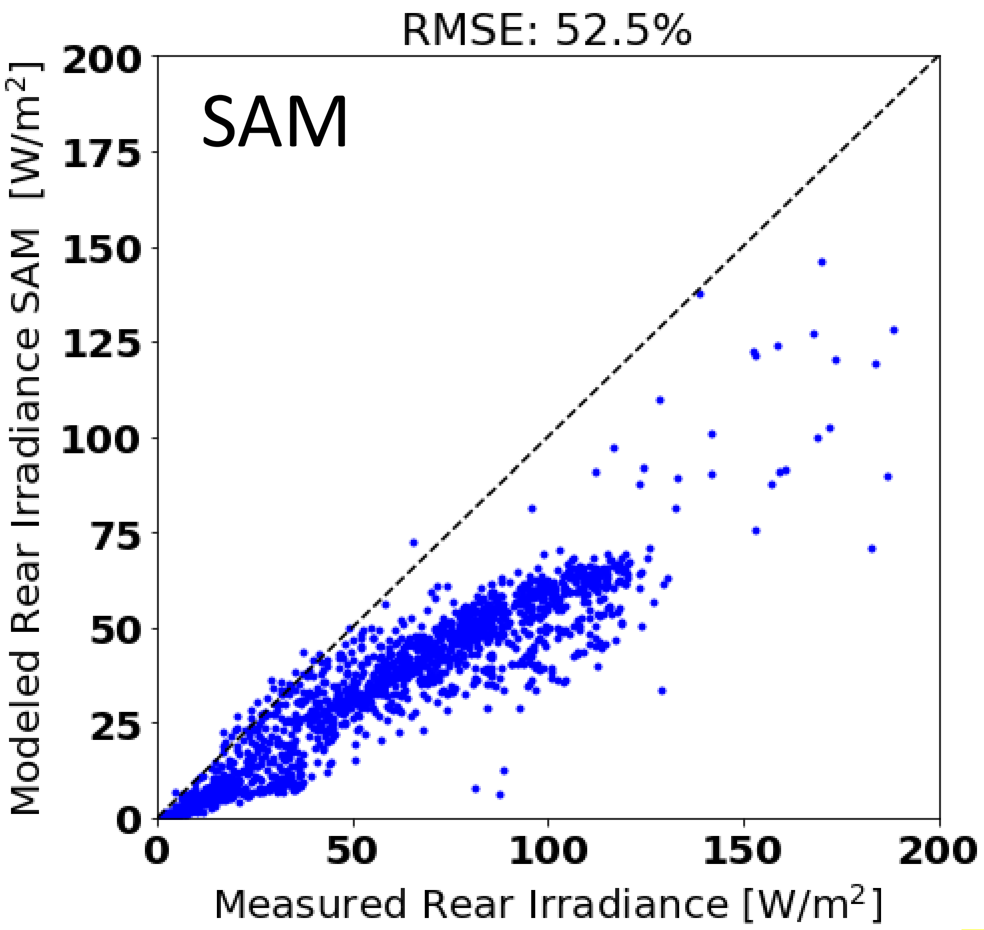
Measured vs Modeled Irradiance
July to November 21st

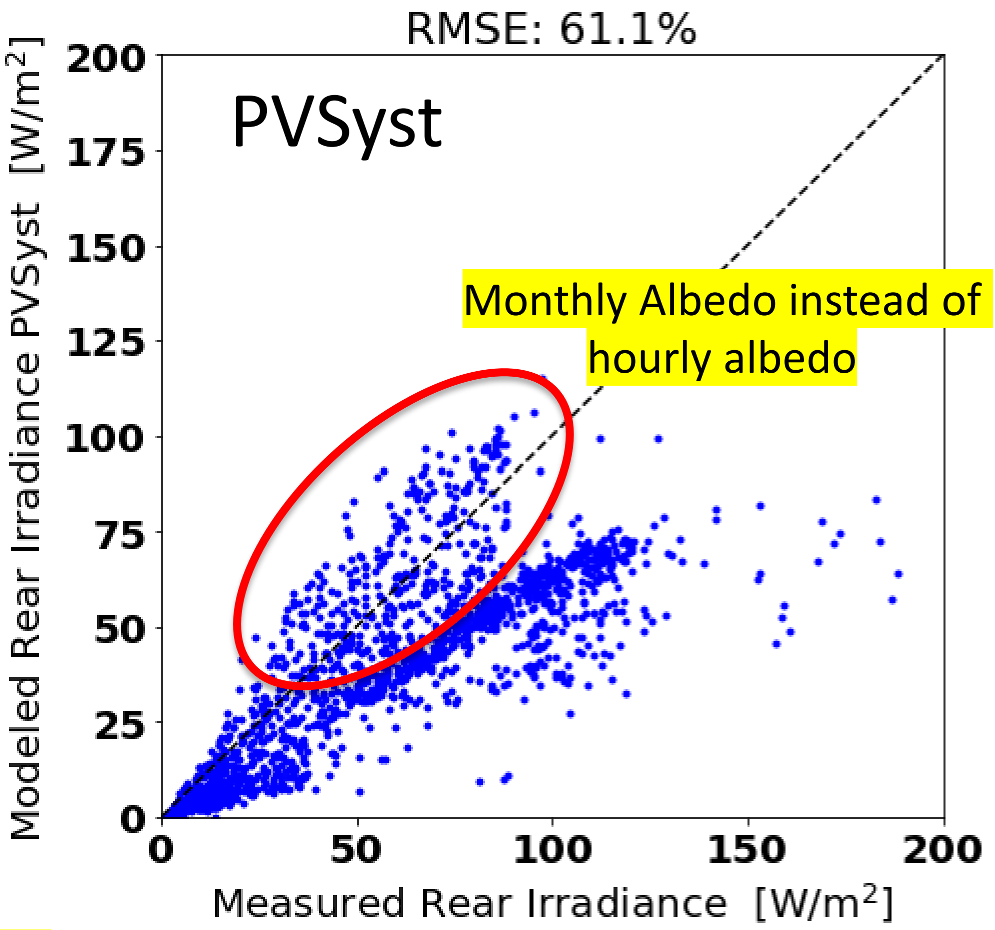




REAR

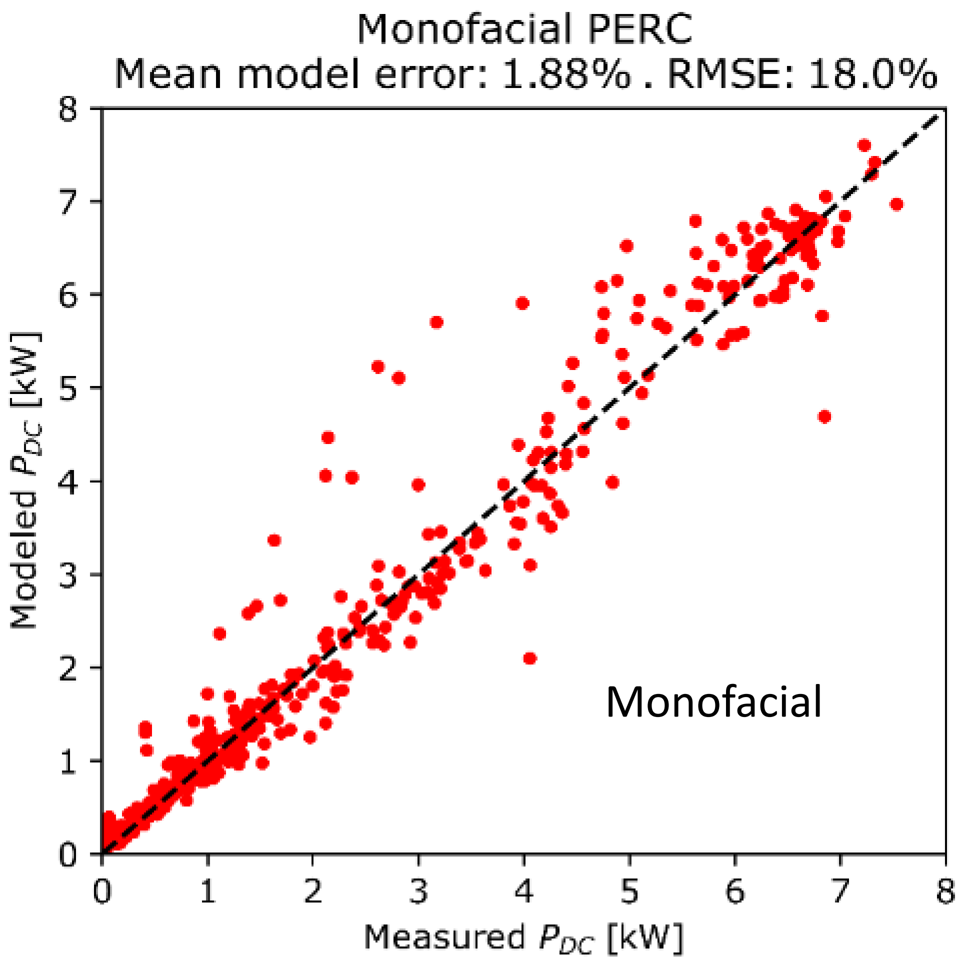
Measured vs Modeled Irradiance
July to November 21st

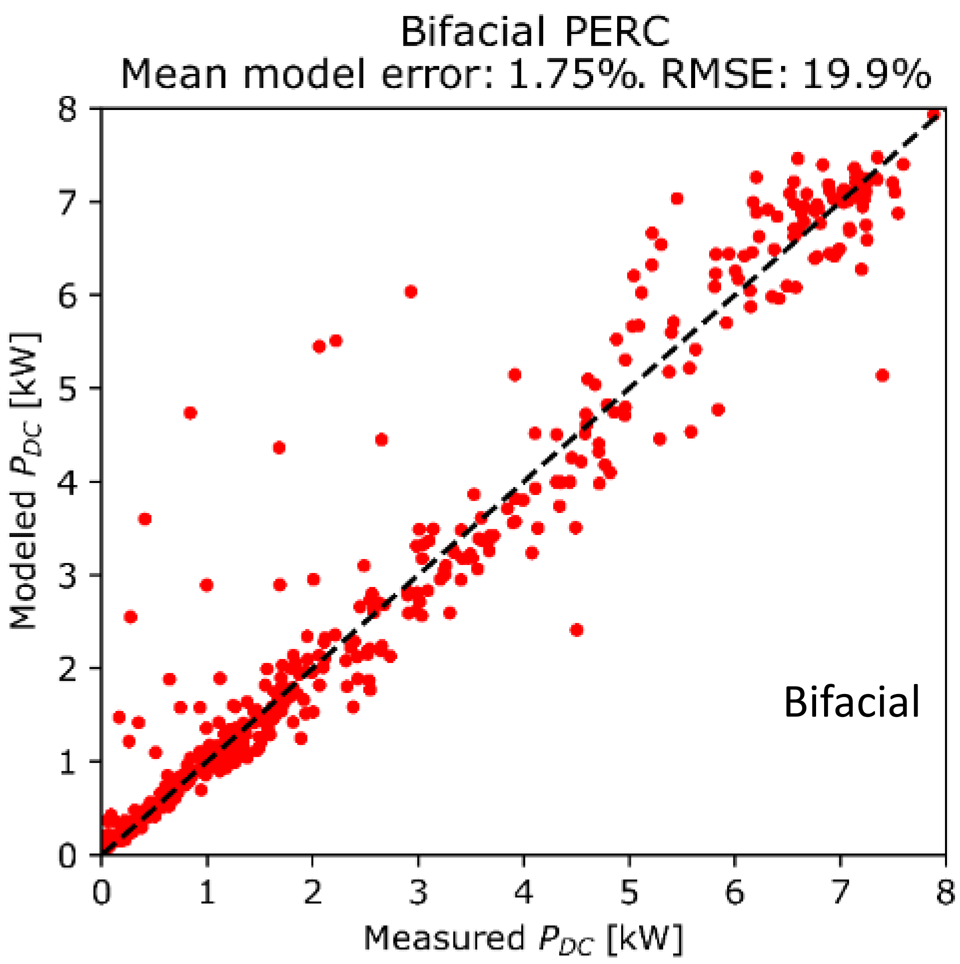




REAR

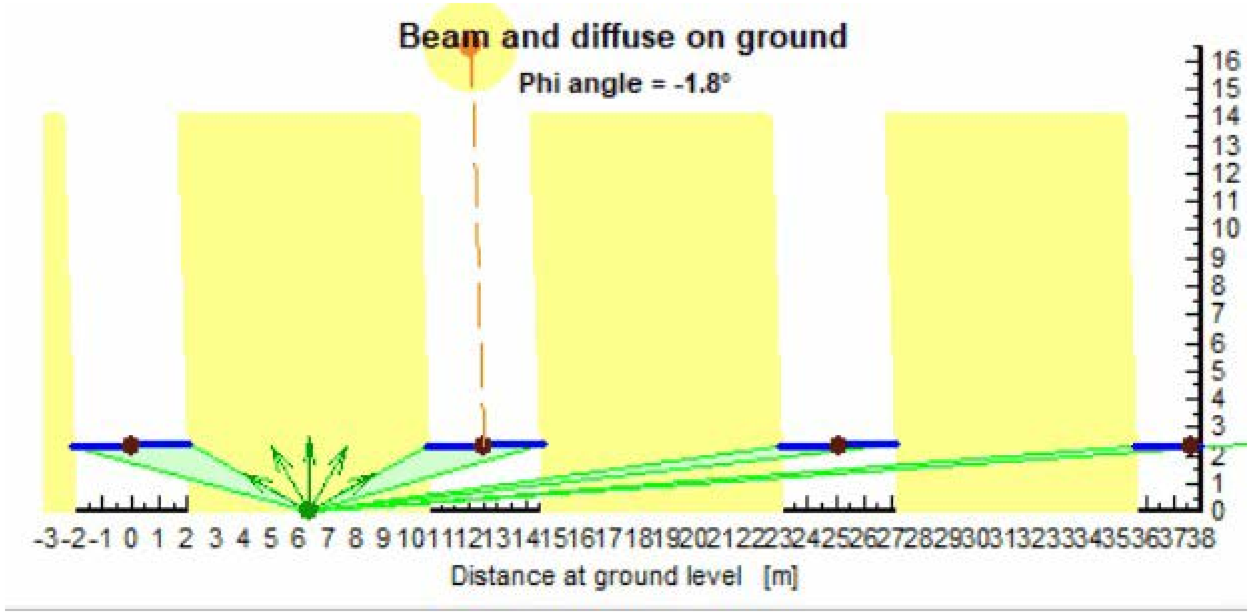
Modeled vs Measured kW_{DC} Power





*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

View Factor Model for Rear Irradiance



PVSyst v6.75

Simple

basic **geometry**

Fast

computationally **inexpensive**

Common

Behind SAM, Pvsyst, and others

So Why Do Raytrace?

For narrowing bifacial gain uncertainty

Initially (~2017), industry was unclear on what bifacial gain to expect, which affected projects bankability. Some articles were unclear on system size and comparison points when reporting their gain. This is better established now

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

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

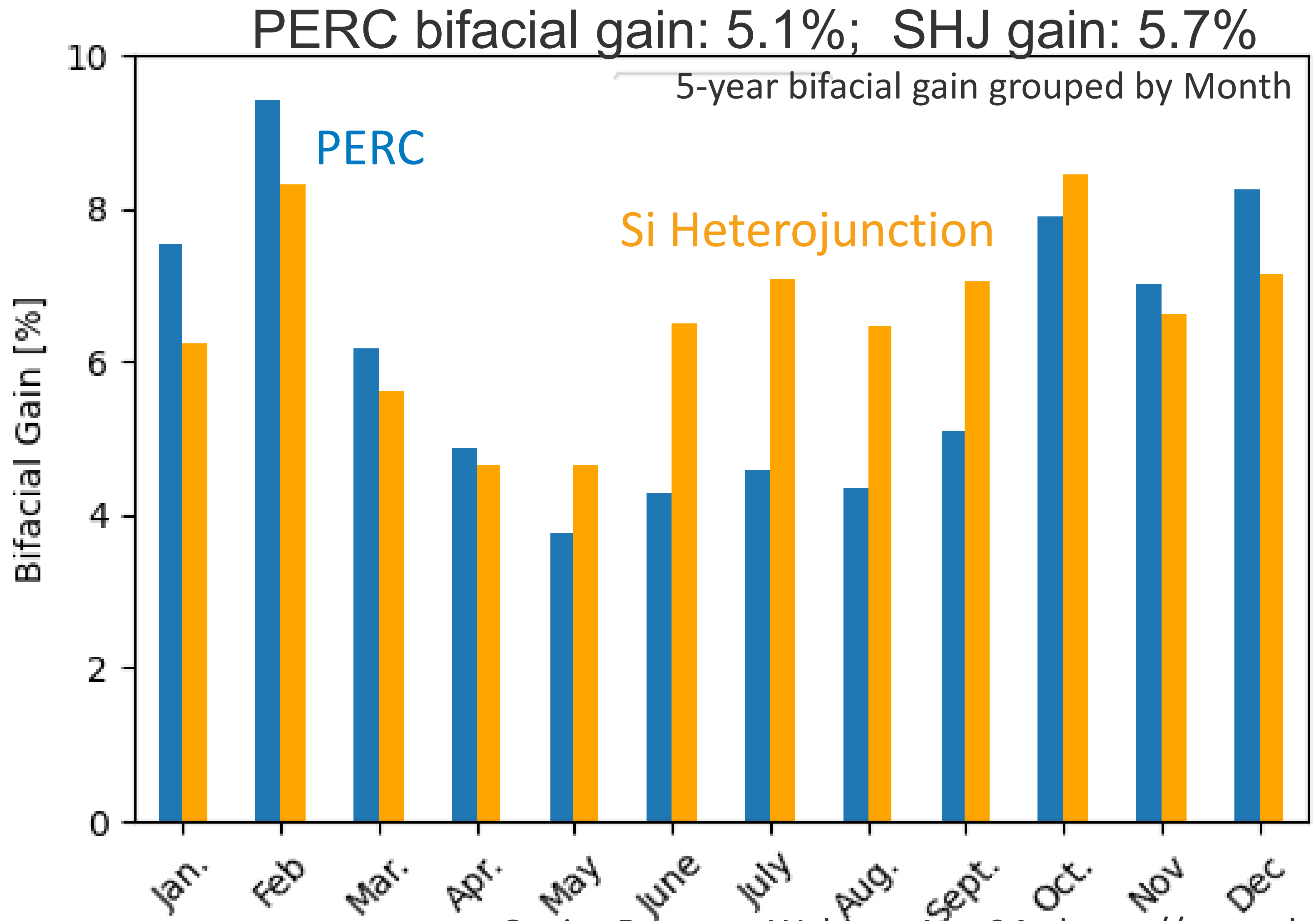
* Only data from May to August were used to eliminate snowing effects.
** Average bifacial gain of multiple test modules was used.
*** The east-west-facing vertical modules measurement in [16] shows great discrepancy between two modules; therefor, it is not included here.
**** Bifacial measurement (12/2016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

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

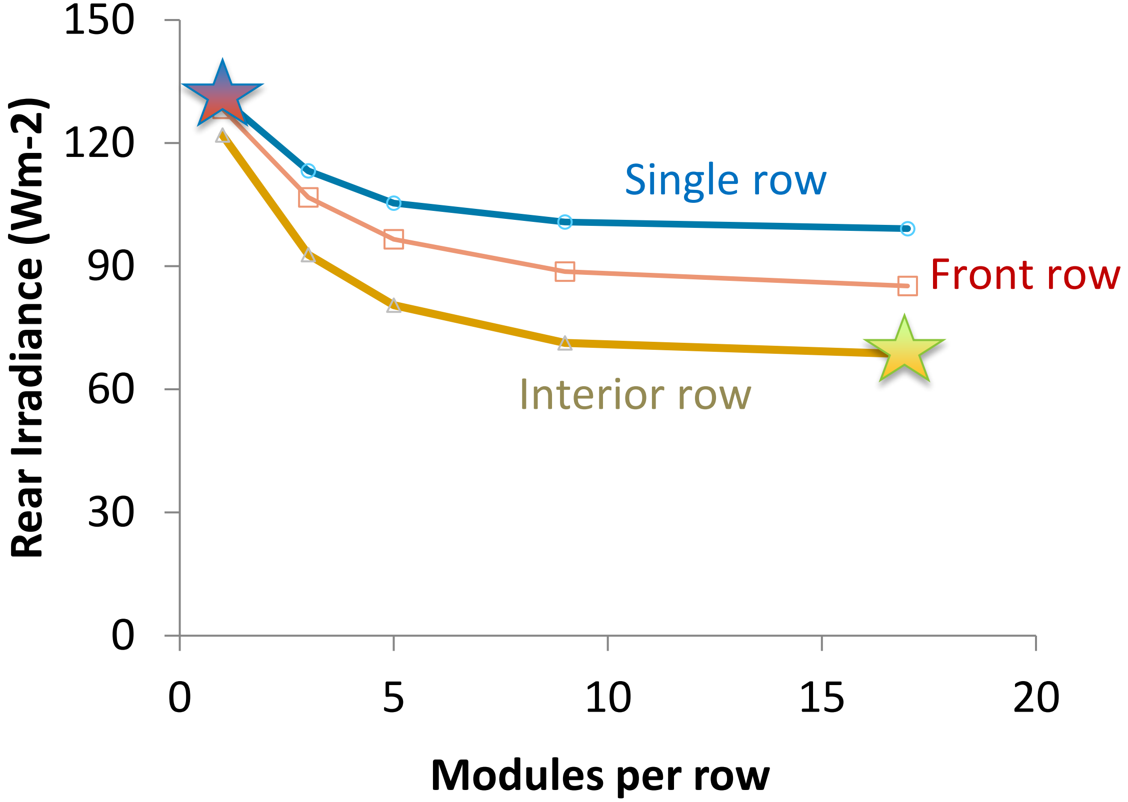
Bifacial gain at NREL's 75kW site

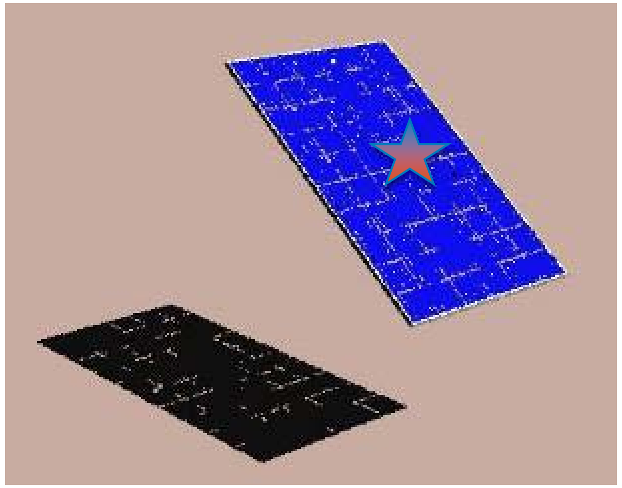
$$\frac{Energy\ bifacial}{Energy\ monofacial} - 1 \quad [\%]$$

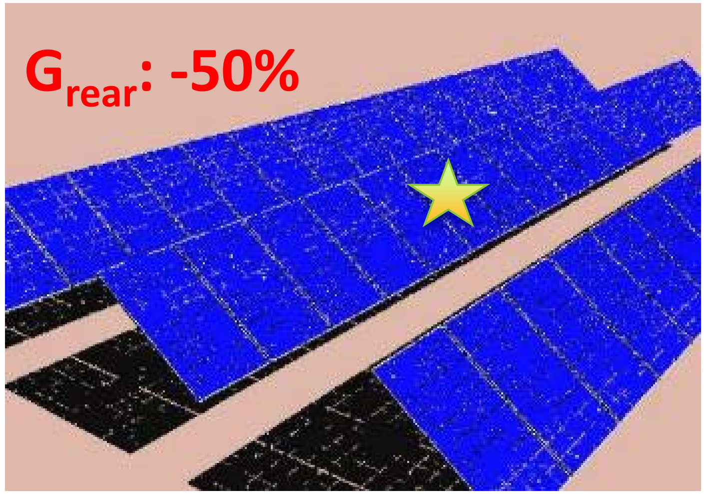


Ovaitt, Duramat Webinar Aug 24 - https://youtu.be/XAW0ihBXLpQ

For small-scale system accuracy



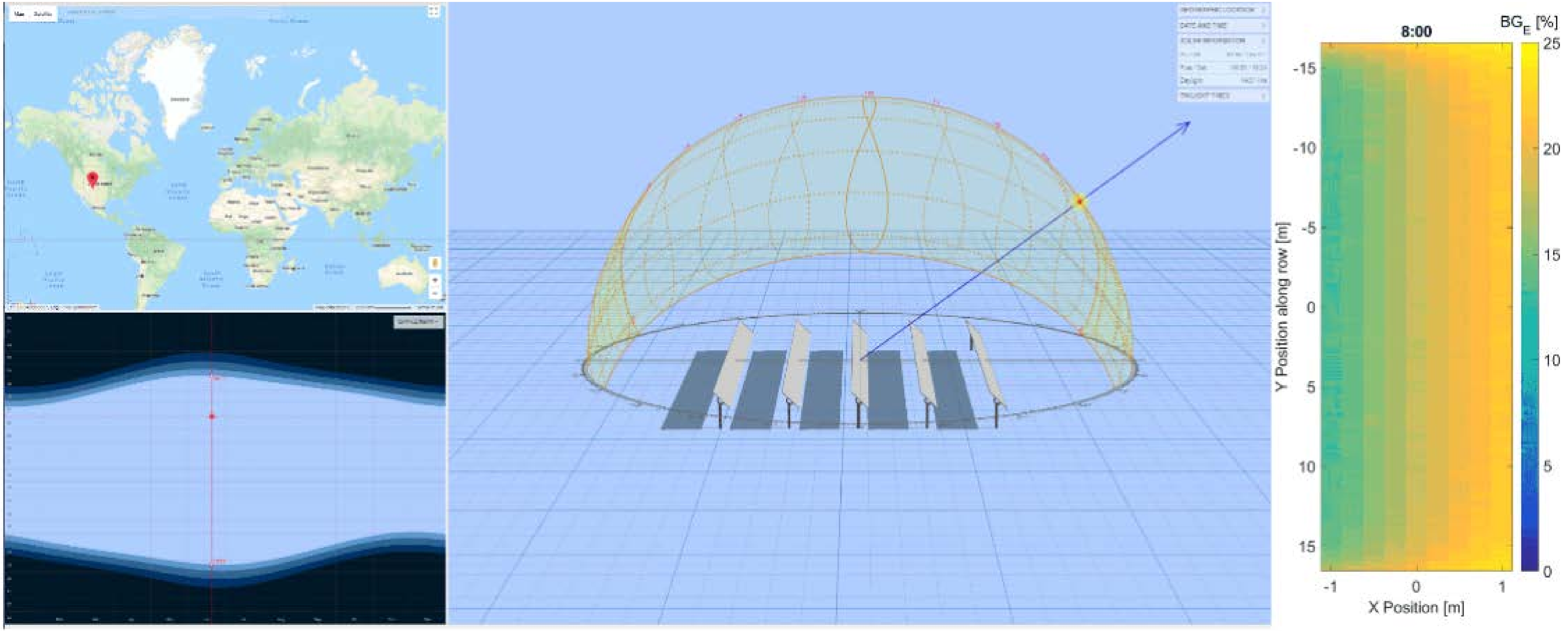




C. Deline et al., "Assessment of bifacial photovoltaic module power rating methodologies – Inside and out," *J. Photovoltaics* **7** (2017).

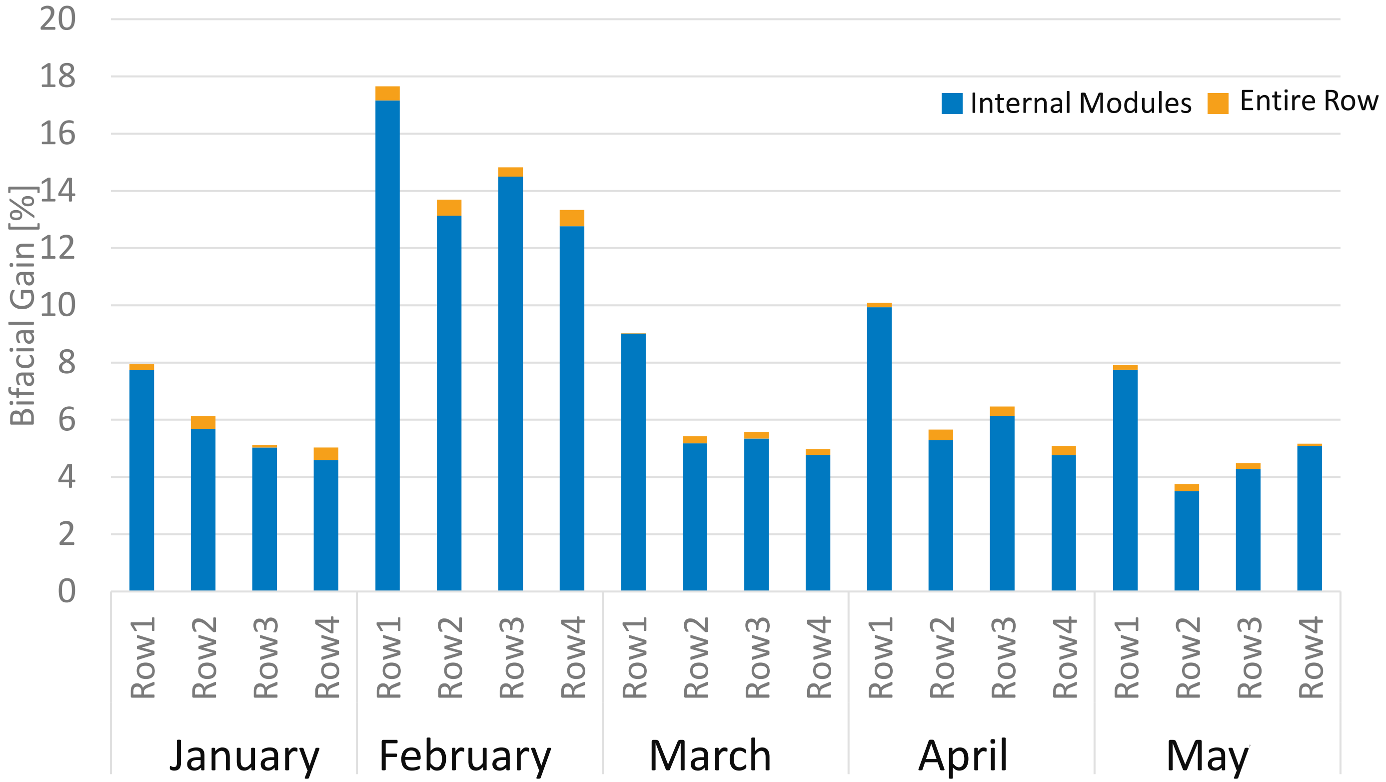
For evaluating Edge-Effects on an array

June 21st row shading and BG_E modeling by hour



© Dr. Andrew J. Marsh, 2014. http://andrewmarsh.com/apps/staging/sunpath3d.html
Thanks to Jose Victor Villarreal Medina for STLs http:/ 3cats-studios.net

For evaluating Edge-Effects on an array



Initial concern with edge effects; if edge modules produce more power than center modules there is potential power not taken advantage off and/or potential electrical mismatch losses.

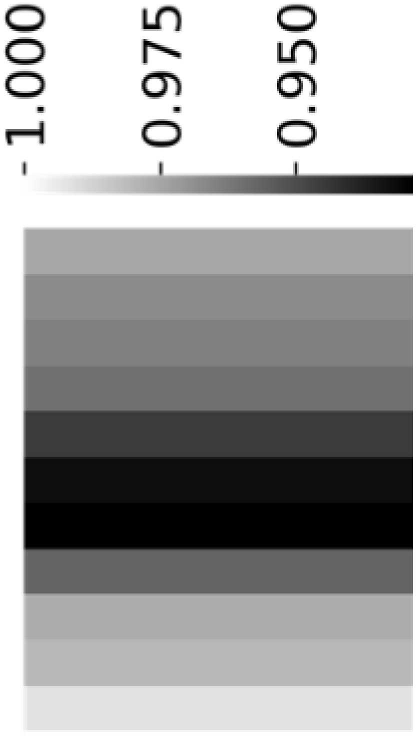
For our 75kW test-site at NREL (10 rows, 20 modules) Increase in bifacial gain of 0.28% yearly.

Most commercial and utility sites now are now >> bigger, so effect not very important anymore.

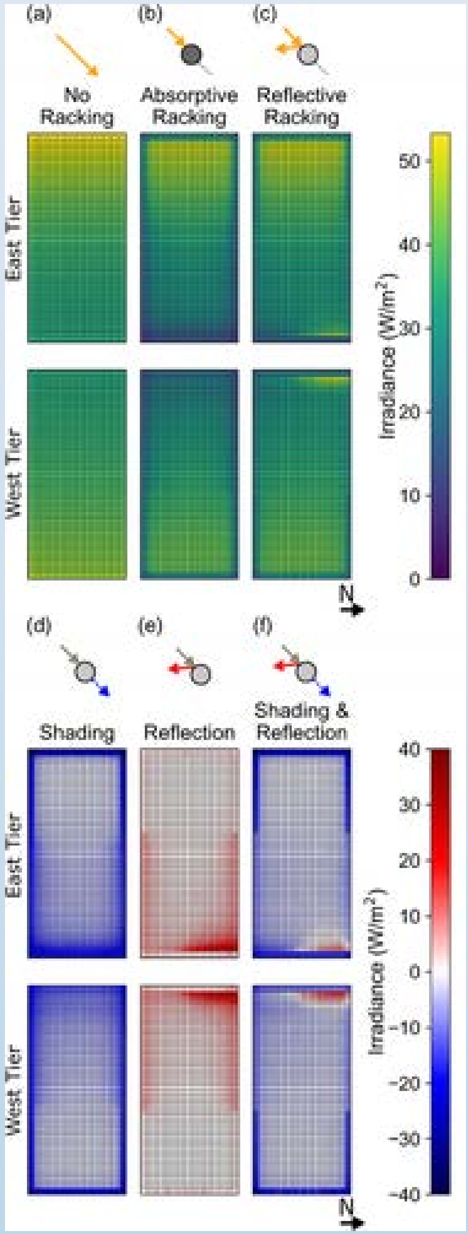
For evaluating racking shading

Initial concern from tracker companies from torquetube shading, leading to research on optimal separation to reduce non-uniformity, or 2-up configuration with spacing
A decade after: no main changes for monofacial racking. However module design now mostly have junction boxes (dead absorption area) in the center.

Short-circuit Current
(Proxy for irradiance)
non-uniformity



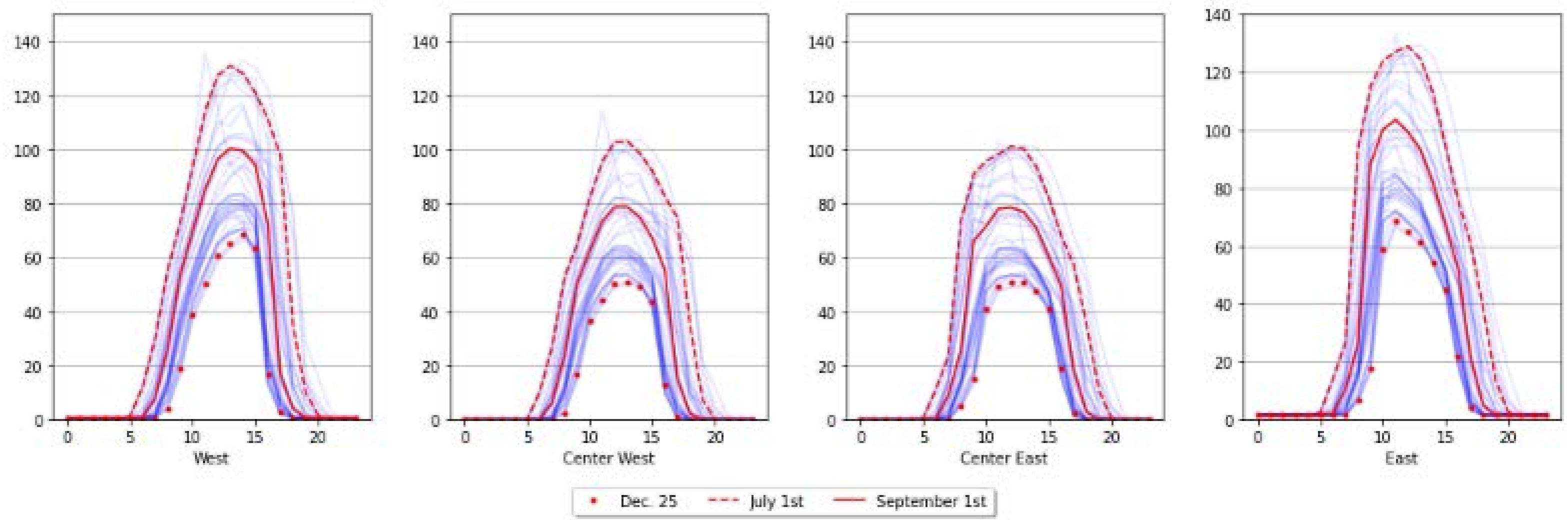
More research into shading effects:



Lewis et al, 2024
10.1002/aesr.202400007

For evaluating sensor positioning

Measured data for 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

Gostein, Ovaitt et al PVSC 2021

For evaluating sensor positioning

Photo: EDF

For evaluating sensor positioning

Photo: EDF

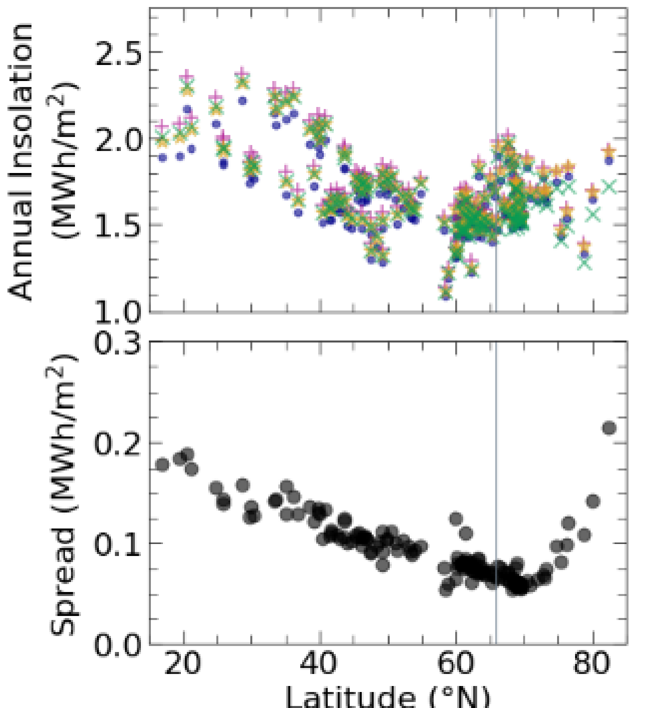
Deline, Ovaitt, et al "**Irradiance Monitoring for Bifacial PV Systems' Performance & Capacity Testing**" Jul 2024 [10.1109/JPHOTOV.2024.3430551](https://doi.org/10.1109/JPHOTOV.2024.3430551)

For evaluating novel configurations and applications

Other novel applications: Floating PV, Building-Integrated PV, etc

Vertical PV:

- Useful for production at higher times-of-use (early morning, late afternoon) and for load-shaping
- For agriPV: higher pitches to reduce self-shading which allow tractors to go through
- For high latitudes: lower AOI for sun, faster snow sheding, good use of snow albedo
- Also used as sound-barriers on highways

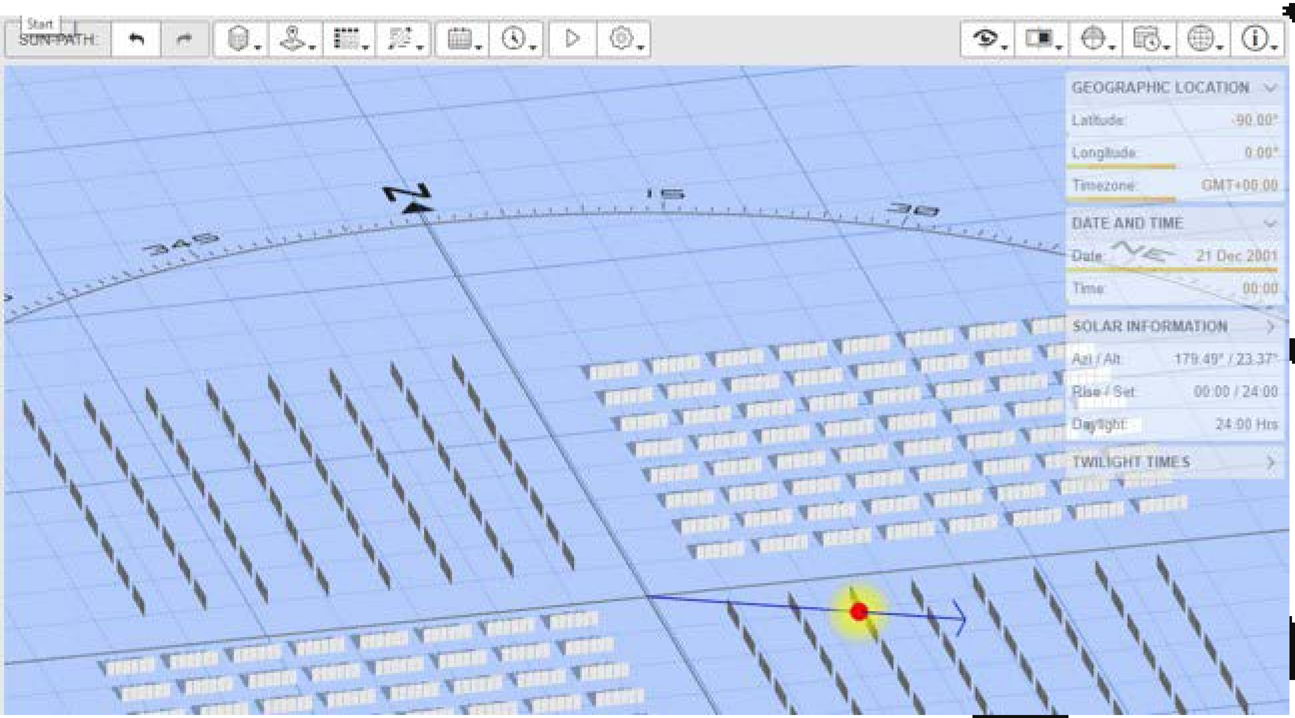


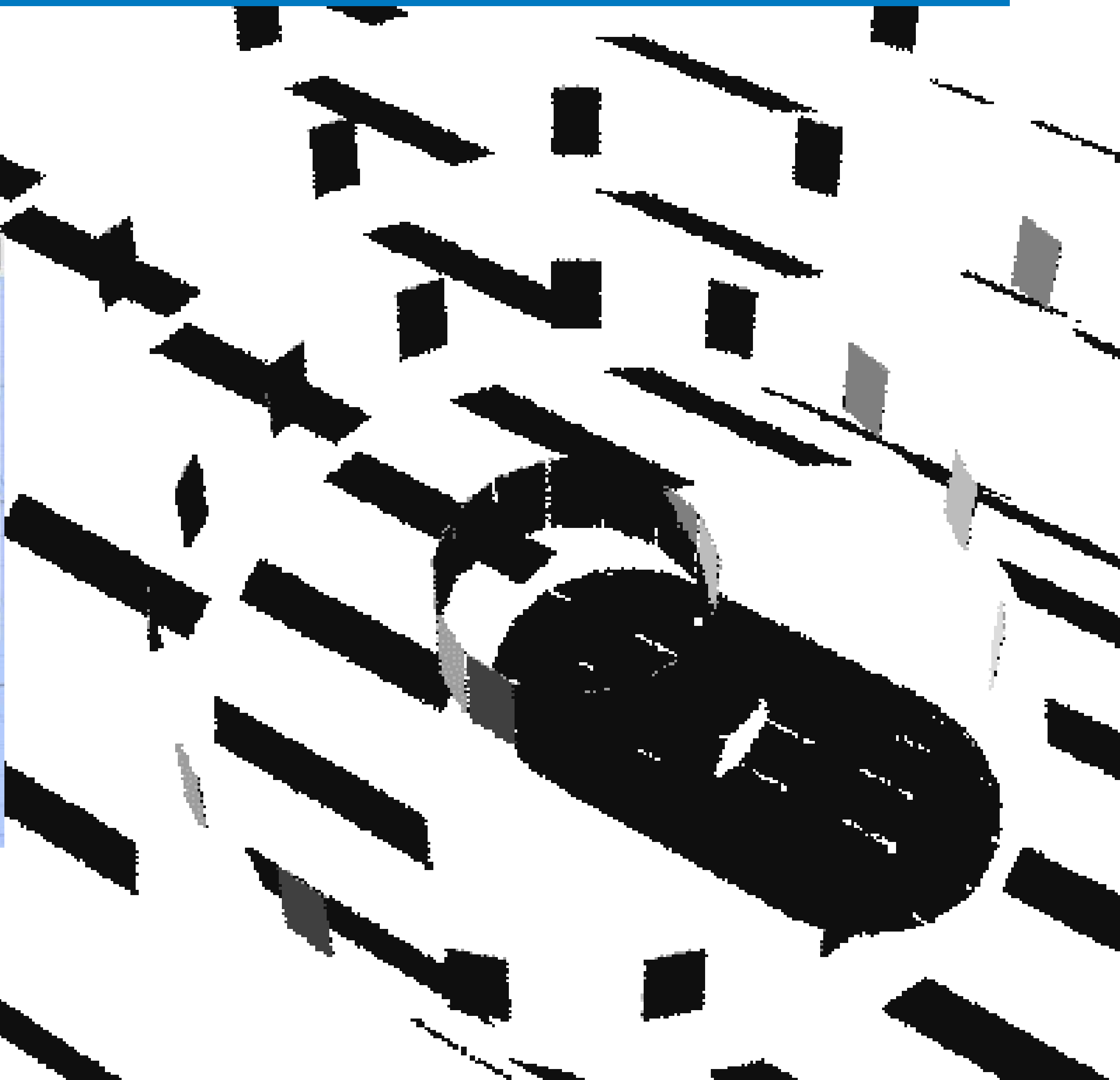
Vertical systems have **higher inter-model variance** than south tilted

High-Latitude PV Model Validation
E. Tonita, S. Ovaitt et al, submitted

For evaluating novel configurations and applications

PV in the South Pole? Yes!





[Babinec, et al… , S. Ovaitt](https://doi.org/10.1016/j.rser.2023.114274)
https://doi.org/10.1016/j.rser.2023.114274

For agrivoltaics

Spatial and spectral characteristics of importance

Novel configurations:

- **More separated panels**
- **Panels with different transmissivity factors (wider space between cells, or thin-film cells with higher transmission)**
- **Higher racking**

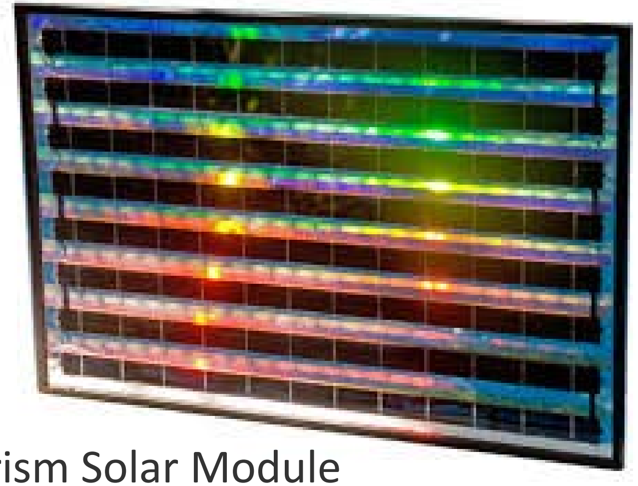
Test-sites are often smaller or a subsection near a field's edge – edge effects not evaluated by view factors

For evaluating materials more accurately

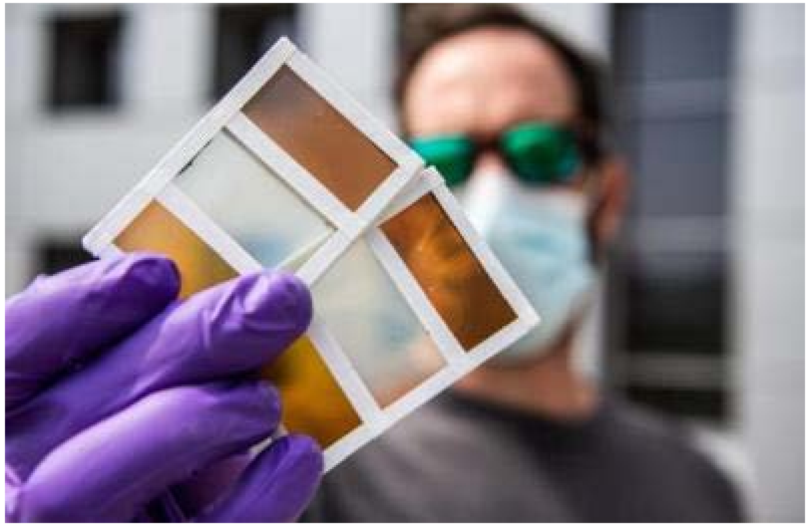
Albedo Optimization Study http://doi.org/10.1002/pip.3811

Irradiance, Energy, and system economics for varying sizes & positions

For evaluating materials more accurately



Prism Solar Module
ca. 2007



Reversible Multicolor Chromism PVSK, Wheeler

Flexible Energy Harvesting Devices

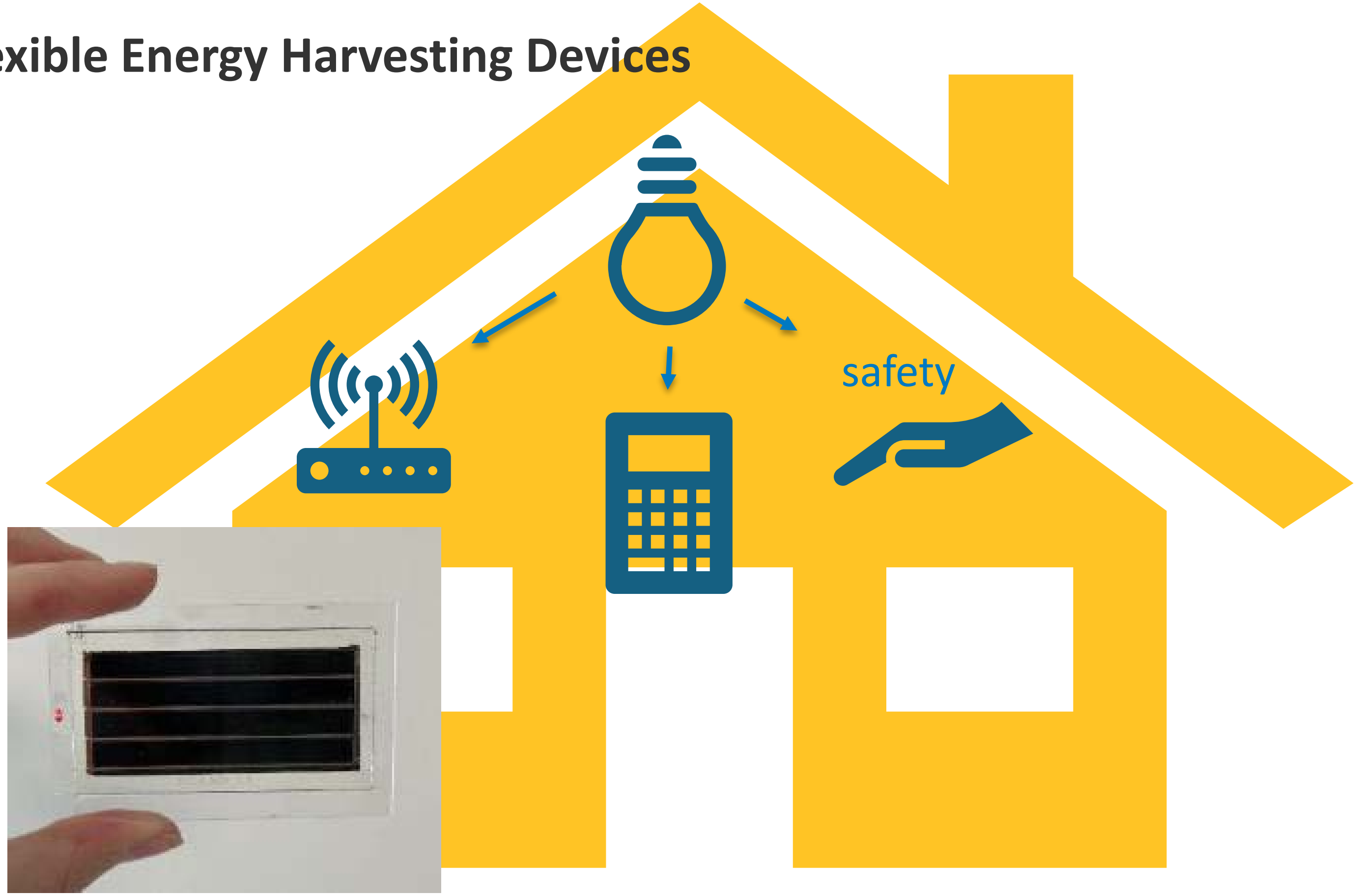
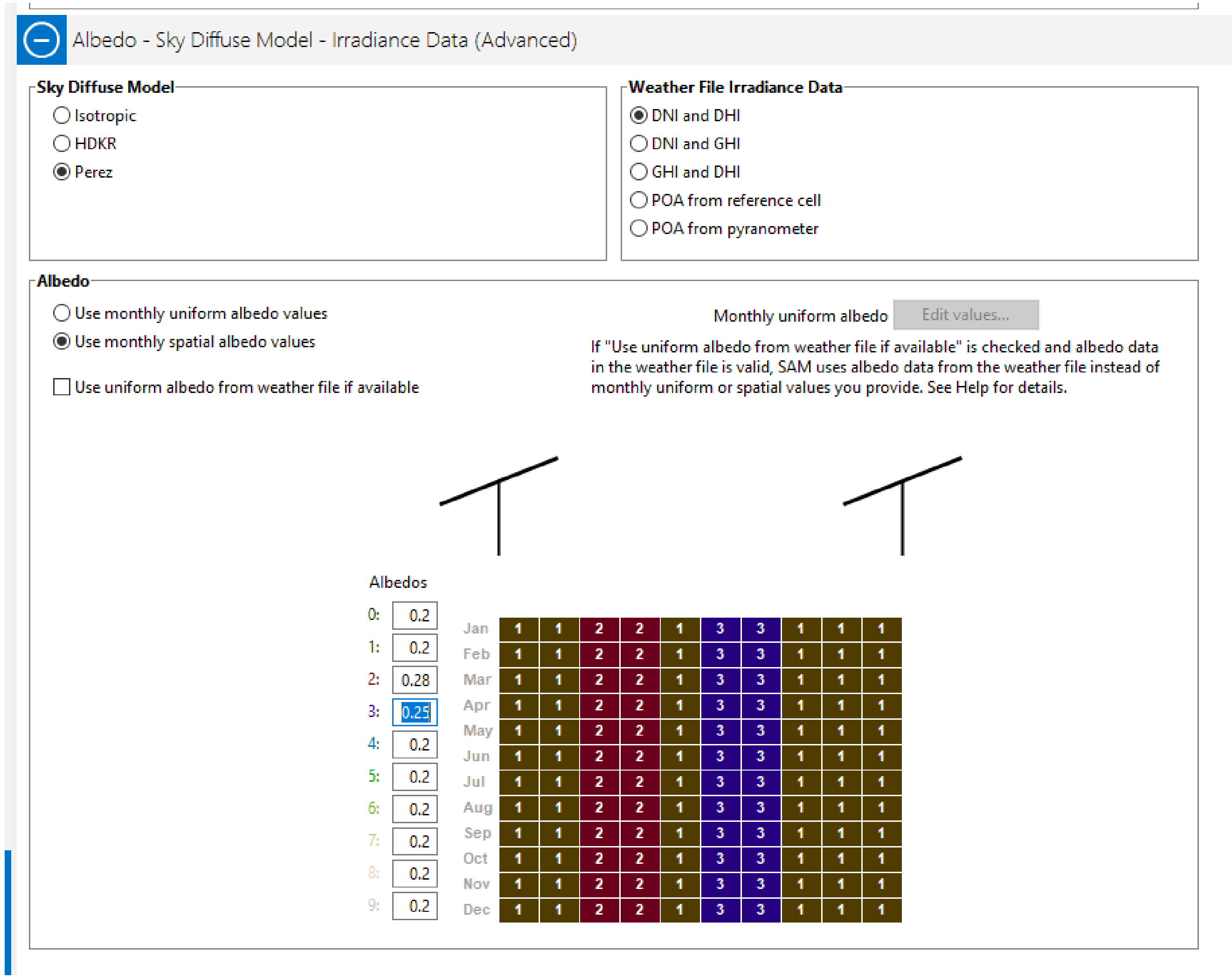
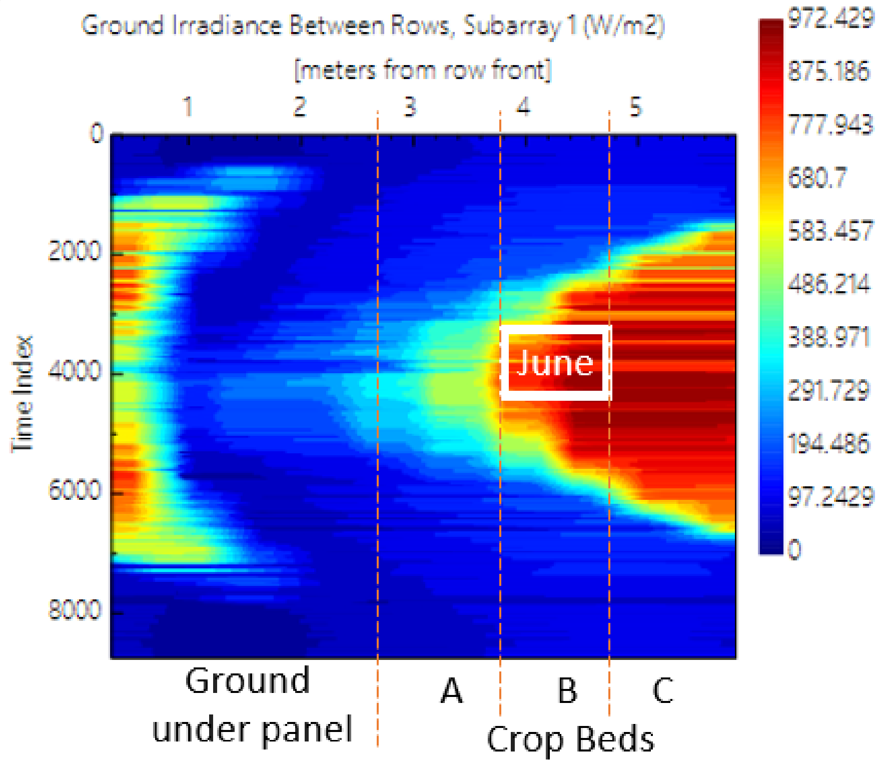


Image: Solaires Entreprises, from article:

https://www.pv-magazine.com/2024/01/29/canadian-startup-offers-35-efficient-indoor-perovskite-pv-modules/

For developing simplified models

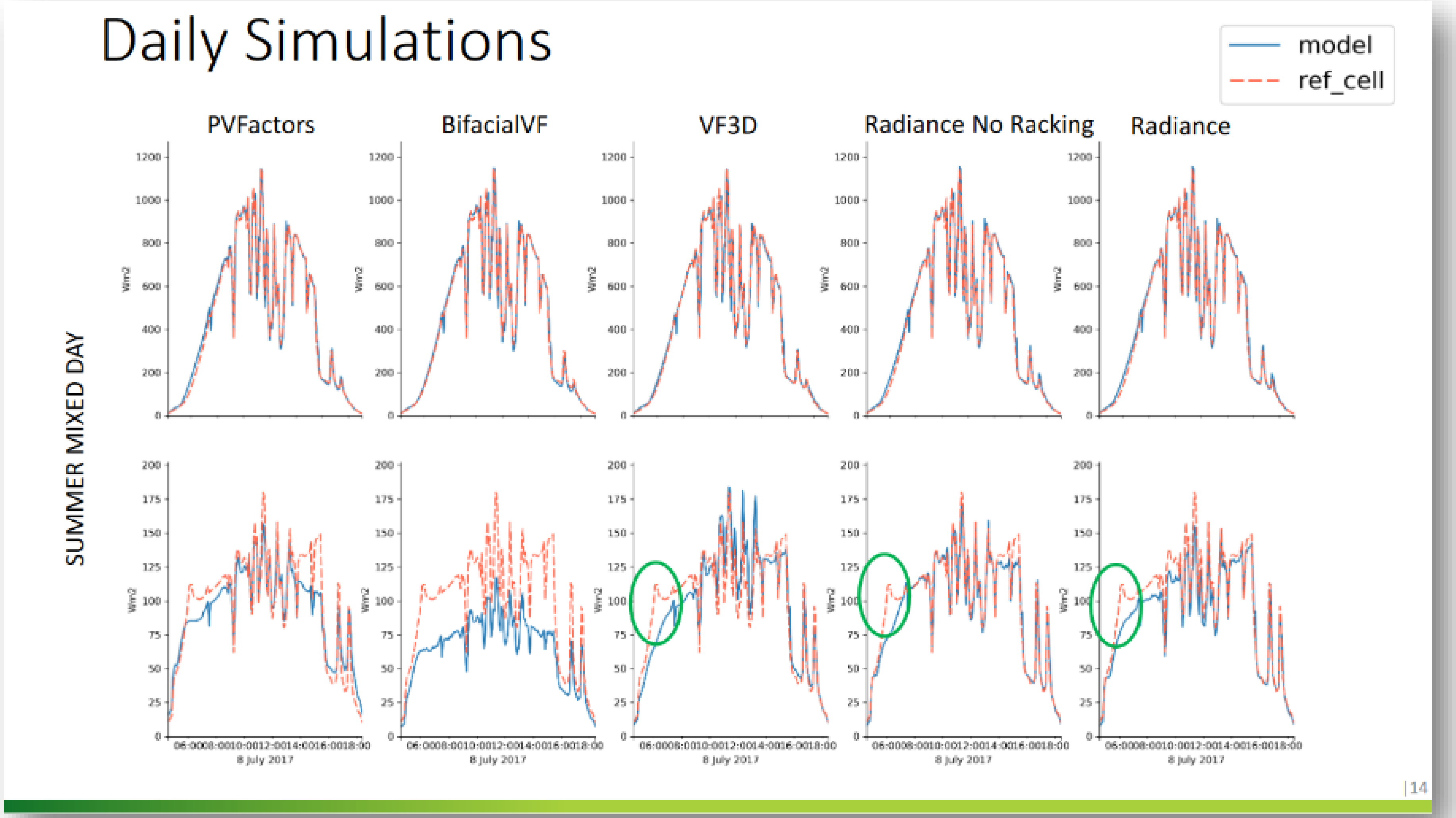




System Advisor Model

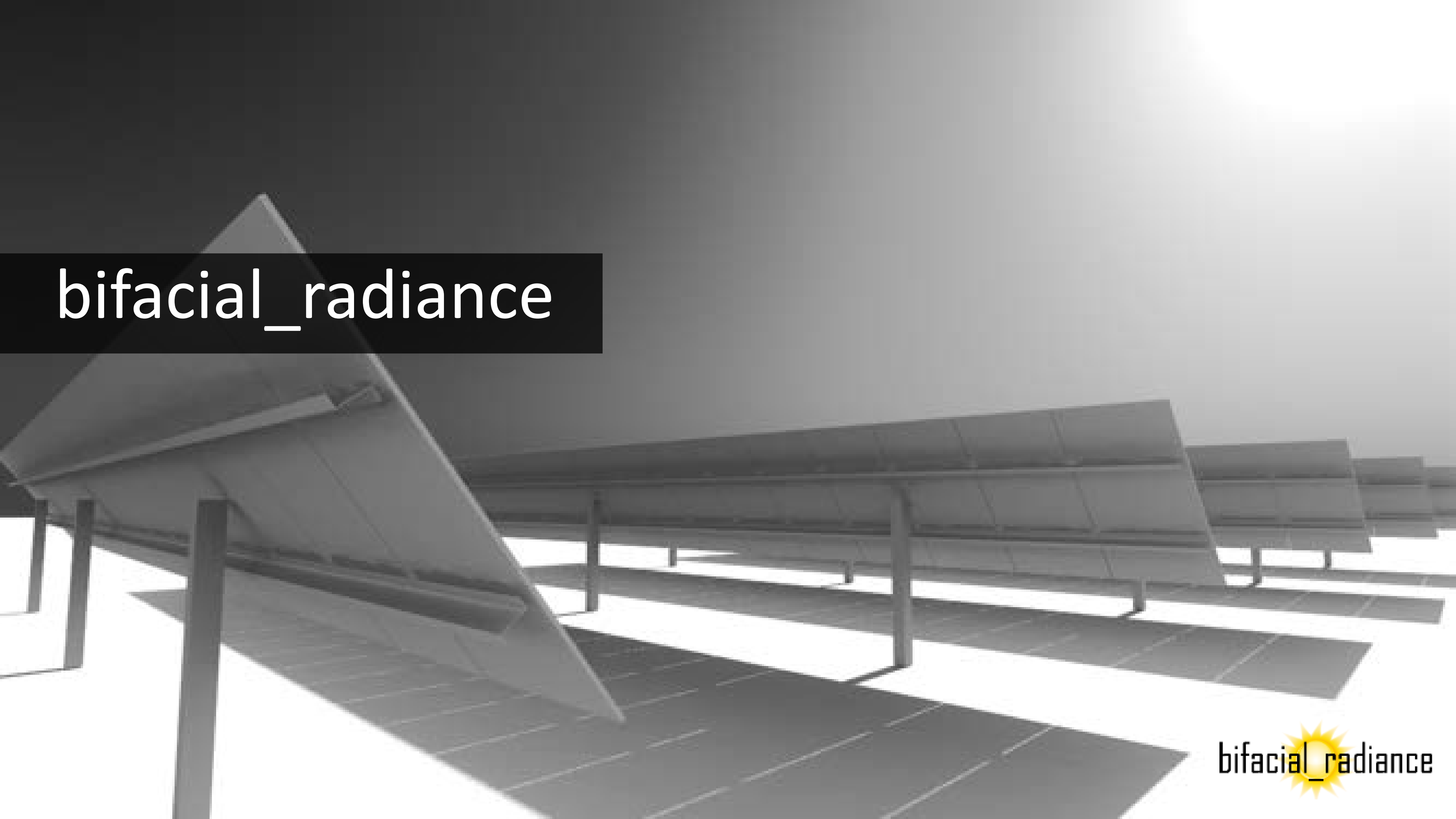
For evaluating accuracy of other models

bifacial_radiance has become the leading model comparison tool in the industry, backed by numerous peer-reviewed publications tailored to PV applications and due to its open-source nature.



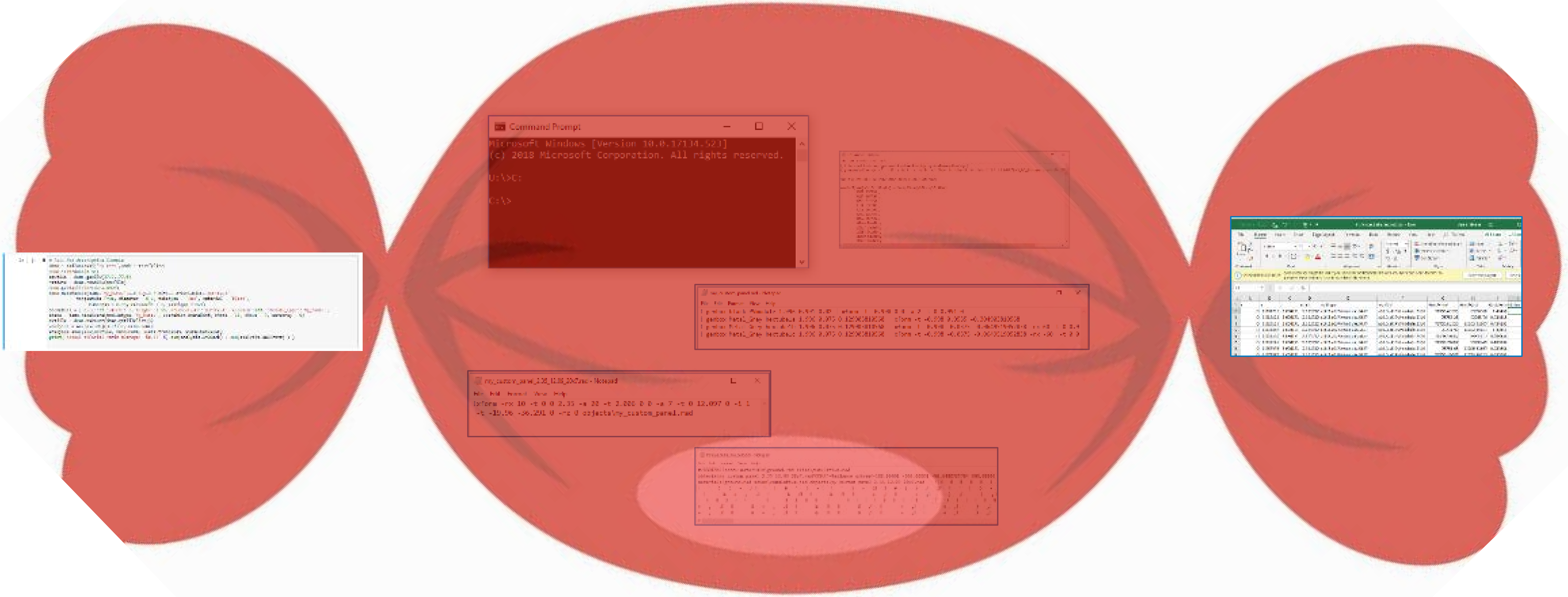
bifiPV 2019, Amsterdam
T. Scalcup A comparison of bifacial PV system modelling tools

bifacial_radiance



bifacial_radiance

bifacial_radiance is a python wrapper developed in 2017 for calling and using Radiance, with specific functions to generate geometry (text files) related to bifacial pv systems



Steps

1. Make Radiance Object

2. Make Sky

3. Make Module

4. Make Scene

cmd gencumsky
cmd gendaylit

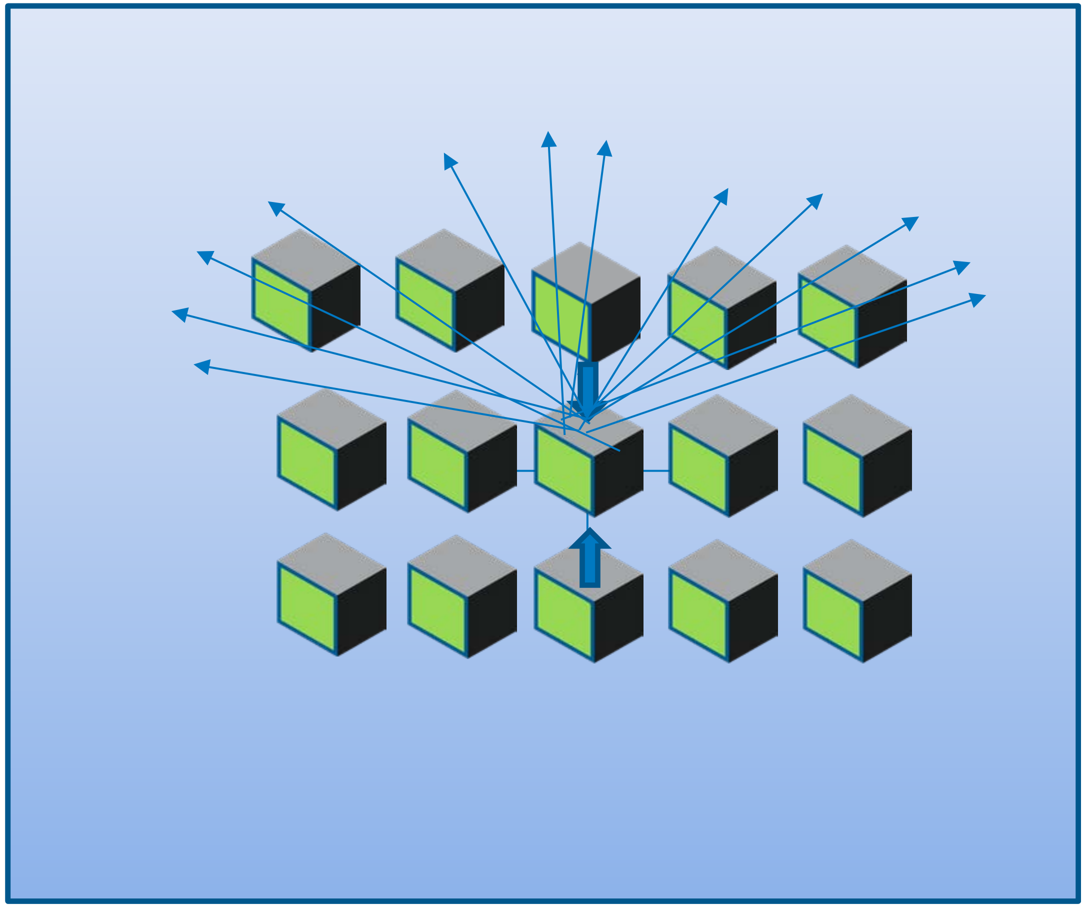
5. Make Oct

cmd oconv

6. Analysis Obj

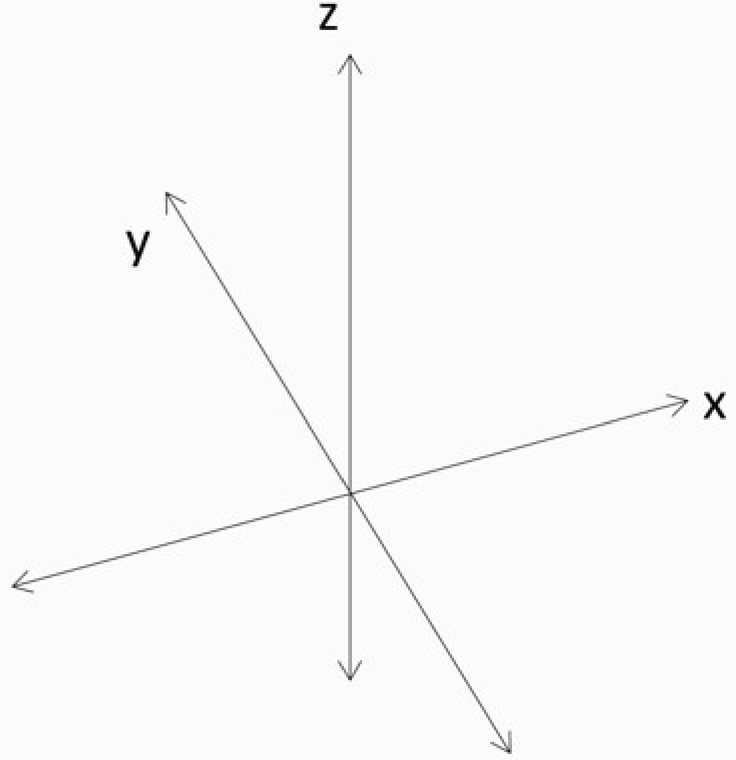
7. Analysis

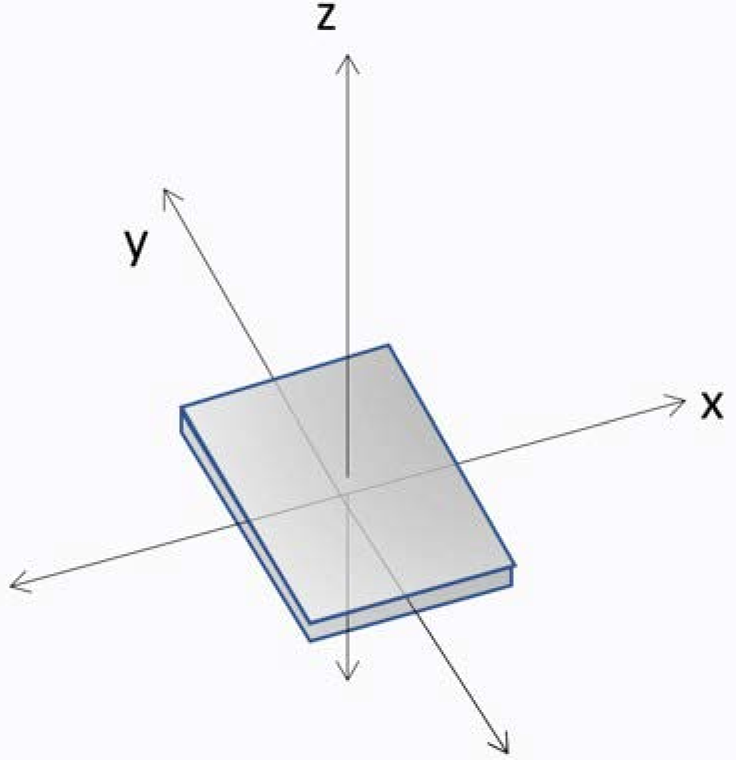
cmd rtrace



Module Object

```
makeModule(name='Panel1', x=1,y=2, numpanels=2,
torquetubeParams={tubetype='round', material='black',
axisofrotationTorquetube=True}, zgap=0.15)
```





Scene Object

```
sceneDict = {'tilt':30, 'pitch':6, 'clearance_height': 2.35,
'azimuth': 180, 'nMods': 5, 'nRows: 3}
makeScene(moduletype='Panel1', sceneDict=sceneDict)
```

tilt

clearance height

nRows

Rtr

place center module in 0 (self. scenex * nMods/2)

Azimuth rotation

```
!xform -rx 30 -t 0 0 2.35 -a 5 -t 1.01 0 0 -a 3 -t 0 6  0 -i 1 -t -2.02 -6.0 0 -rz 90 objects\Panel1.rad
```

nMods

self.scenex

Place center row (or row wanted) on 0 rtr * (rowwanted-1)

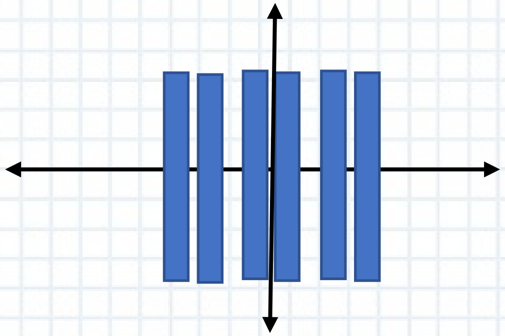
Object to Replicate

Multiple Scene Objects

```
sceneDict1 = {'tilt':30, 'pitch':6,
    'clearance_height': 2.35,
    'azimuth': 180, 'originx': 0,
    'origin': 0}
```

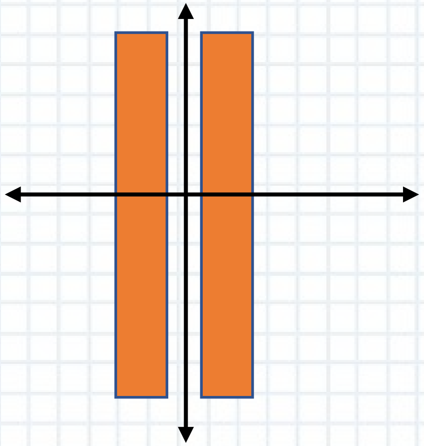
Array A:

3rows x 4 trackers of 5 panels in 2-up landscape…
rtr/GCR, tracking angle, Hub height



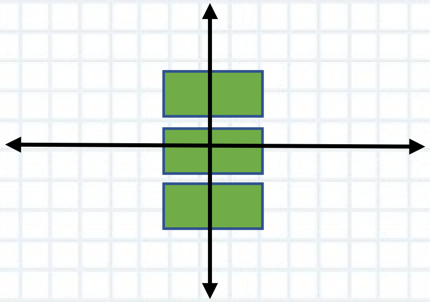
Array B:

2 trackers of 20 panels… 1 UP…
rtr/GCR, tracking angle, Hub height



Array C:

3 rows of fixed tilt… surface azimuth 180, clearance 0.4m, 1-up.
Etc etc.

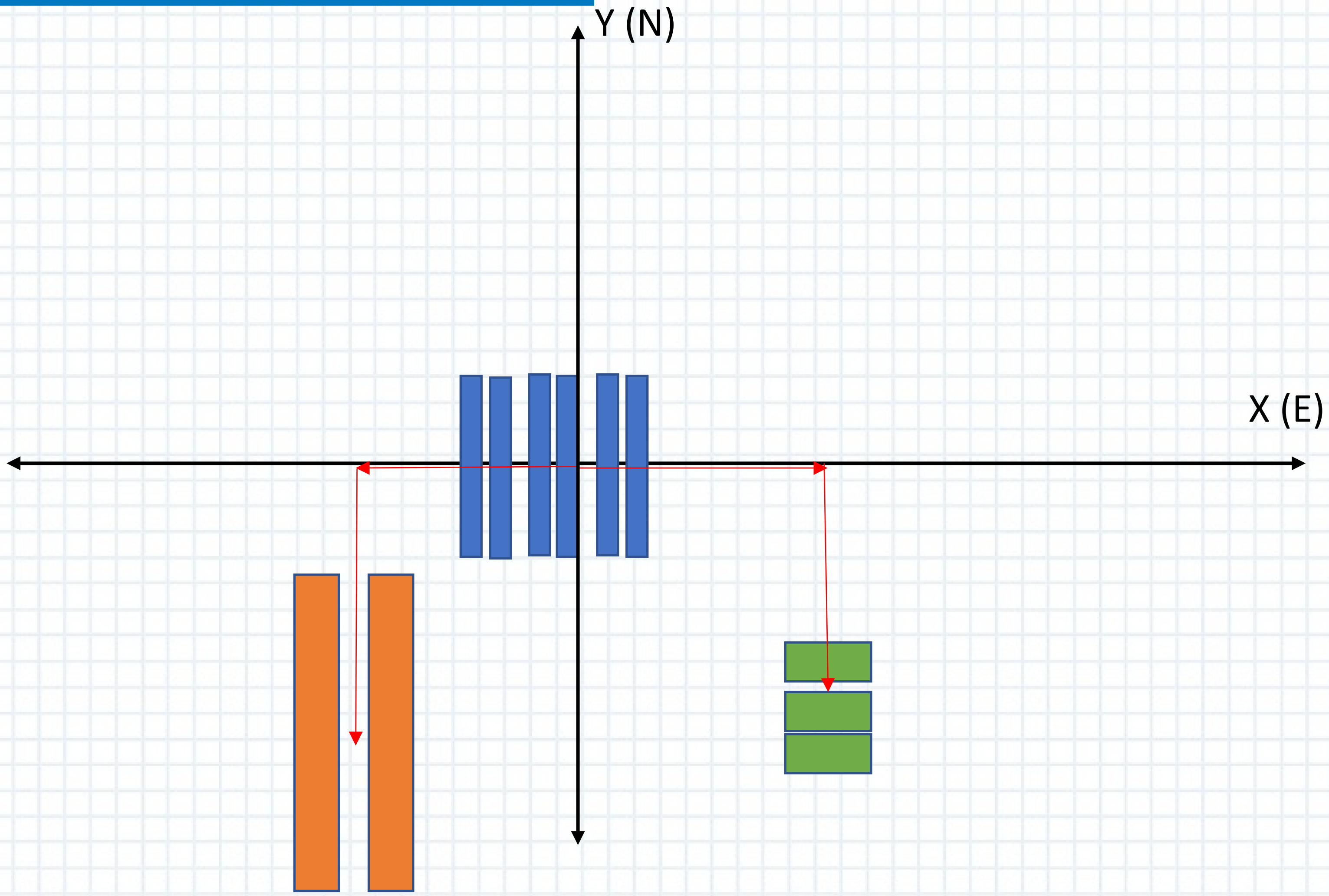


Multiple Scene Objects

Array A:
3rows x 4 trackers of 5 panels in 2-up landscape…
rtr/GCR, tracking angle, Hub height

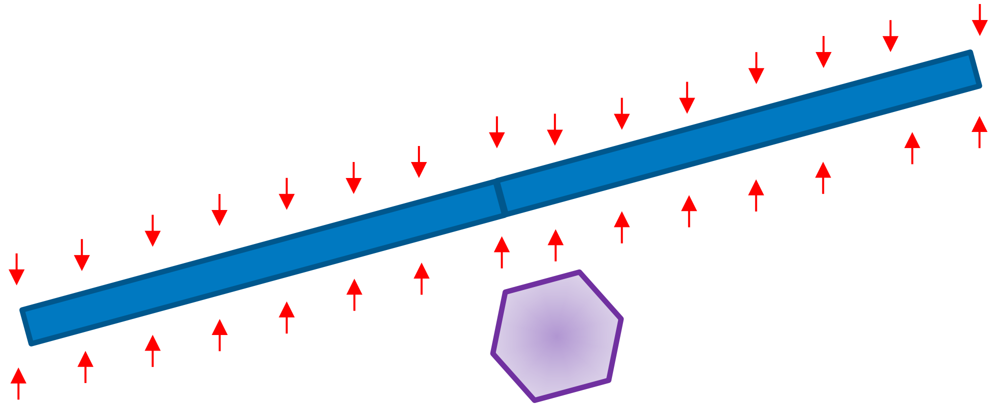
Array B:
2 trackers of 20 panels… 1 UP…
rtr/GCR, tracking angle, Hub height

Array C:
3 rows of fixed tilt… surface azimuth 180, clearance 0.4m, 1-up.
Etc etc.



Analysis Object

```
analysis.moduleAnalysis(scene=scene,
modWanted=1, rowWanted=1, sensorsy=9, sensorsx=6)
```

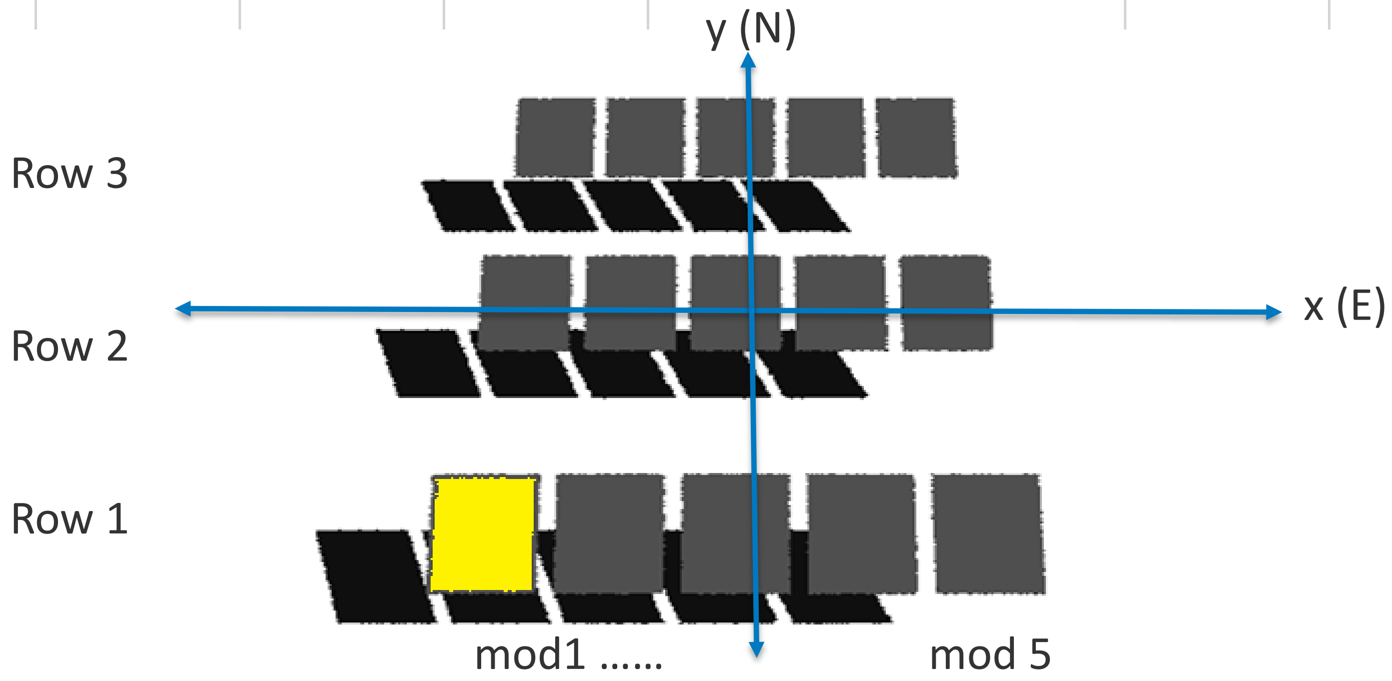


How an example might look like

```
metdata = demo.readWeatherFile(epwfile, coerce_year=2024) #, starttime='2024-08-27_0900')
timeindex = metdata.datetime.index(pd.to_datetime('2024-08-27 09:00:0 -7'))
demo.gendaylit(timeindex=timeindex)
module = demo.makeModule(name='PVModule',x=1, y=2)
sceneDict = {'tilt':30,'pitch':6,'clearance_height':2.35,'azimuth':180, 'nMods': 5, 'nRows': 3}
scene = demo.makeScene(module,sceneDict)
octfile = demo.makeOct()
analysis = br.AnalysisObj()
frontscan, backscan = analysis.moduleAnalysis(scene=scene, modWanted=1, rowWanted=1, sensorsy=6)
results = analysis.analysis(octfile, name='demo_results', frontscan=frontscan, backscan=backscan)
```

How results might look like

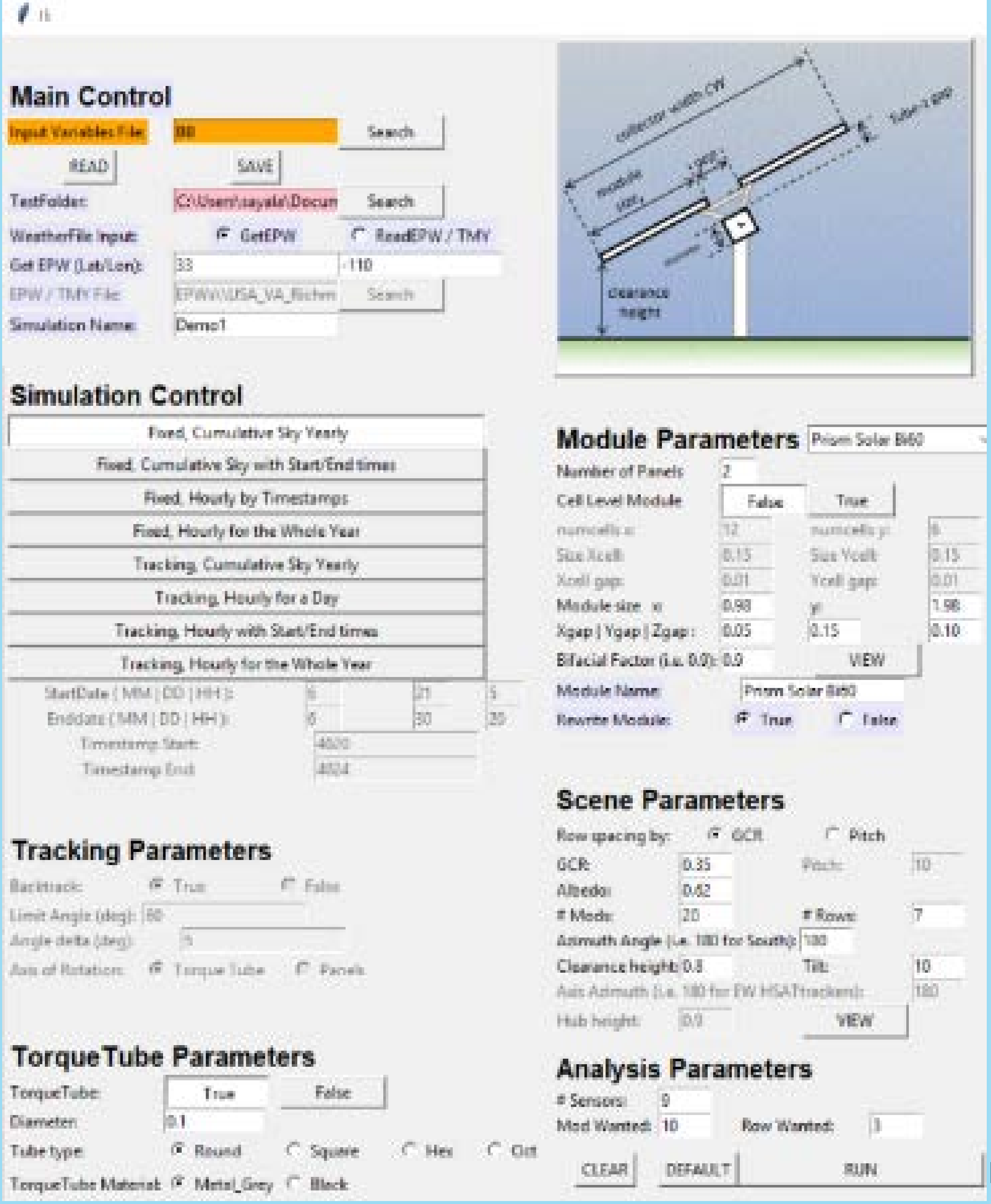
	A	B	C	D	E	F	G	H	I
1	x	y	z	rearZ	mattype	rearMat	Wm2Front	Wm2Back	Back/Fron
2	-2.02	-6.62909	2.511044	2.491991	a0.0.a0.PVModule.6457	a0.0.a0.PV	819.4329	120.6899	0.147284
3	-2.02	-6.38165	2.653901	2.634848	a0.0.a0.PVModule.6457	a0.0.a0.PV	819.5414	119.2702	0.145533
4	-2.02	-6.13422	2.796758	2.777705	a0.0.a0.PVModule.6457	a0.0.a0.PV	819.6494	117.2294	0.143024
5	-2.02	-5.88678	2.939615	2.920563	a0.0.a0.PVModule.6457	a0.0.a0.PV	819.7573	116.7875	0.142466
6	-2.02	-5.63935	3.082472	3.06342	a0.0.a0.PVModule.6457	a0.0.a0.PV	819.0627	115.982	0.141603
7	-2.02	-5.39191	3.225329	3.206277	a0.0.a0.PVModule.6457	a0.0.a0.PV	819.1603	116.3723	0.142063
8									



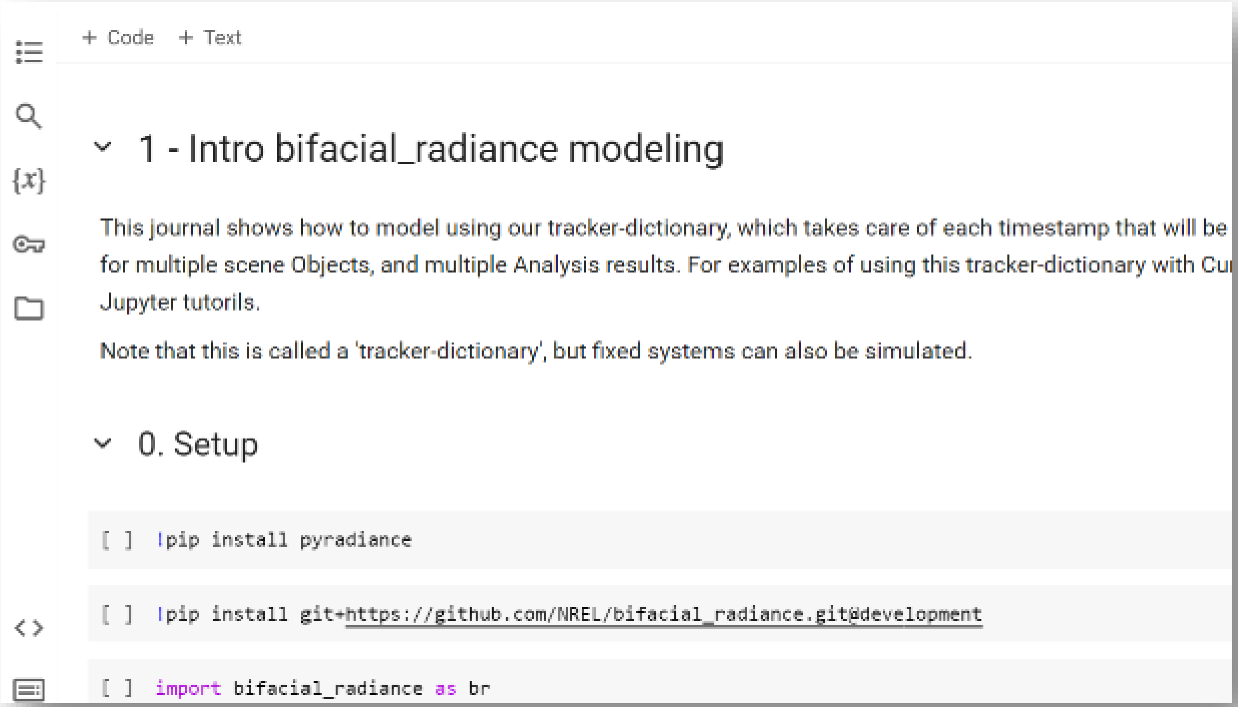
How to interact with bifacial_radiance

Training @ Youtube | Documentation @ readthedocs

Jupyter tutorials



Demo



Demo uses Google Collaboratory

Nothing installed on your computer

Click & run

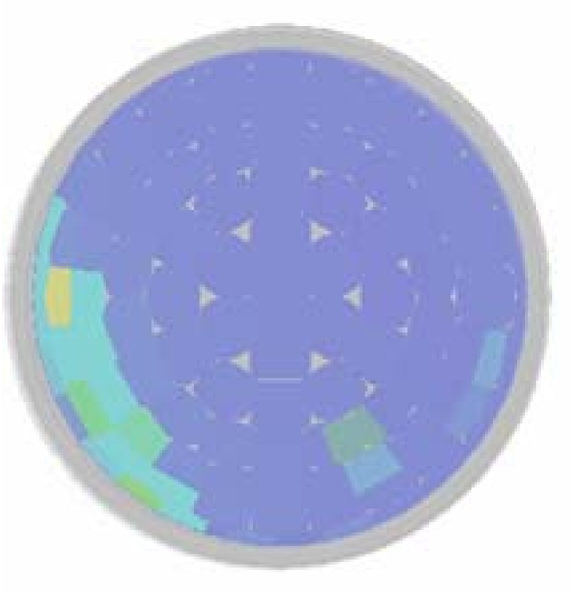
*Needs Google account

Can run on phone

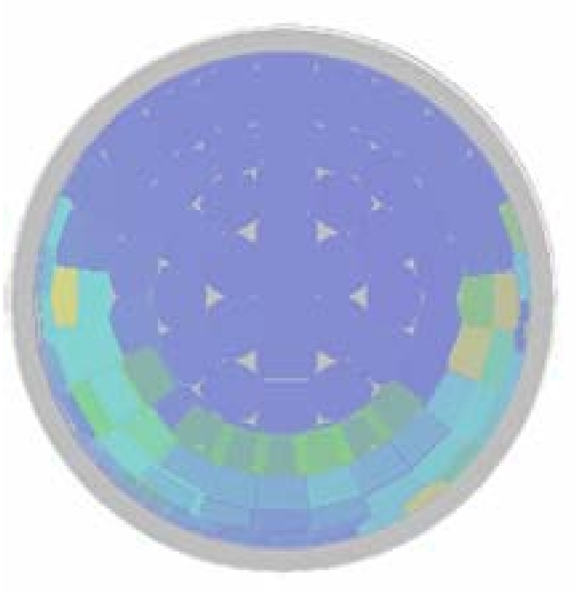
https://tinyurl.com/bifrad24

Cumulative Sky by Tracker Angle

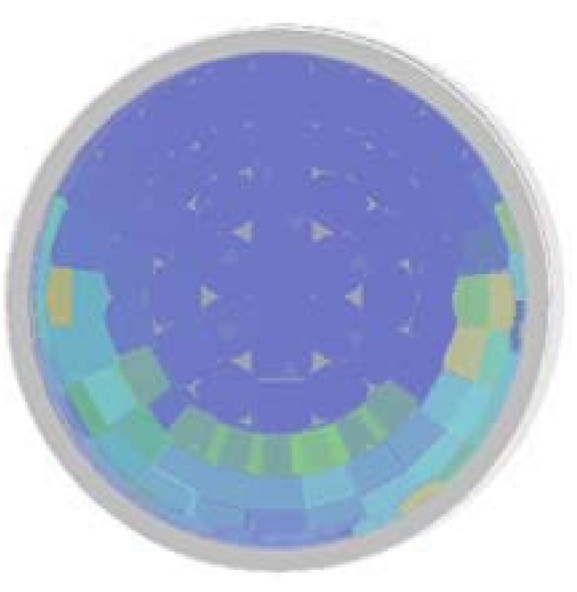
Cumulative Skies



Simulate Hourly
~4380 simulations



Simulate Daily
~365 simulations



Simulate Monthly
~12 simulations

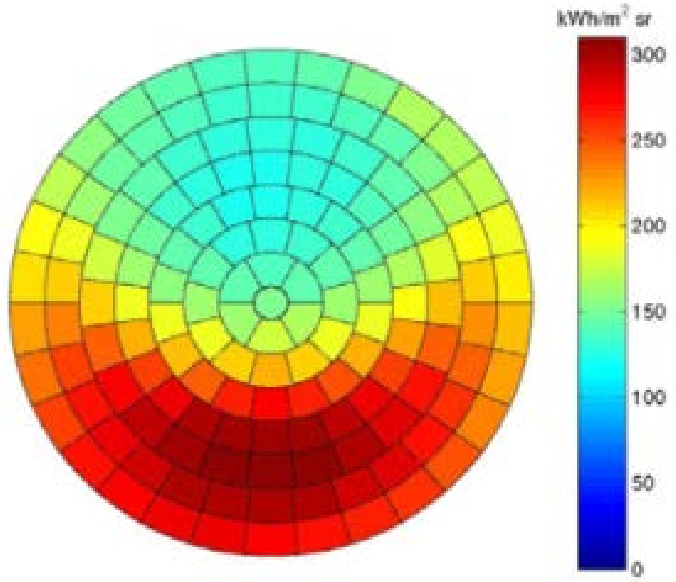


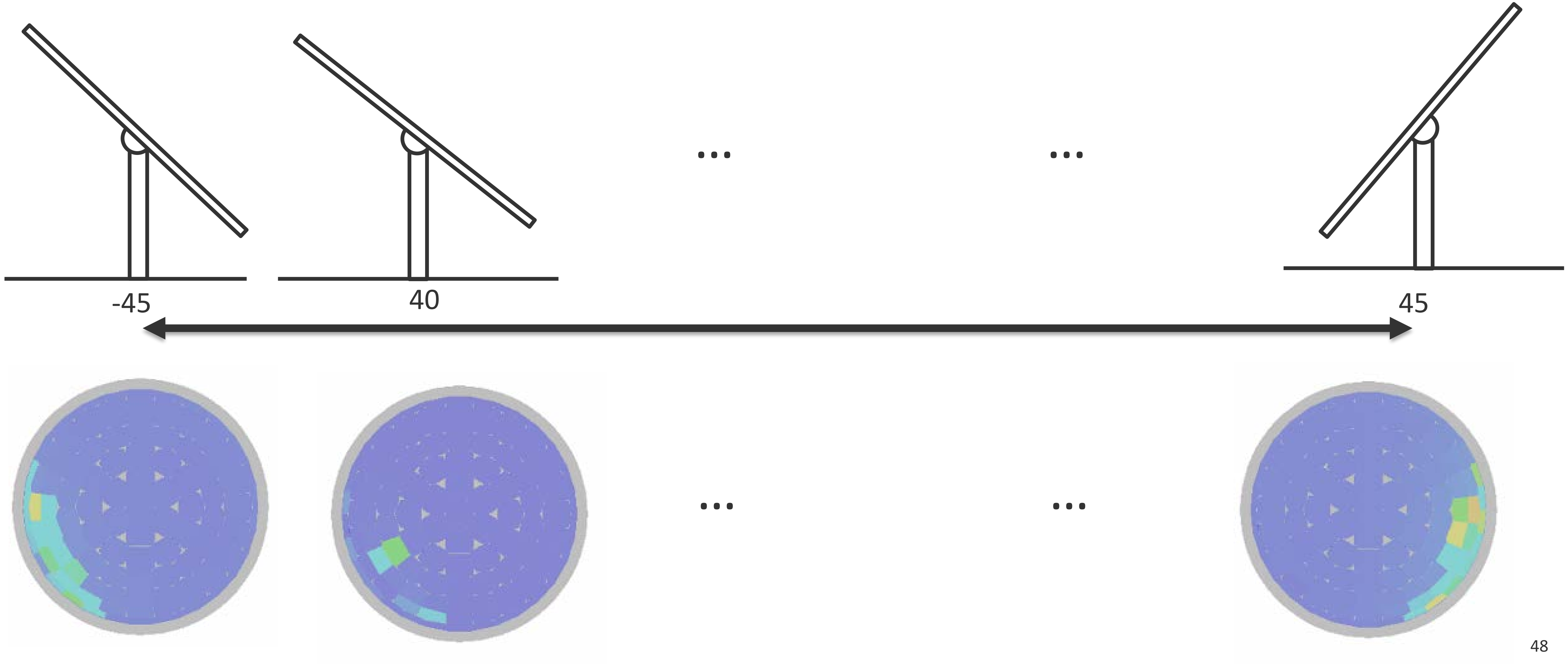
Figure 1 Cumulative diffuse sky radiance distribution for Oslo (based on 10yr mean solar data).

*Robinson & Stone, 2024

Simulate Yearly
~1 simulations

Cumulative Sky by Tracker Angle

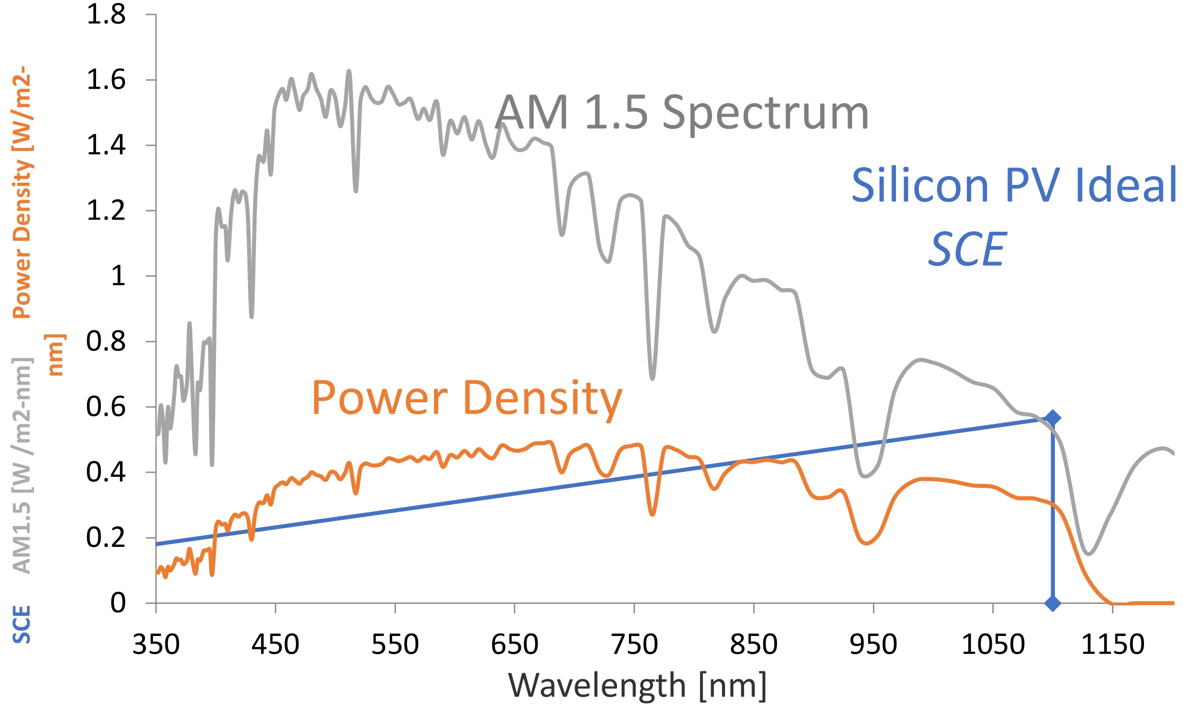
-45 to 45: ~19 simulations



Spectral Simulations

Why model spectrally?

PV has an ideal spectrum conversion efficiency



In order to maximize the production of electricity, the most effective portion of the incident solar spectrum should be available for PV energy conversion.

Material degradation and other processes are also spectrally sensitive

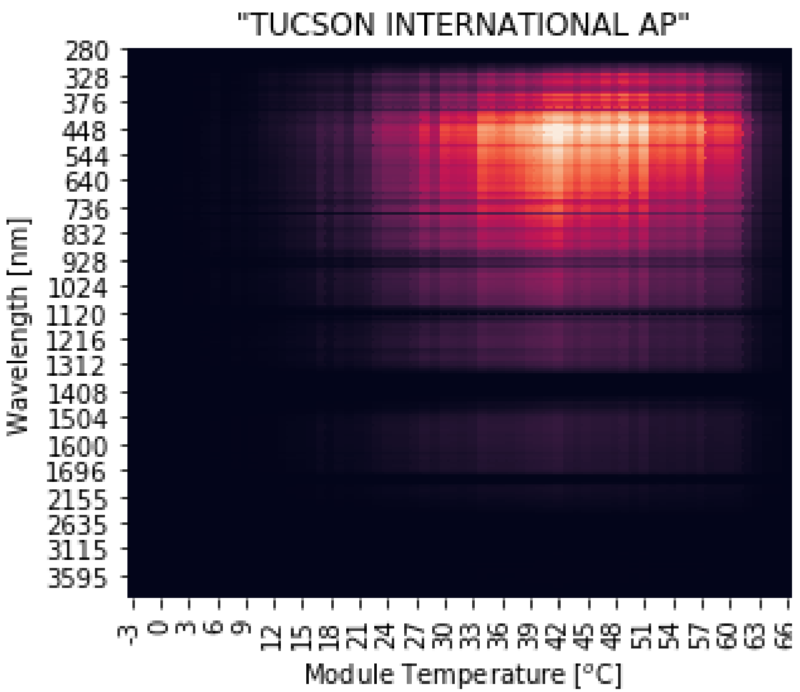
Relative Humidity

spectral Irradiance [W/m2-nm]

$$D = C\int_{0}^{t=8760} e^{\frac{-E_a}{RT(t)}} RH(t)^n \int_{280\,nm}^{500\,nm} \left[e^{-C_2\lambda} G(\lambda,t)\right]^x d\lambda dt$$

Arrhenius Equation

Exponential degradation of the material as a function of wavelength



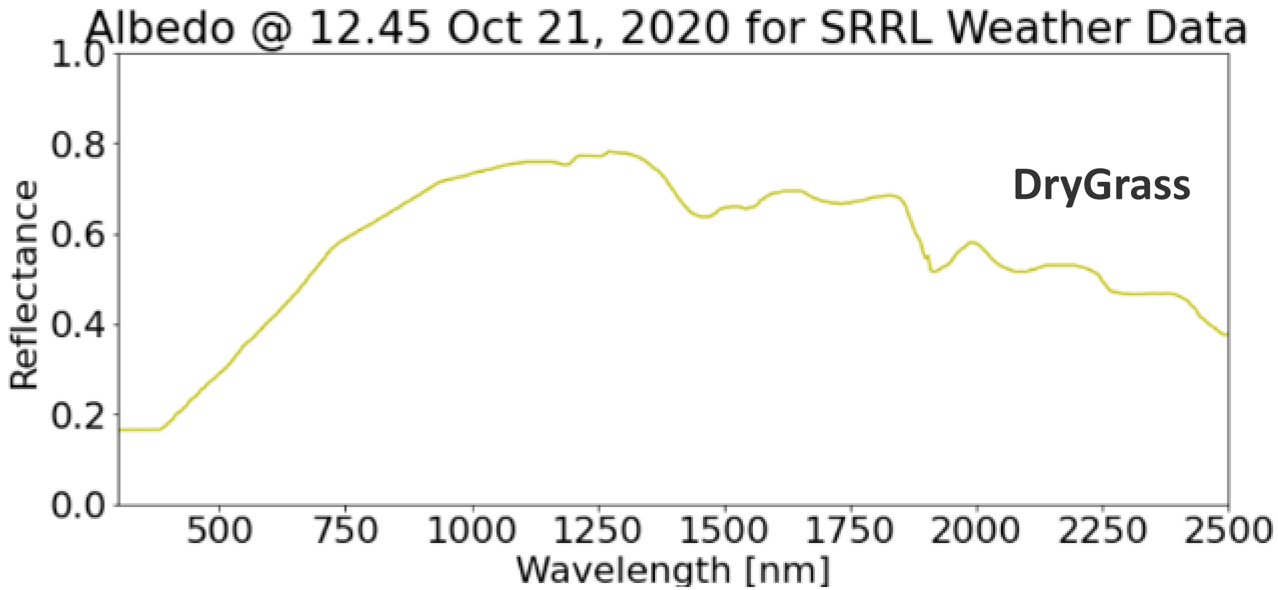
UV stress test currently within PV module IEC standards (15 kWh/m^2) amounts to ~3 months in the field

pySMARTS

https://github.com/NREL/pySMARTS

Wrapper for **SMARTS** (Simple Model of the Atmospheric Radiative Transfer of Sunshine) developed by Dr. Christian Gueymard.
https://www.nrel.gov/grid/solar-resource/smarts.html

```
DNISpectra =
pySMARTS.SMARTSTimeLocation(
IOUT='01', YEAR='2024',
MONTH='08', DAY='27', HOUR='14',
LATIT='40.8', LONGIT='-111.9',
ALTIT='1.3', ZONE='-7') #
```



pySMARTS

py-SMARTS

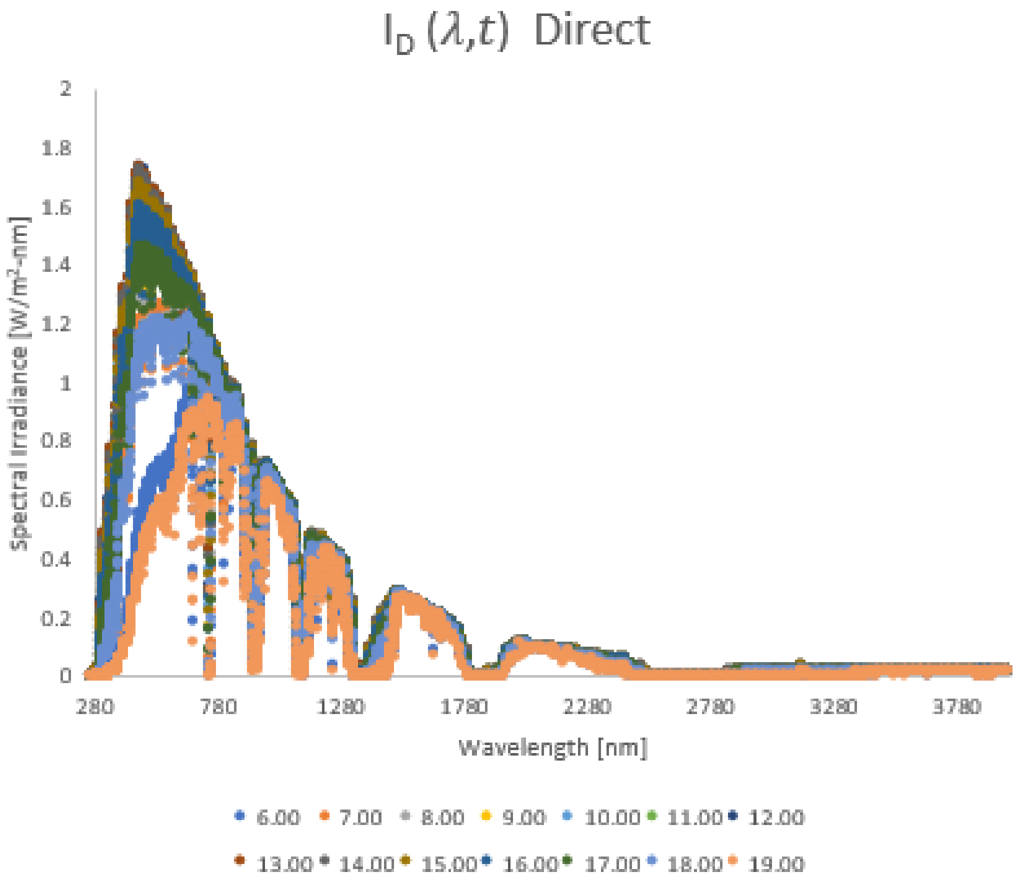
Finetune Spectra with Temperature, RH, Pressure, Precipitation and Aerosol data

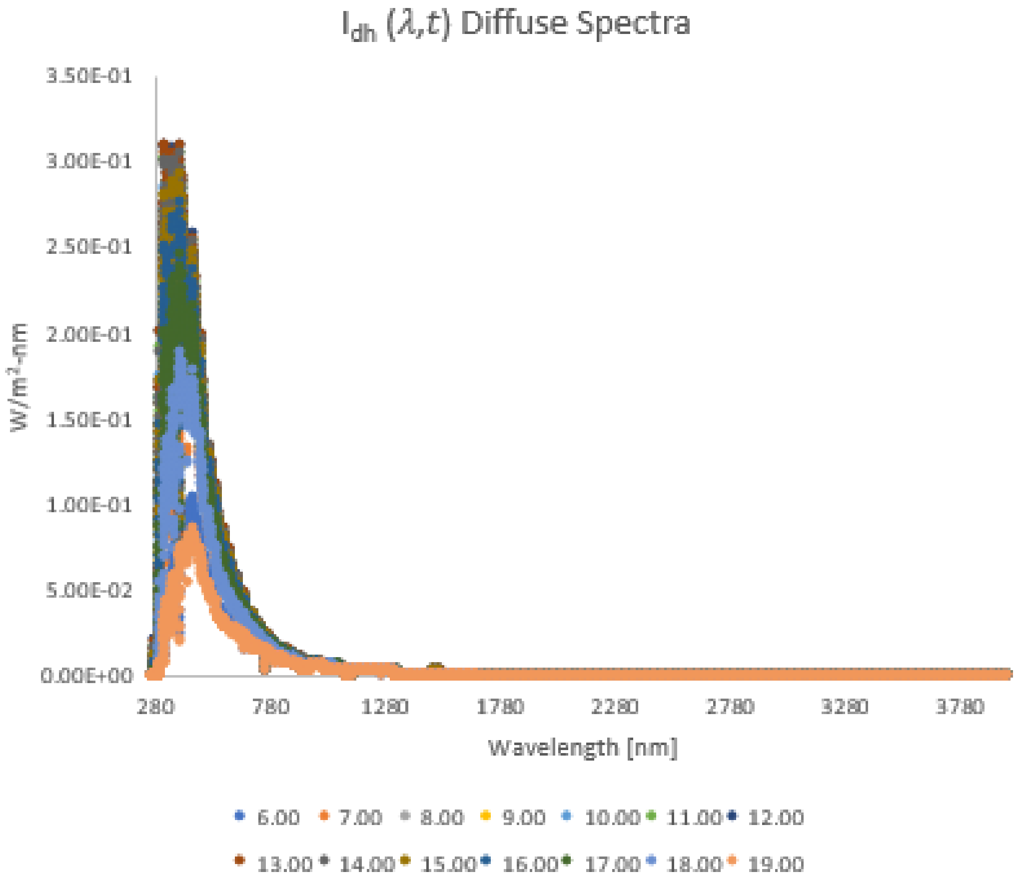
[EXAMPLE DATA SOURCE: https://midcdmz.nrel.gov/](https://midcdmz.nrel.gov/)

- Aerosol Optical Depth (AOD) measurements are available since 06/13, updated every 24 hours.
- A Spectrafy SolarSIM-D2+ is providing direct normal spectral models since 09/16, updated every 60 seconds.
- A Spectrafy SolarSIM-G is providing global horizontal spectral models since 04/21, updated every 60 seconds.
- An EKO MS-300LR Sky Scanner has mapped luminance and irradiance, from 06/2000 to 08/2002, every 15 minutes.

```
YEAR='2020'; MONTH='10'; DAY='21'; HOUR = '12.75'
LATIT='39.74'; LONGIT='-105.17'; ALTIT='1.0'; ZONE='-7'
TILT='33.0';  WAZIM='180.0'; HEIGHT='0'
material='DryGrass'
min_wvl='280'; Max_wvl='4000'

TAIR = '20.3'
RH = '2.138'
SEASON = 'WINTER'
TDAY = '12.78'
SPR = '810.406'
RHOG = '0.2205'

WAZIMtracker = '270'
TILTtracker = '23.37'
tracker_tetha_bifrad = '-23.37'

TAU5='0.18422'      # SRRL-GRAL "Broadband Turbidity"
TAU5 = '0.037'     # SRRL-AOD [500nm]
GG = '0.7417'      # SSRL-AOD Asymmetry [500nm]
BETA = '0.0309'    # SRRL-AOD Beta
ALPHA = '0.1949'   # SRRL-AOD Alpha [Angstrom exp]
OMEGL = '0.9802'   # SRRL-AOD SSA [500nm]
W = str(7.9/10)    # SRRL-PWD  Precipitable Water [mm]
```

Spectral Irradiance generated with SMARTS



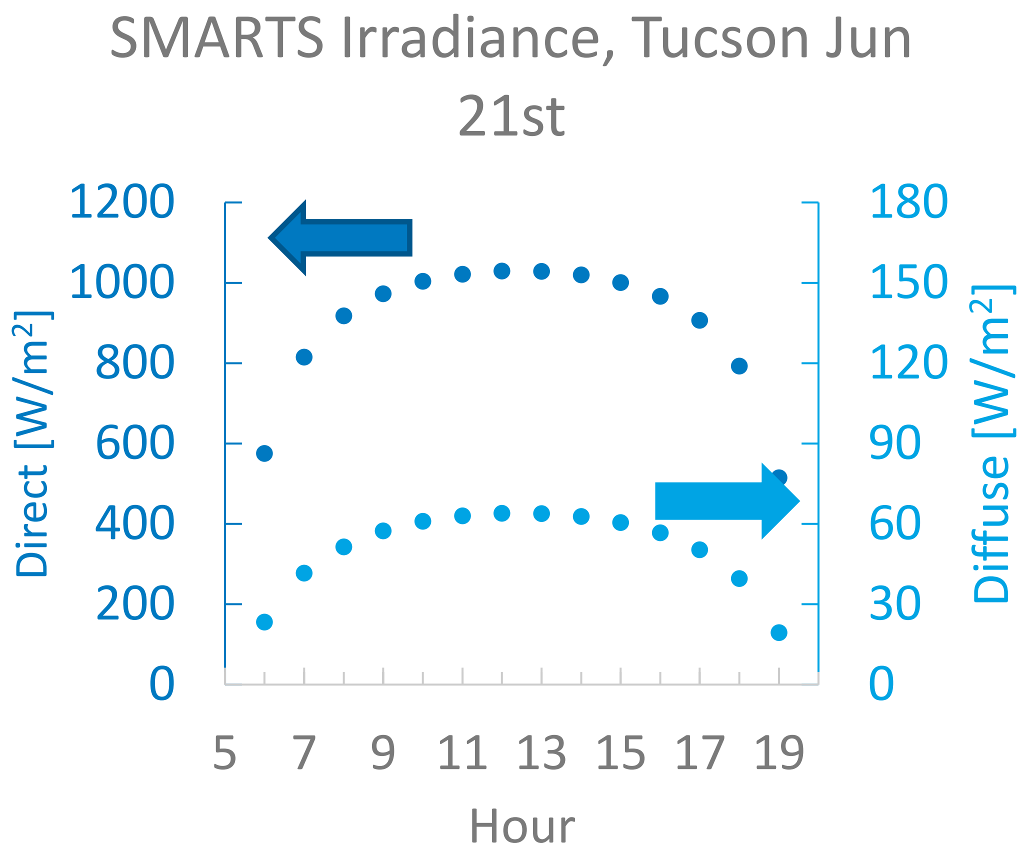


June 21st

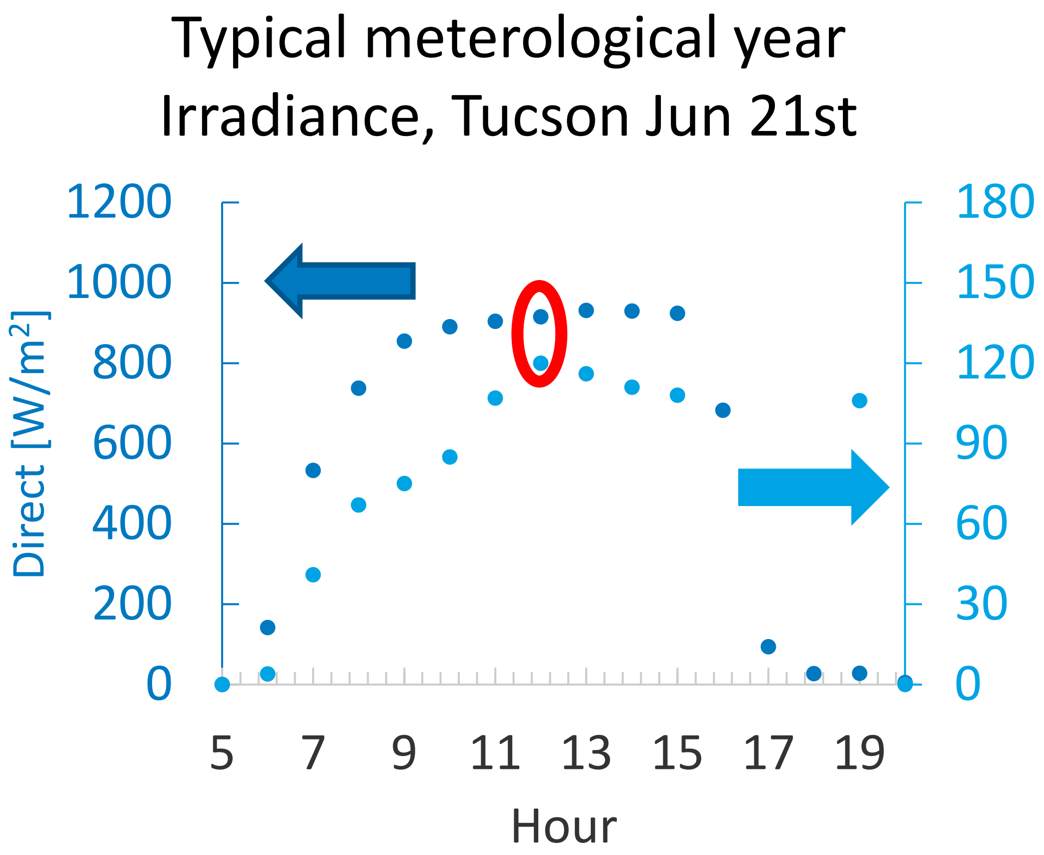
Spectra for non-ideal weather?

June 21st

Ideal



Weather



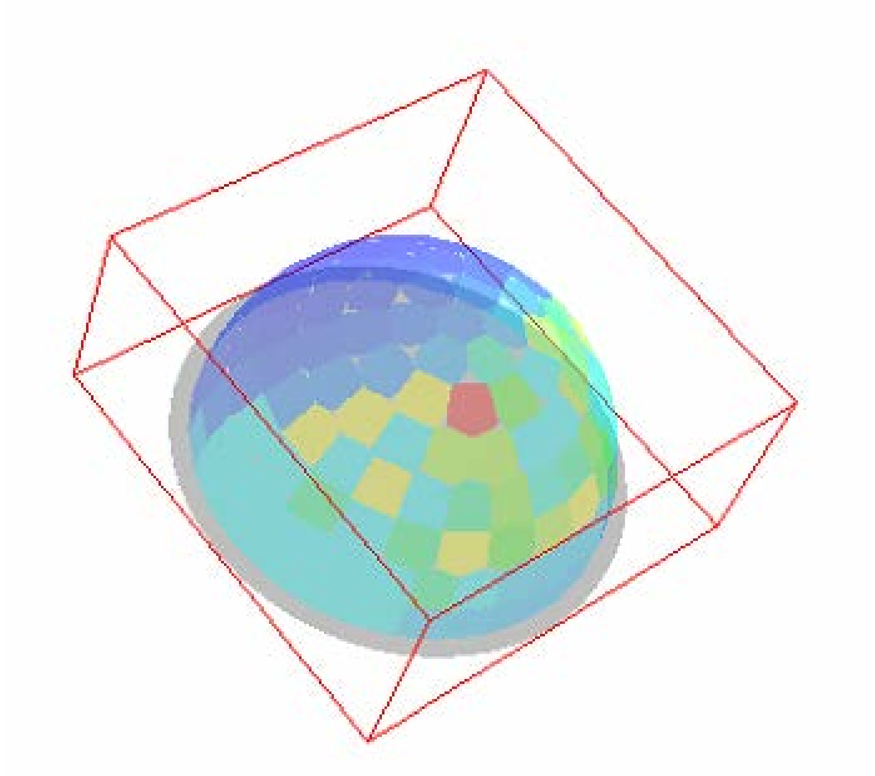
$$I^*_{scaled}(\lambda) = \frac{I_{meas}}{\int I^*(\lambda)\, d\lambda} \times I^*(\lambda)$$

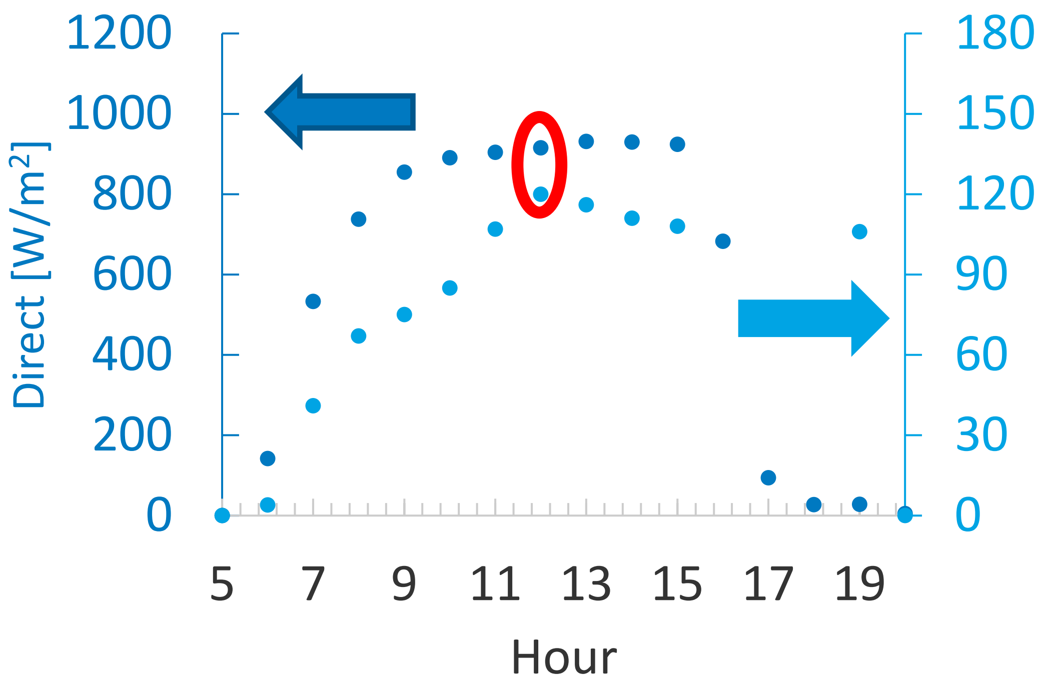
Current spectral method in bifacial_radiance

June 21st, 2 PM

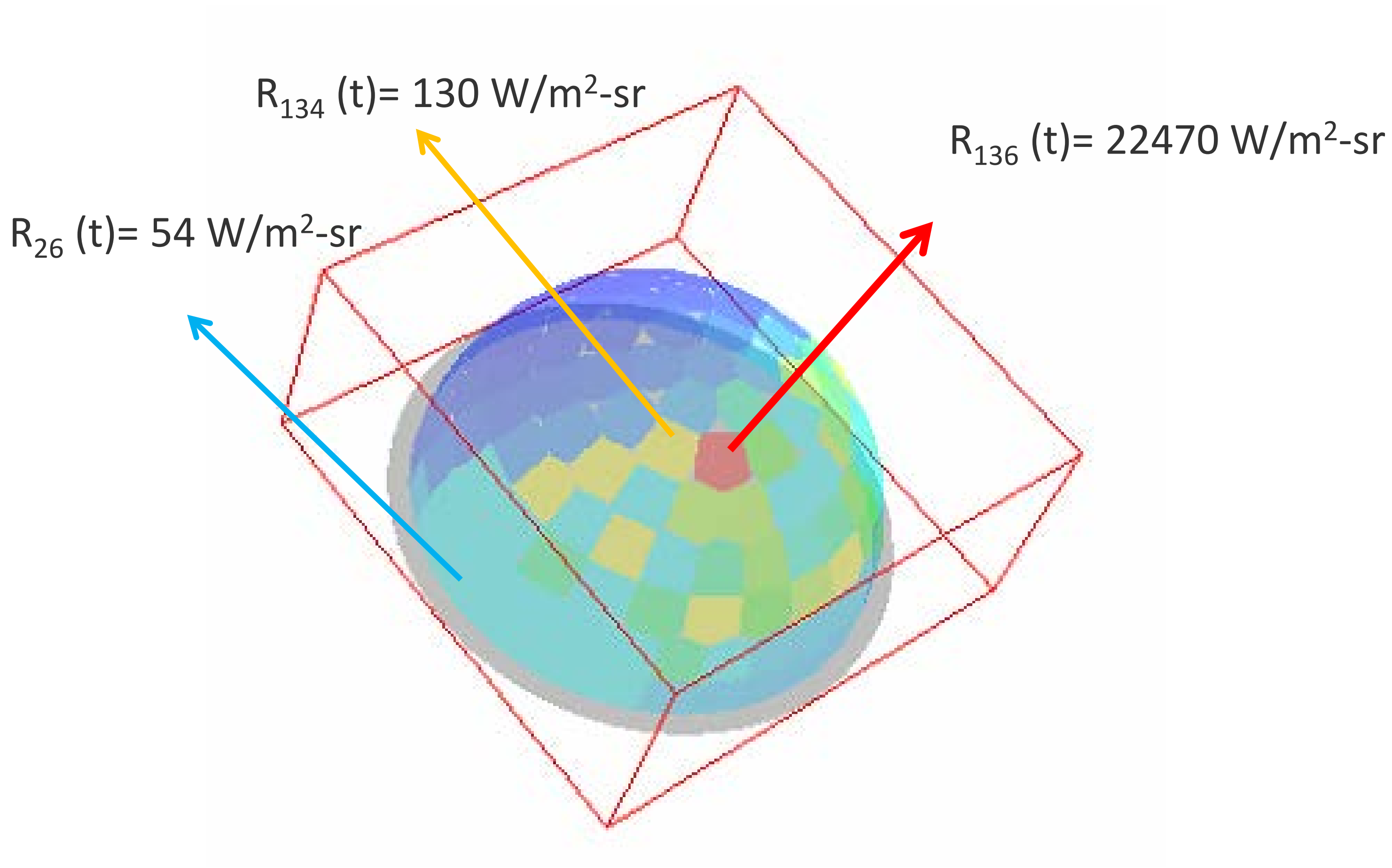
DNI: 930 W/m^2

DHI: 111 W/m^2

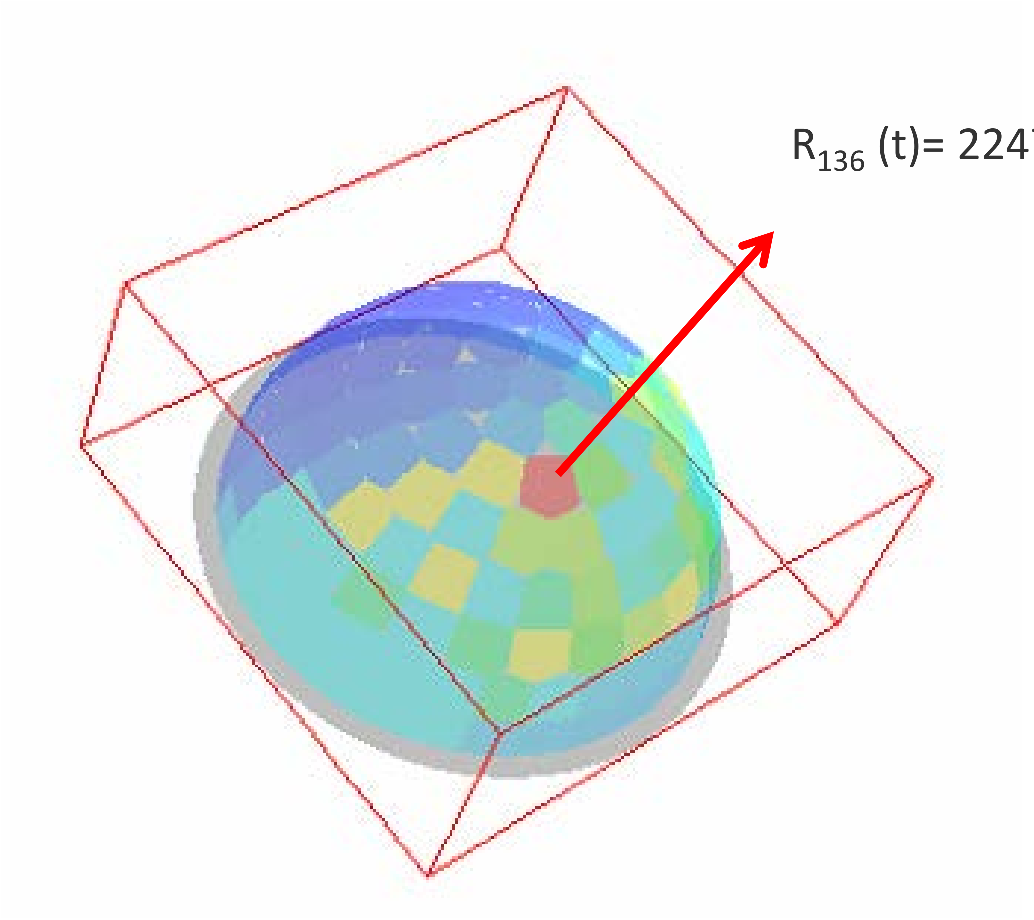




Current spectral method in bifacial_radiance



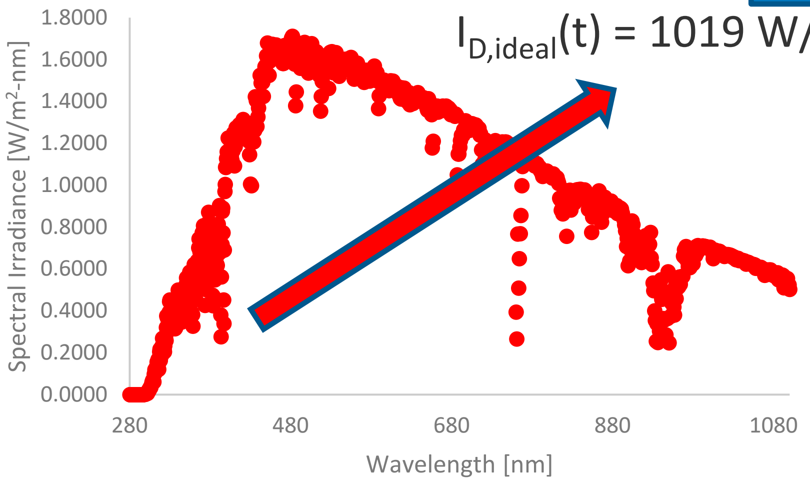
Current spectral method in bifacial_radiance



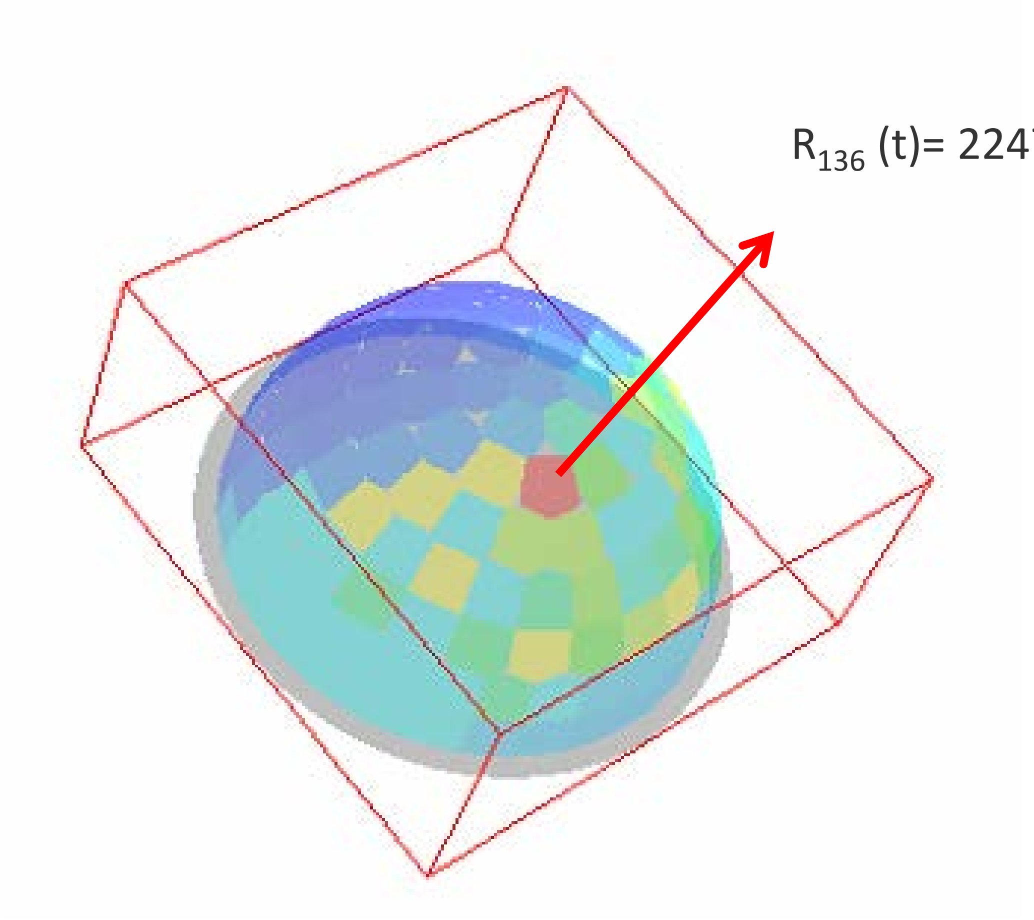
R_{136} (t)= 22470 W/m²-sr

SMARTS

$\frac{I_D(\lambda,t)}{I_{D,ideal}(t) = 1019\ W/m^2}$ =

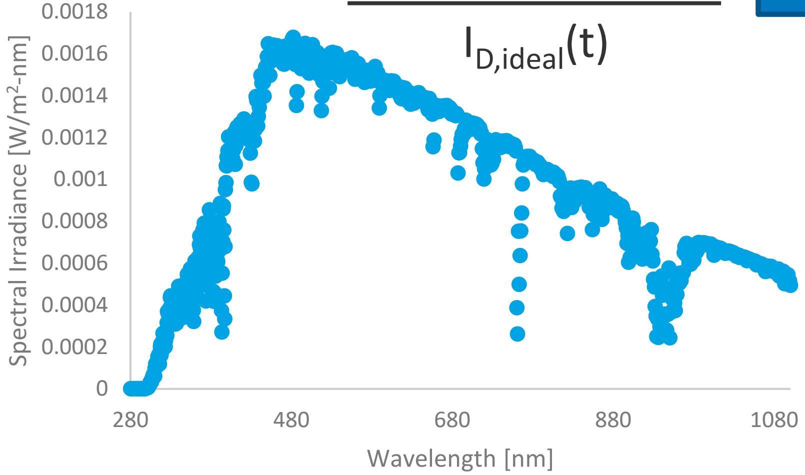


Current spectral method in bifacial_radiance

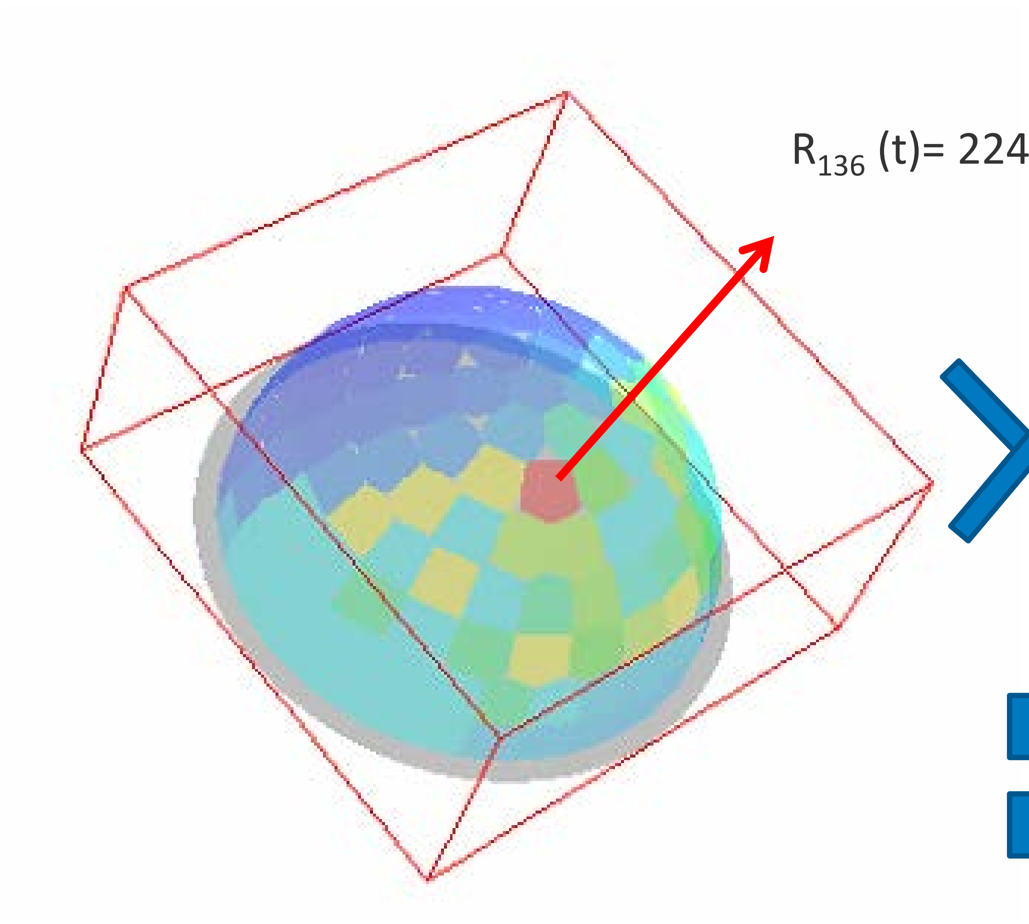


R_{136} (t)= 22470 W/m^2-sr

$$\frac{I_D(\lambda,t)}{I_{D,ideal}(t)} = I_{D,norm}(\lambda,t)$$



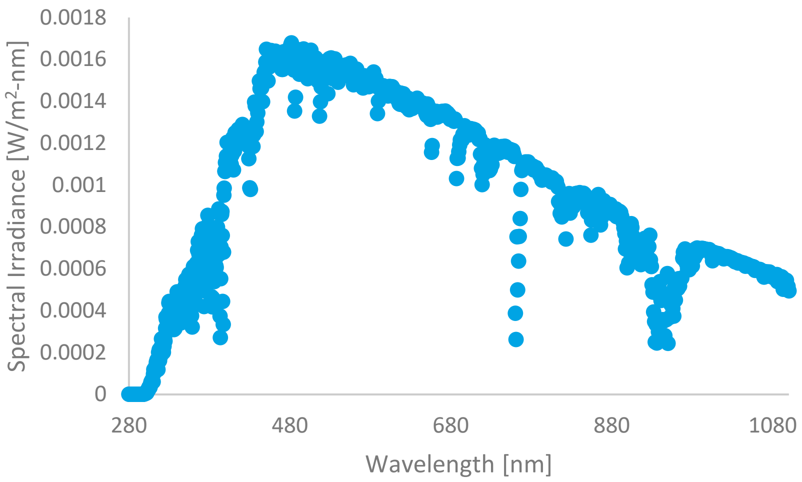
Current spectral method in bifacial_radiance



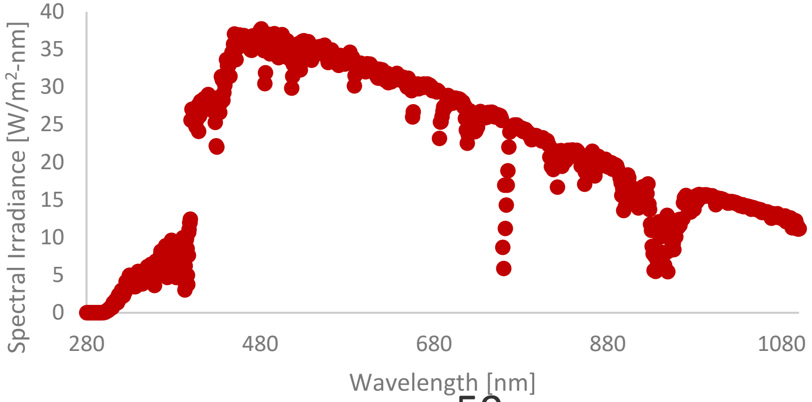
R_{136} (t)= 22470 W/m^2-sr

× =

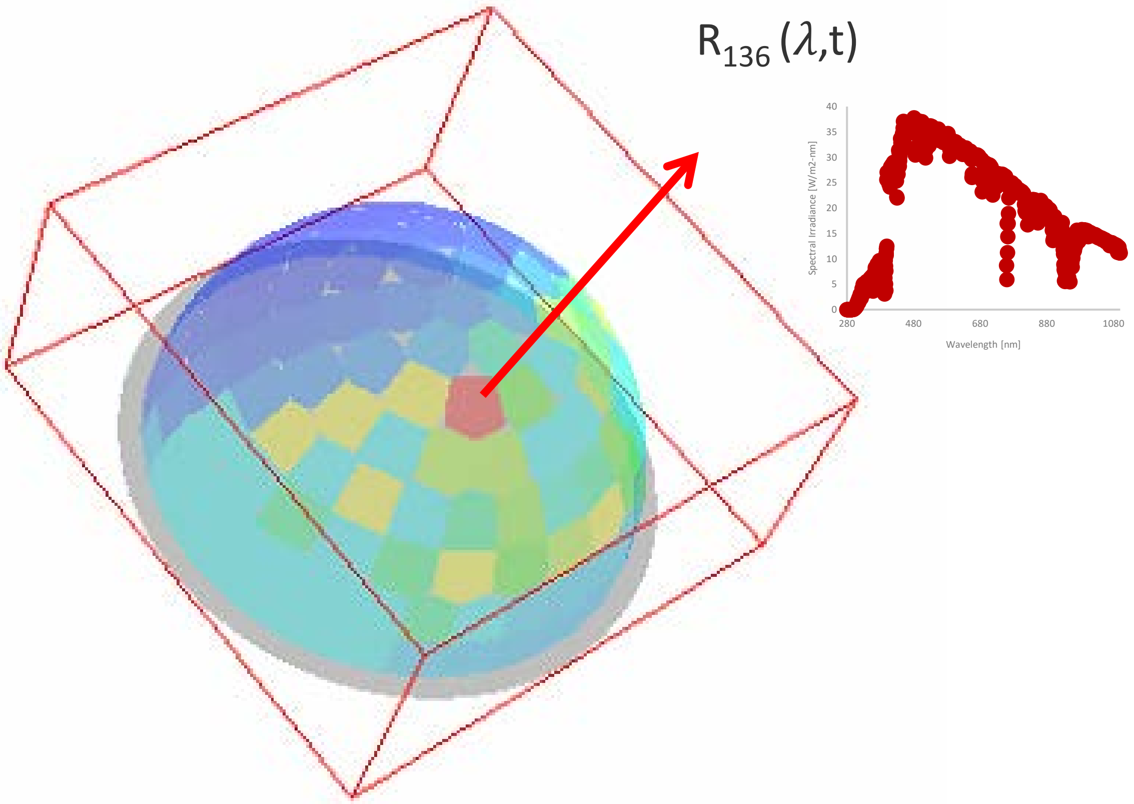
$I_{D,norm}(\lambda, t)$



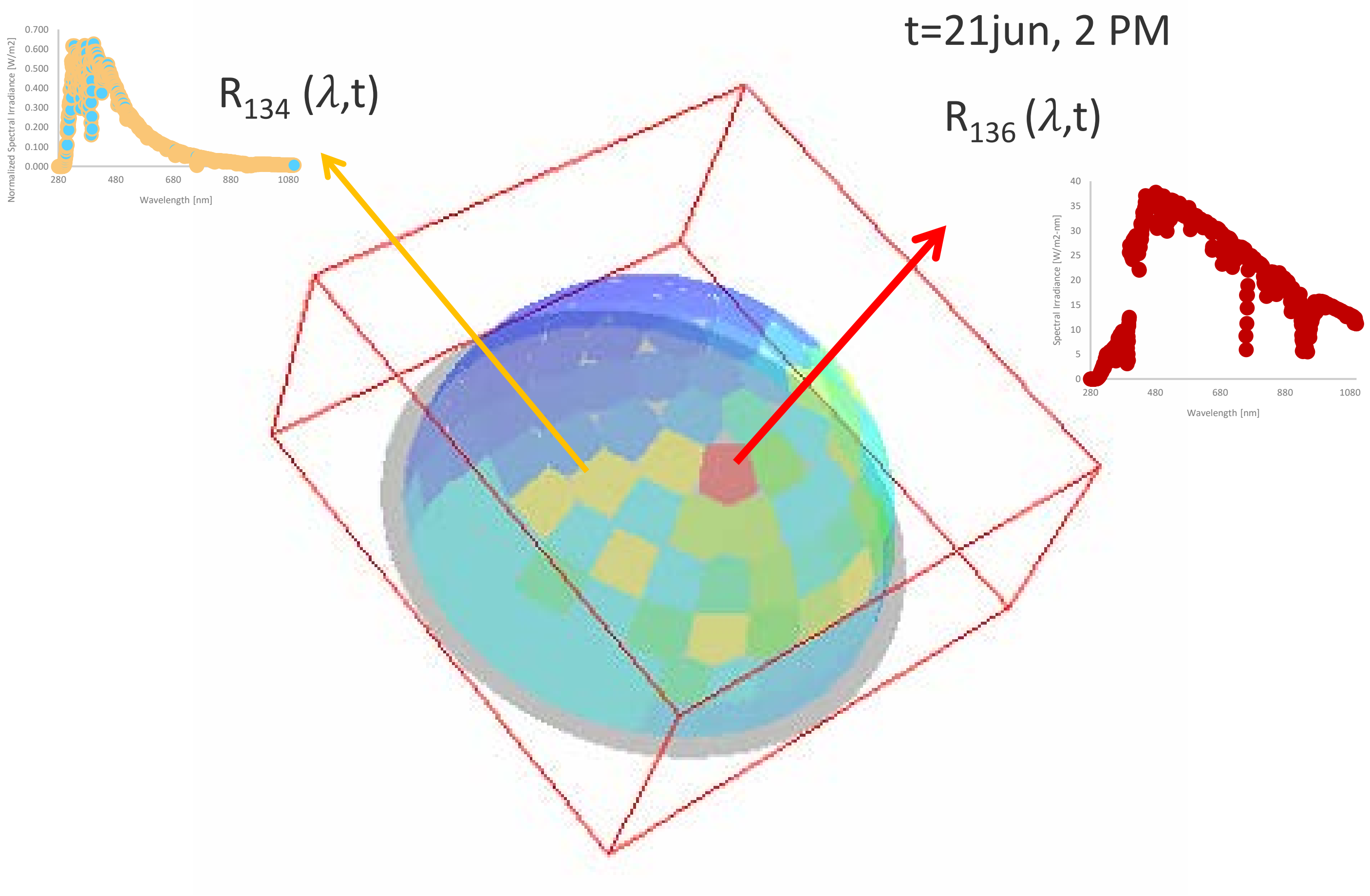
$R_{136}(\lambda, t)$



Current spectral method in bifacial_radiance



Current spectral method in bifacial_radiance



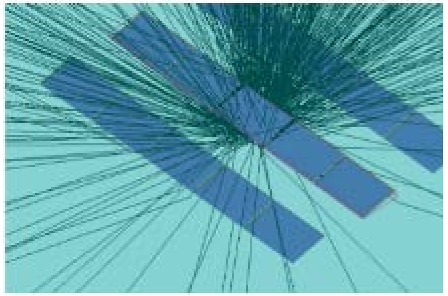
More details: S. Ovaitt dissertation, UofA 2019

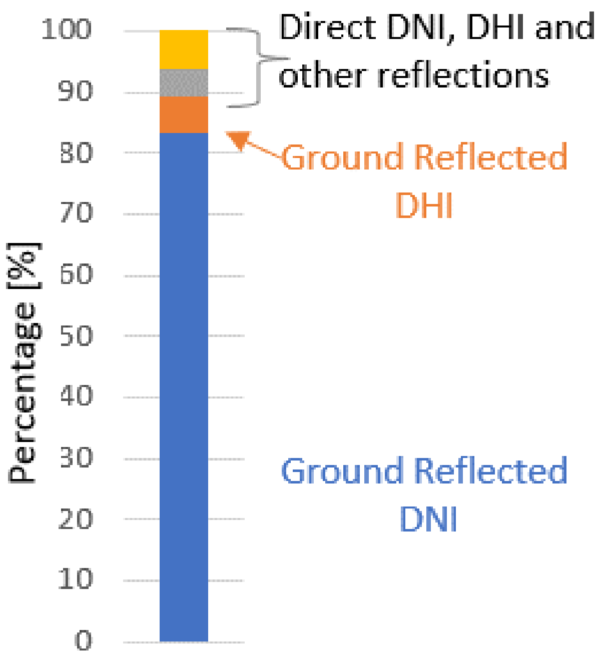
Spectral Simulations: simplified method

Foto de C. Deline

Simplified Model

Raytrace Spectrally vs $Grear_{\lambda} = Grear_{DNI_{\lambda}} + Grear_{DHI_{\lambda}} + Grear_{DHI\_reflected_{\lambda}} + Grear_{DNI\_reflected_{\lambda}}$





Sources contributing to the day's rear-irradiance

Correction Factors

SMARTS

$$Grear_{dni\_direct_{\lambda}} = \frac{Grear_{DNIdirect}}{\sum DNI_{\lambda}} * DNI_{\lambda}$$

$$Grear_{dhi\_direct_{\lambda}} = \frac{Grear_{DHIdirect}}{\sum DHI_{\lambda}} * DHI_{\lambda}$$

$$Grear_{dhi\_reflected_{\lambda}} = \frac{Grear_{DHIgroundreflected}}{\sum DHI_{\lambda} Alb_{\lambda}} * DHI_{\lambda} * Alb_{\lambda}$$

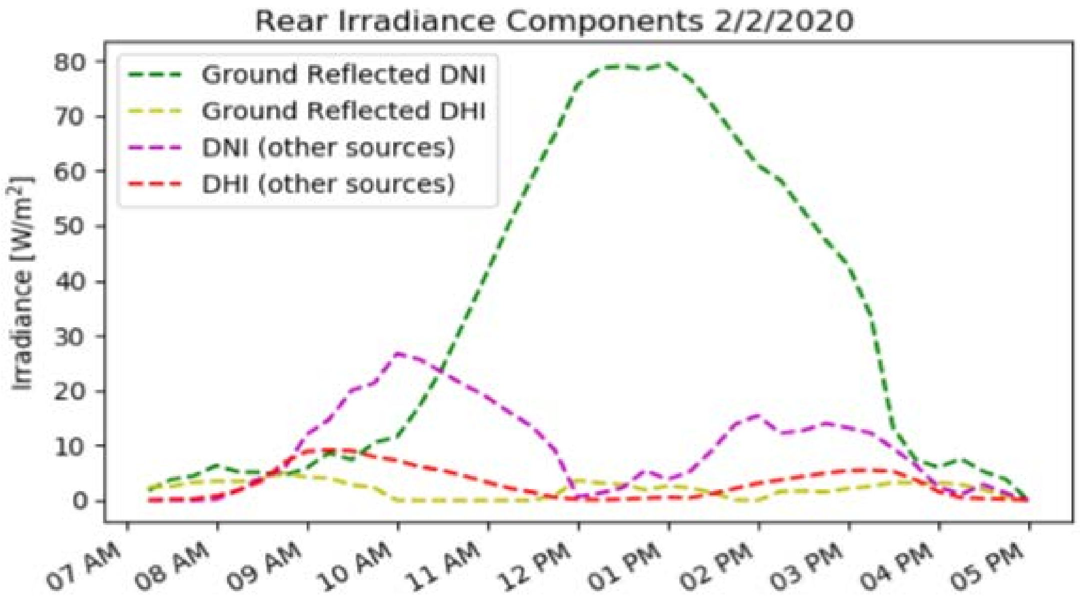
$$Grear_{dni\_reflected_{\lambda}} = \frac{Grear_{DNIgroundreflected}}{\sum DNI_{\lambda} Alb_{\lambda}} * DNI_{\lambda} * Alb_{\lambda}$$

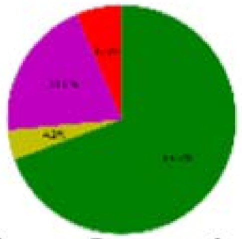
Contributions can be calculated with 5 non-spectral simulations, setting DNI = 0, DHI = 0, DNI & alb = 0, & DHI & alb = 0.

Simplified Model

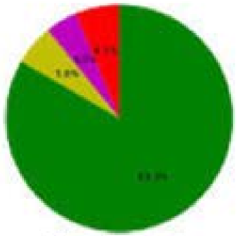
Contributions can be calculated with 5 non-spectral simulations:

1) Baseline
2) DNI = 0
3) DHI = 0
4) DNI & alb = 0
5) DHI & alb = 0.

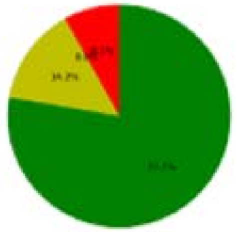




Linear Regression



Raytrace

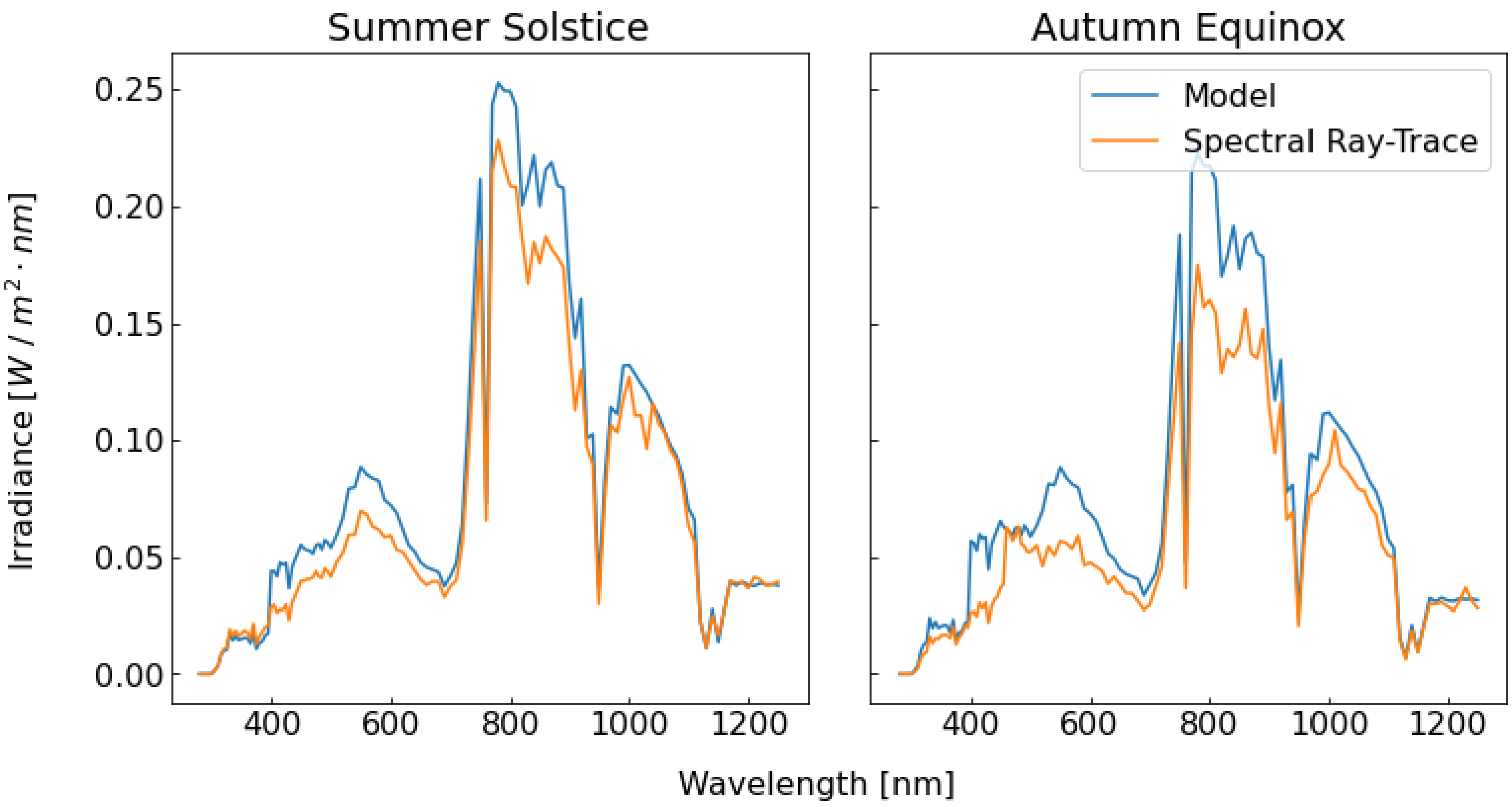


View Factor

Figure 6 Decomposition of the rear irradiance from **spectral** simulations using linear regression into ground reflected DNI & DHI, and DNI & DHI from other sources. The pie charts compare the decomposition method (upper) with those from modified **non-spectral** raytrace simulation (middle) and modified **non-spectral** view factor simulation (Lower).

M. Monarch, S. Ovaitt 2020 https://www.nrel.gov/docs/fy20osti/77582.pdf

Simplified Model & Spectral Ray-Trace Irradiance

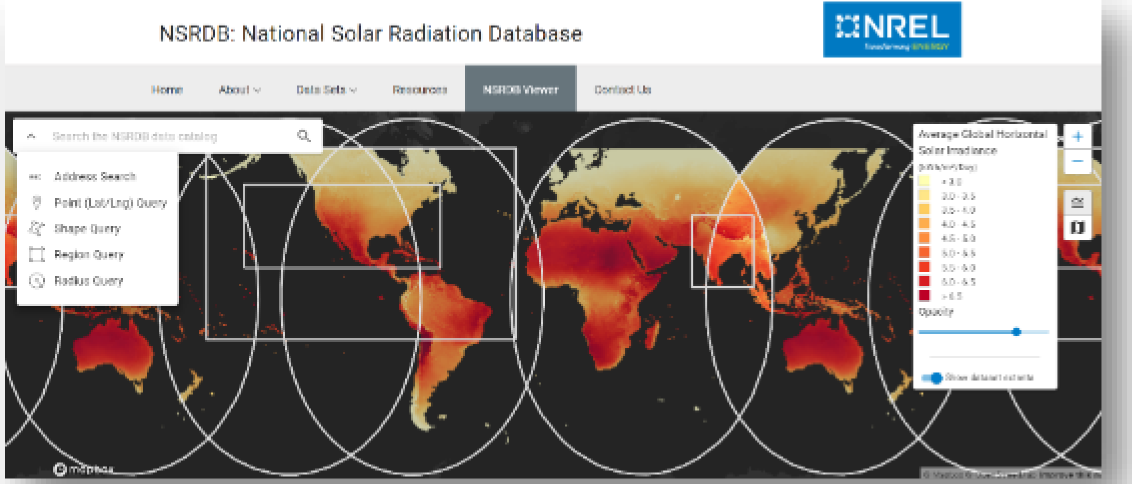


M. Brown, S. Ovaitt, PVSC 2022 Proceedings

Irradiance & Albedo Data

NSRDB

https://nsrdb.nrel.gov/data-viewer



- We started with EPW.
  - Great availability
  - Have found with comparing with pvlib some overirradiance, or negative values → some data cleanup and validation eneded.
- Have moved to using NREL's NSRDB (psm3) – API and AWS access
- Many other options specially on satellite data. For PV, ground data is sometimes preferable

SolarAnywhere®

"SolarAnywhere is the **most trusted, accurate & validated** solar resource dataset available"

SOLARGIS

"Multiple independent studies have found Solargis to be the **most reliable solar database**"

SOLCAST

"Produce highly accurate historical irradiance estimates with the **lowest uncertainty available on the market.**"

Jensen et al. Worldwide benchmark of modeled solar surface irradiance. PVPMC2022 pvlib

https://github.com/pvlib

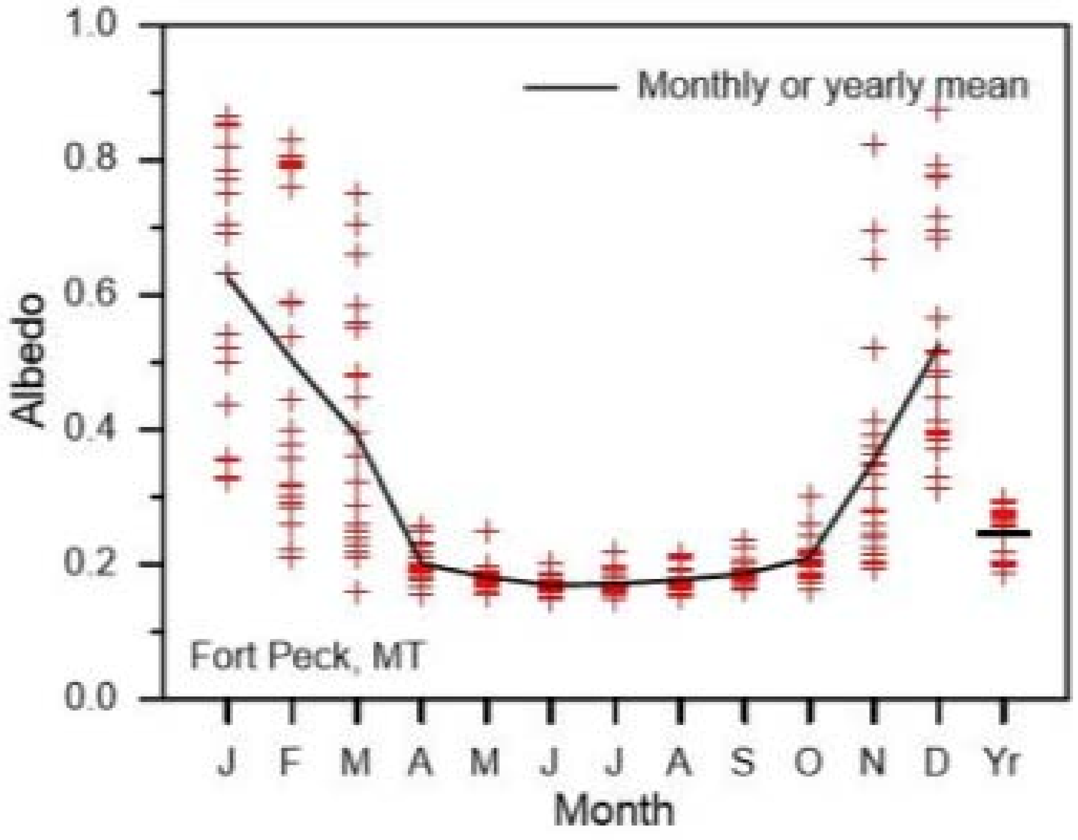
Supports for retrieving data from 12 open solar irradiance datasets.

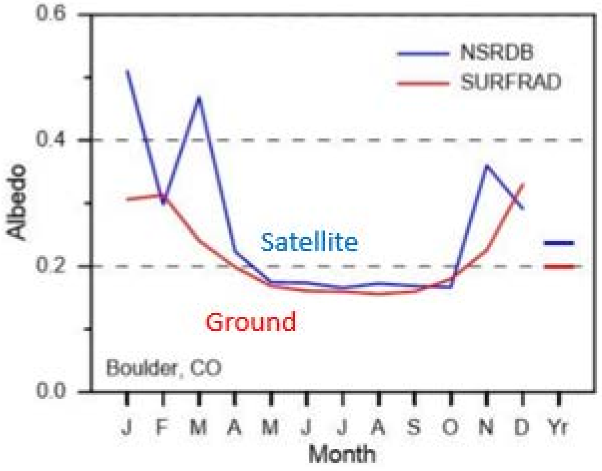
- NSRDB (National Solar Radiation Database)
- Solargis
- SolarAnywhere
- Solcast
- TMY2 & TMY3 (deprecated)
- EPW (EnergyPlus Weather Files)
- PVGIS (Photovoltaic Geographical Information System)
- CAMS (Copernicus Atmosphere Monitoring Service)
- BSRN (Baseline Surface Radiation Network)
- SURFRAD (Surface Radiation Budget Network)
- SRML (Solar Radiation Monitoring Laboratory)
- ACIS (Applied Climate Information System)
- CRN (Climate Reference Network)
- Solrad (NOAA)
- MIDC (Measurement and Instrumentation Data Center)

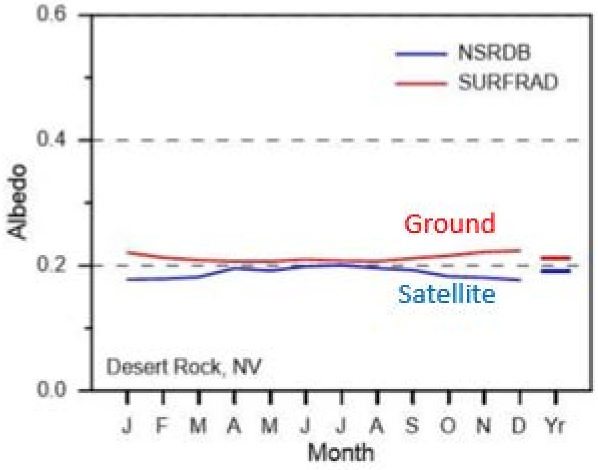
Jensen et al. DOI: 10.1016/j.solener.2023.112092.

Albedo Data

- Monthly and year-to-year variability depends on location and ground surface, especially snow
- Site-measured albedo has best accuracy, but satellite data has better coverage.







Ground data for 37 stations available from the DuraMAT website:
https://datahub.duramat.org/project/albedo-study

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

Conclusions

- Solar arrays are very repetitive, which makes *bifacial_radiance* python wrapper very useful. Lots of customization on module, scene options, and common features requested by industry.
- Open source; established as state-of-the-art for other irradiance tools comparisons. Current roadmap is more agrivoltaic usage, and continue simplified model development.
- We are using gendaylit and gencumsky, and our own spectral concoction. Moving to the new hyperspectral Radiance modeling sounds great!

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