NREL
Transforming ENERGY

Illuminating Agrivoltaics at NREL

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Sarah Kurtz UCMerced AgriPV Webinar Series, Jun 2024

InSPIRE

Contents

The InSPIRE Project-

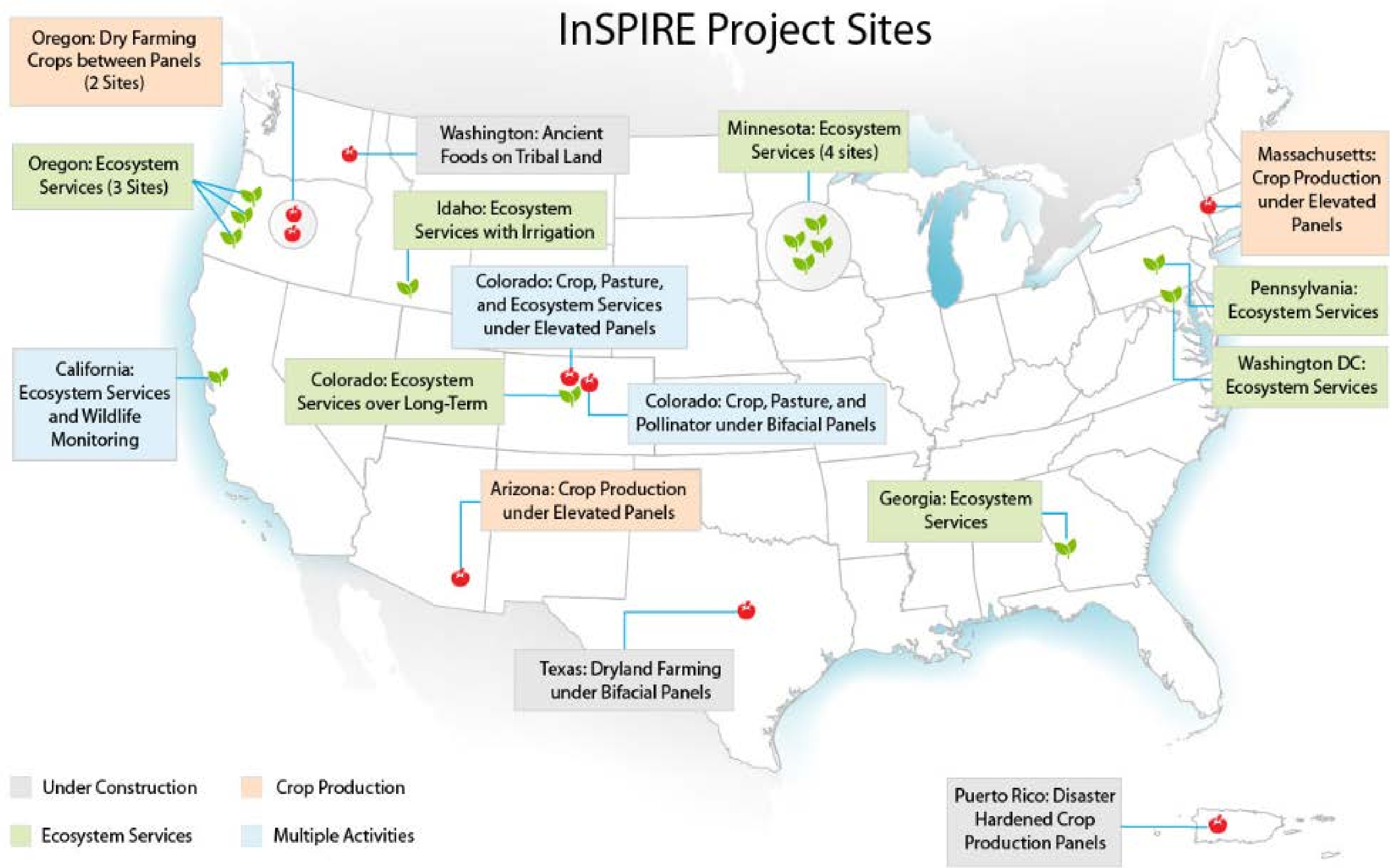
Innovative **S**olar **P**ractices **I**ntegrated with **R**ural **E**conomies and **E**cosystems

- InSPIRE has 24 active field research projects across the U.S.

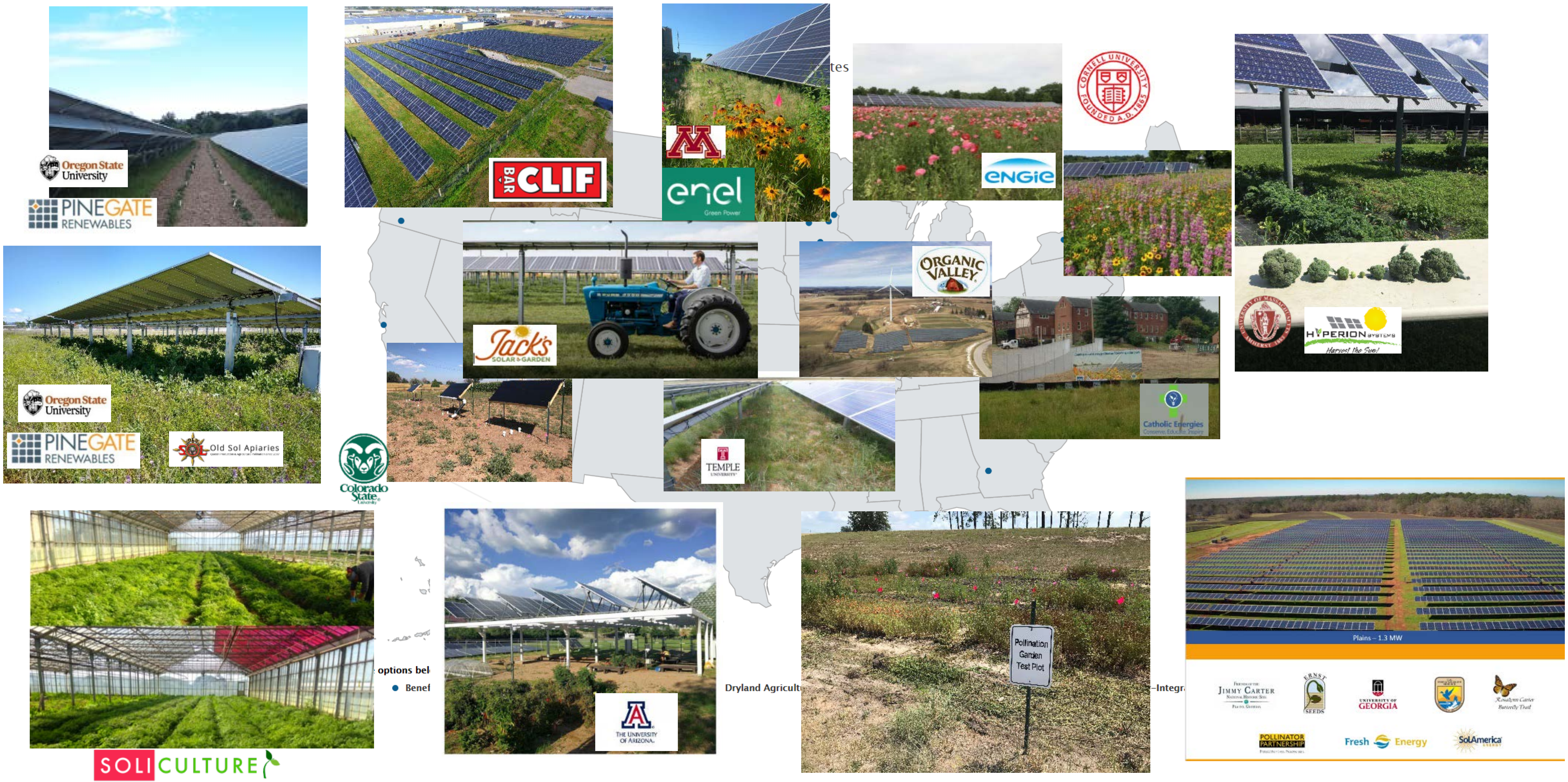
- **Analytical research:**
  - Cost-benefit tradeoffs of different agrivoltaic configurations
  - Assessing research gaps and priorities
  - Tracking agrivoltaic projects across the U.S.

- **Field-based research:**
  - Novel agrivoltaic and traditional utility-scale PV designs integrated with multiple activities
  - Assessing agricultural yields and irrigation requirements in arid environments
  - Grazing standards and best practices
  - Pollinator habitat and ecological services

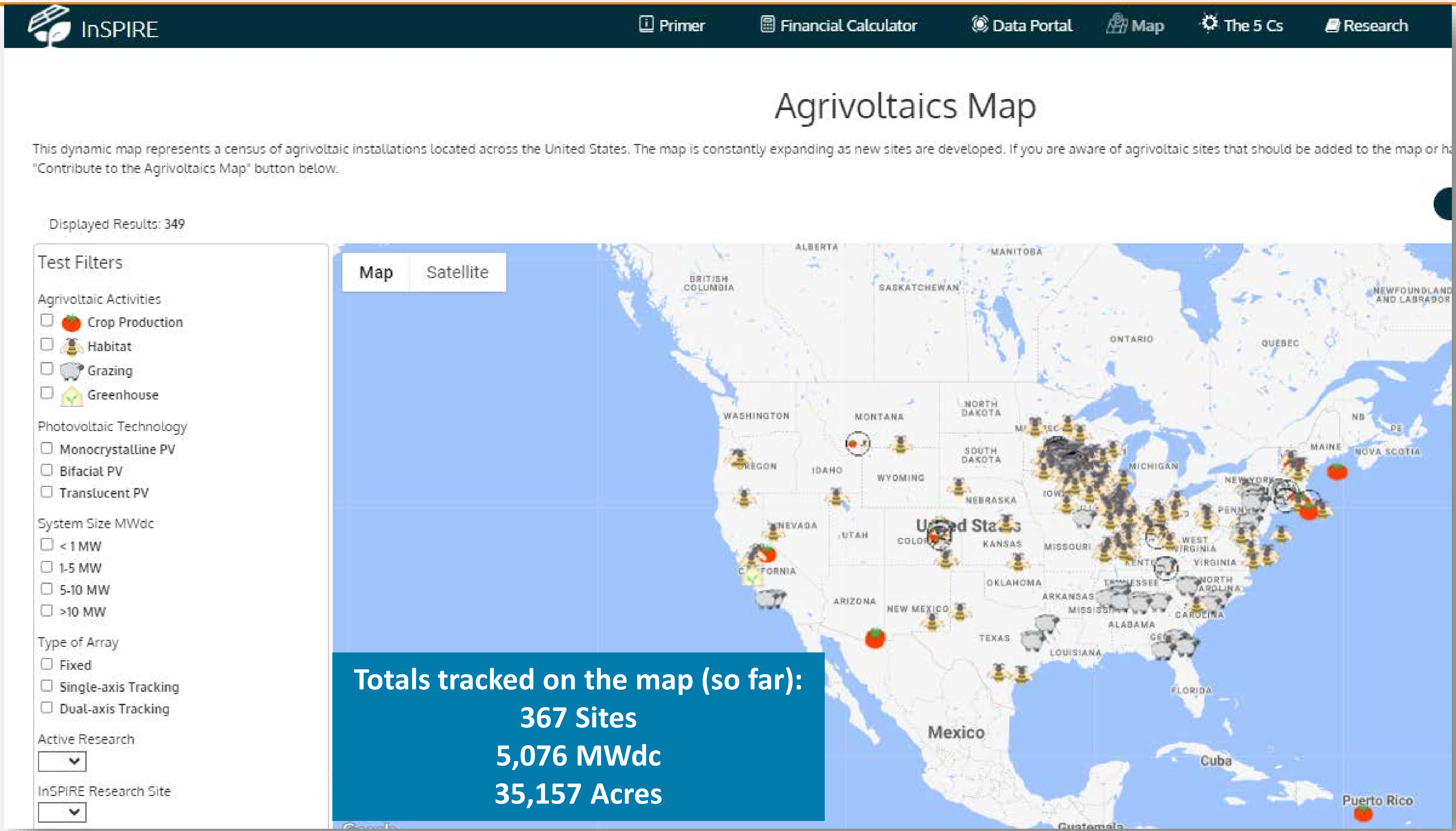
https://openei.org/wiki/InSPIRE



InSPIRE Project Research Sites



Current Status of Agrivoltaics



Totals tracked on the map (so far):
367 Sites
5,076 MWdc
35,157 Acres

Interactive Map (updated weekly): https://openei.org/wiki/InSPIRE/Agrivoltaics_Map

Motivation & Objectives

Agrivoltaic stakeholders seek to understand **plant & vegetation suitability** for **different solar configurations** across **varied geographies**.

Existing modeling tools are inaccessible and geographically limited.

Approach:

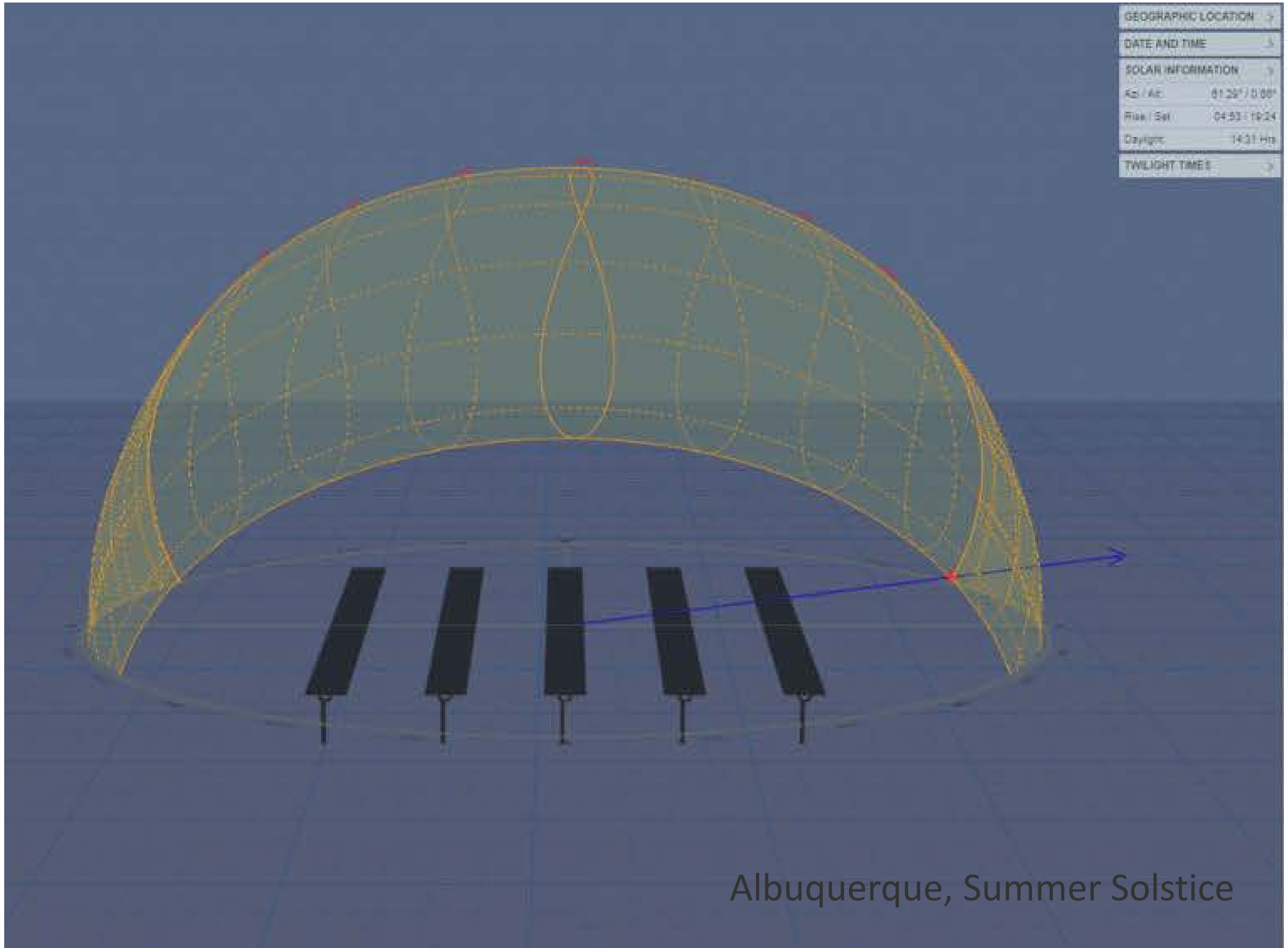
-Implemented ground-irradiance calculations into the System Advisor Model

-Improved raytracing weather-to-module performance with ground-irradiance calculations

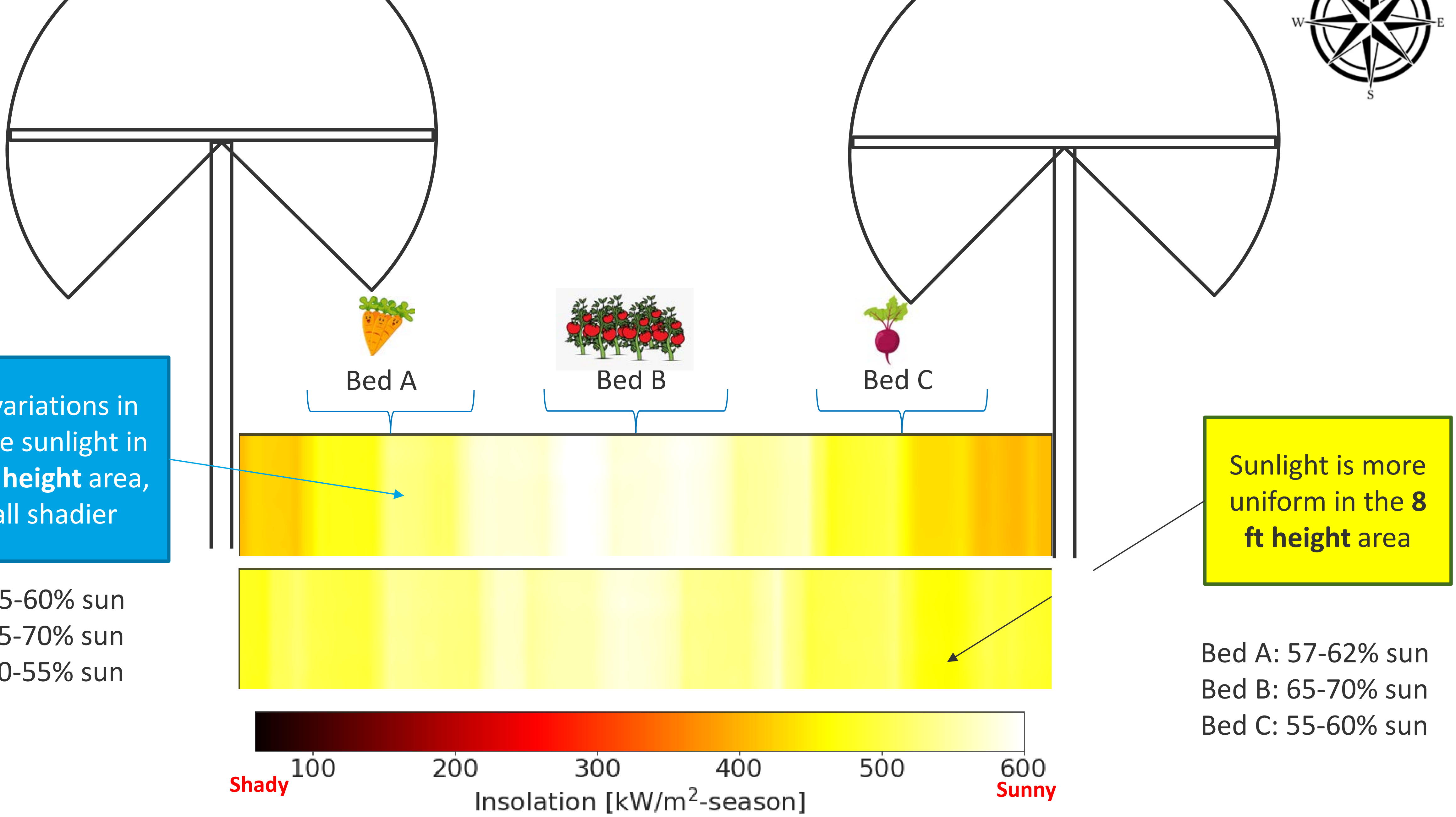
-Creating a dataset for farmers, solar developers, and researchers to easily compare different agrivoltaic configurations for any location in the United States.

Photo by Werner Slocum / NREL

Shade moves throughout the day, especially when the trackers move too!



Crop Beds and Shading at Jack's Solar Garden
Colorado, USA



More variations in available sunlight in the **6 ft height** area, overall shadier

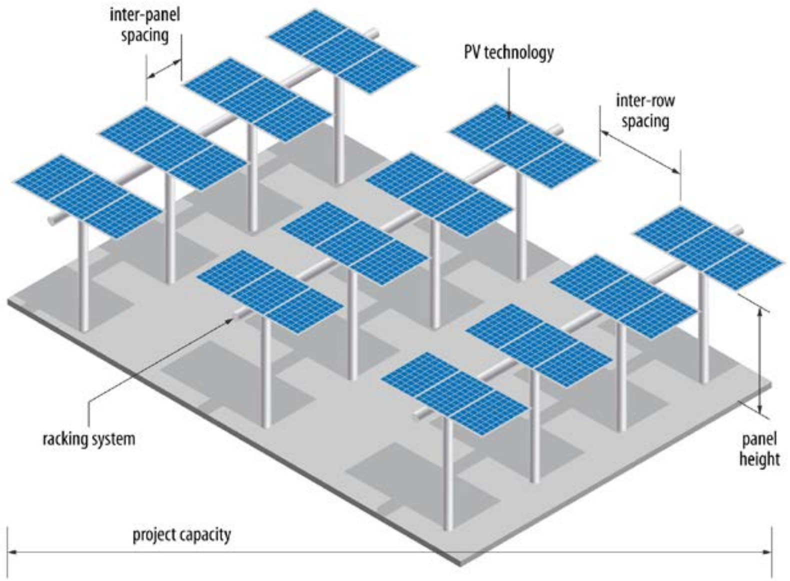
Bed A: 55-60% sun
Bed B: 65-70% sun
Bed C: 50-55% sun

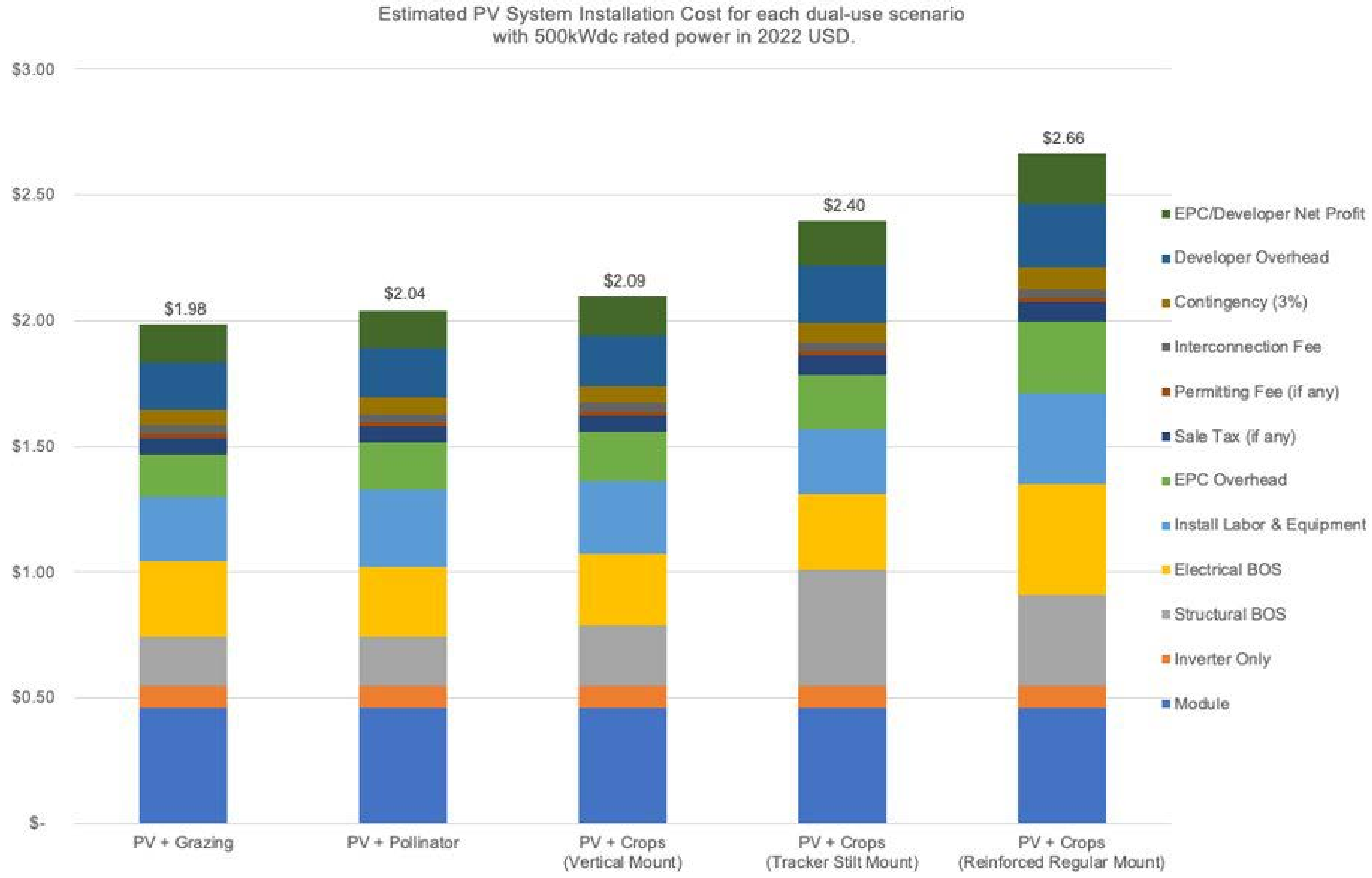
Sunlight is more uniform in the **8 ft height** area

Bed A: 57-62% sun
Bed B: 65-70% sun
Bed C: 55-60% sun

Cost Factors to Consider for Agrivoltaics

- Capital Cost Considerations
  - Module type and equipment
  - Panel height
  - Racking/Tracking system
  - Land acquisition costs
  - Installation labor costs
  - Site preparation costs





Kelsey Horowitz, Vignesh Ramasamy, Jordan Macknick and Robert Margolis. 2020. *Capital Costs for Multi-Land Use Photovoltaic Installations*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-77811
https://www.nrel.gov/docs/fy21osti/77811.pdf

Results are for 500-kW systems. Results can vary at lower and higher installed capacities

Crop yields as a function of crop placement: Broccoli in Massachusetts

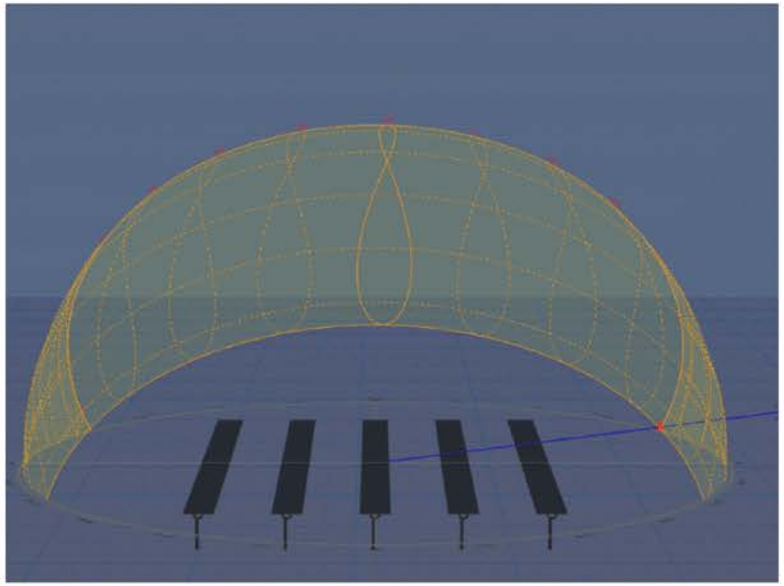
Massachusetts Test Facility

Herbert et al., under review

Broccoli Harvested in different locations under panels

Modeling Pipeline

AgriPV modeling starts with light and ends in currency.



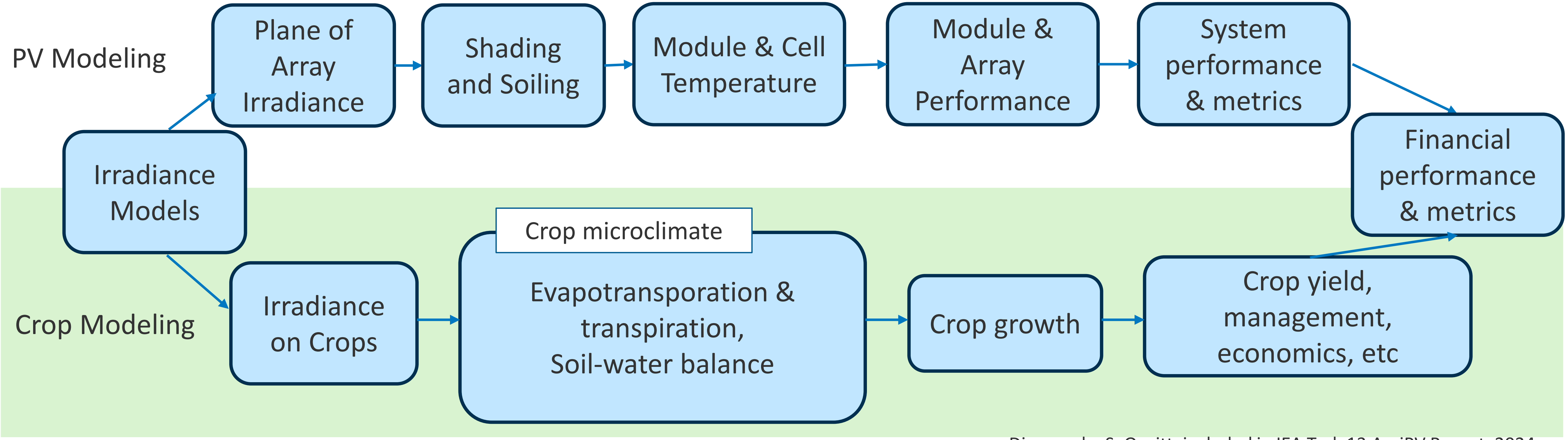
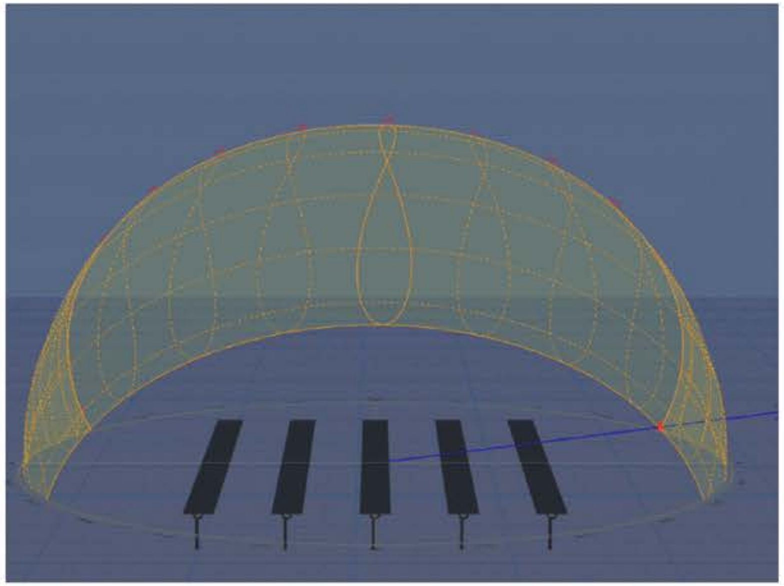
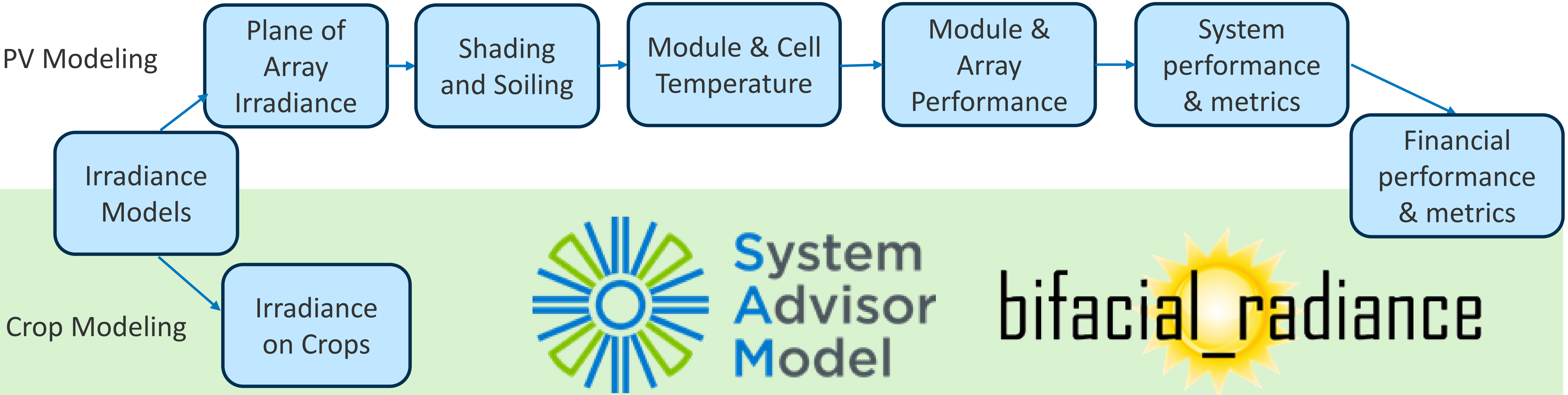


Diagram by S. Ovaitt, included in IEA Task 13 AgriPV Report, 2024

Modeling Pipeline

NREL tools include sophisticated PV modeling capabilities and can provide calculations of irradiance on crops.





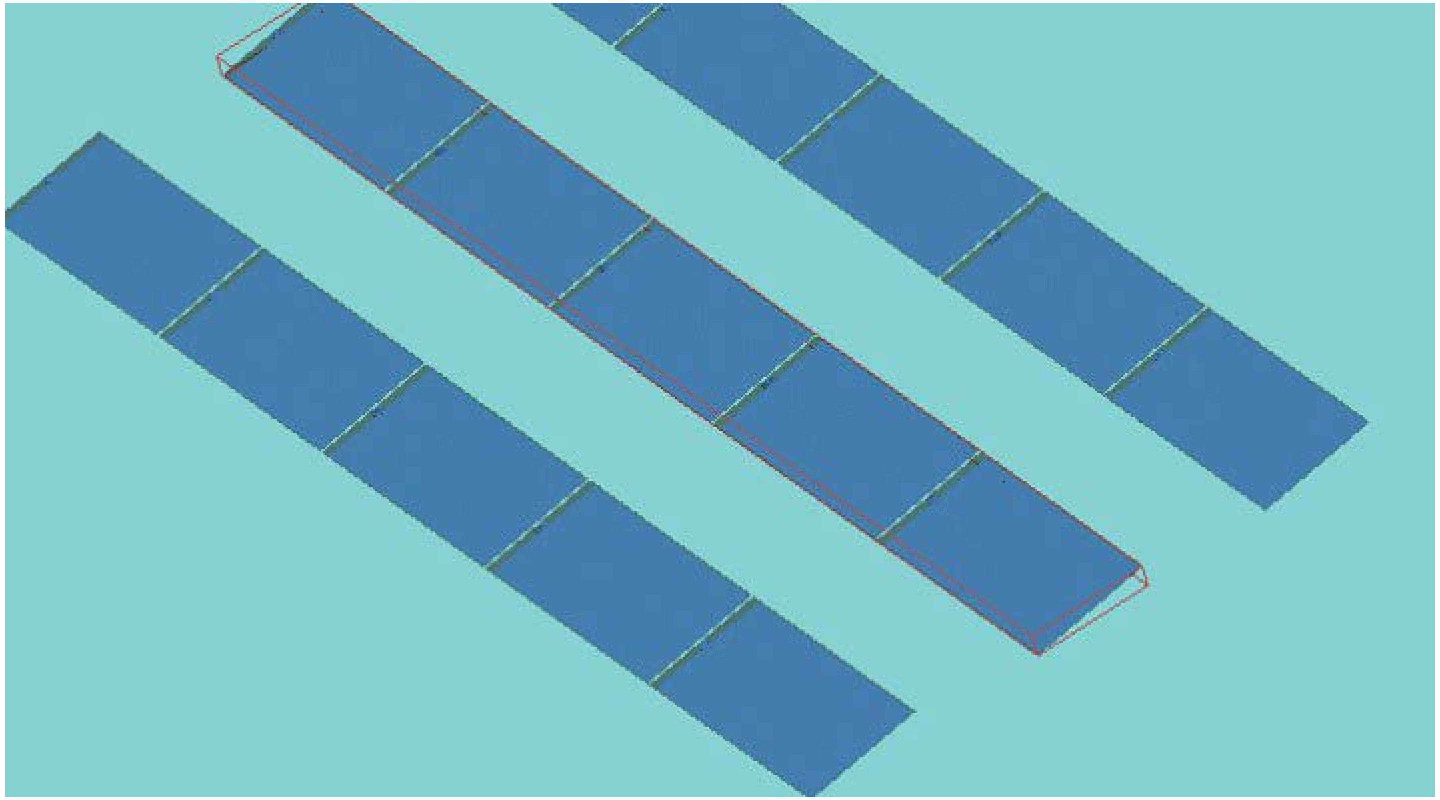
System Advisor Model

bifacial_radiance

bifacial_radiance

Validated NREL's Open Source Bifacial (and AgriPV) raytracer

https://github.com/NREL/bifacial_radiance



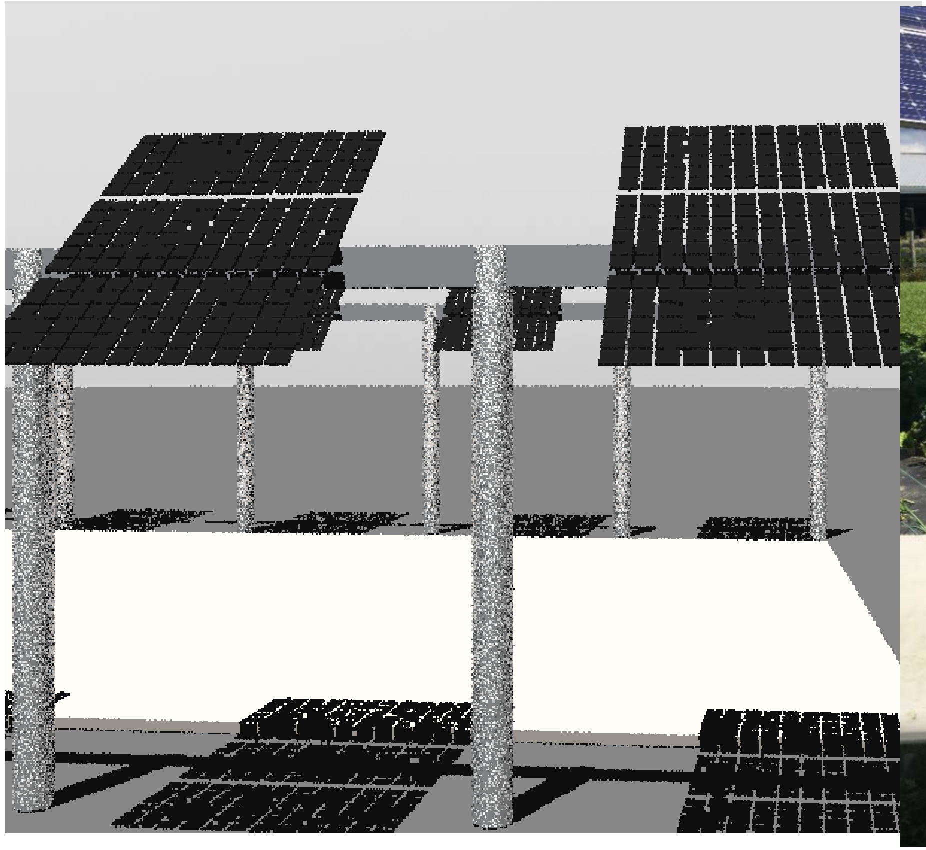
bifacial_radiance

- Uses backward ray-trace to evaluate the irradiance (W/m^2) at any location in the scene. Much customization!
- Weather → Irradiance → Module Performance calculations with PVLib

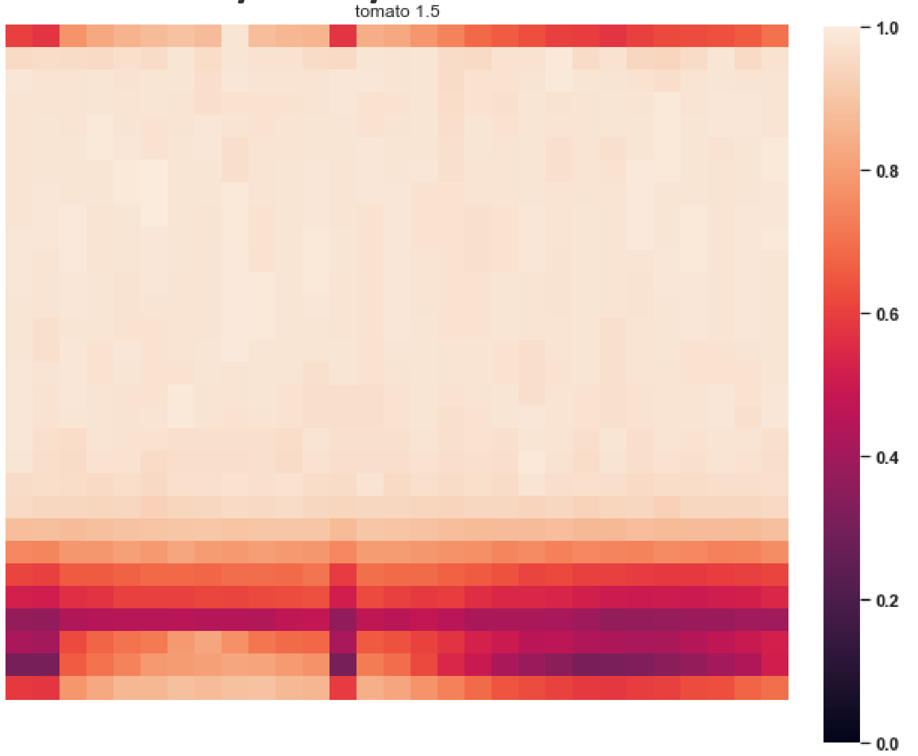
bifacial_radiance

Validated NREL's Open Source Bifacial (and AgriPV) raytracer

AgriPV Examples:



Ground Insolation Heatmap
03/15-06/30 Cumulative



View Factor Models for Rear (& Ground) Irradiance

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

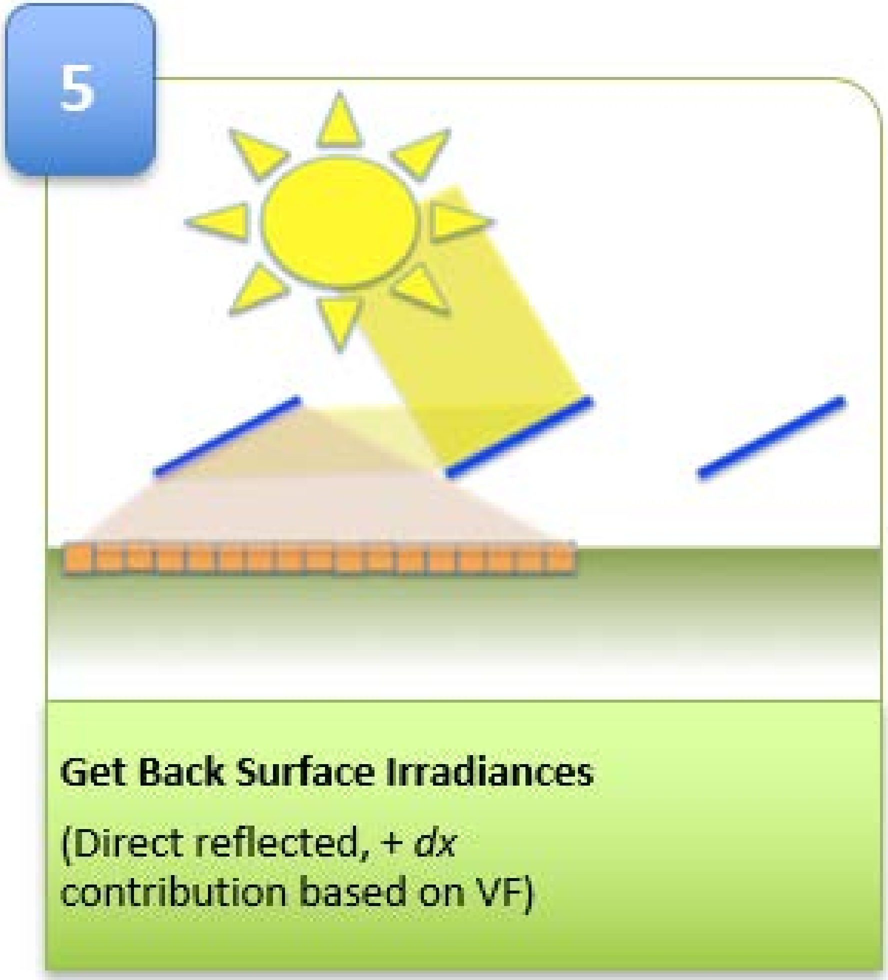
$$\mathrm{G_{rear}} = G_{DNI,rear} + \sum_{i=1°}^{180°} VF_i \cdot F_i \cdot G_i \ ;$$

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

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

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

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

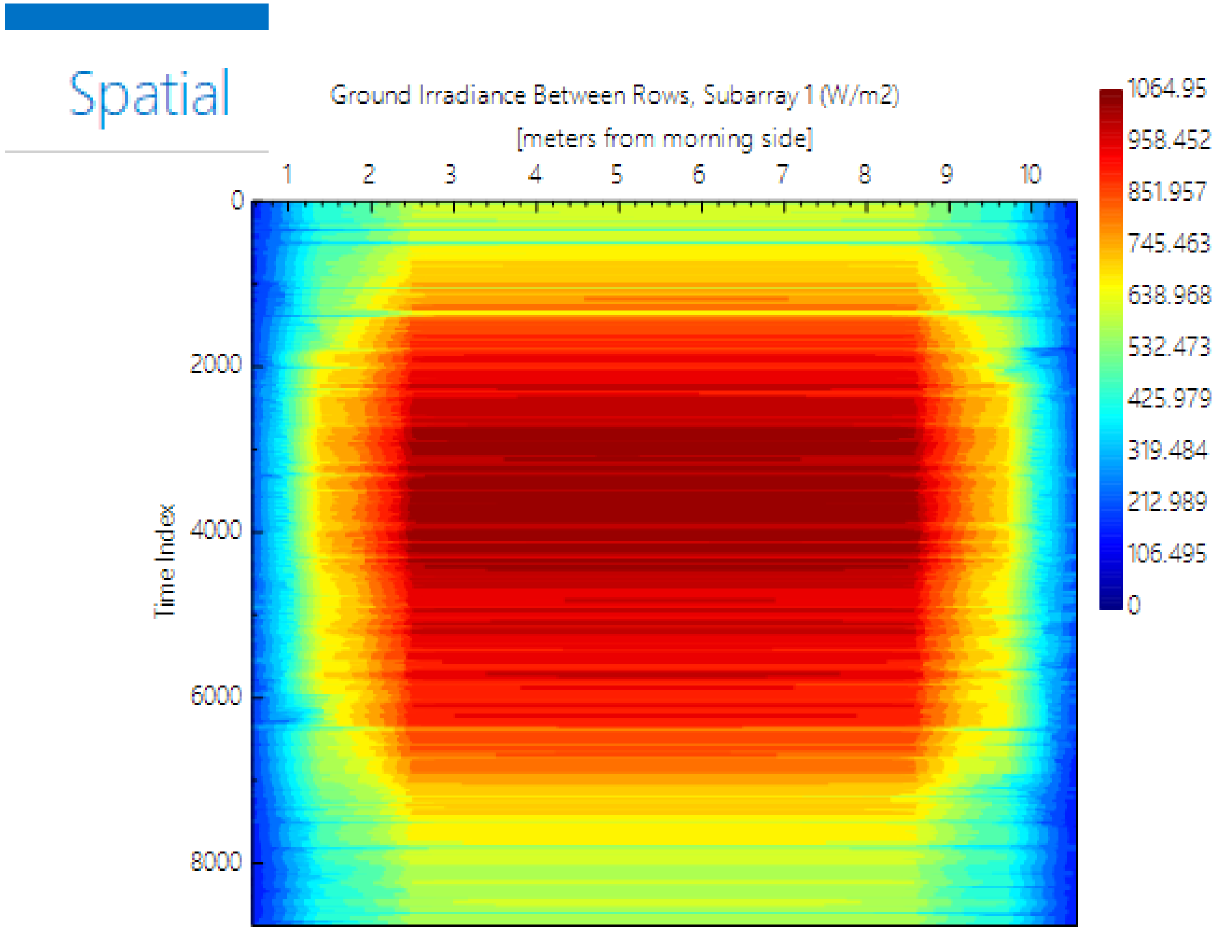
System Advisor Model (SAM)
Free, Due diligence tool with AgriPV features

System Advisor Model

Tailor:
- Spatial albedo variations as input
- AgriPV-tailored modules can be captured with transparency factor (%) input
- Easy yearly spatial ground output

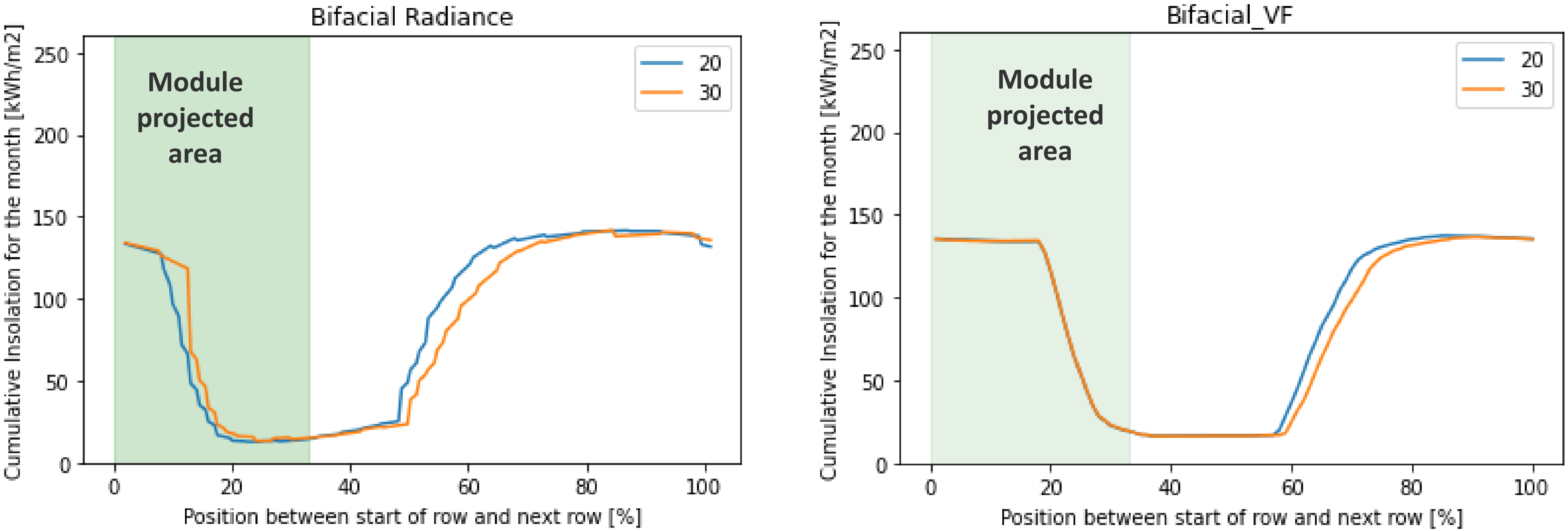
Free due diligence program interface, also accessible through pySAM

The detailed economics inputs can capture impact of configuration changes on PV revenue and incentives.



https://sam.nrel.gov/

View factor vs Raytrace

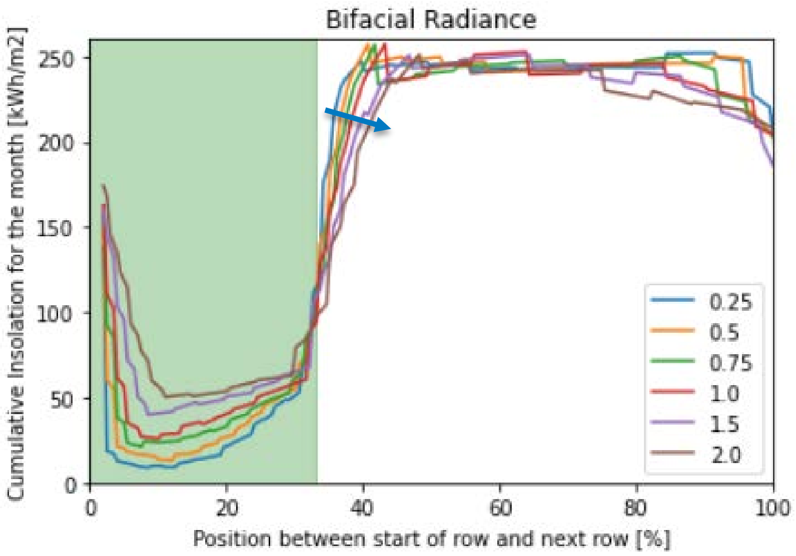


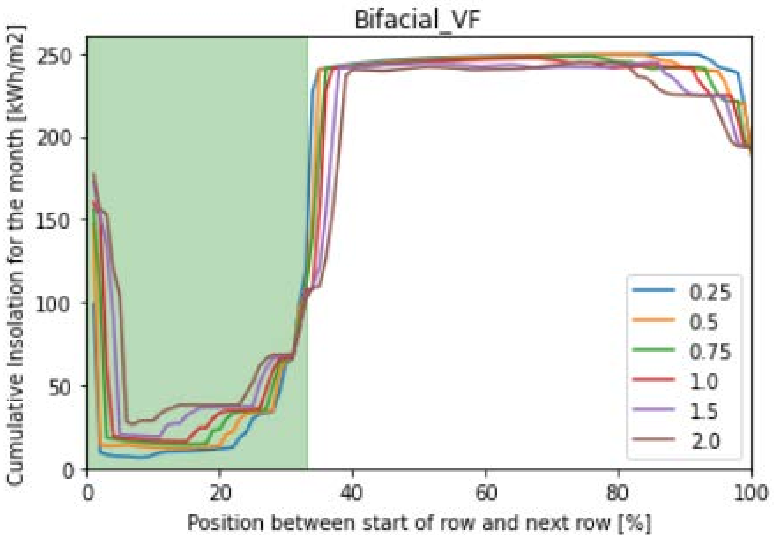
Sun 'lower' on the horizon, so main shade not underneath modules

More details on Ovaitt, PVSC 2023 Proceedings

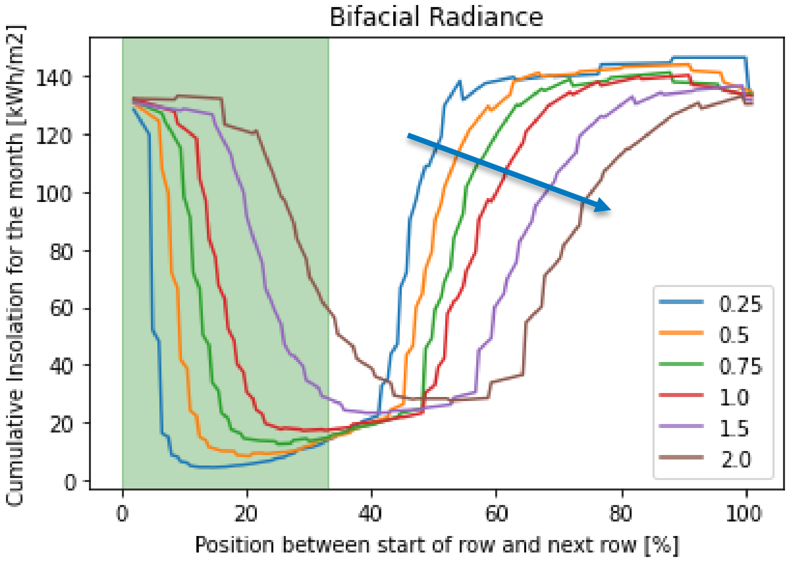
Clearance Height Comparisons

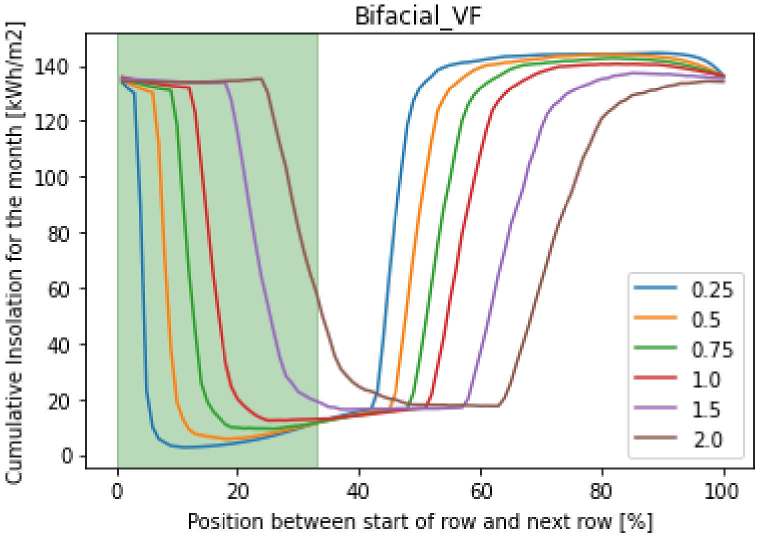
June





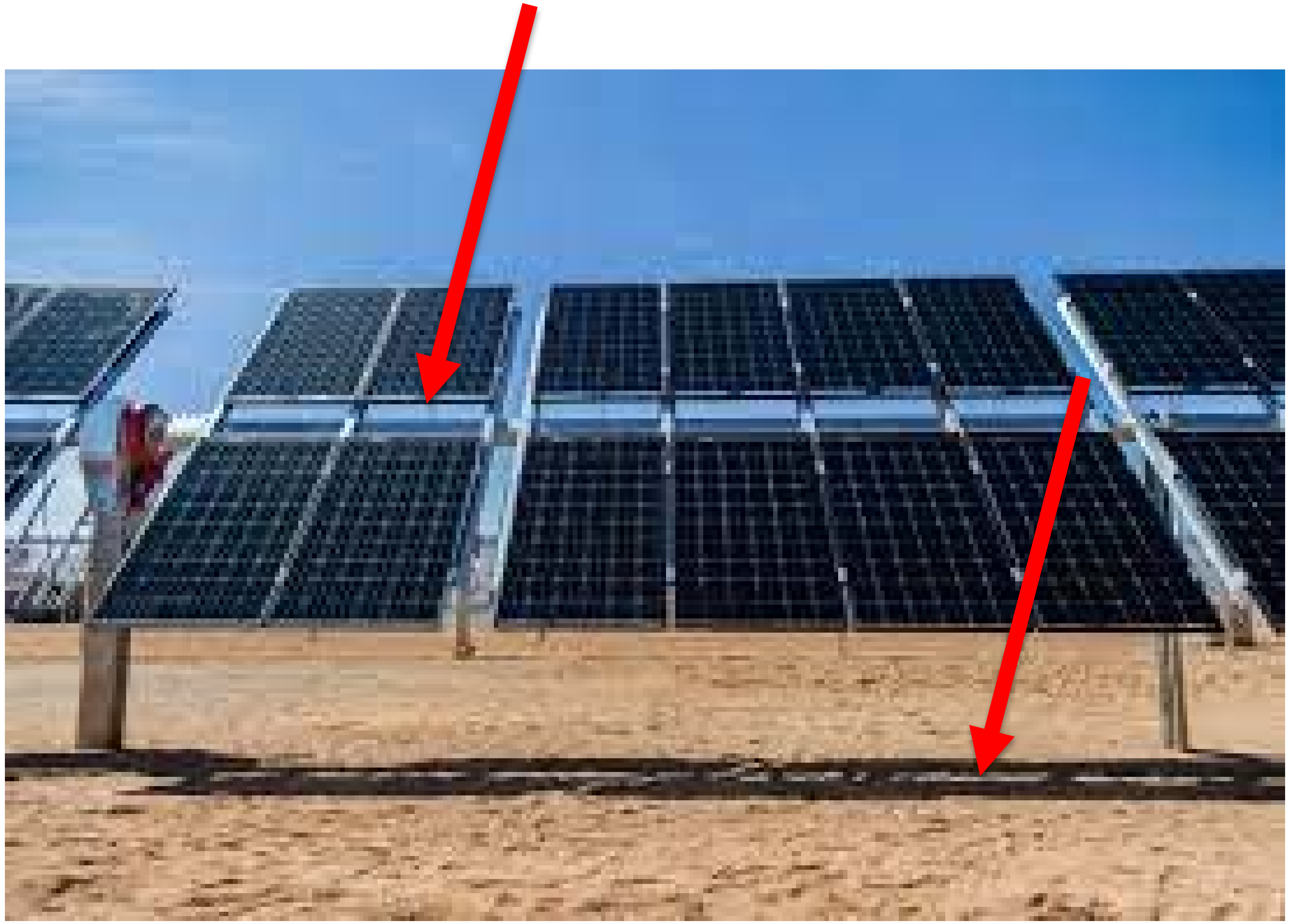
October





Transmission Factor Comparisons

View factor uses a ‘transmission factor’ to account for space between cells, and space between modules along the row (xgap). Here we are testing to see if it can also account for spaces between modules across the collector width (ygap)



Soltec.com image borrowed from Google

Transmission Factor Comparisons

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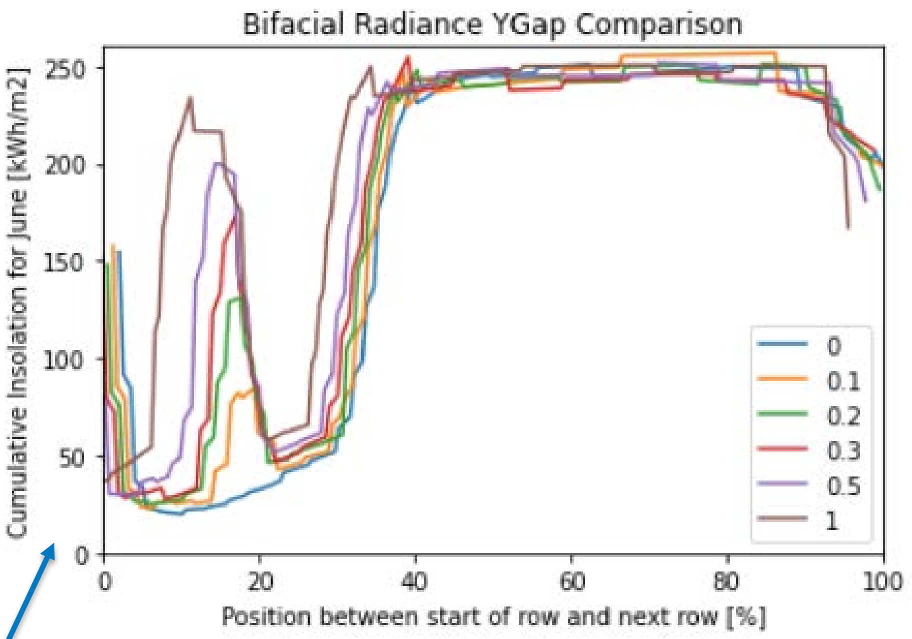
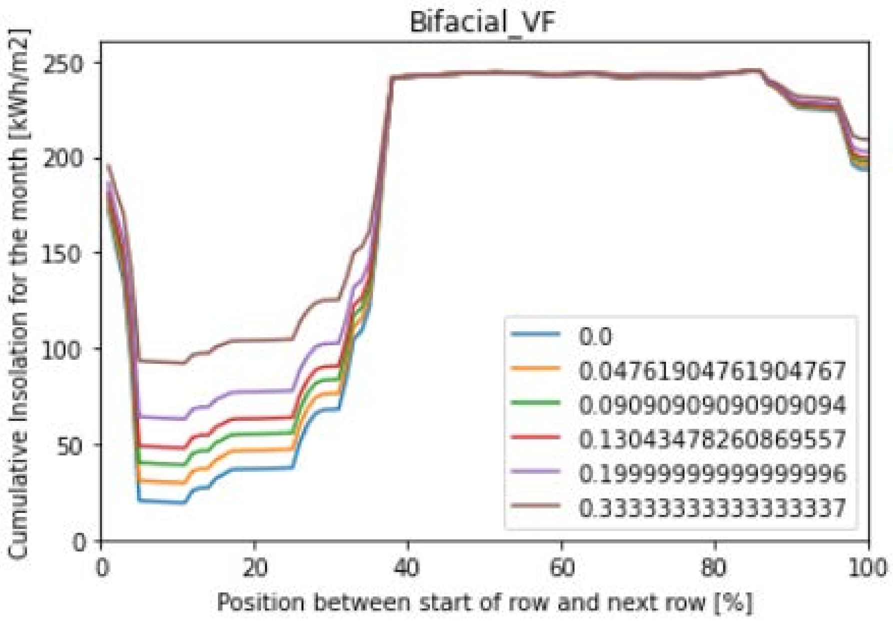


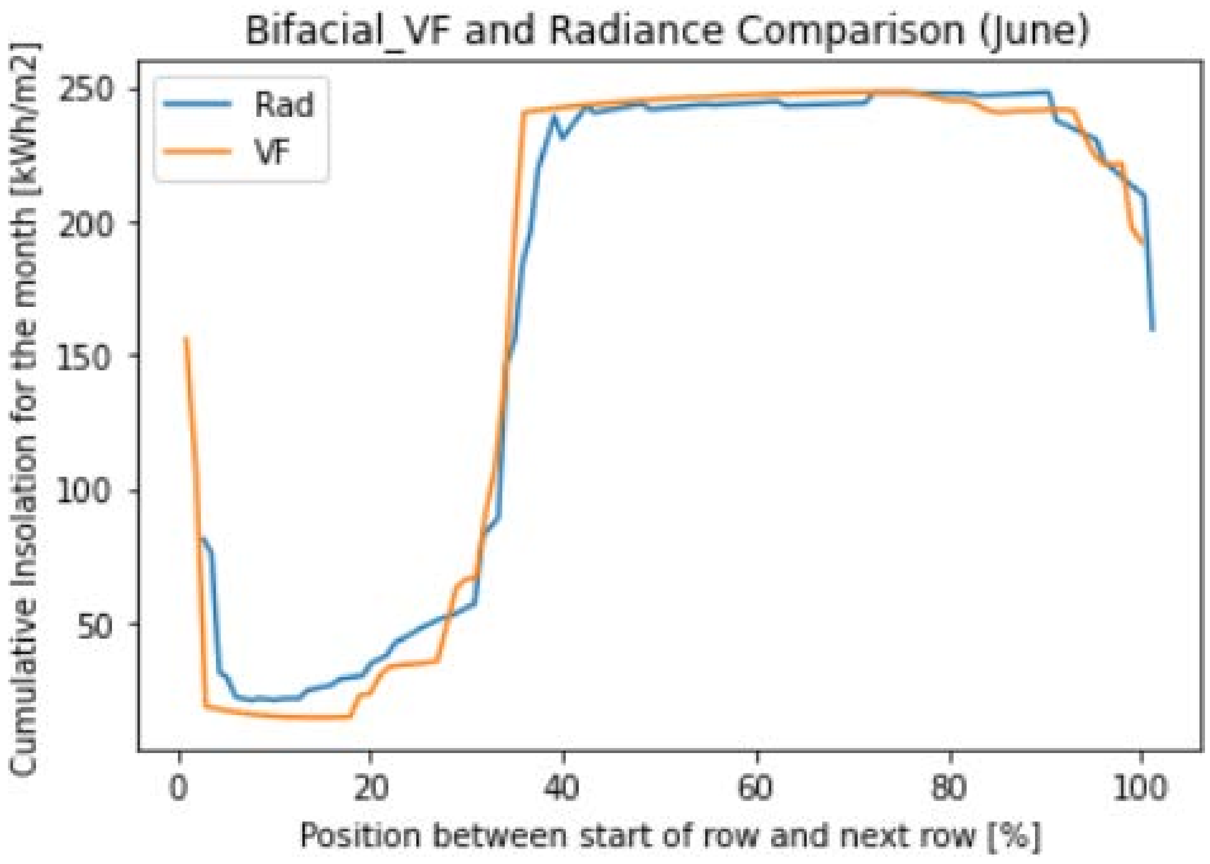


There might be a bit of alignment issue of the data here to investigate also

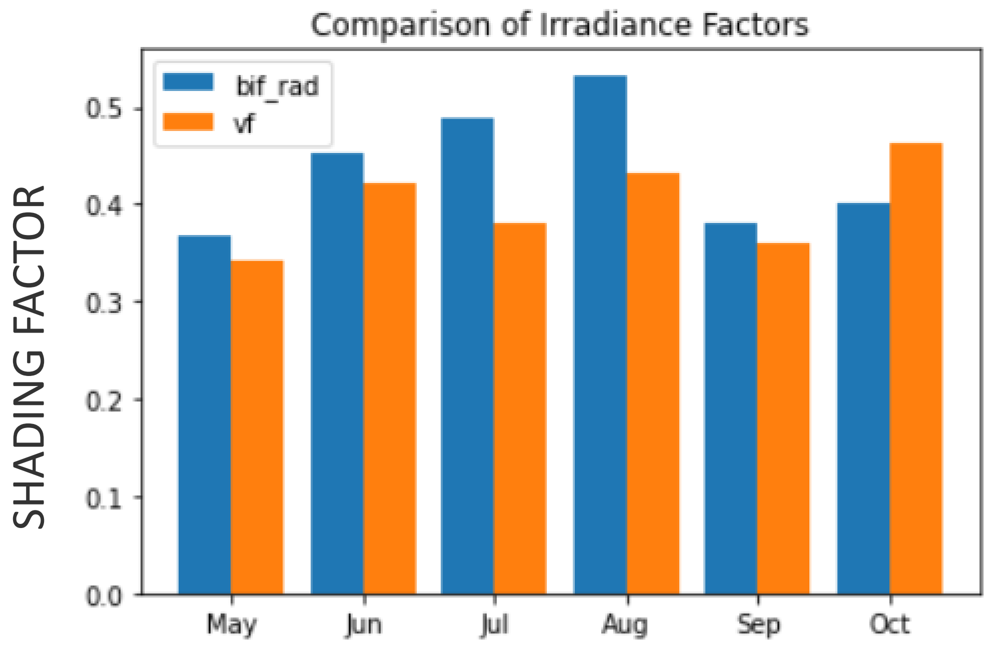
Also, compare if the FWHM of the 'lobe' matches the average ground irradiance projected by the VF

Next: Model the same simulation on bifacial_radiance with racking; the spacings between modules are usually blocked to some extent by the racking.

Monthly GROUND Irradiance Factor Evaluation

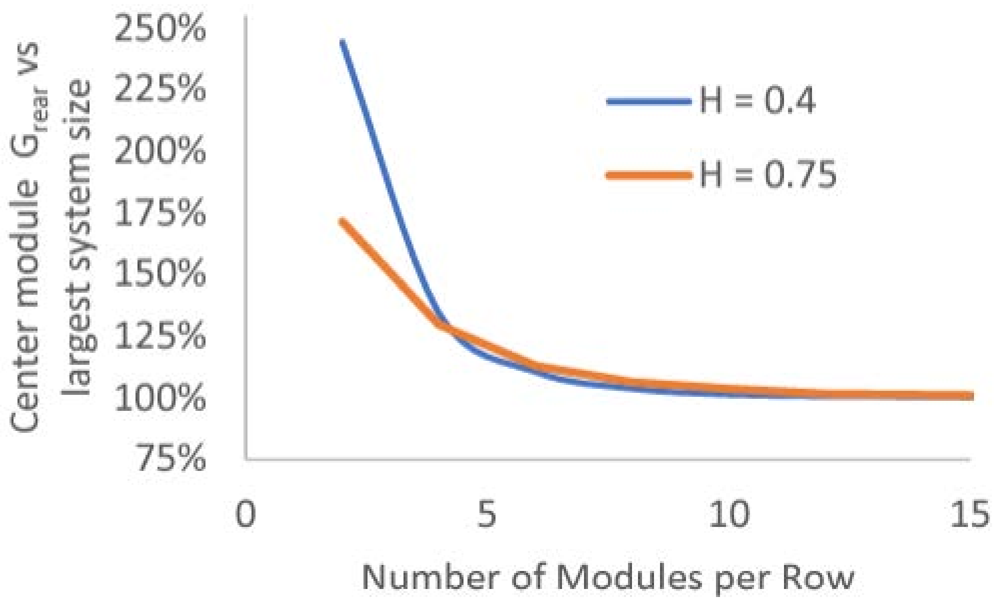


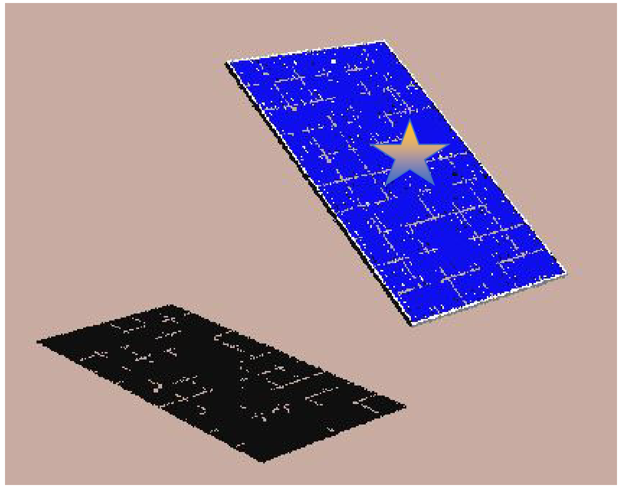
$$\text{Shading Factor} = 1 - \frac{Gground_{MIN}}{GHI}$$

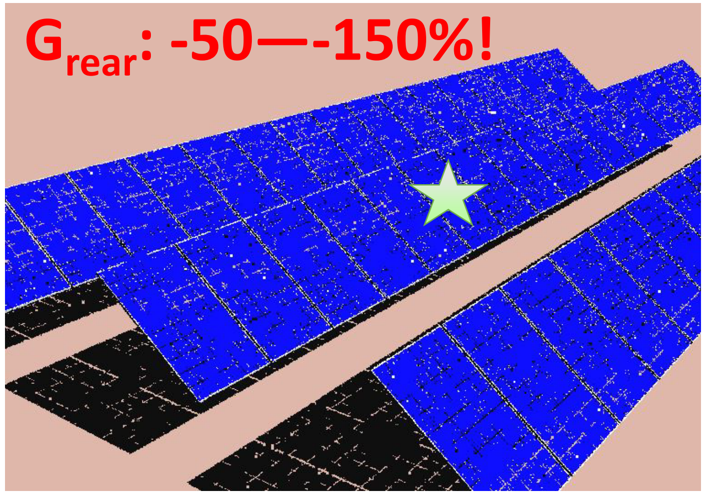


System Size for representative Self-shading

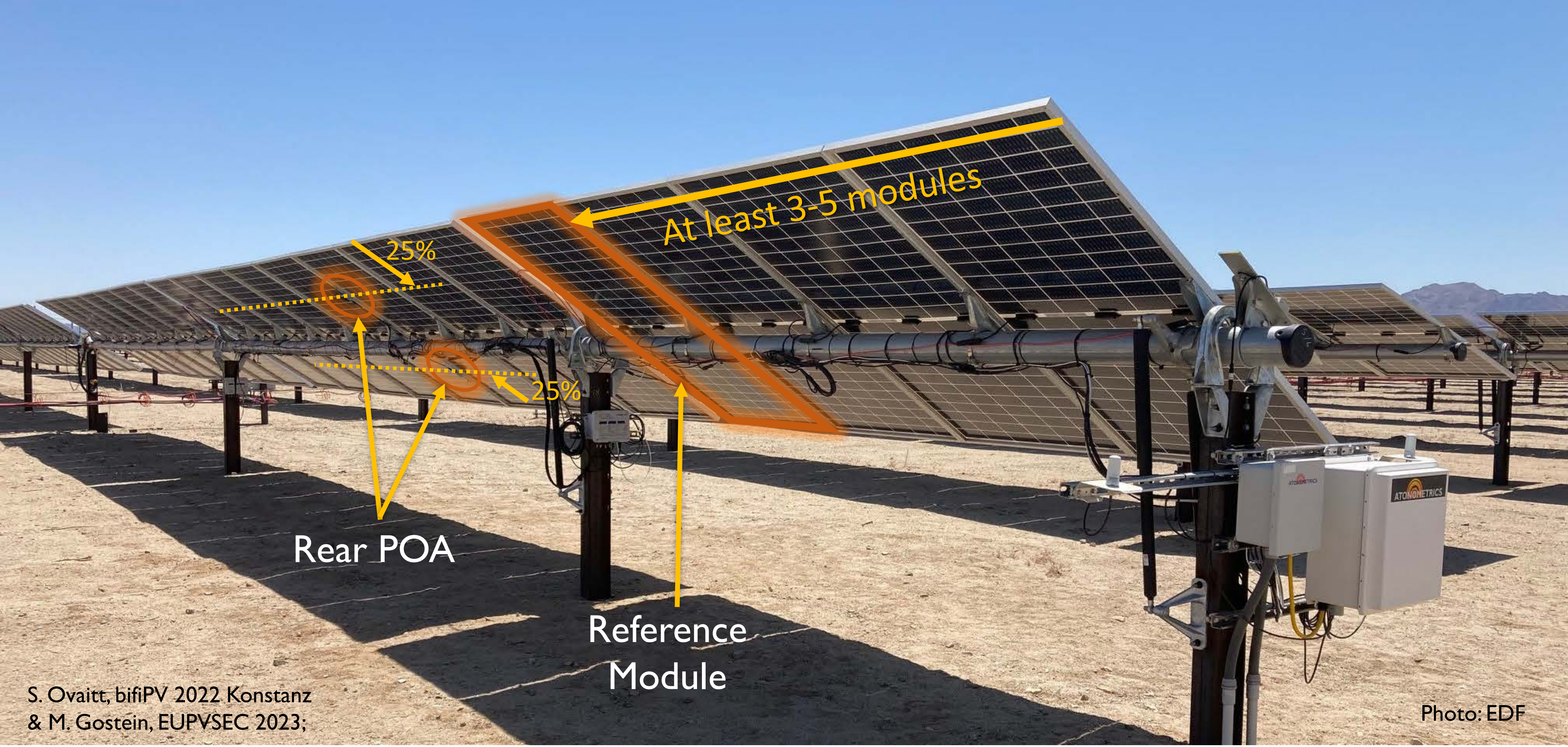
"Steady-state Rear Irradiance"







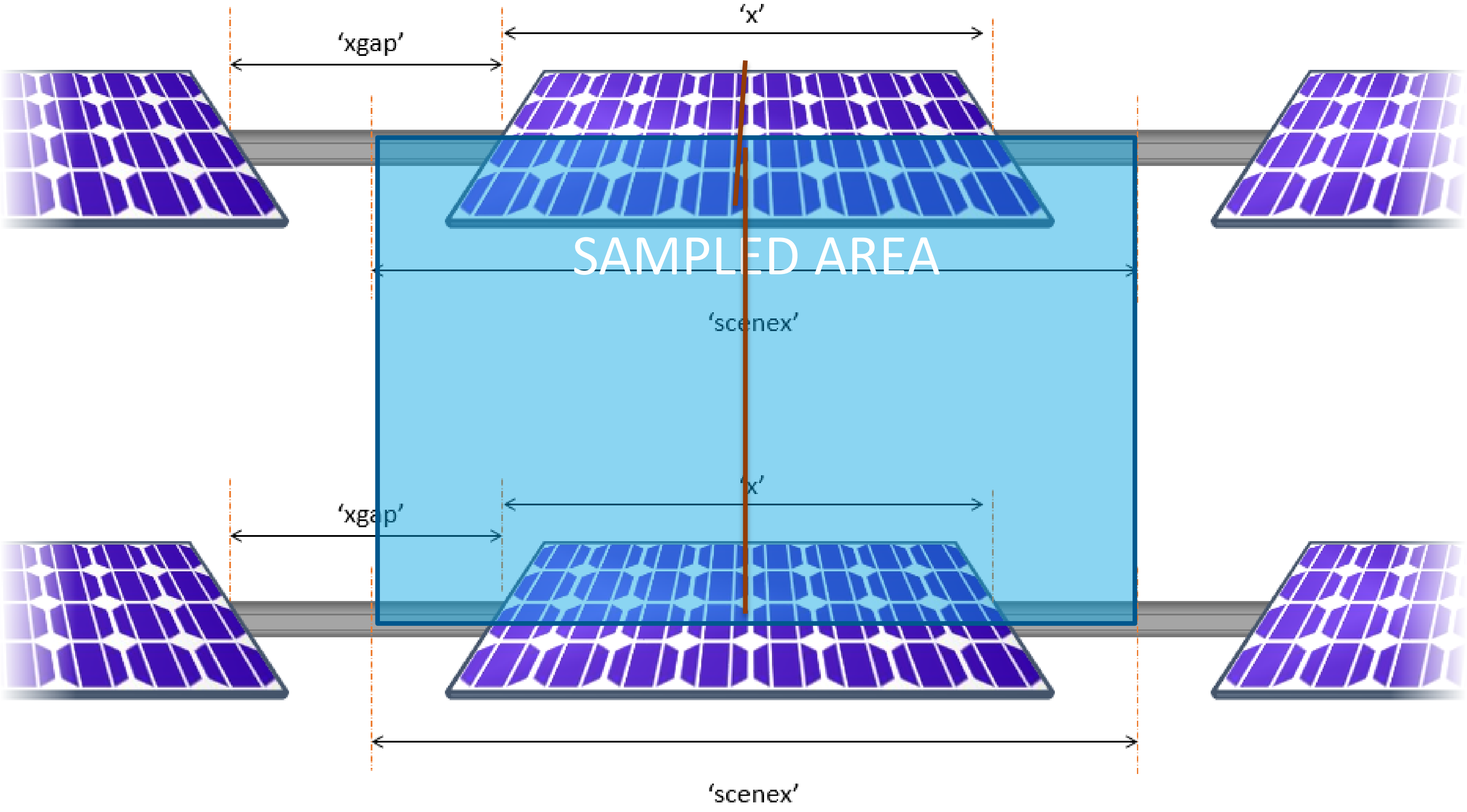
C. Deline et al., Assessment of Bifacial Photovoltaic Module Power Rating Methodologies – Inside and Out, J. Photovoltaics **7,** 2017
Ovaitt et al, Model and Validation of Single-Axis Tracking with Bifacial PV, JPV 2019. 10.1109/JPHOTOV.2019.2892872



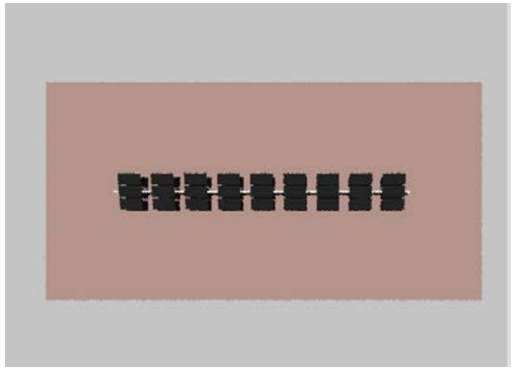
Positioning of sensors for rear-irradiance

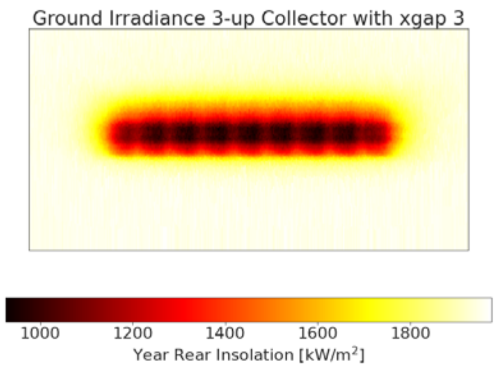
Irradiance modeling details - Metrics

Ground Irradiance "Repeatable Unit"



Smaller sites with edge effects, model all area

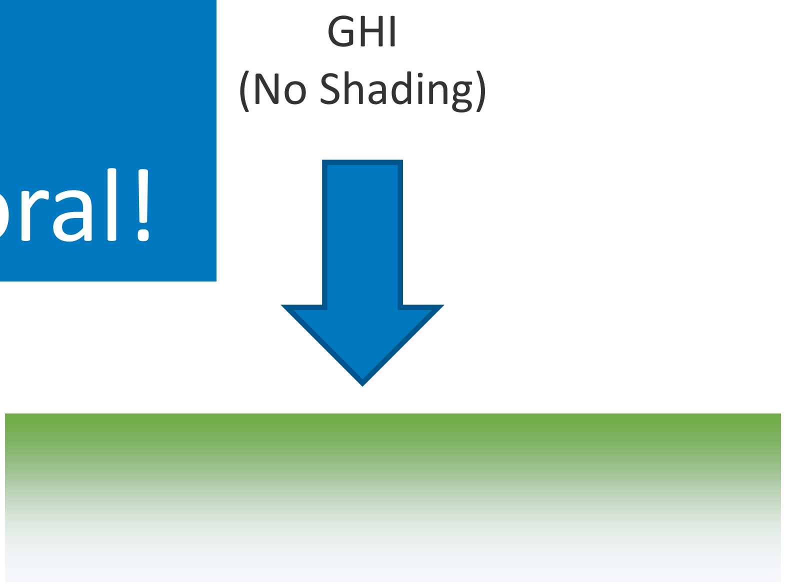


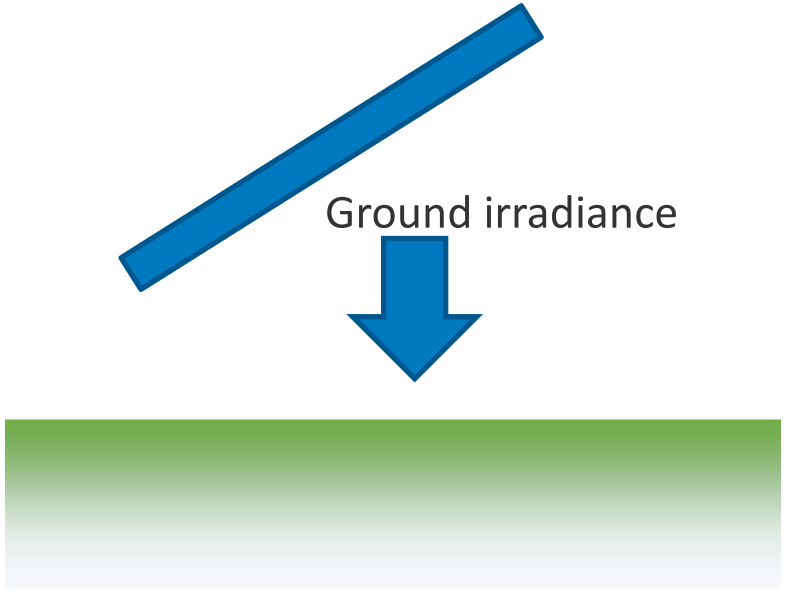


Crop beds sizes/location

(image not accurate as trackers will both be pointing the same way., except for cleaning algorithms, or for “A” frames or “waves”

Metrics: Spatial & temporal!





Irradiance Factor = Ground Irradiance / GHI ⟷ **Shading Factor**

"Min Irradiance Levels on Ground" [%] = $\frac{\text{min(Ground irradiance)}}{\text{GHI}}$ ⟷ "Min Shading Levels on Ground" = (1 - $\frac{\text{min(Ground irradiance)}}{\text{Unshaded}}$

"Average Irradiance Levels on Ground" [%] = $\frac{\text{mean(Ground irradiance)}}{\text{GHI}}$ ⟷ "Average Shading Levels on Ground" = (1 - $\frac{\text{min(Ground irradiance)}}{\text{Unshaded}}$

OTHERS

$$\text{nonuniformity} = \frac{Max - Min}{Max} x100\ [\%]$$

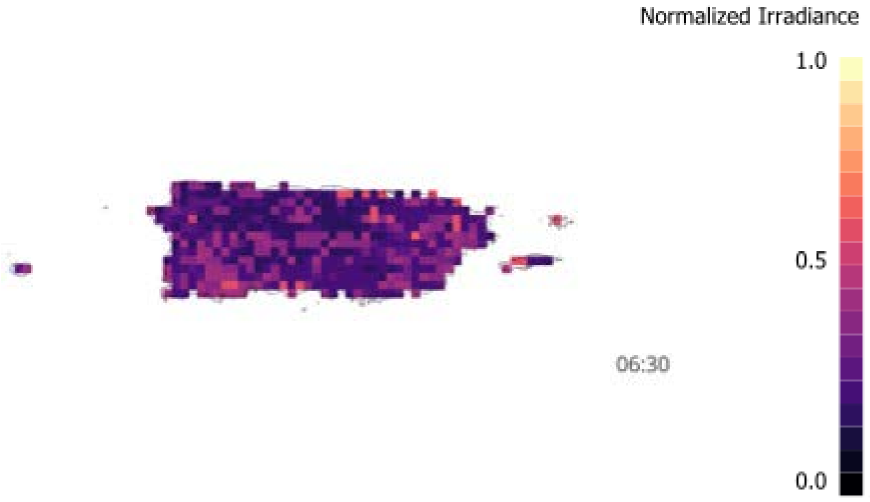
$$\text{Bifacial Gain in Irradiance} = \frac{\sum Grear}{\sum Gfront} x100\ [\%]$$

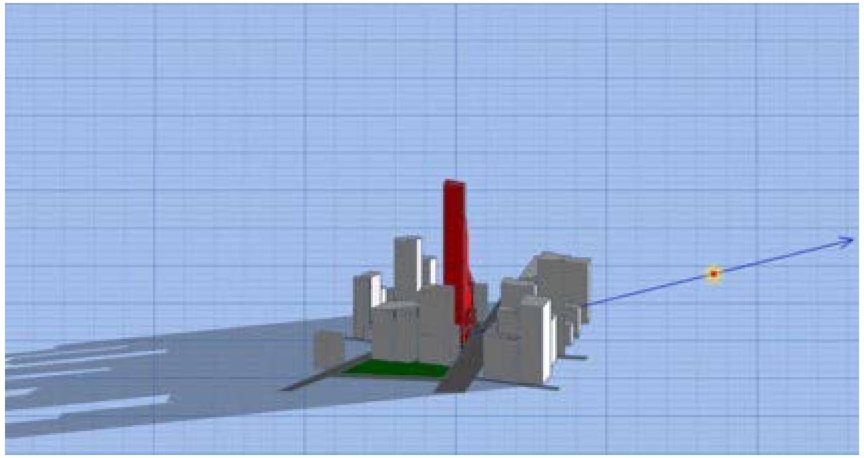
Test-bed Irradiance

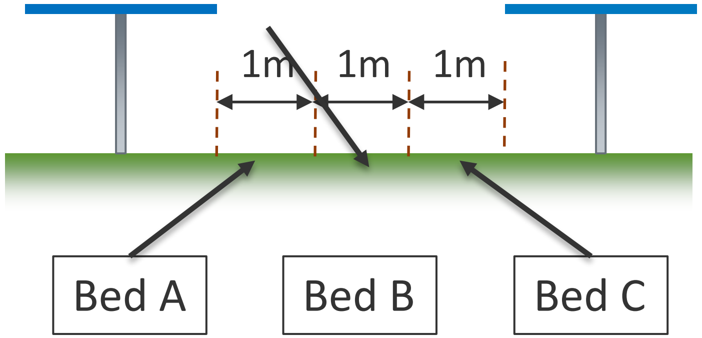
Bed A Normalized Irradiance

Bed B Normalized Irradiance

Bed C Normalized Irradiance







Irradiance transformations

Understanding Irradiance and Photosynthesis

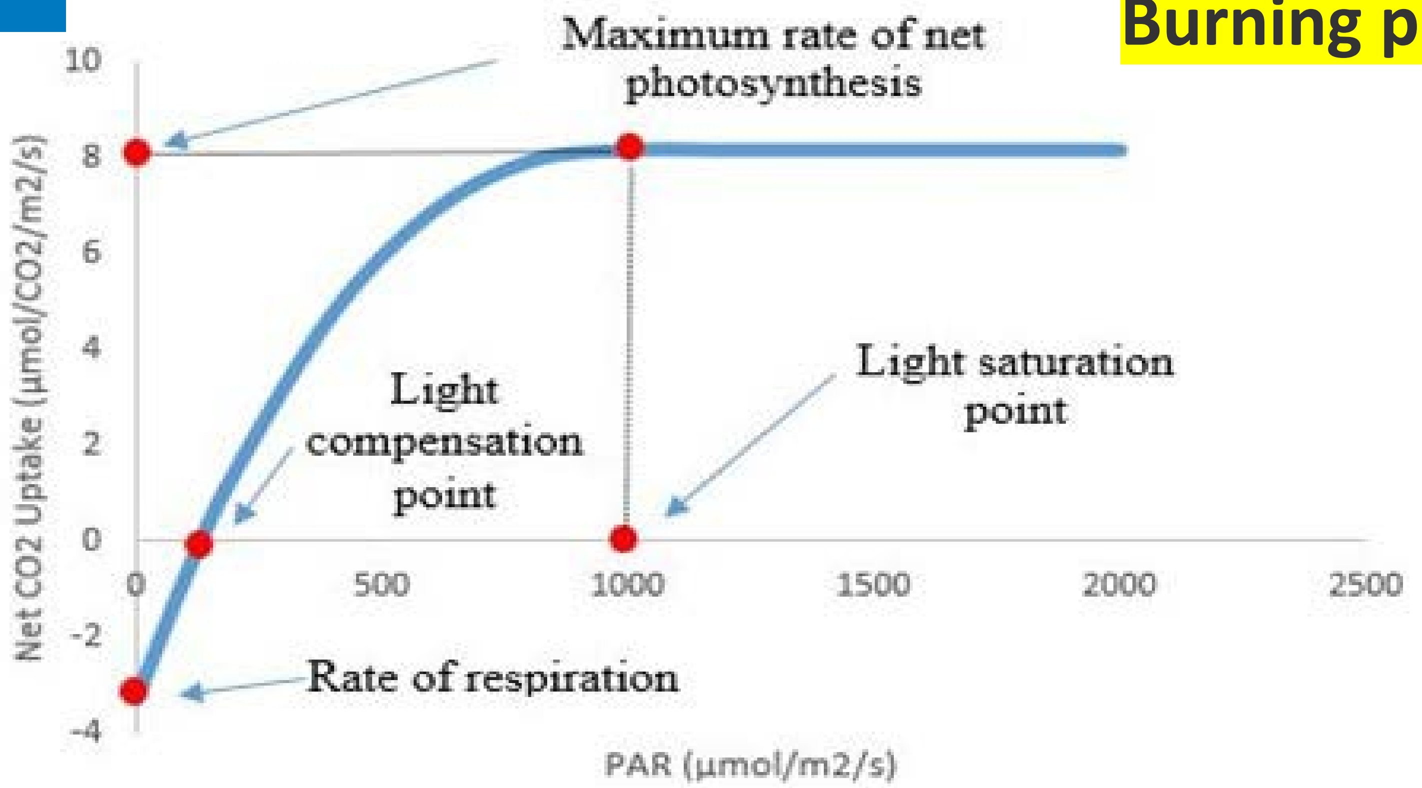
Key Terms

- **Photosynthetically Active Radiation (PAR)** – wavelength region of radiation involved in photosynthesis
  - 400-700 nm
  - Units MJ/m2·d for light intensity,
  - Some give it units of µmol (of photons) m-2 s-1, but this is PPFD
- **Photosynthetic Photon Flux Density (PPFD)** - the amount of photosynthetically active photons hitting a surface per unit area per unit time.
  - Units are µmol (of photons) m-2 s-1.
- **Photosynthetic rate** - Units: µmol(CO2) m–2 s–1
  - Light Saturation Point (LSP): This point where the light intensity does not increase the photosynthesis rate.
  - Light Compensation Point (LCP): The point where release of carbon dioxide through respiration by the plant is be less than the total carbon dioxide used by the plant for photosynthesis. Otherwise the net photosynthesis will be null or negative.

PAR for some Crops

Burning point?

Note: Many Papers use PPFD and PAR interchangeably. Many graphs have PAR on the x-axis using the units of PPFD.



https://www.pthorticulture.com/en/training-center/influence-of-light-on-crop-growth/#:~:text=More%20light%20generally%20equates%20to,called%20the%20light%20saturation%20point.

TABLE 3
CROPS CLASSIFICATION

Category		LSP µmol·m^{-2}·s^{-1}	PAR MJ/m^{2}·d	LCP µmol·m^{-2}·s^{-1}	PAR MJ/m^{2}·d
I	I —A	<400	<3.13	<22	<0.17
	I —B			>22	>0.17
II	II —A	400~700	3.13~5.48	<22	<0.17
	II —B			>22	>0.17
III	III —A	>700	>5.48	<22	<0.17
	III —B			>22	>0.17

Wang 2017, "Analysis of Light Environment Under Solar Panels and Crop Layout" 10.1109/PVSC.2017.8521475

Irradiance to PAR:

- Spectral calculation, modeling or mesaurement
- Percentage
- Some other more complicated models

Global IRR → PAR → PPFD → PR

General Light Intensity | Photosynthetic Light Intensity | Photosynthetic Photon Intensity | Photosynthetic Rate

Back-Envelope Calculation: PAR is approximately 43% of Full Spectrum. To PPFD it's just units conversions

$$GI * 0.43(3600J/1Wh) * 10^{-6} * (127.79umol/m^2\text{-sec} / 1MJ/m\text{-day})$$

Tucson Typical Meteorological Year for Solstice Day 6/21

	B	C	D	E	F	G
1	TUCSON INTERNATIONAL	AZ	-7	32.133		
2	Time (HH:MM)	ETR (W	ETRN (W/m	GHI (W/m^2)	Energy on the Ground (Wh/m2	
3	1:00	0	0	0	0	
4	2:00	0	0	0	0	
5	3:00	0	0	0	0	
6	4:00	0	0	0	0	
7	5:00	0	0	0	0	
8	6:00	55	893	8	8	
9	7:00	301	1322	162	162	
10	8:00	565	1322	382	382	
11	9:00	809	1322	599	599	
12	10:00	1018	1322	772	772	
13	11:00	1177	1322	913	913	
14	12:00	1274	1322	1004	1004	
15	13:00	1304	1322	1037	1037	
16	14:00	1264	1322	1002	1002	
17	15:00	1157	1322	918	918	
18	16:00	991	1322	741	741	
19	17:00	776	1322	328	328	
20	18:00	527	1322	197	197	
21	19:00	262	1322	112	112	
22	20:00	34	694	1	1	
23	21:00	0	0	0	0	
24	22:00	0	0	0	0	
25	23:00	0	0	0	0	
26				SUM:	8176	Wh/m2
27						
28			CONVERSION	1 Wh	3600	J
30			PAR	Full Spectrum	29.4336	MJ/m2-day
31			PAR	400-700NM, 43%	12.656448	MJ/m2-day
32			PAR	With 30% Shading from t	8.8595136	MJ/m2-day
33			CONVERSION	1 MJ/m-day	127.79	umol / m2 - sec, PPFD
34				With 30% Shading from t	1132.157243	umol / m2 - sec, PPFD

Metrics

WHAT IS Daily Average Sunlight Formula ?

Area calculation for evaluations: ?

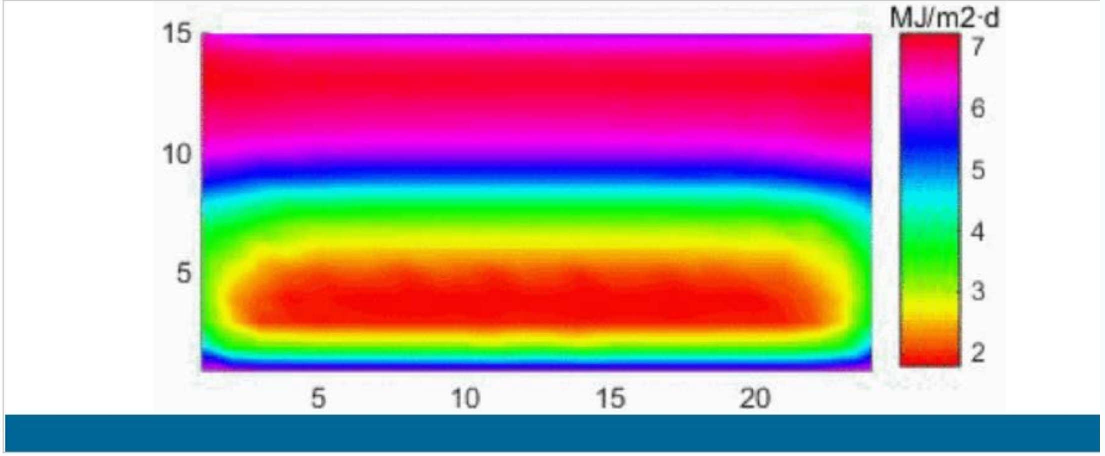


Fig. 4.
Daily average PAR distribution at the height of 0.2 m

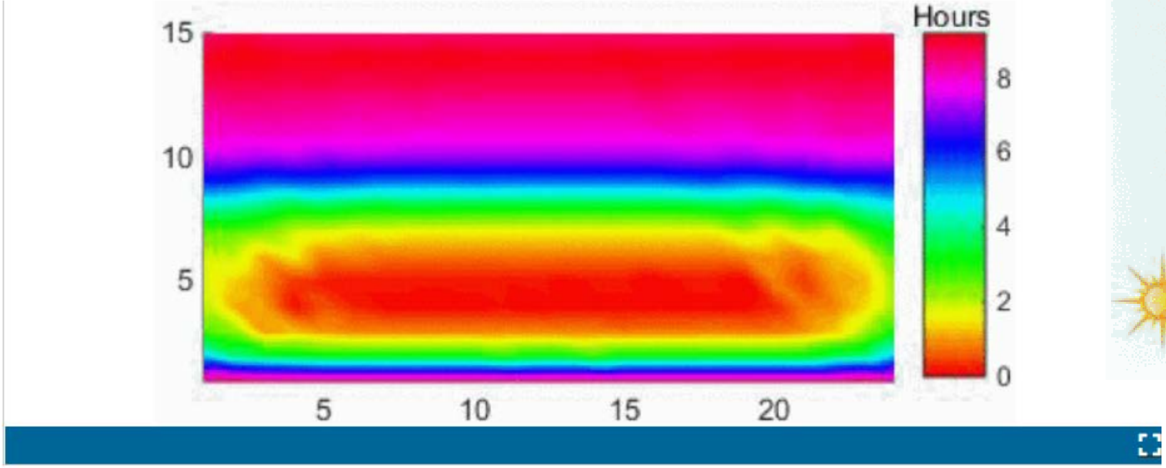
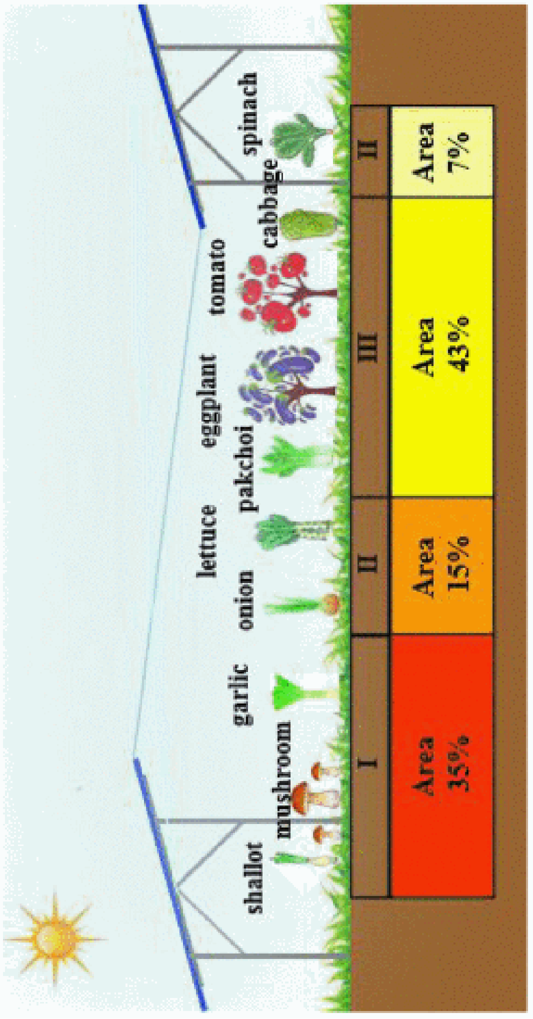
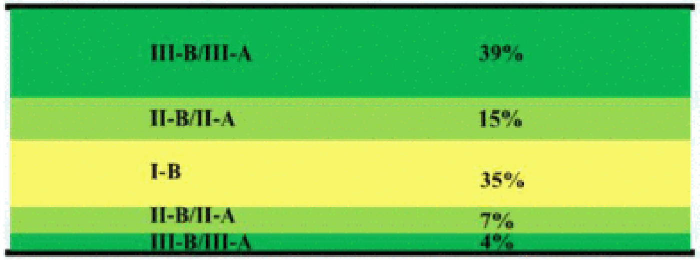


Fig. 5.
Daily average sunlight hours distribution at the height of 0.2 m



b. Based on sunshine hours



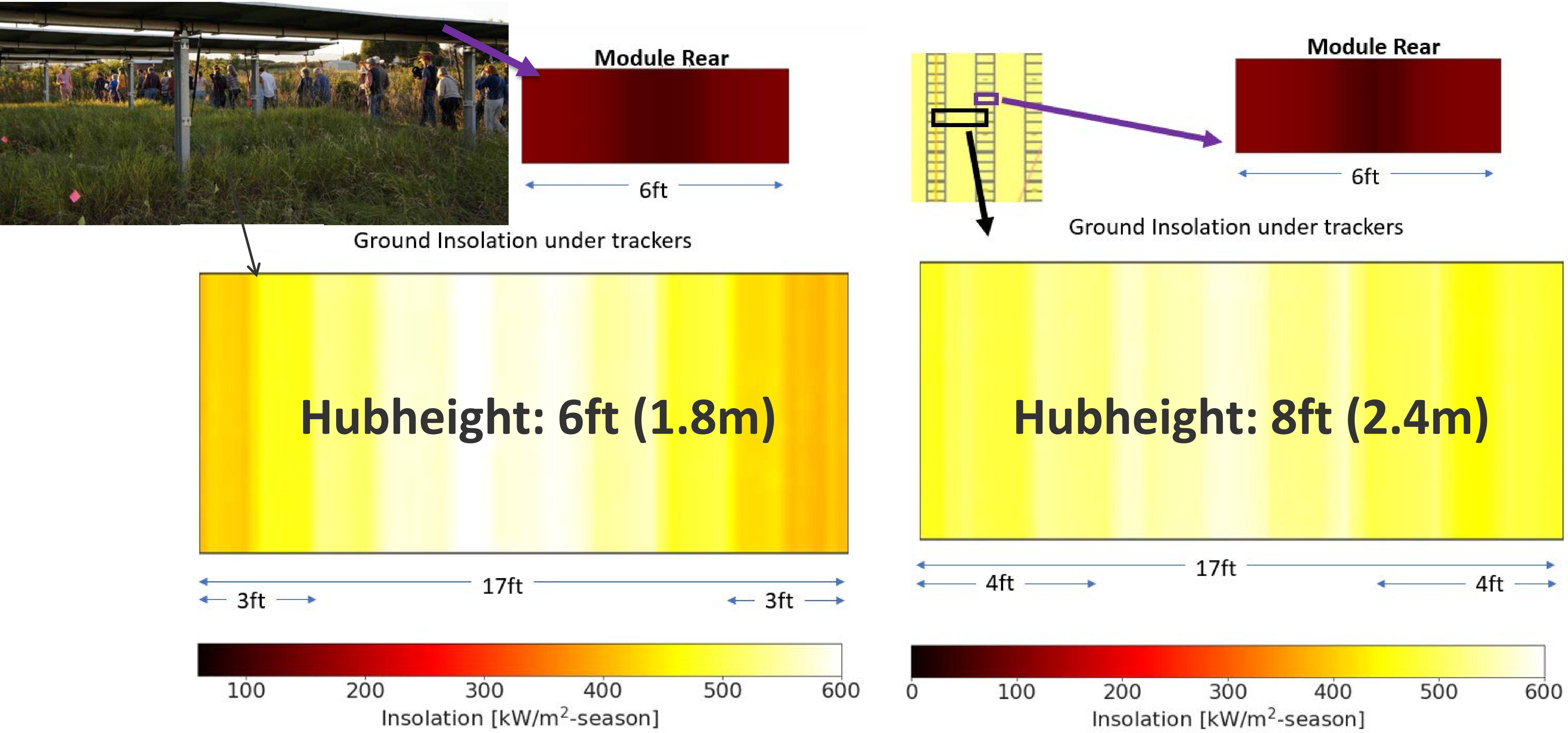
c. Based on double indexes

Contrast height	0 m	0.5 m	1m
Fullsunlight PAR(MJ/m²·d)	7.84	7.84	7.84
Average PAR (MJ/m²·d)	4.73	4.75	4.83
Maximum PAR(MJ/m²·d)	7.05	7.33	7.52
Minimum PAR (MJ/m²·d)	1.91	1.48	1.10
High PAR area ratio (>5.5 MJ/m²·d)	40.0%	44.3%	47.%
Low PAR area ratio (<3.0 MJ/m²·d)	31.4%	36.4%	37.1%

Wang (2017) **Analysis of Light Environment Under Solar Panels and Crop Layout, 44th I EEE PVSC** **DOI:** 10.1109/PVSC.2017.8521475

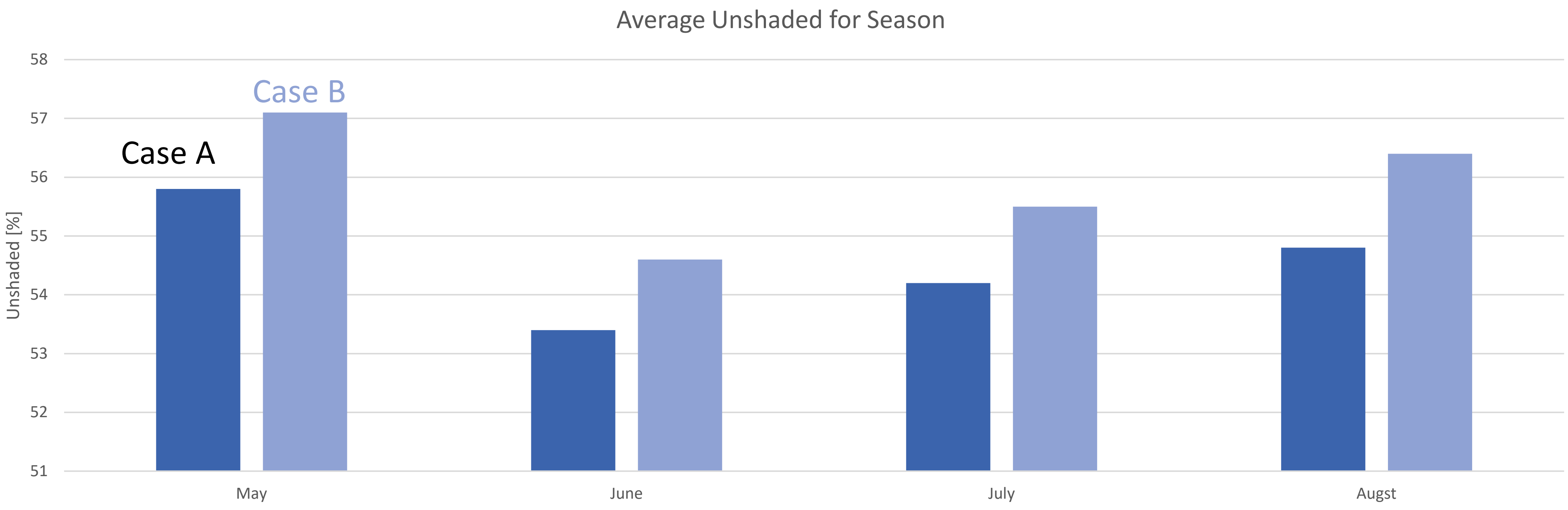
Selected AgriPV Modeling examples

Jack Solar's



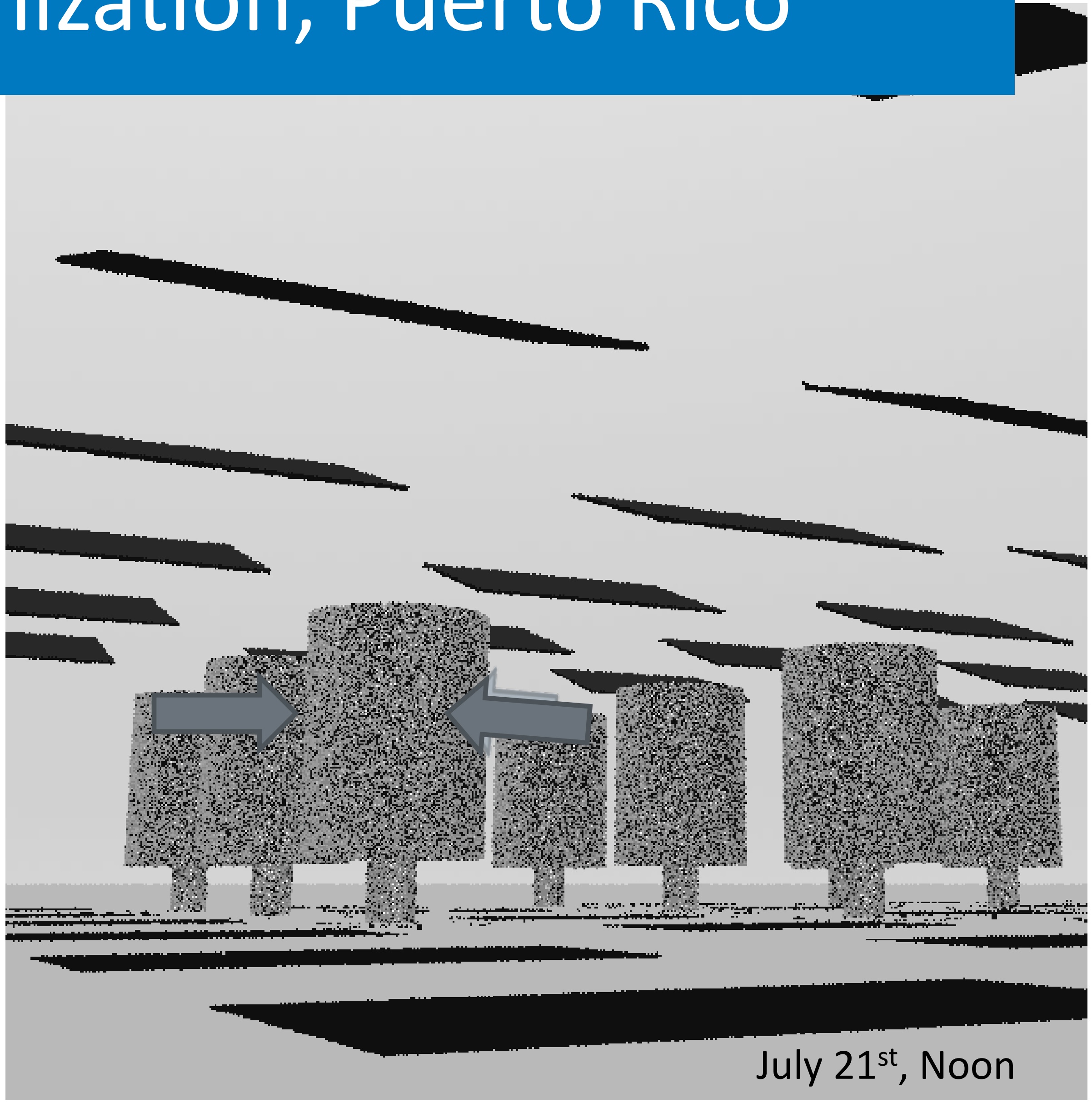
Module Rear
6ft
Ground Insolation under trackers
Hubheight: 6ft (1.8m)
17ft
3ft
3ft
100
200
300
400
500
600
Insolation [kW/m2-season]
Module Rear
6ft
Ground Insolation under trackers
Hubheight: 8ft (2.4m)
17ft
4ft
4ft
0
100
200
300
400
500
600
Insolation [kW/m2-season]

Unshaded %: Average Insolation / GHI by Month

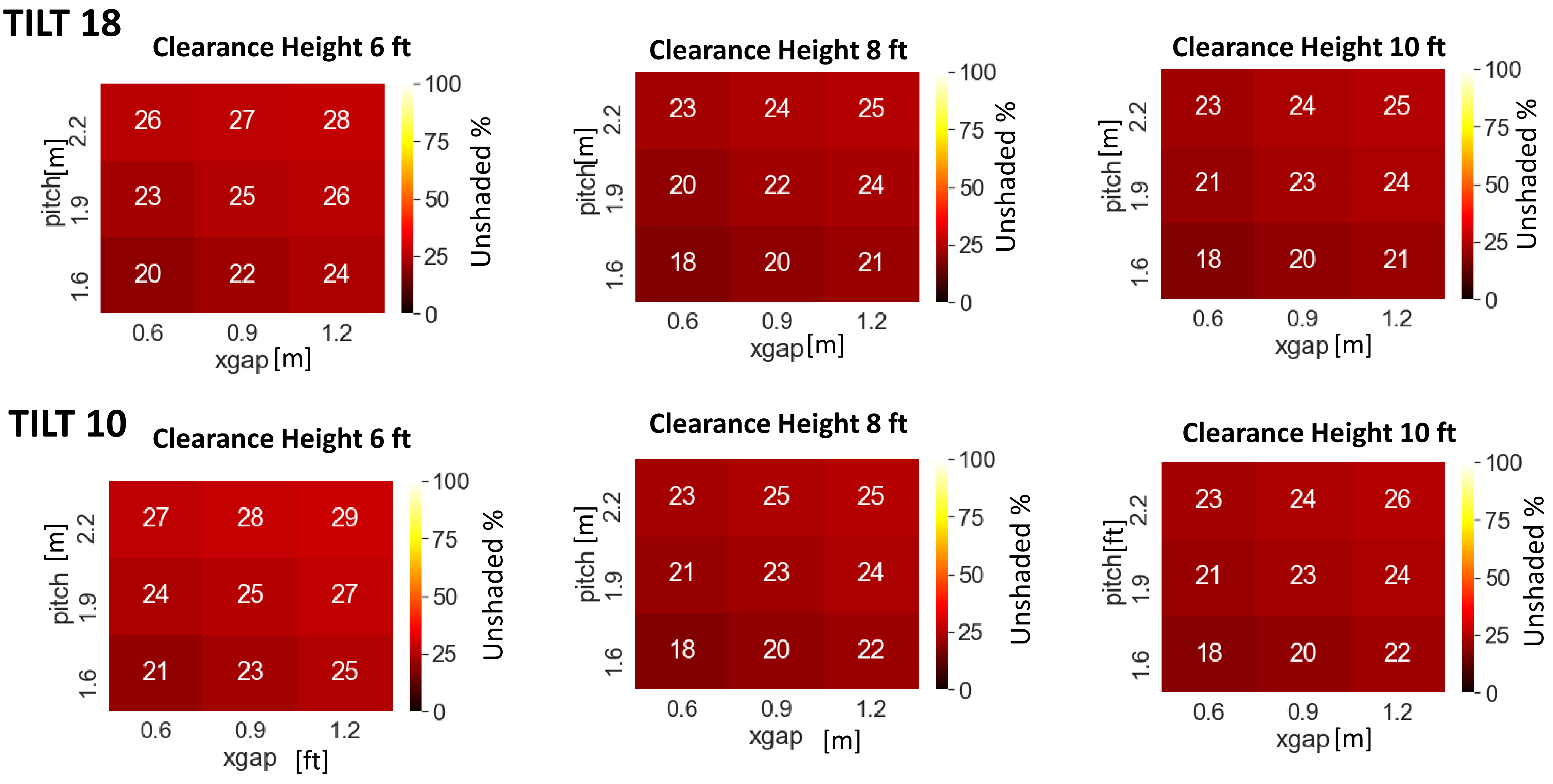


$$\text{Unshaded}\% = \frac{\bar{G}_{ground}}{GHI} x100\ [\%]$$

Coffee-Tree Site Optimization, Puerto Rico

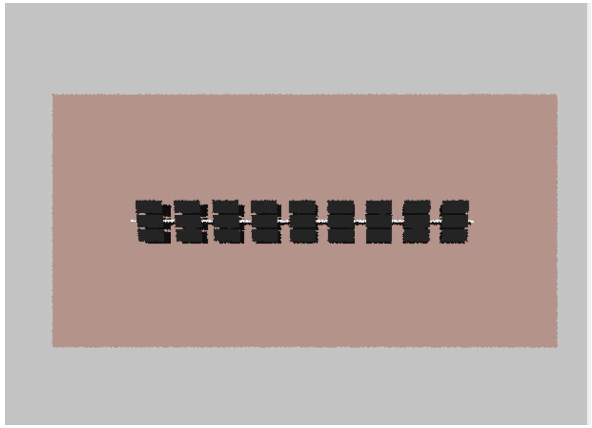


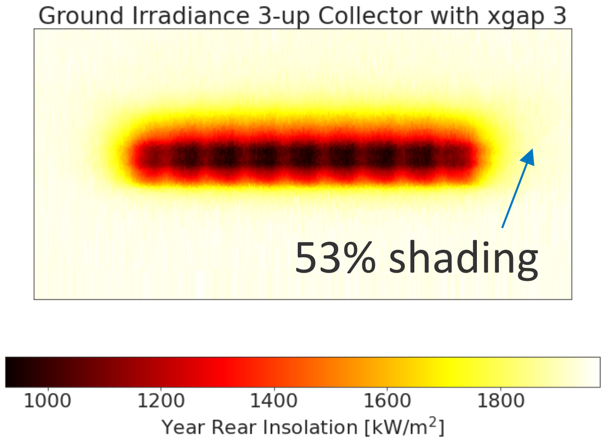
$$\text{Unshaded\%} = \frac{G coffee\ tree\ Average\ (N,S,E,W)}{GHI} x100\ [\%]$$

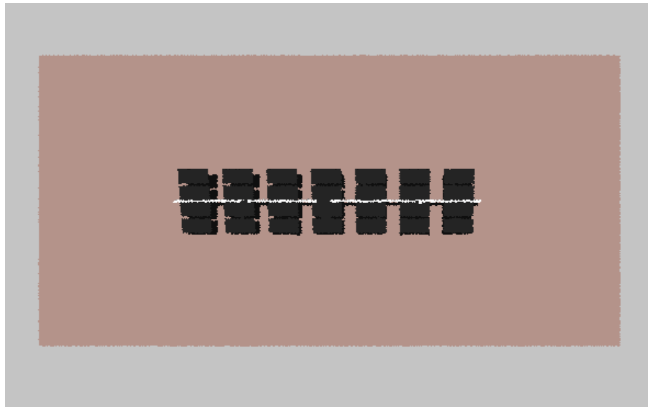


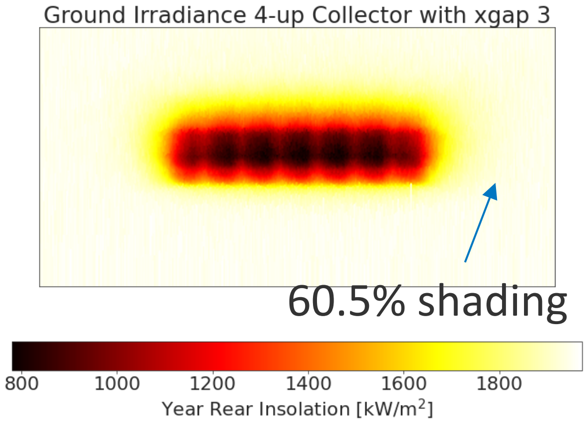
For all options examined, the radius of the tree is too close to the area between modules, so there is too much shading. Suggesting to at least double the pitch, also for easiness to access crops and of safety spacing between branches, leaves, and the electrical components of the PV.

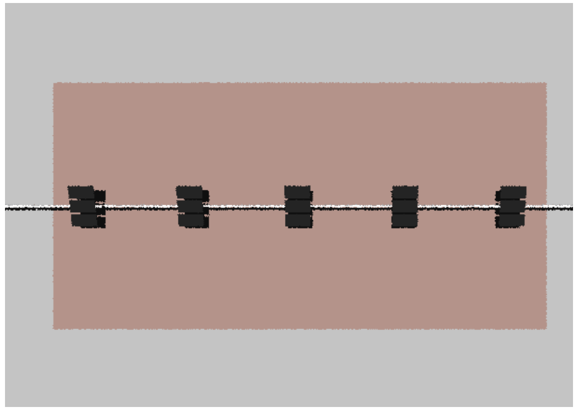
Specific Site Evaluation

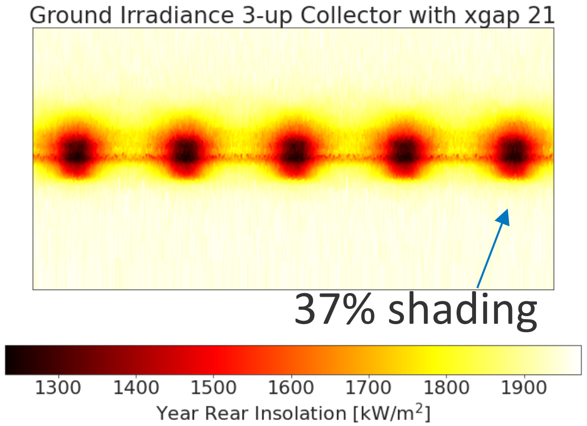


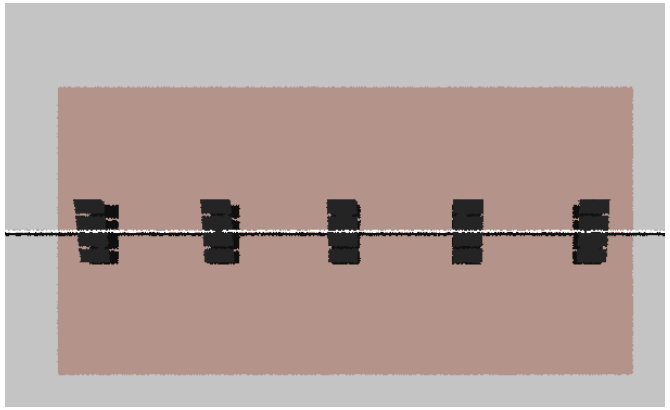


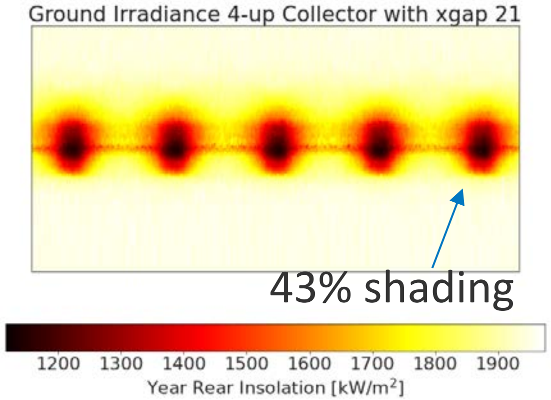








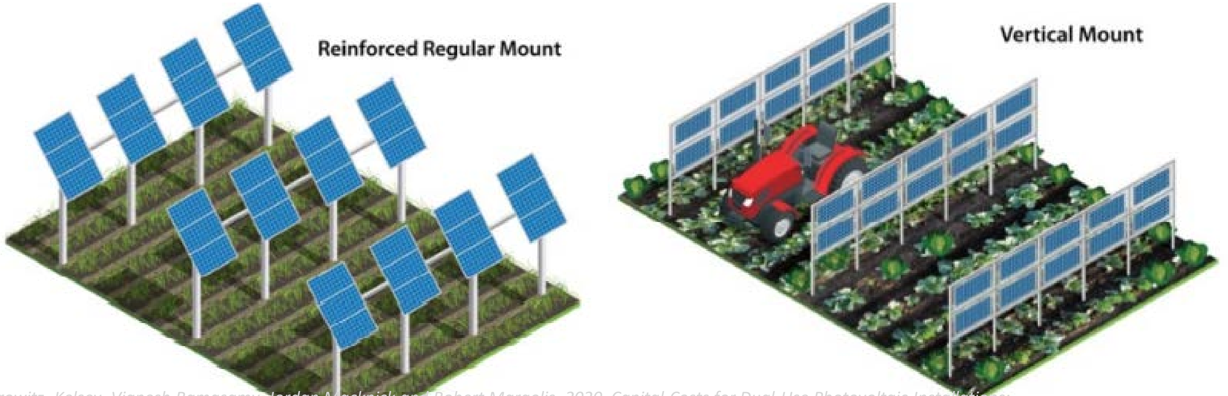




Scenario	System Type	Racking	Panel Tilt	Hub Height (m)	Row Spacing (m)	Panel Spacing (m)
1	Conventional utility-scale	1-axis tracking	-50° to 50°	1.5	5	0
2	Elevated panels	1-axis tracking	-50° to 50°	2.4	5	0
3	Elevated & intra-row spaced panels	1-axis tracking	-50° to 50°	2.4	5	1
4	Utility-scale with 2x edge-to-edge spacing	1-axis tracking	-50° to 50°	1.5	8	0
5	Utility-scale with 3x edge-to-edge spacing	1-axis tracking	-50° to 50°	1.5	11	0
6	Conventional utility-scale	Fixed tilt	Latitude*	1.5	Variable**	0
7	Elevated panels	Fixed tilt	Latitude*	2.4	Variable**	0
8	Elevated & intra-row spaced panels	Fixed tilt	Latitude*	2.4	Variable**	1
9	Utility-scale with 2x edge-to-edge spacing	Fixed tilt	Latitude*	1.5	Variable**	0
10	Vertical bifacial	Fixed vertical	90°	2	8.6	

Summary of Simulated Designs

*For fixed-tilt systems:
Panel Tilt = min(latitude, 40°)
**Row spacing set to prevent interrow shading on winter solstice at 9am



Horowitz, Kelsey, Vignesh Ramasamy, Jordan Macknick and Robert Margolis. 2020. Capital Costs for Dual-Use Photovoltaic Installations: 2020 Benchmark for GroundMounted PV Systems with Pollinator-Friendly Vegetation, Grazing, and Crops. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-77811. https://www.nrel.gov/docs/fy21osti/77811.pdf.

US AgriPV Maps

Pull NSRDB data for 50,000+ locations in the United States

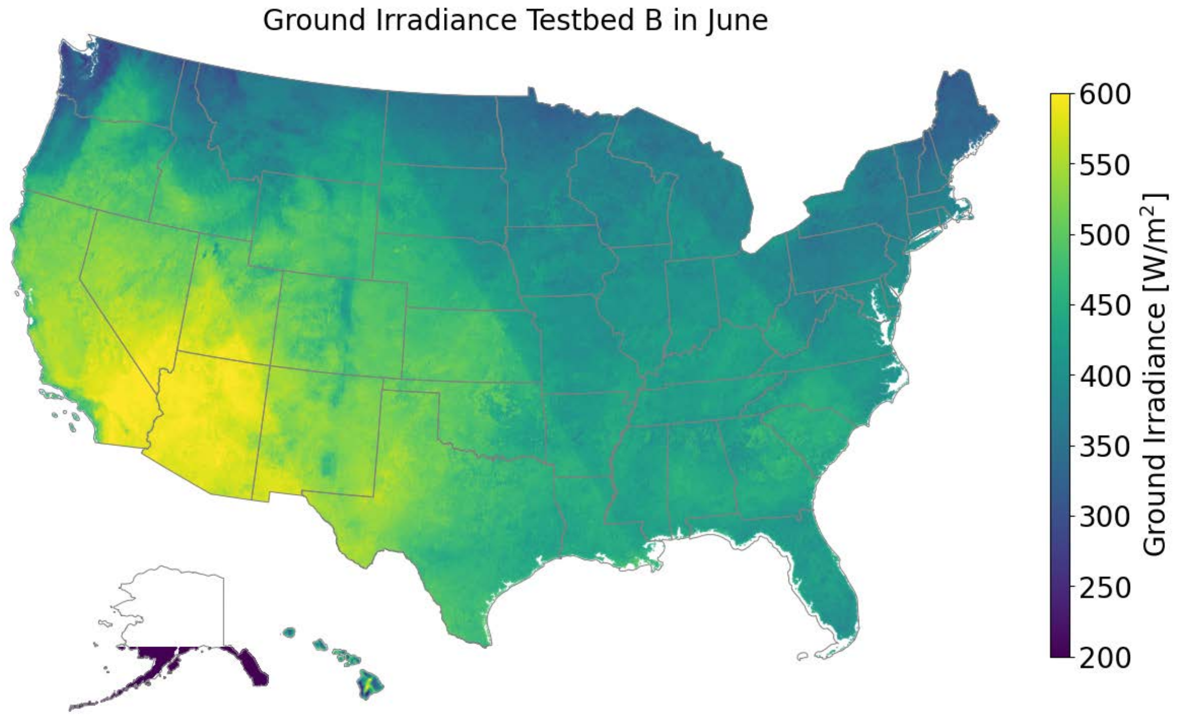
Define solar configurations for analysis with bifacial_radiance & SAM

Run HPC simulations

Compile & process simulation data

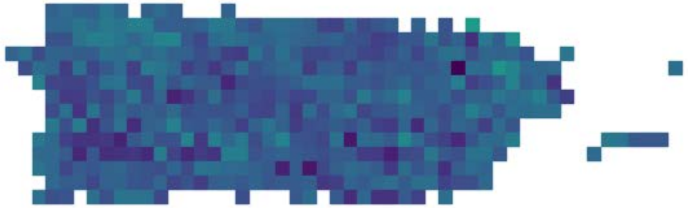
Publish simulation data with maps & analysis

Develop online tool to streamline data access & visualization

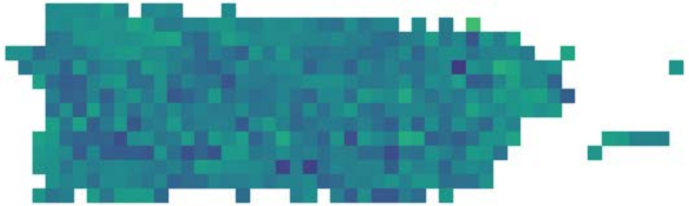


Edge-to-Edge Irradiance Factor June 12th

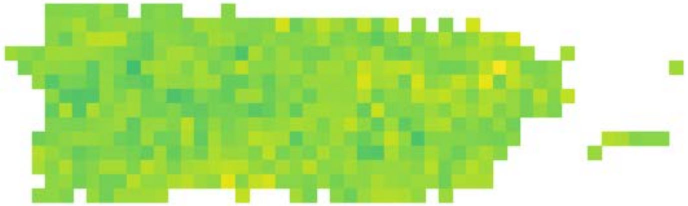
Conventional Design



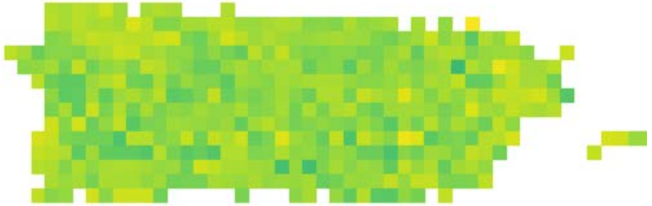
Elevated Panels



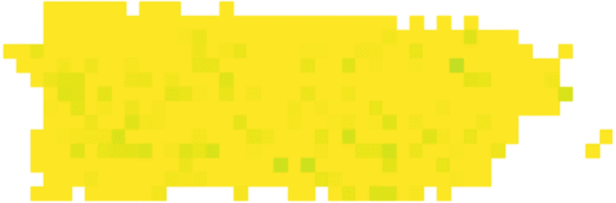
Elevated Panels & 1 m module-gaps

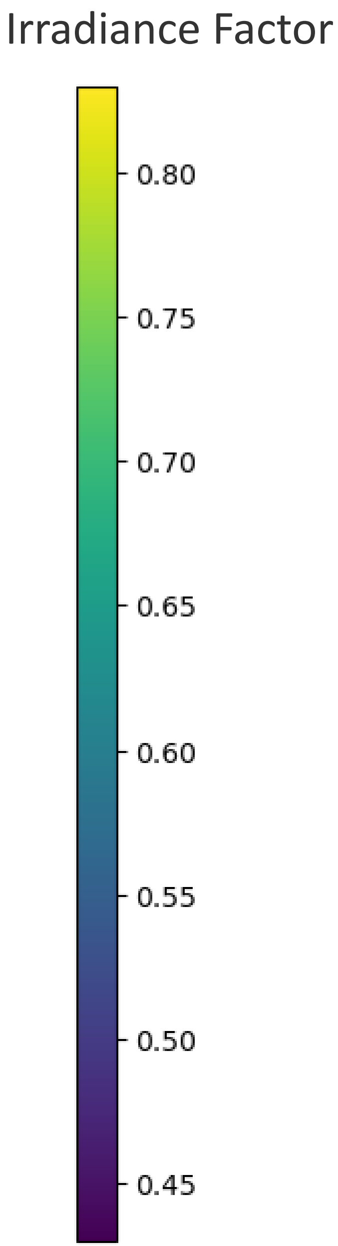


Wider Spacing 0.25 GCR



Wider Spacing 0.18 GCR





GCR: Ground Cover Ratio

Bifacial PV Field & NREL

75 kW bifacial HSAT
5 bifacial technologies

Drone Video

75 kW Bifacial Experimental Single-Axis Tracking Field

- ❑ 5 bifacial technologies, including PERC & SHJ
- ❑ 3 Monofacial counterparts
- ❑ +8 Rear Irradiance Sensors (IMT, K&Z, Licor)
- ❑ Module and Row electrical data
- ❑ 3 Albedometers + 1 rotating albedometer
- ❑ Custom Irradiance Evaluating Module “Hydra”
- ❑ Spectral rear data (some)
- ❑ Weather and more spectral and albedo data <60 m from field from SRRL

Summer 2022, 2023, 2024

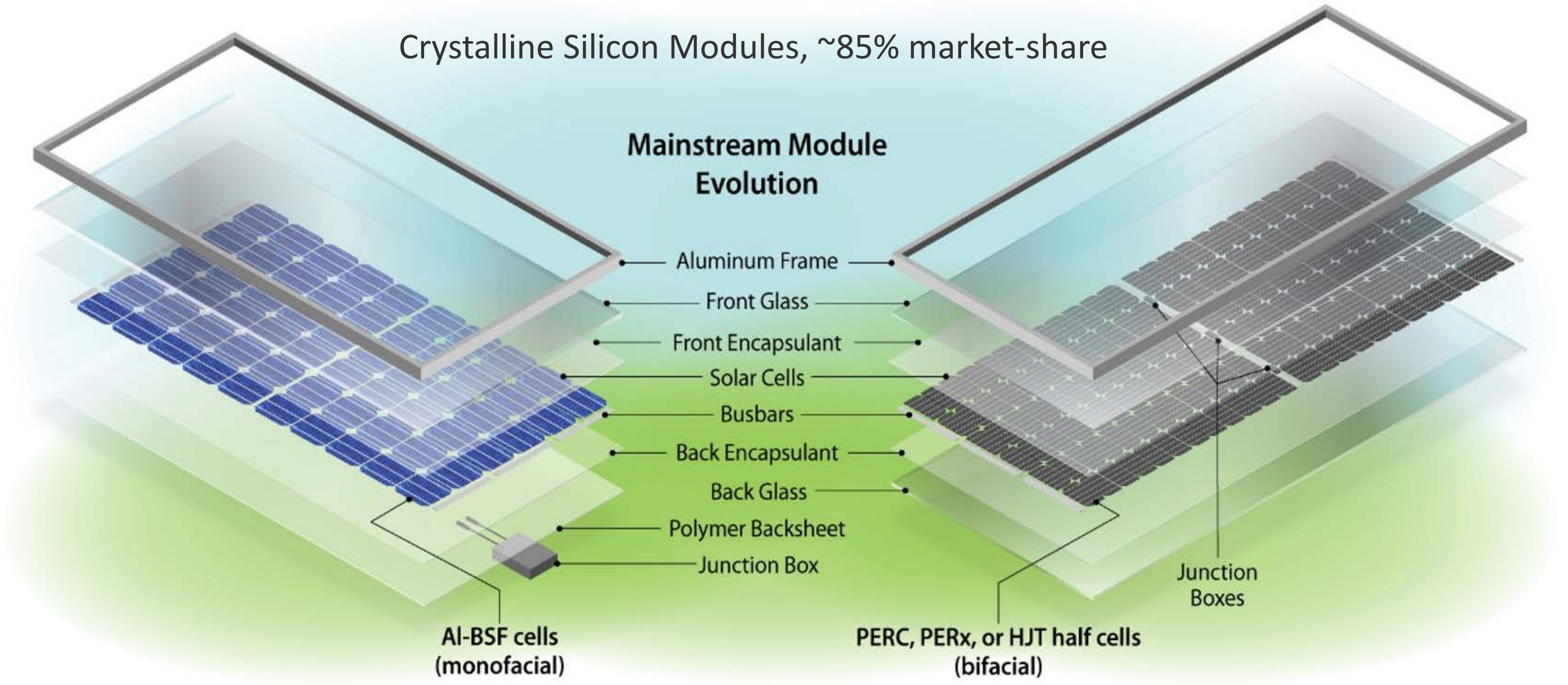
- ❑ AgriPV deployment: Pollinator Habitat, Crops & Pasture Grass
- ❑ Albedo materials testing (2022)

Open Source on

https://datahub.duramat.org/dataset/best-field-data

Modules Continuously Evolve

Crystalline Silicon Modules, ~85% market-share



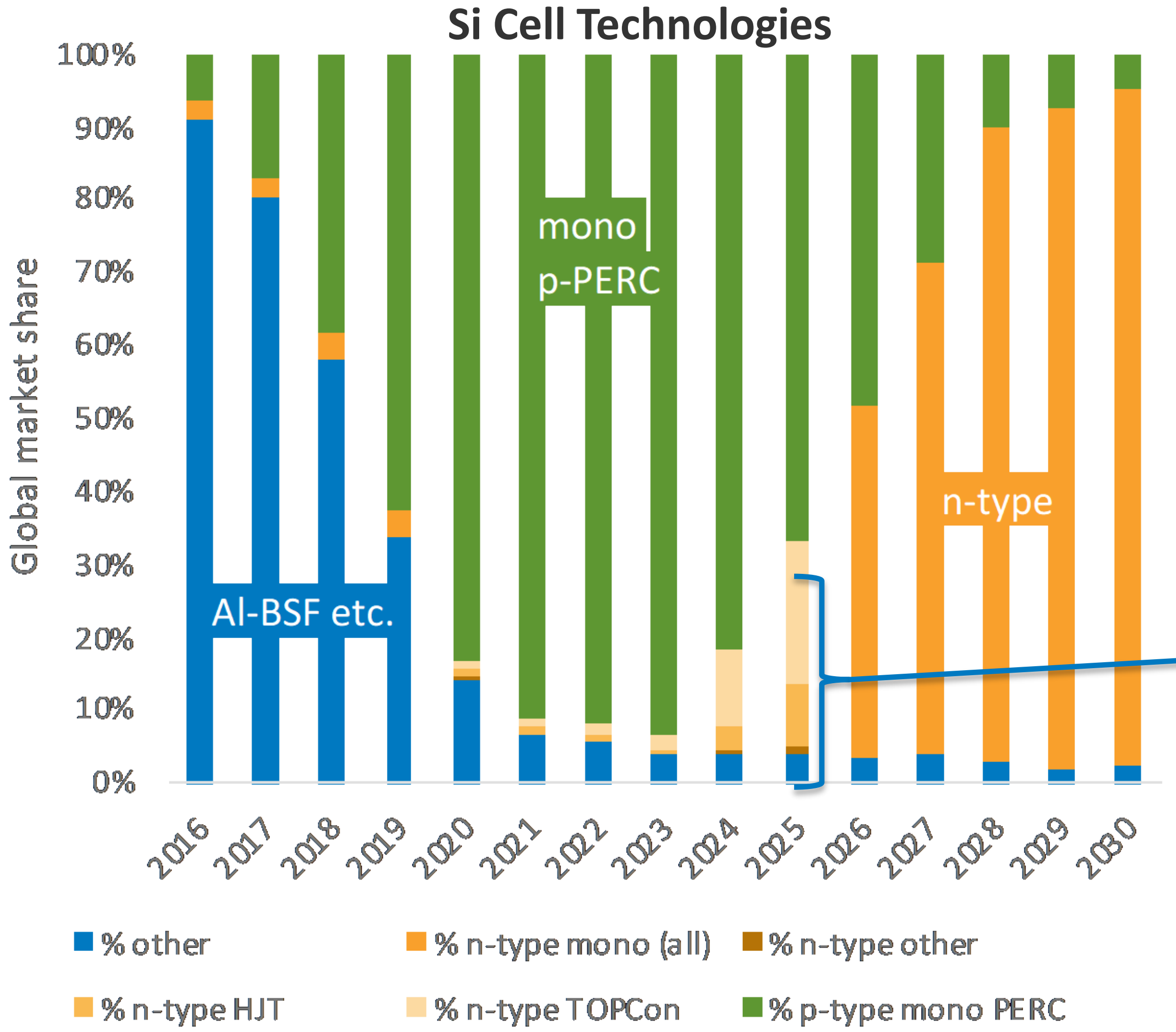
Pre-2015 module, 20-25 year life

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.

New Technology + Explosive Growth

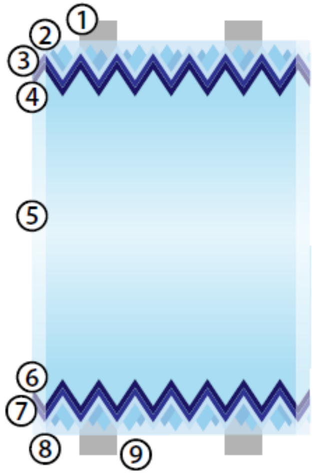
Module bifaciality factor $\phi = \frac{P_{Rear}}{P_{Front}}$



HJT

23-25% cell efficiency

ϕ ~0.85 – 0.95

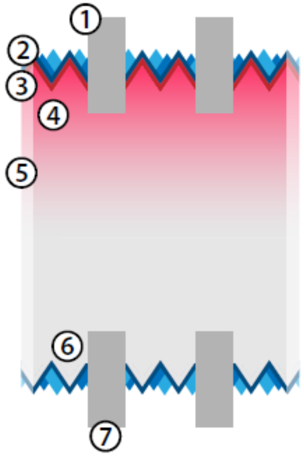


1. Frontside fingers (busbars optional) compromised of low-temperature screen-printed Ag pastes or electroplated Ni/Cu/Sn/Ag
2. TCO by PVD (typically ITO for high optical transmission and low sheet resistance)
3. p^+ doping and full-area emitter formation by PECVD of a-Si:H
4. Intrinsically doped a-Si:H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

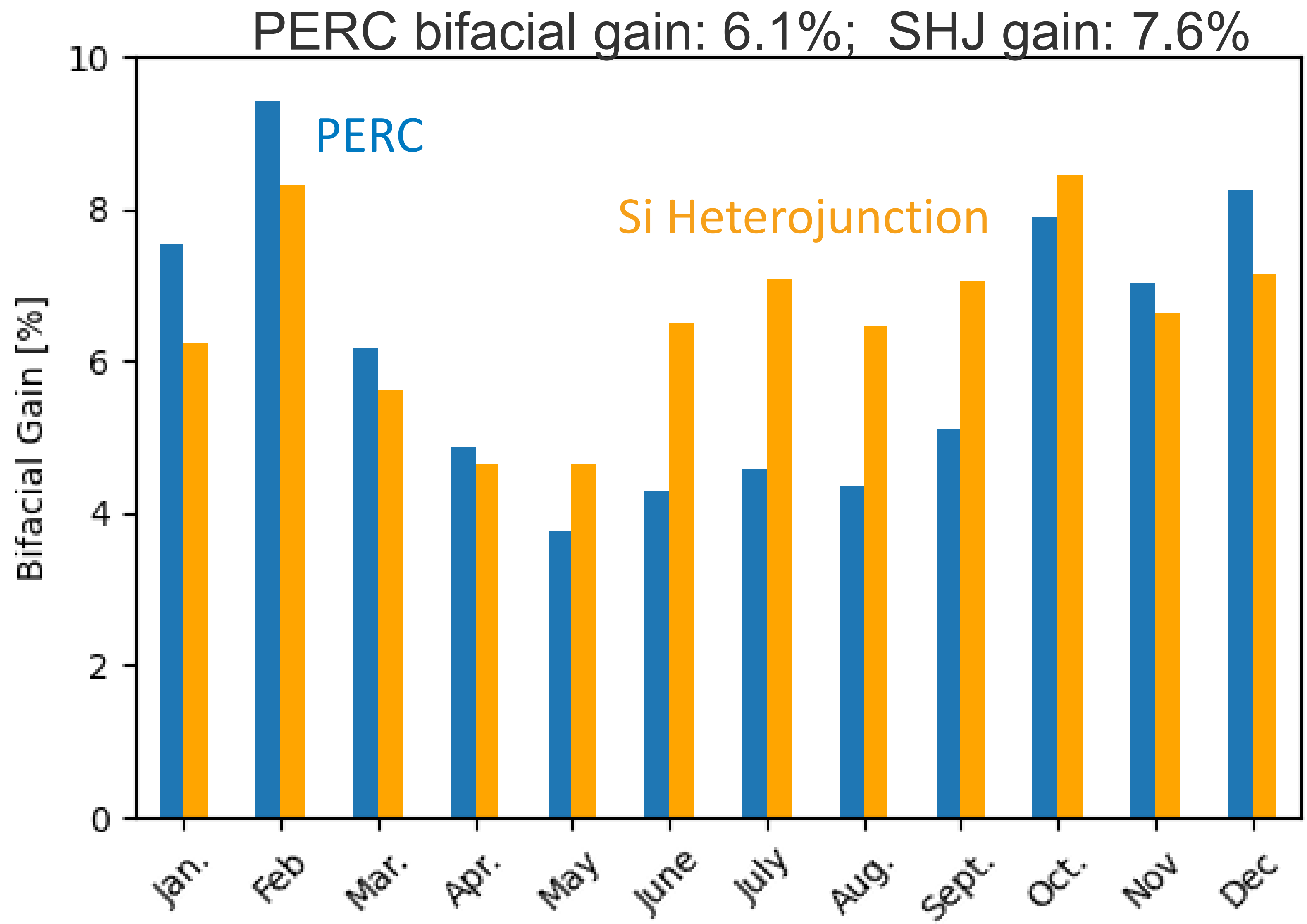


1. Ag and Al front metallization by screen-printing or PVD
2. SiN_x ARC and passivation layer by PECVD
3. PECVD or ALD of AlO_x surface passivation layer
4. p^+ doping and full-area emitter formation by ion implantation or BBr_3 diffusion
5. High lifetime n-type base wafer
6. Tunnel oxide passivated 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

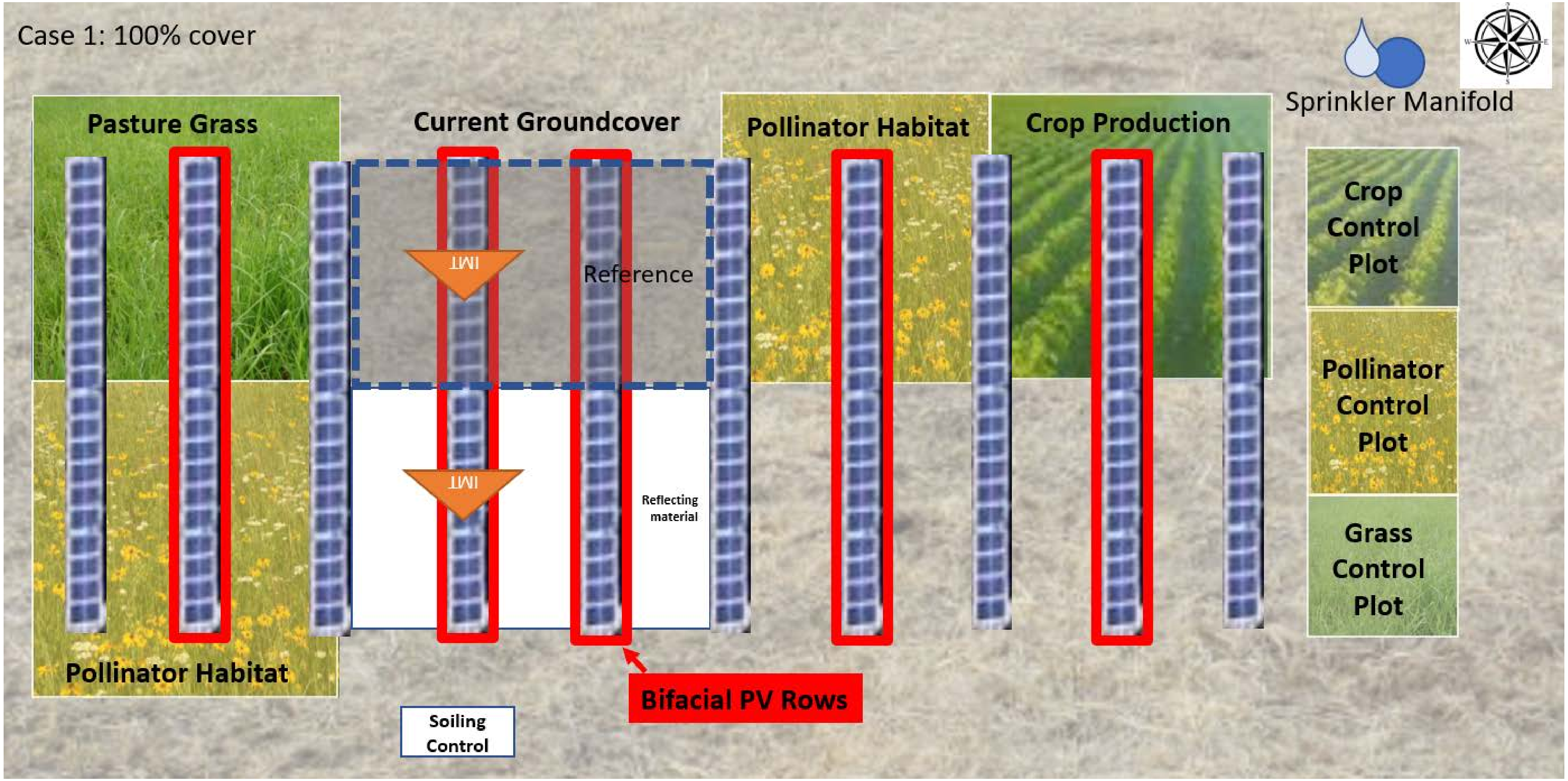
3-year Technology Performance

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

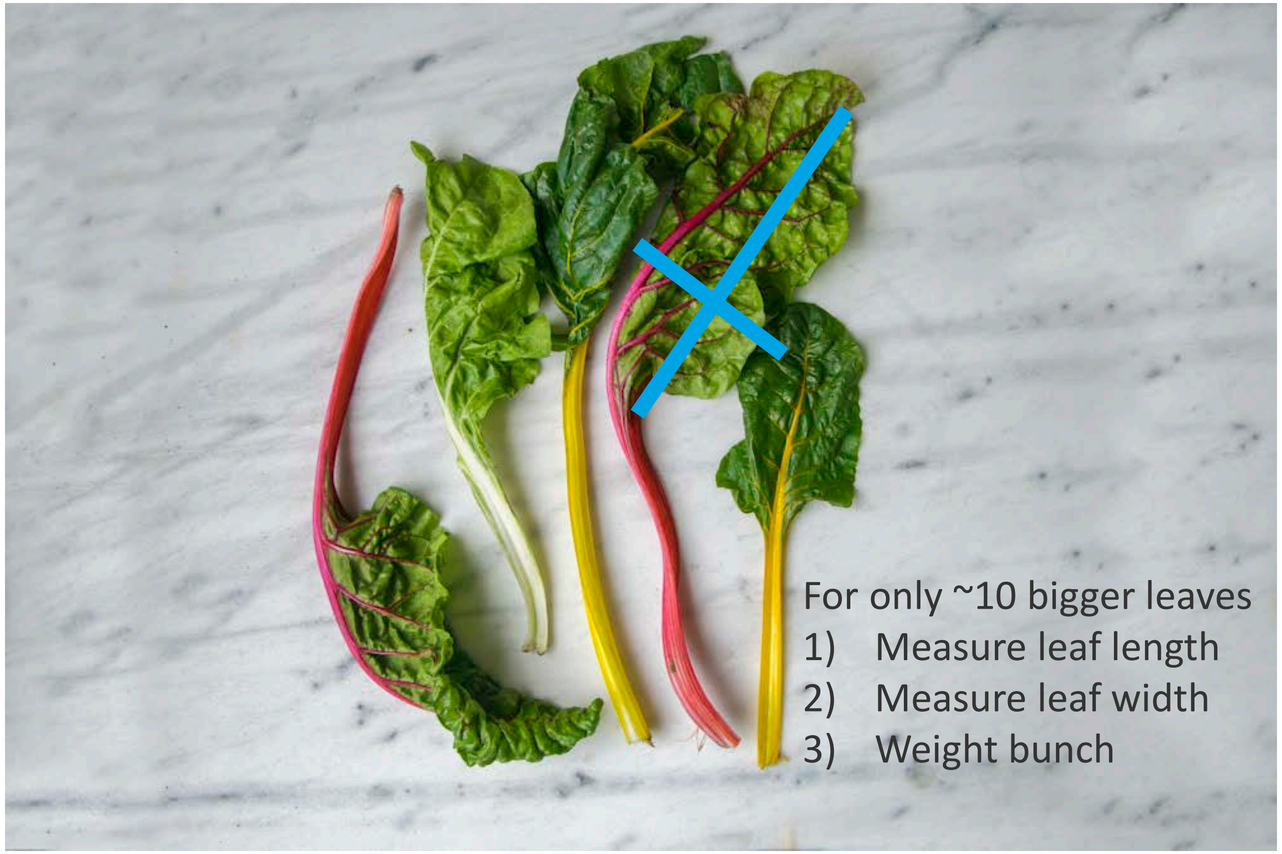
*Grouped by Month

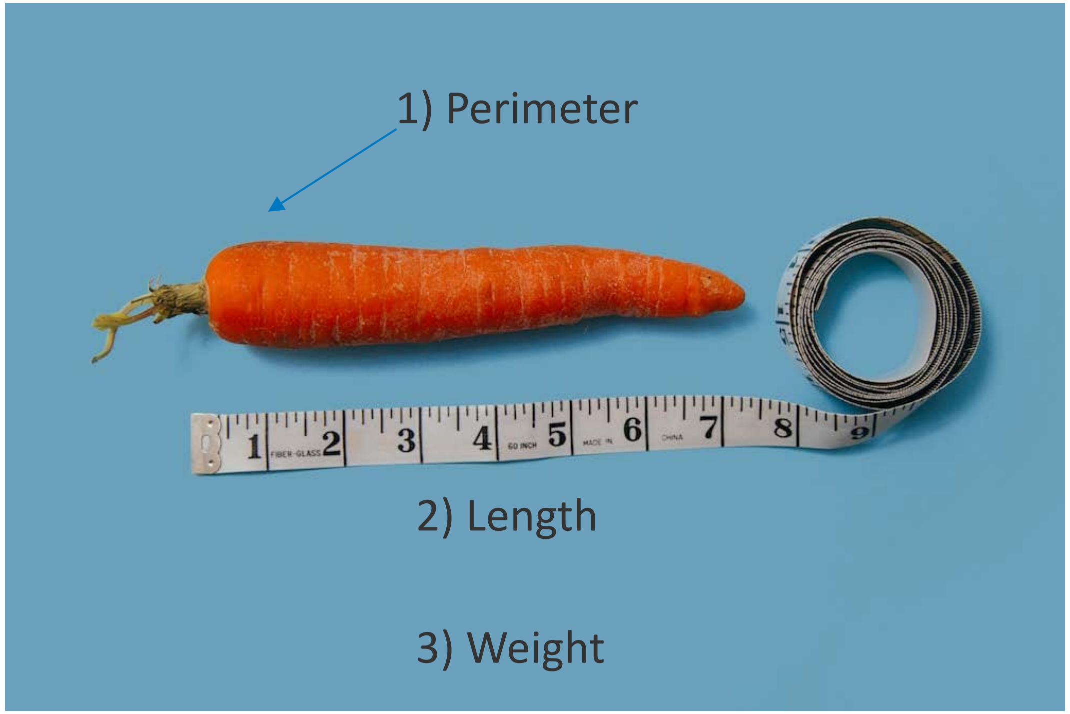


Sensors/Data Collected Discussion



Data collection





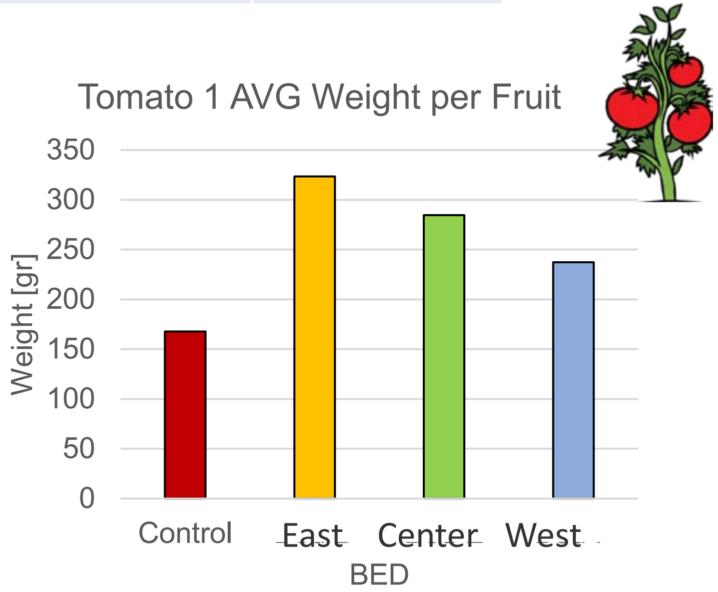
Also phenological measurements – does it have flowers, fruits? Are leaves eaten?

2023: Results

Best yield, based on production weight

	Control	East Bed	Central	West Bed
Chard			x	
Kale		x		
Basil				x
Carrot	x			
Tomato		x		
Tomato		x		
Pepper 1				x
Pepper 2			x	

- Most plants performed at least equal or better inside the solar panel array than in the control. Carrots here the only that performed better on the control.
- Tomato 1 was harvested earlier at the control than under the panels
- Basil flowered earier on the control as well.



Take good quantitative and qualitative notes of harvesting, plant state, and general O&M

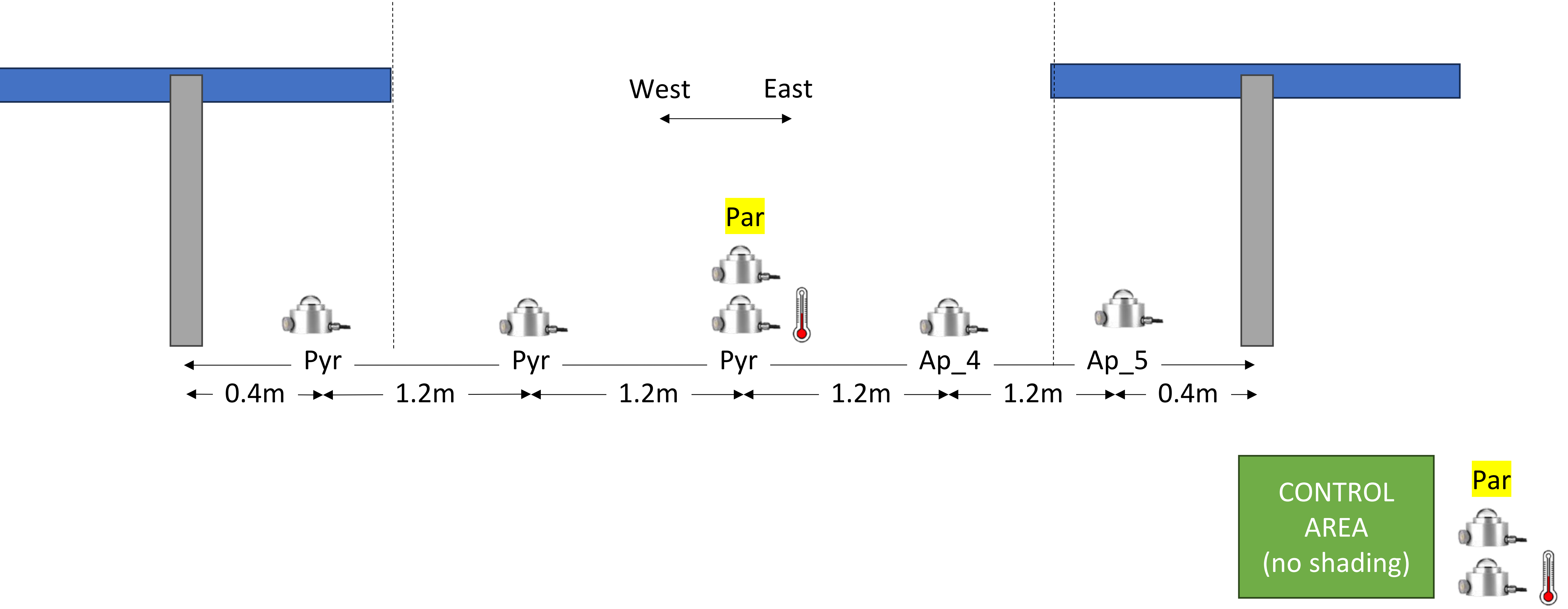
Harvesting team notes examples

'4 stripey jump insects'
'3 broken leaves'
'1 fly’
‘2 gnats’
'jumpy bugs'
'2 leaves snapped'
'1 leaf very consumed. 1 slightly consumed. 6 moderately consumed'
'2 leaves with insect damage'
'5 leaves with bites taken'
'had preying mantis babies'
'mostly burn and unharvestable'

'few small bites'
'bottom leaves browning'
'was on the brink of death, growing again'
'was on brink of death but has made a recovery'
'some kind of sticky substance on the plant, it's unhappy'
'deer ate all the leaves'
'plant pulled/eaten'
'pulled due to aphids'
'Most plants were pulled due to aphid infestation. If no harvest weight is given, no leaves were marketable'
'leaning heavily'
'(is actually the second plant, 1st plant is gone)'

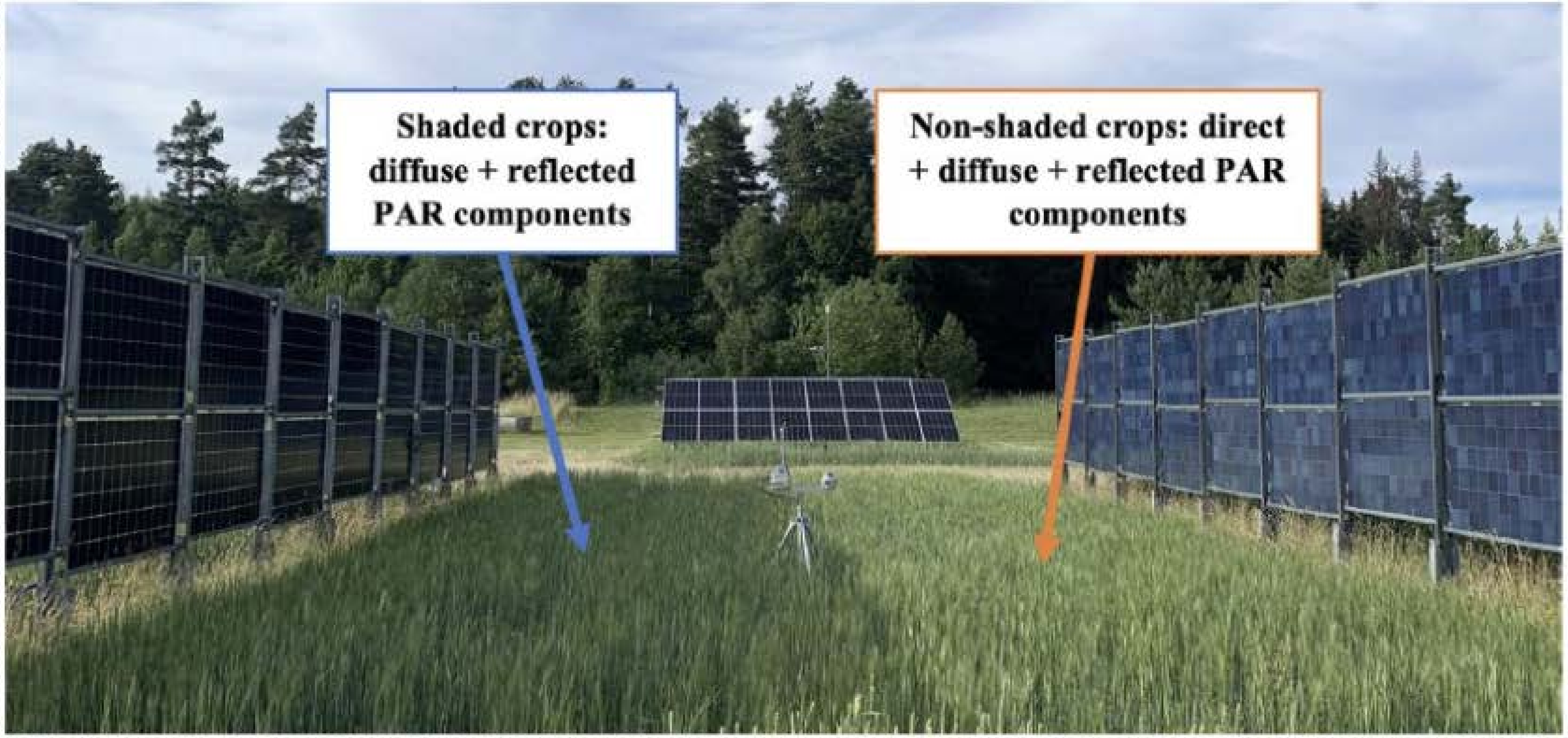
Irradiance to PAR Study at Barn

Oct-April 2024



Irradiance to PAR Study

Photosynthetically active radiation decomposition



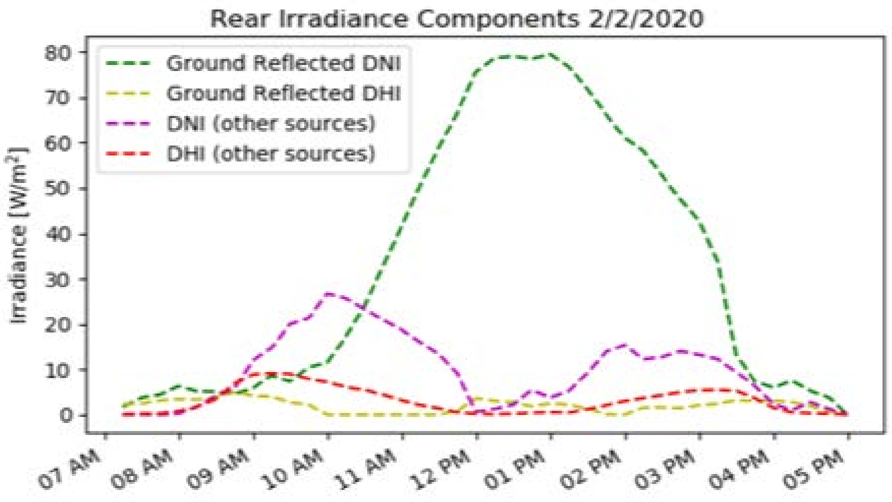
Ma Lu, S., Yang, D., Anderson, M. C., Zainali, S., Stridh, B., Avelin, A., & Campana, P. E. (2024). Photosynthetically active radiation separation model for high-latitude regions in agrivoltaic systems modeling. Journal of Renewable and Sustainable Energy, 16(1).

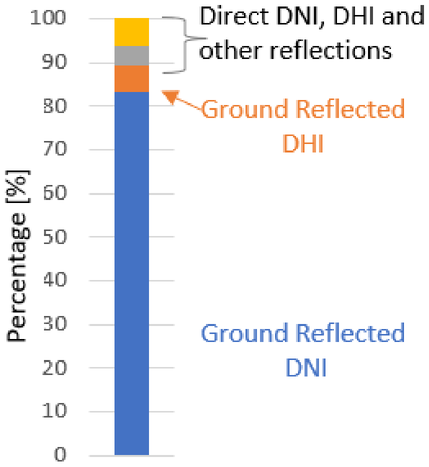
IRR → PAR → PPFD → PR

General Light Intensity | Photosynthetic Light Intensity | Photosynthetic Photon Intensity | Photosynthetic Rate

New Method in development at NREL using Spectral Generator pySMARTS

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





Sources contributing to the day's rear-irradiance

py-SMARTS

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

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

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

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

Adapting Grear to Gground, from Brown, PVSC 2022

AgriPV-related sensors

Minimal/typical for capacity testing and performance tracking:

- Weather data (Amb Temp, Wind speed), at least from satellite nearby; local better.
- Front referencecor pyranometers
- Temperature sensors
- Bifacial systems: Albedometer (GHI and GRI), Rear Irradiance measurements

What about AgriPV?

- Ground temperature and humidity
- Ground PAR (control). Irradiance/PAR inside array
- Precipitation data

Sensors to go deeper and/or study novel things:

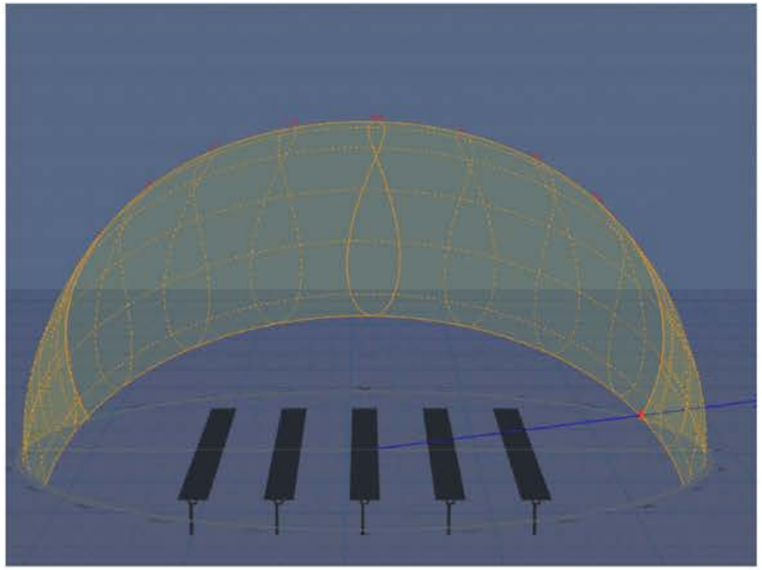
- More weather data (DNI, DHI, Wind direction), wind inside field
- More module and ground temperature sensors distributed throughout
- Module level optimizers – module level data allows comparisons inside the same technology that might be over different crops or areas.
- Spectrophotometer data for front, rear, or ground. These tend to be difficult to keep at quality and expensive.
- Hanheld reflectometer to measure albedo on crop areas (i.e. take measurement per sqft and average), and/or different types of albedometers to understand ground spectral effects (broadband like CM11 or Apogee pyranometers, IMT reference cells)

Other considerations:

- AgriPV: Recommended prior characterization of soil content for nutrients, but also for 'concern elements' in PV (lead, Cd, etc), and then continued measurements after each year
- Characterizing your modules, and your weather before installation gives an important data point. IV Curves and IR upon installation at minimum; EL and QE suggested.
- Keep spare and control modules.
- Keep good O&M and agrivoltaic/harvesting logs.

Modeling Pipeline

AgriPV modeling starts with light and ends in currency.



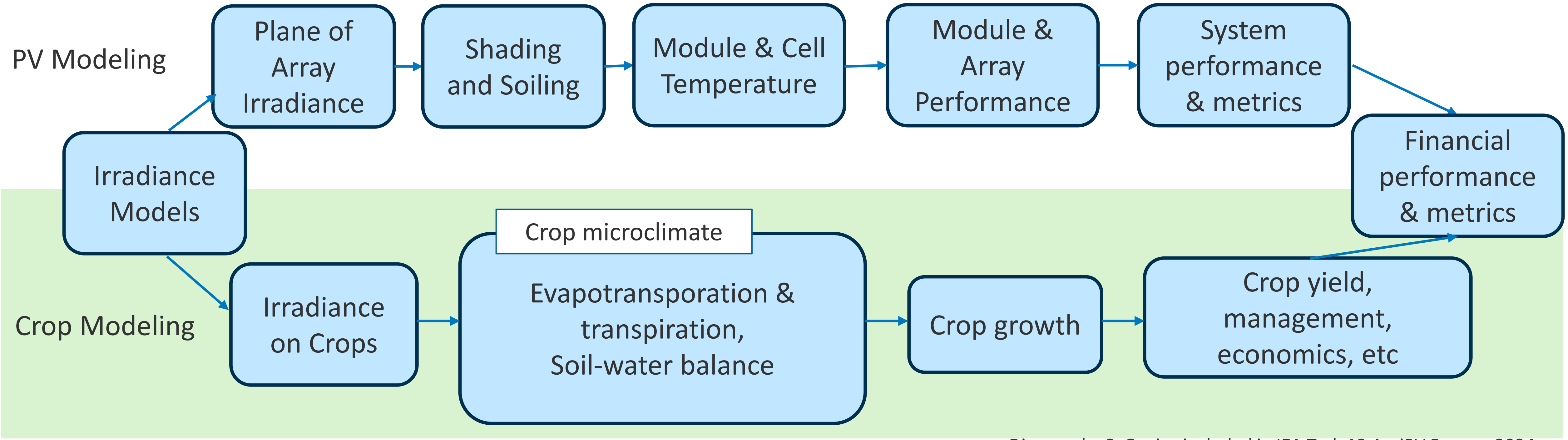


Diagram by S. Ovaitt, included in IEA Task 13 AgriPV Report, 2024

Modeling Pipeline

Crop growth

Future goals is to connect irradiance models to crop models. In particular, establishing a feedback loop of crop height to consider irradiance at the new heights.

- Simple Crop Model?
- STICS (considers height): https://www.sciencedirect.com/science/article/pii/S1161030102001107
- PACE open-source software has it implemented, but disregards plant height on the calculations.

silvana.ovaitt@nrel.gov

https://openei.org/wiki/InSPIRE

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