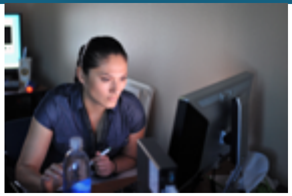
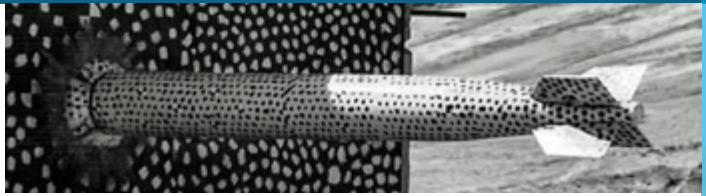
# Bifacial Photovoltaic Performance Optimization Using Ray Tracing and High Performance Computing





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*PRESENTED BY*


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# Outline

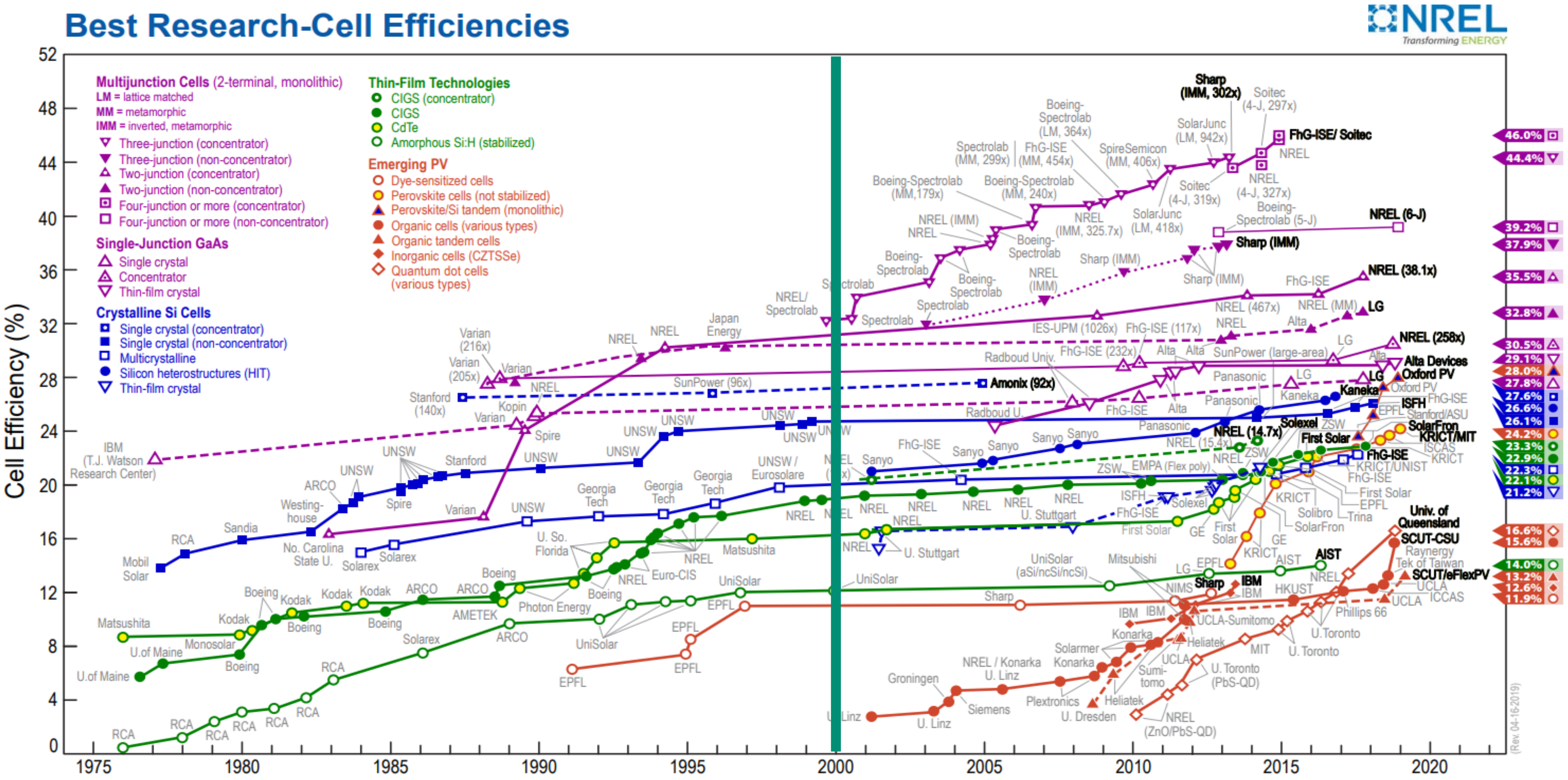
- Introduction to Bifacial cells, modules, and systems
- Bifacial performance, gains
  - Prism Solar example from Sandia
- Bifacial PV advantages for high latitudes
- Approaches to modeling backside irradiance
  - View factor models
  - Ray tracing
- Ray tracing examples
  - Height off ground
  - Cell packing density
  - System size
  - Torque tube shading
- Future modeling needs and High Performance Computing





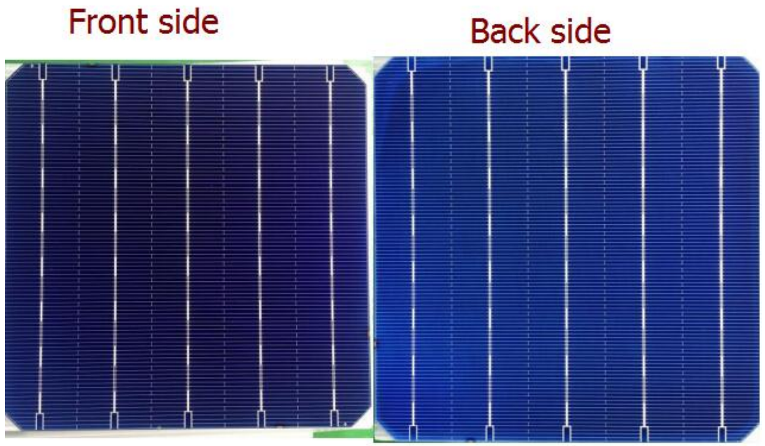
# The R&D path to increased cell efficiency is slow and expensive

- Since 2000, the rate of efficiency increase for Single crystal and Multicrystaline Silicon PV has been very slow. LCOE decreases have come largely from lowering CapEx and OpEx.
- How can you increase PV system output by ~10% or more with only 1-3% increase in cost?
  - Answer = “Bifacial PV”



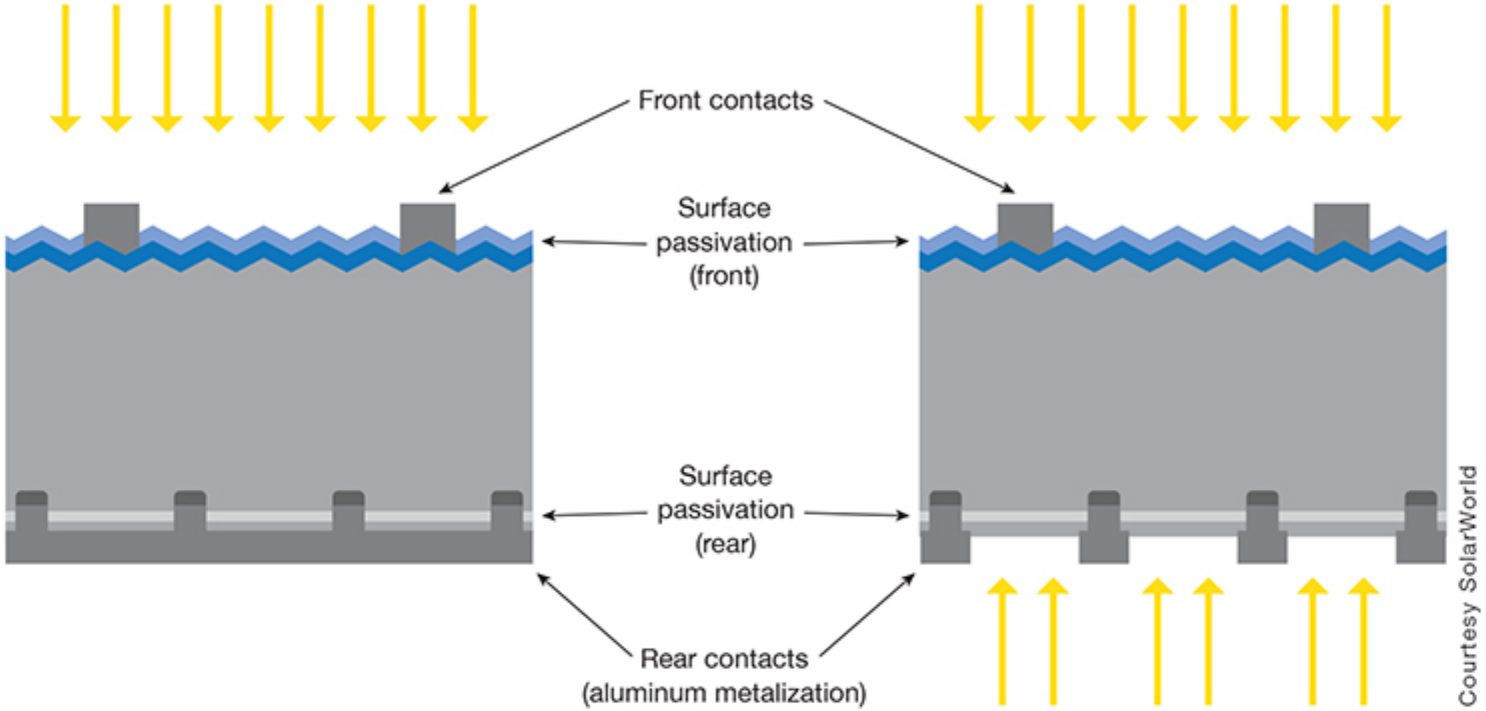
# Modern PV cell designs are easily optimized for bifacial

- Replacing the monolithic backside metallization allows light to enter the cell from the back.
- Many types of modern PV cells are easy to make bifacial
    - PERC, PERT, PERL, HIT, Etc…



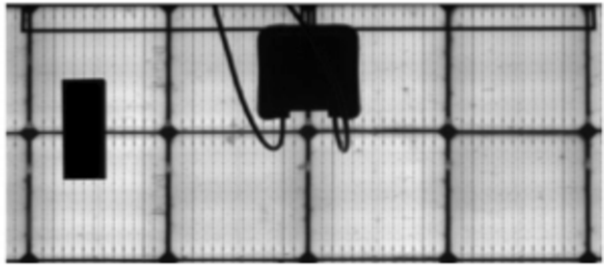

Bifaciality = $\frac{Rear\ side\ power\ rating}{Front\ side\ power\ rating}$

PERC: 65% - 75% bifaciality
N-PERT: >90% bifaciality
HIT: >92% bifaciality

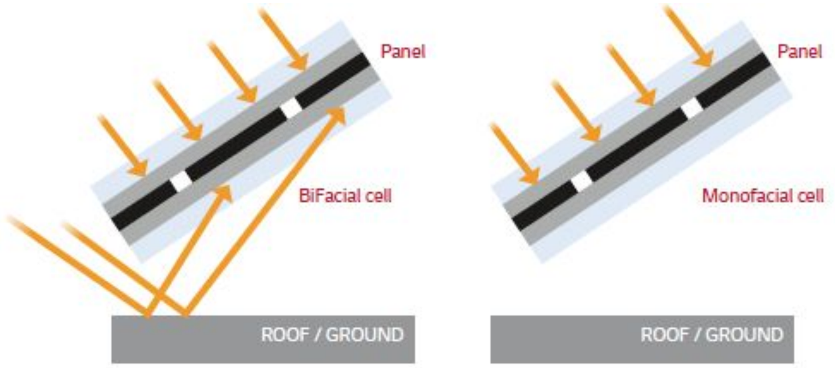


# Bifacial Photovoltaics Modules

- Require transparent backsheet
  - Glass-glass designs are popular but they are heavy
  - Transparent polymer backsheets are being tested.
- Framed vs. frameless
  - Framed modules are easier to mount to racks
  - Frames can shade backside cells
  - Frameless clamps are more expensive
  - Frameless modules require more packaging materials for shipping.
- J-box and label <u>should not</u> cover cells.



- 2017 ITRPV predicted bifacial modules will comprise about 10% of market today and almost 40% of market by 2027.



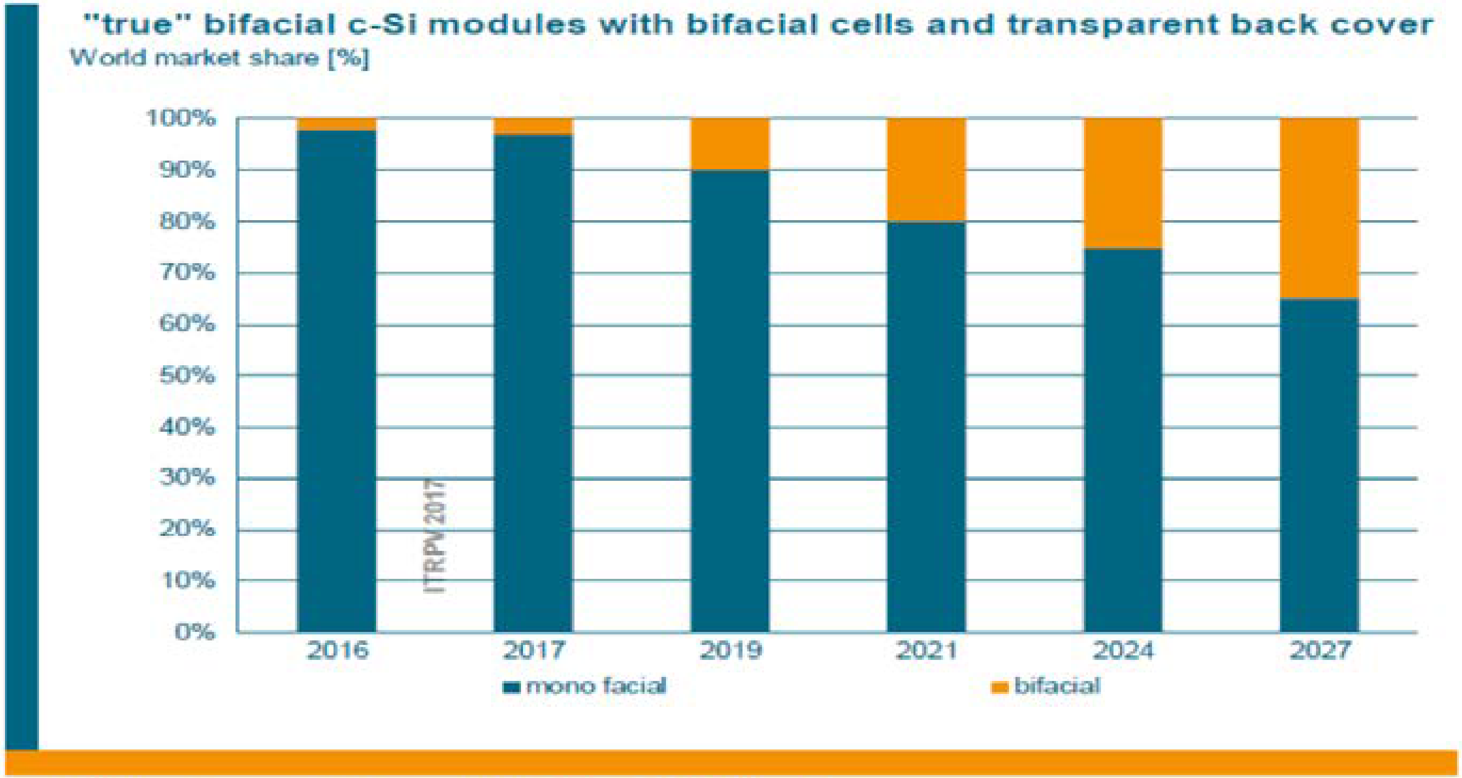




Fig. 43: Worldwide market shares for monofacial and "true" bifacial modules.

Source: ITRPV report 20171

# Bifacial Gain & PV System Performance

$$\text{Bifacial gain [\%]} = \left(\frac{e_{bifacial} - e_{monofacial}}{e_{monofacial}}\right) \times 100$$

$e_{bifacial}$ = specific energy yield (kWh/kWp) of bifacial

$e_{monofacial}$ = specific energy yield (kWh/kWp) of monofacial system at same site and orientation

Bifacial gains increase significantly when orientation of array is not optimized for monofacial (e.g., west-facing, vertical)

System size and GCR are inversely proportional to bifacial gain and and performance.

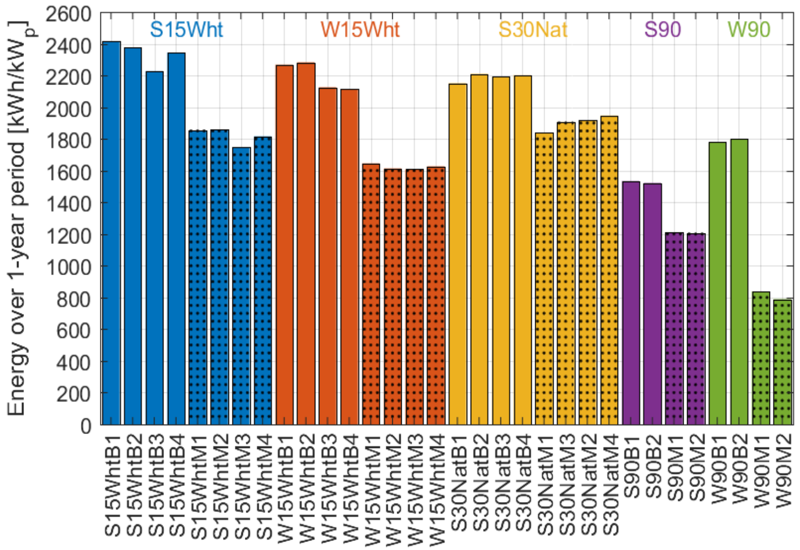
Shadows on the ground reduce backside irradiance for all nearby modules.

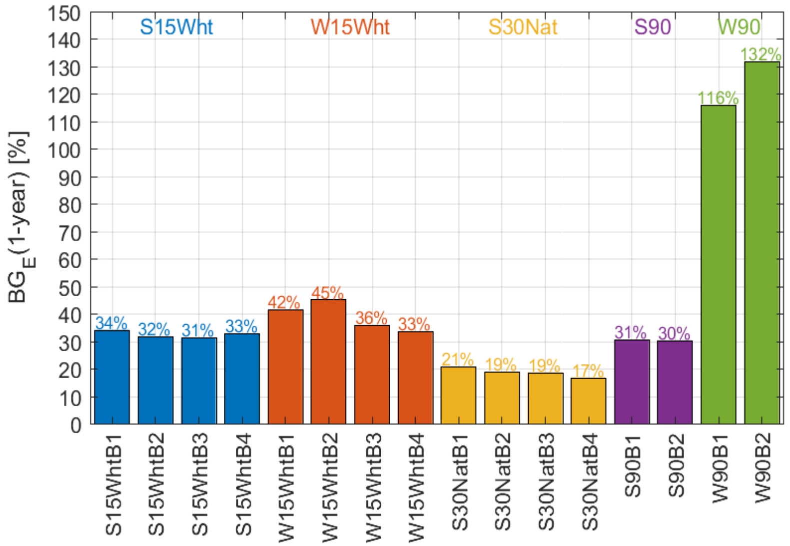
Small isolated systems have significantly higher gains due to unshaded ground surrounding system. Also true for large row-row spacing.

Photo Credit: LONGi

Photo Credit: Sandia National Laboratories

# Bifacial Gain Example- Prism Solar, Albuquerque, New Mexico




- Module level monitoring
- High and low albedo
  - 0.2 and 0.6
- All Gains > 17%
- Gains >100% for West-facing vertical modules

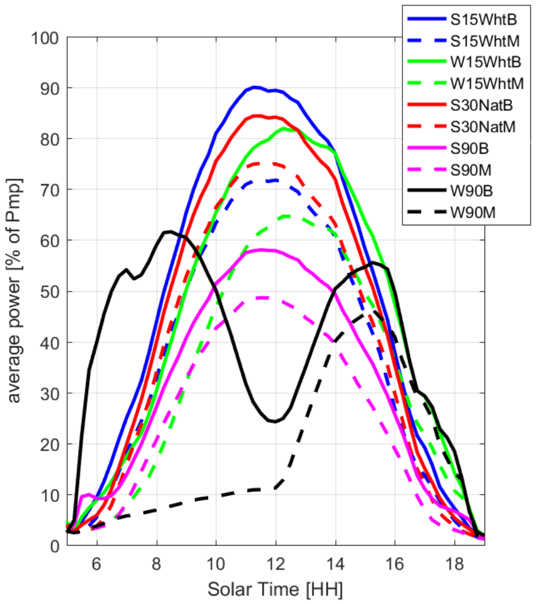
How is this possible?

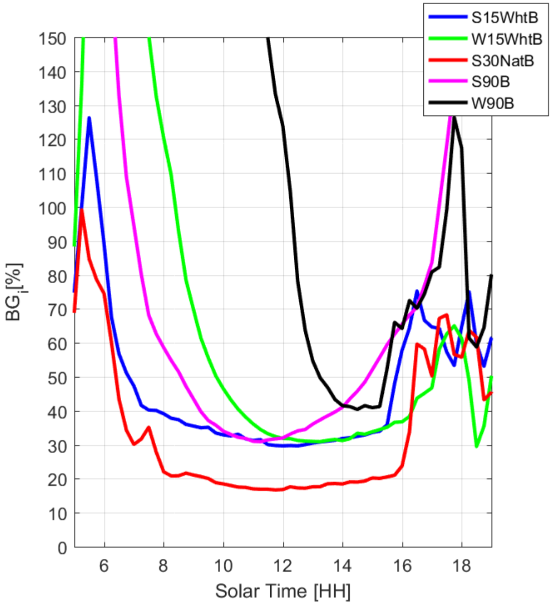
- Temperatures rise over the day.
- Bifacial production in morning (from backside) is greater than afternoon production.
- E-facing vertical system would produce more energy but have lower bifacial gain.

Power from W90B peaks earlier than from S-facing systems.

- Shading in evening reduces cuts off potential power production later in the afternoon.


## Average power and Bifacial Gain by hour




Stein, J.S., Burnham, L., and, Lave, M. 2017. One Year Performance Results for the Prism Solar Installation at the New Mexico Regional Test Center: Field Data from February 15, 2016 - February 14, 2017 . Albuquerque, NM, Sandia National Laboratories. SAND2017-5872.

# Features of High Latitudes for PV

- Large range in length of day (short in Winter, but long in Summer)
- Large range in Solar Azimuth (Sun rises and sets in NNE and NNW in Summer)
- Smaller range in Solar Elevation
- Cold temperature (PV performs better at colder temperatures: 0.5%/°C)
- Snow (highly reflective and can cover PV modules and block light)

Bifacial test site in Fairbanks, AK

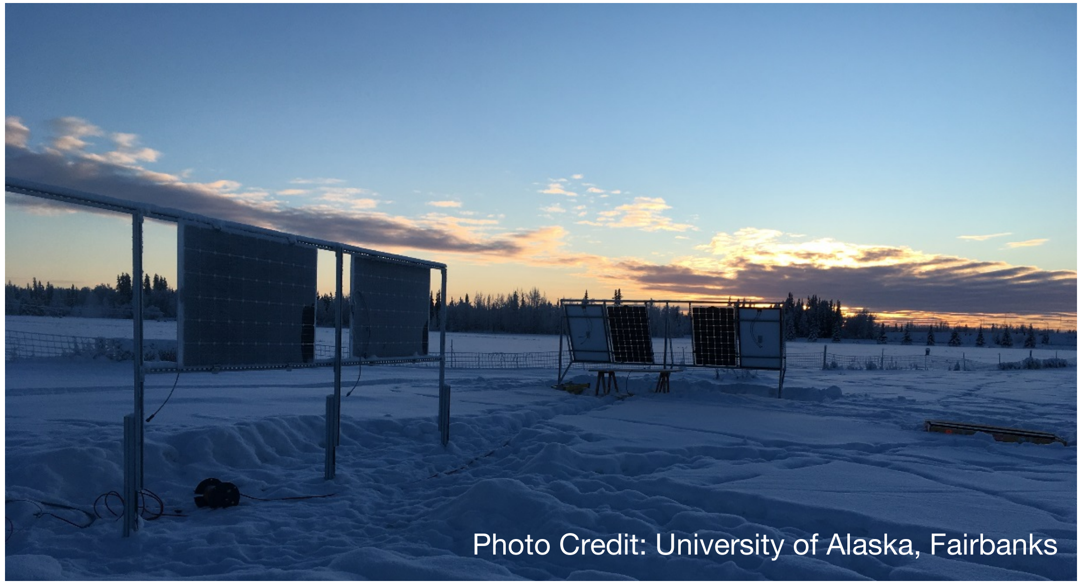
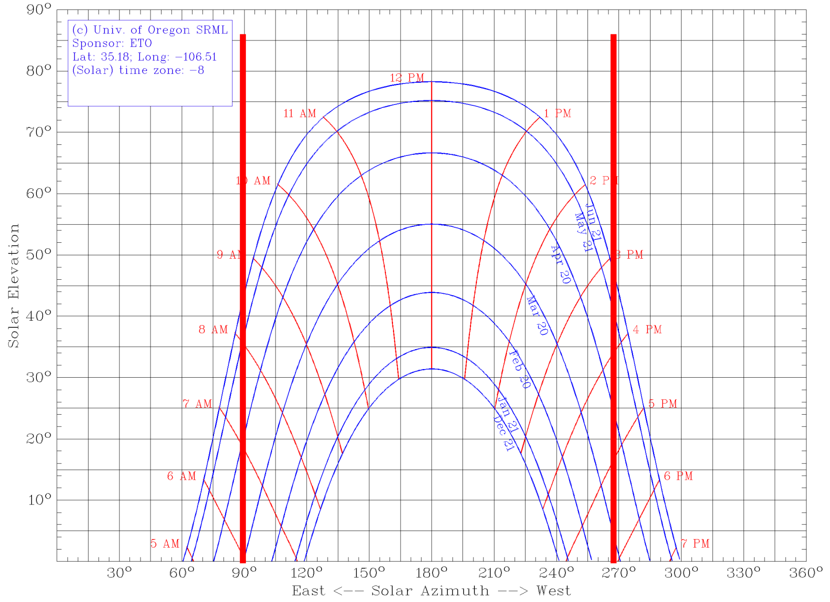
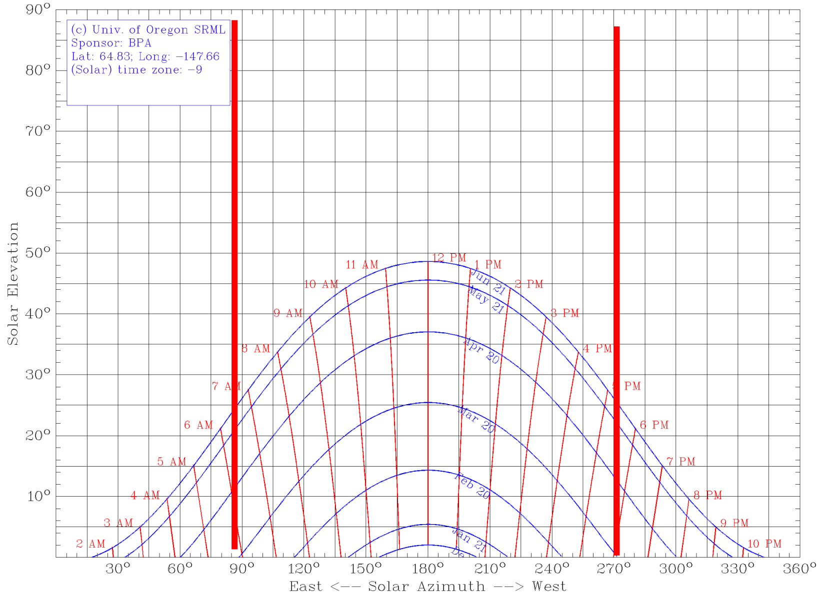


Photo Credit: University of Alaska, Fairbanks

Albuquerque, NM (35° N)



Fairbanks, AK (64° N)

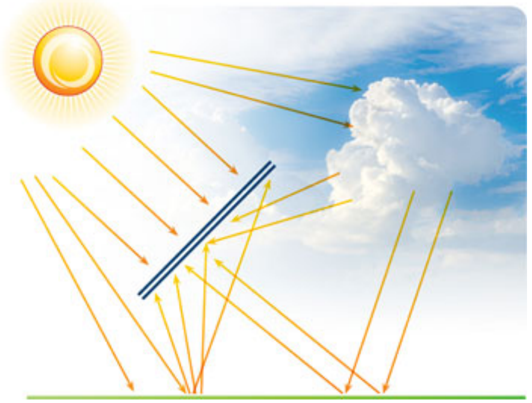


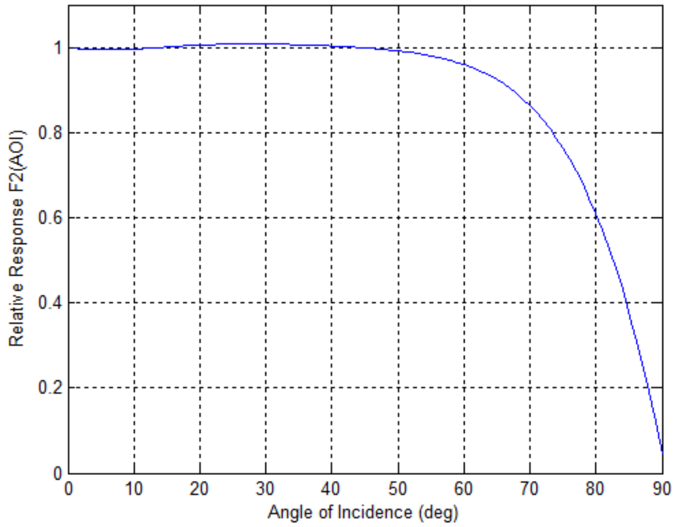
Vertical bifacial in Turku, Finland

# Very Simple Model of Bifacial PV Performance

## Model Assumptions

- Weather from typical meteorological year (TMY) stations
  - GHI, DNI, DHI, Temperature, Wind Speed, Snow
- Plane-of-array irradiance:
  - Beam + Sky Diffuse + Ground-reflected
    - Beam reduced at high angles of incidence due to reflection losses using Sandia's F2 Model
  - No snow periods: Albedo = 0.25
  - Snow on ground: Albedo = 0.7
  - Bifacial POA = front + back irradiance*bifaciality factor
    - Bifaciality factor = 90% for this simulation.
  - Albedo for bifacial reduced by 25% to account for shadow effects (based on empirical data).
- Sky diffuse calculated with Perez transposition model
- Module temperature: $T_m = T_a + E(e^{a+b*WS})$
- Cell temperature: $T_c = T_m + E/E_0*\Delta T$
- Module power: $P_{mp} = P_{mp0} * E/E_0*(1+\gamma[T_c-25])$
- Module parameters from spec sheet (Power rating, temp coefficient ($\gamma$))






GHI = Global Horizontal Irradiance
DNI = Direct Normal Irradiance
DHI = Diffuse Horizontal Irradiance

Stein, J.S., 2018. Solar PV Performance and New Technologies in Northern Latitude Regions. Alaska Rural Energy Conference, Fairbanks, AK.

# Model Validation

Validation was done by comparing model to measurements made at Sandia

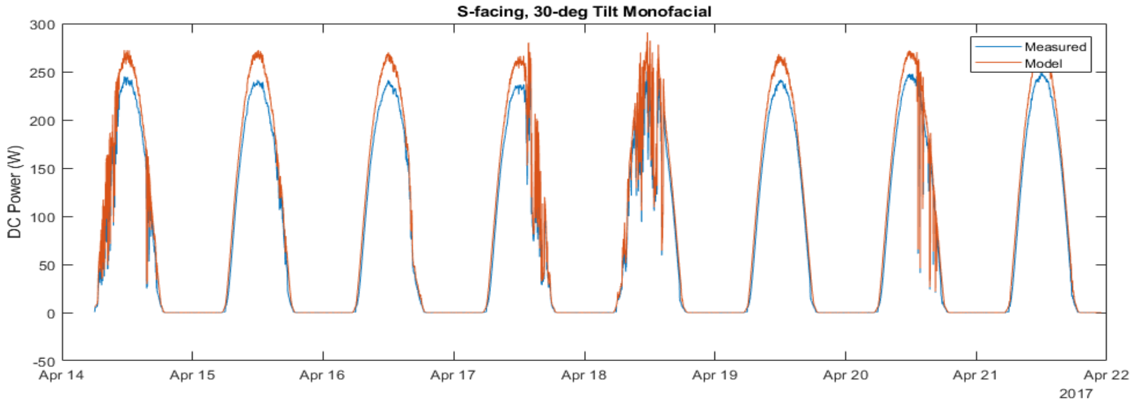
- Five orientations (each with monofacial and bifacial), Two albedos
- Module-level DC current and voltage measurements (module on microinverters).

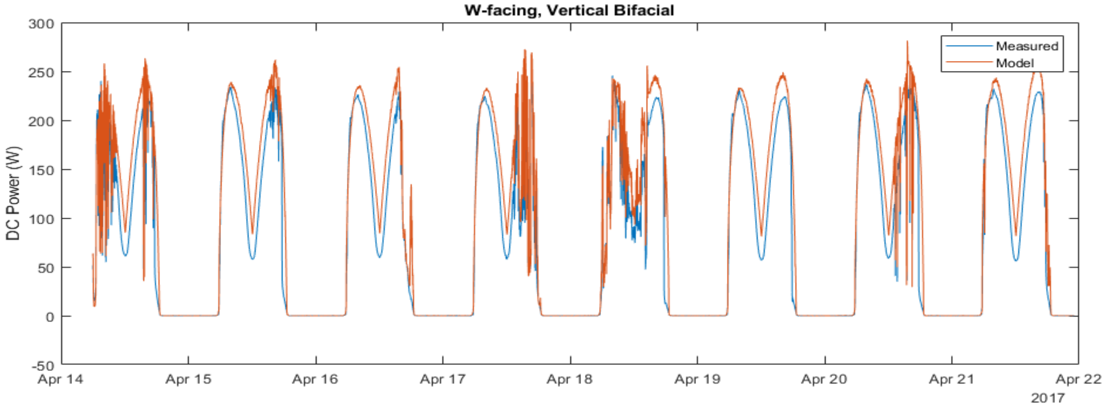
**Inputs:**

- Measured DNI, GHI, DHI, Air Temp, Wind speed, Albedo, Module spec sheet parameters ($P_{mp0}$, $\gamma$)

**Results:**

- Model slightly overestimates the measured system output.
  - Soiling is not included in model.

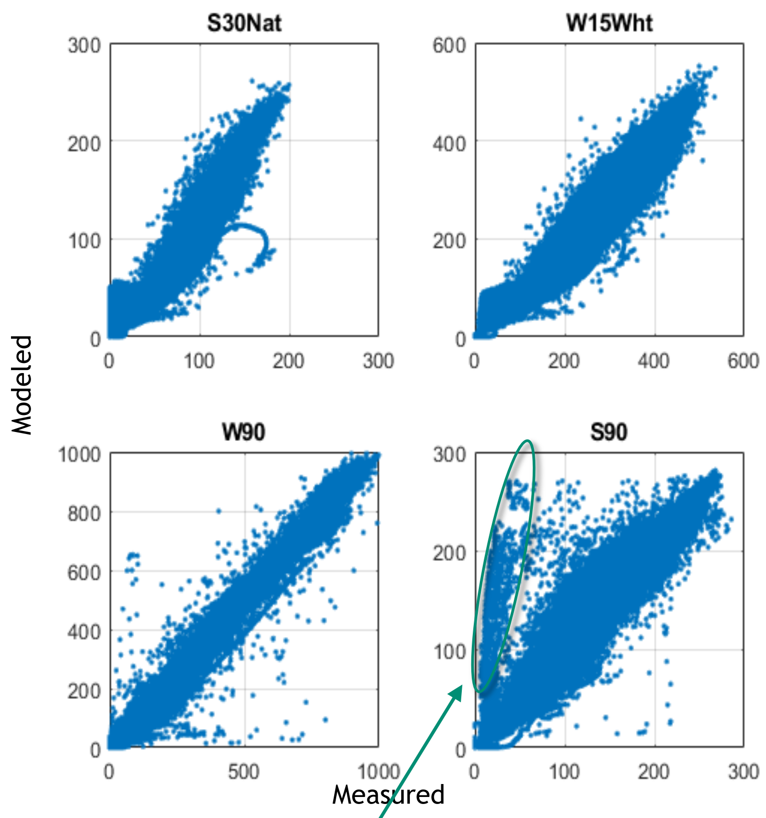


# Model Validation Results

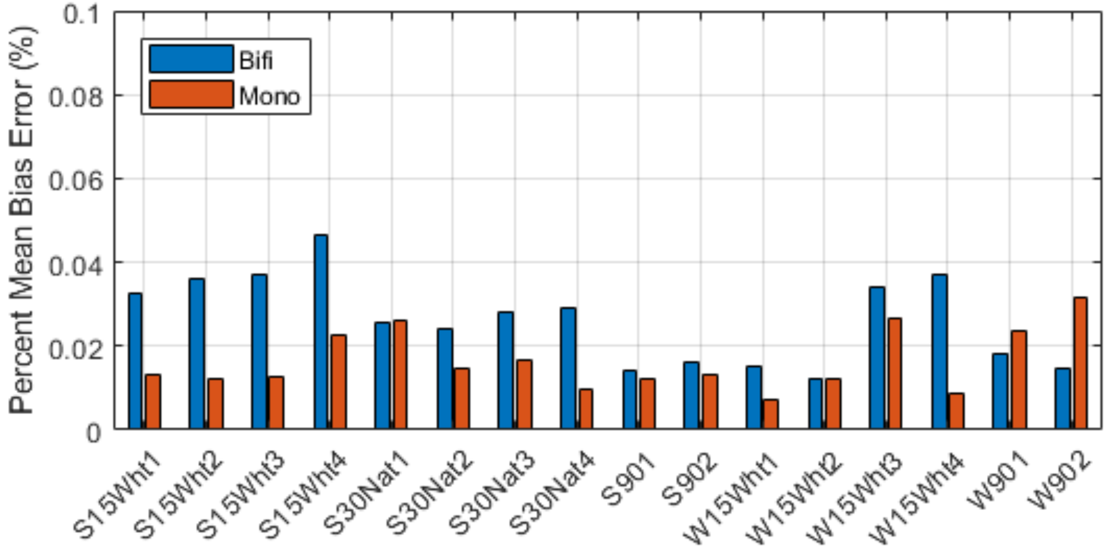
## 6 Month Comparison (Jan-June 2017)

Back Side Irradiance




Shading from power pole

- Mean bias errors are all below 5%
- Back side irradiance model is very good for W90, W15, and S15.
- Minor systematic errors for S30, and S90
    - S90 has known shading



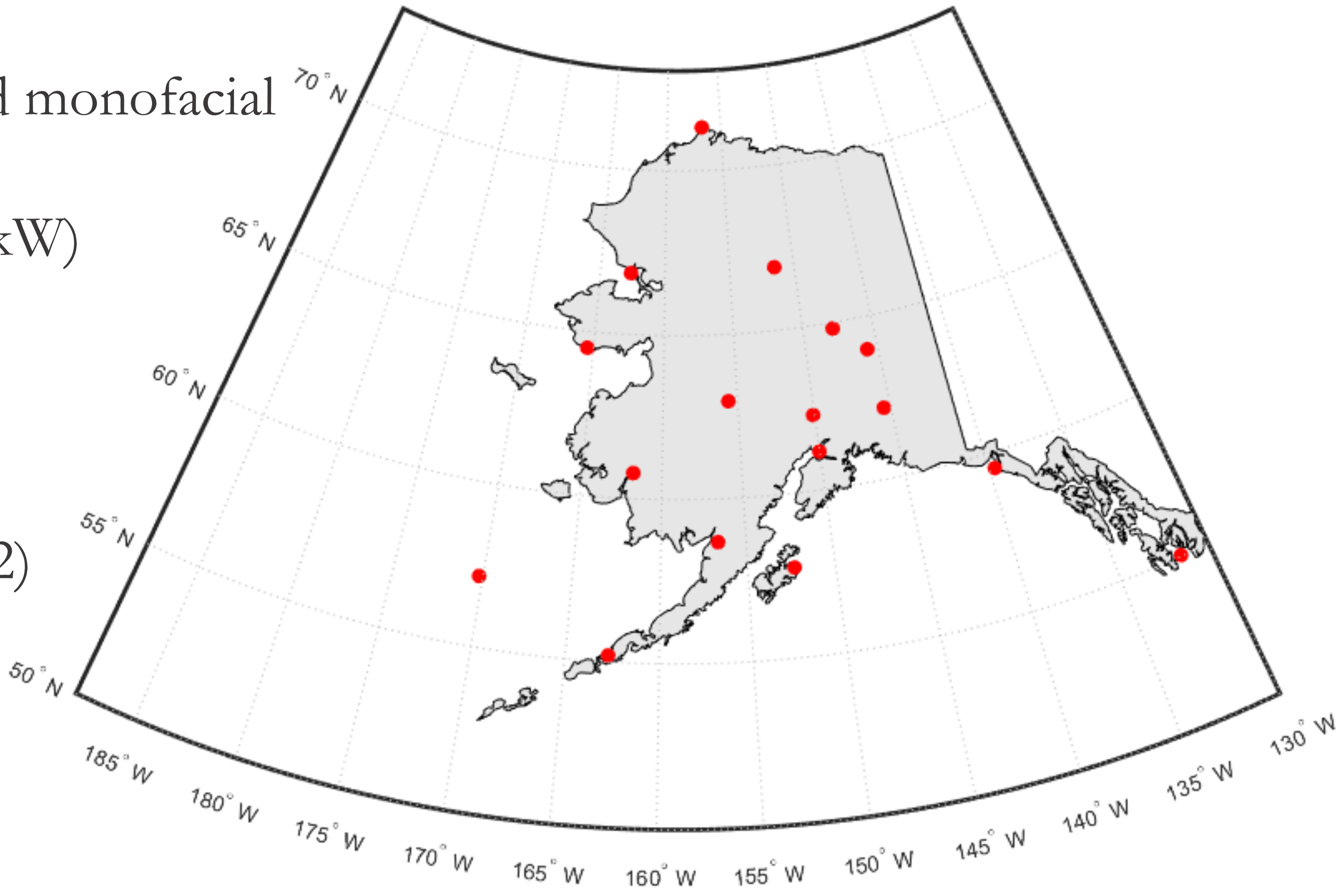
# Predictive Alaska Model Scenarios

## Compare two design options:

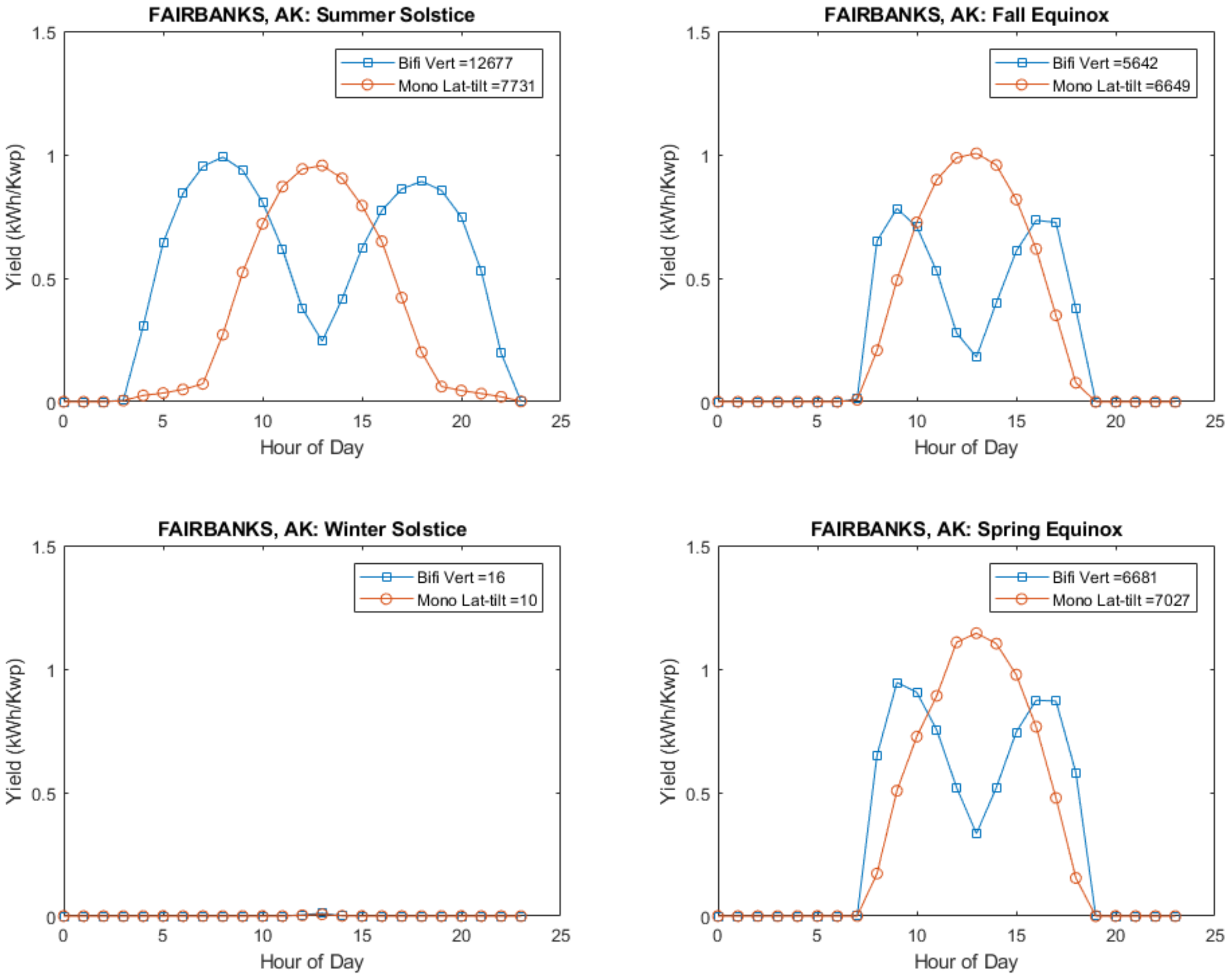
- South –Facing, Latitude-tilt standard monofacial PV (1 kW)
- East-Facing, Vertical bifacial PV (1 kW)

## Weather Inputs

- 17 weather stations in Alaska
  - Included Phoenix, AZ for comparison
- Typical Meteorological Years (TMY2)
  - Months are selected from long record
  - Assembled into synthetic year
    - 8760 hours of data
  - Meant to be representative

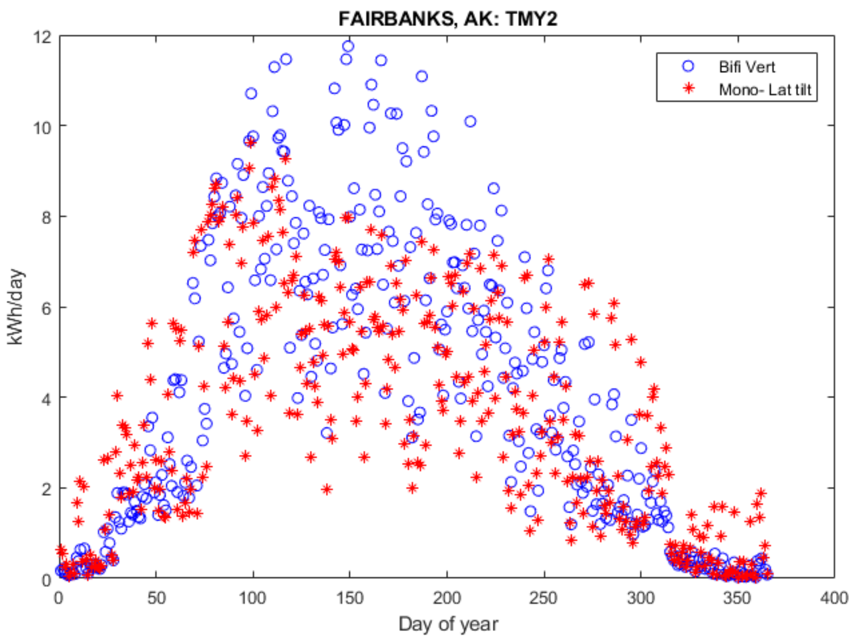


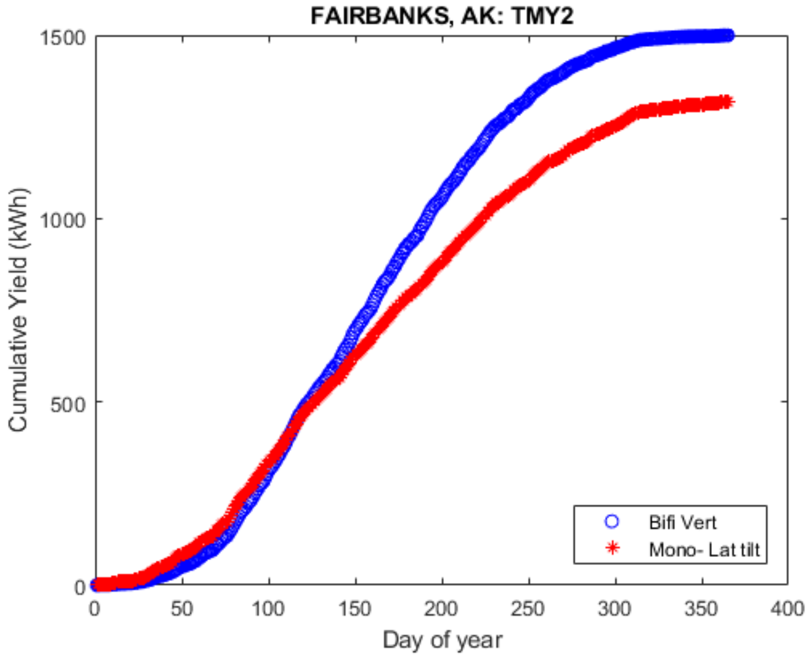
# Model Examples: Fairbanks (Clear Sky)

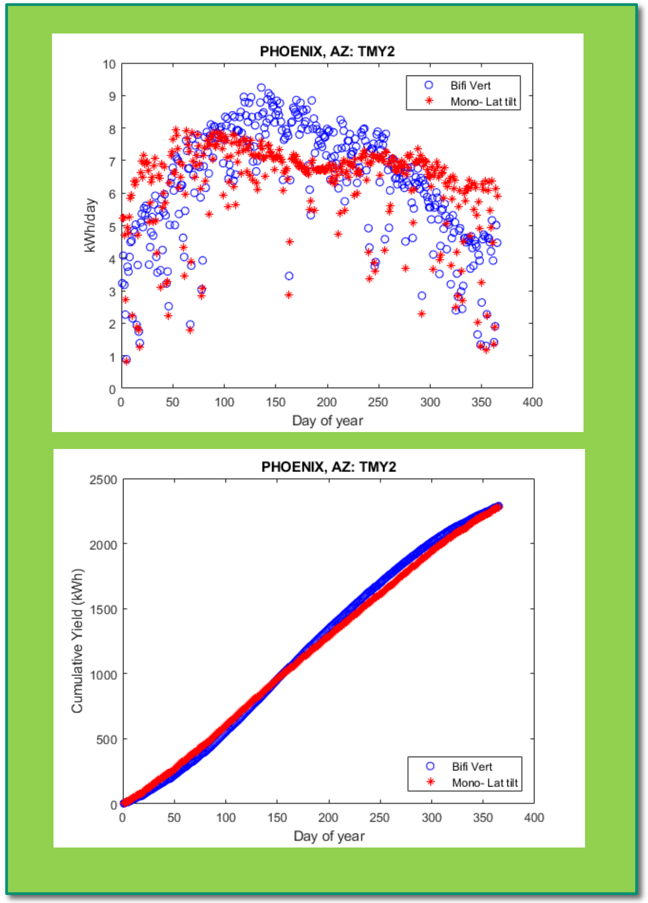



- E-W Vertical bifacial has potential to produce power earlier and later in day.
- Great for combining with latitude tilt PV systems

# Model Examples: Fairbanks (TMY2)



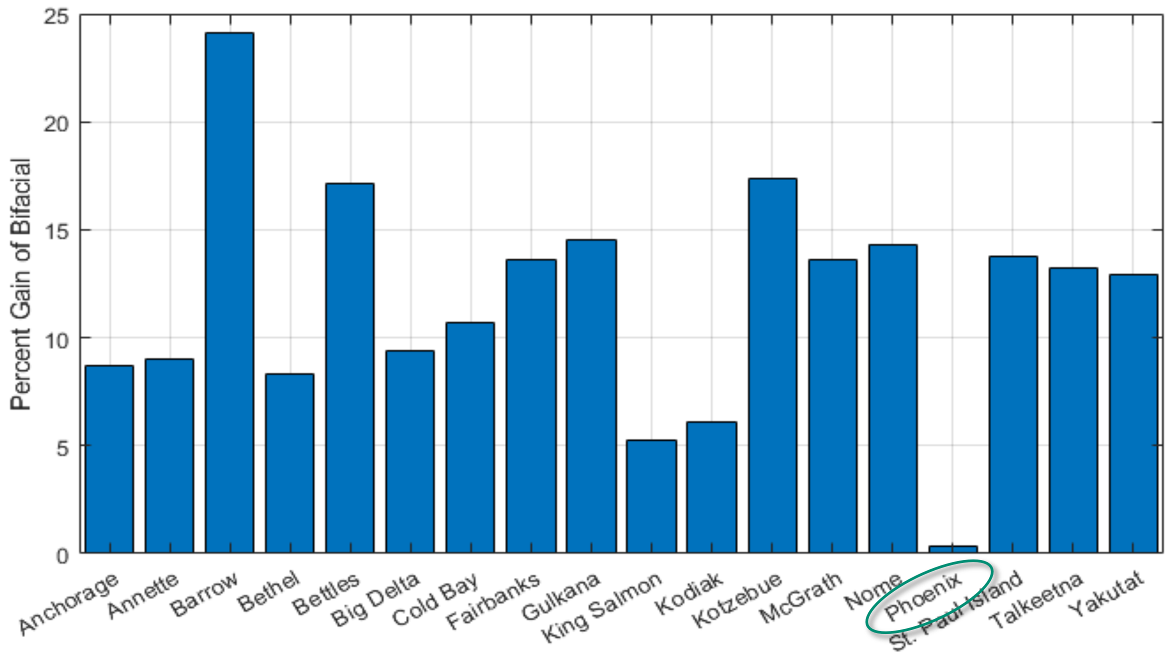



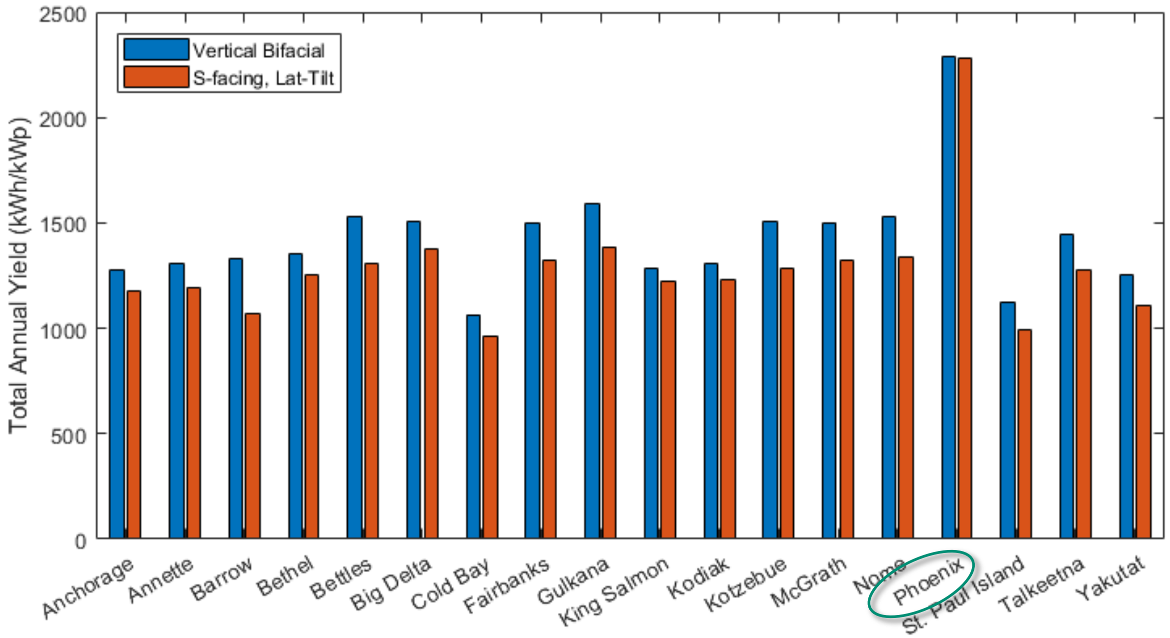

- This patterns repeats for most Alaska sites:
  - Early in year Lat-tilt system is better, but total energy is small
  - From Spring to early Autumn Vertical bifacial system significantly outperforms Lat-tilt monofacial.
- In Phoenix, vertical bifacial performs about the same as Lat-tilt monofacial.
  - We have confirmed this in Albuquerque, NM with measurements.

# Results for all sites

- E-facing Vertical Bifacial outperforms S-facing Latitude-Tilt systems in Alaska.
  - Bifacial advantages increase with latitude and duration of snow on ground.
  - Power profile starts earlier and ends later, which may help with integration issues.

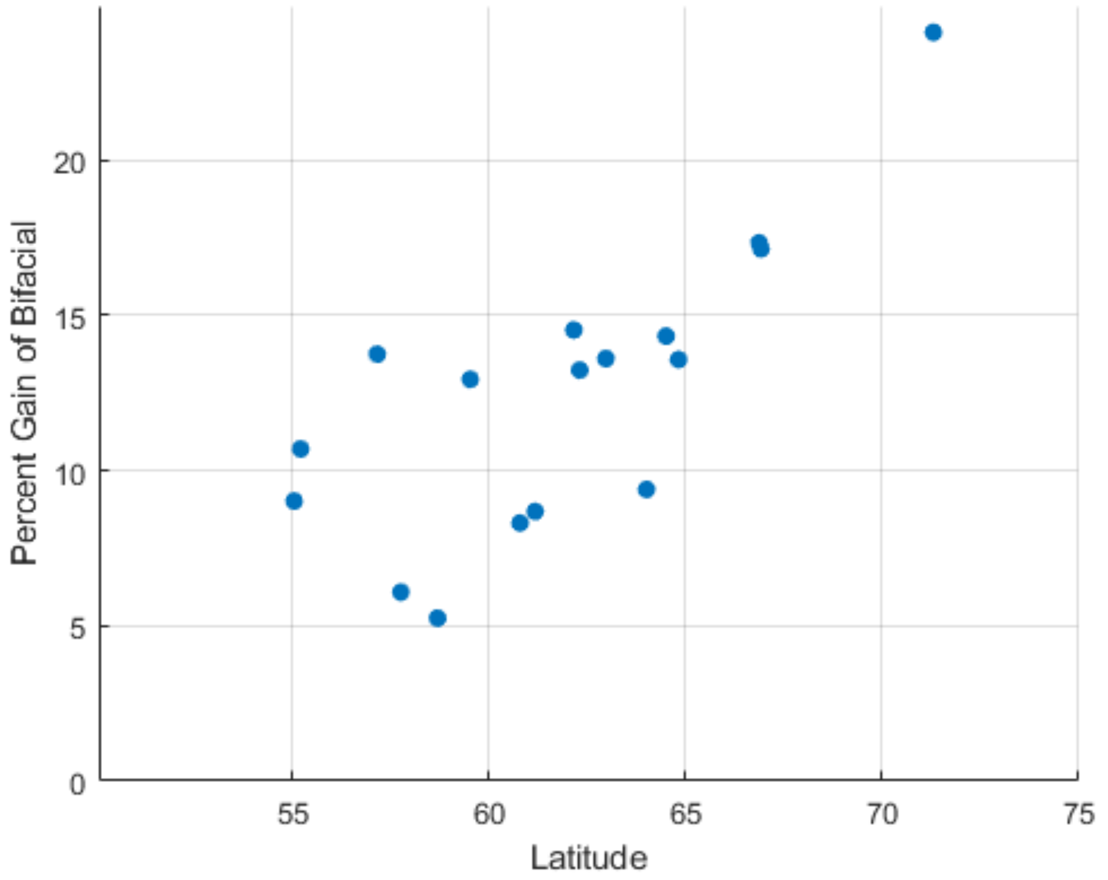
- Vertical bifacial takes advantage of large range in solar azimuths
- Vertical bifacial collects light from highly reflective snow covered ground.



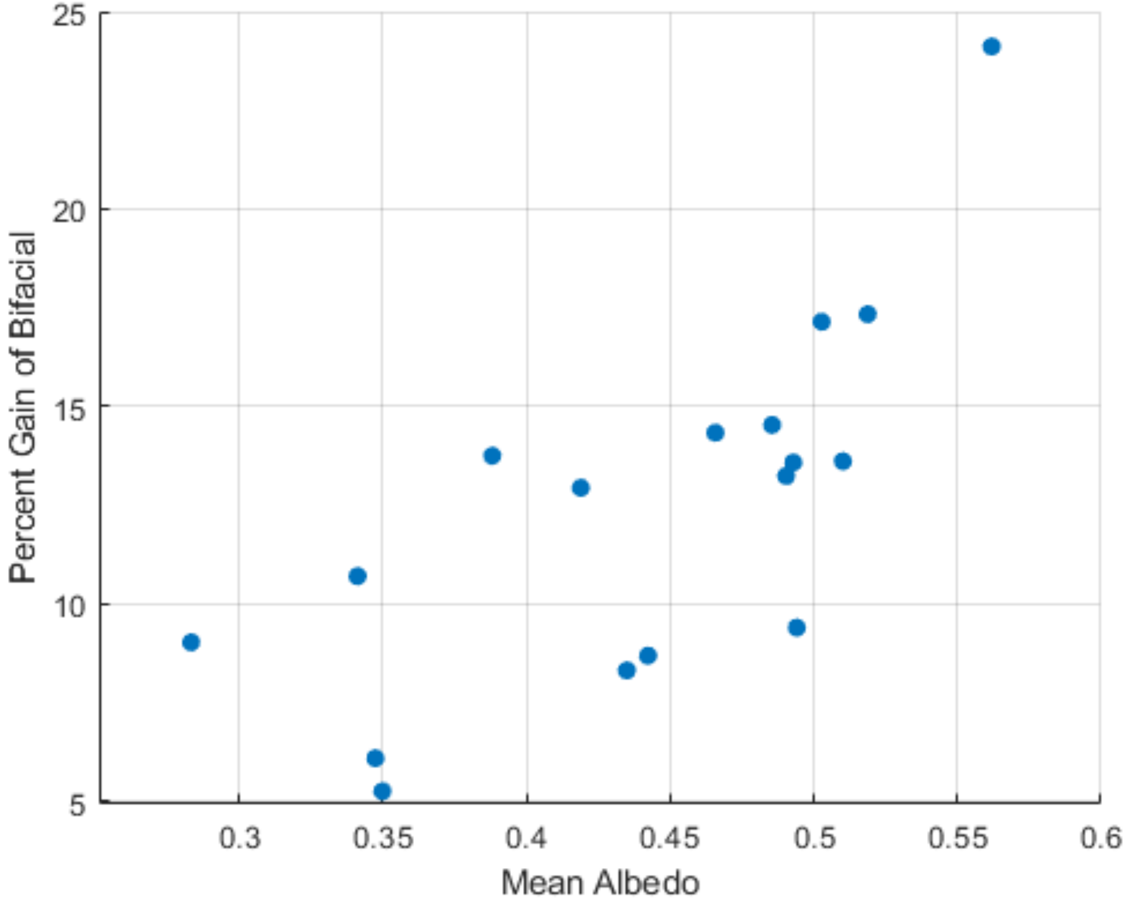



# Model Sensitivity Results

Effect of Latitude




Effect of Albedo (Snow)




Annual mean albedo

Both Latitude and Snow duration are positively correlated and both are positively correlated with E-facing, vertical bifacial gains.

# Modeling Backside Irradiance

$$\text{Rear Irradiance Ratio} = \frac{G_{rear}}{G_{front}}$$

$G_{front}$ is calculated using conventional transposition models

- e.g., Perez, Hay & Davies, etc.

$G_{rear}$ depends on many factors

- Ground-reflected irradiance (albedo, tilt, height, row-spacing, position in row, Sun position)
  - Sunlit ground
  - Shaded ground
- Sky-diffuse irradiance (tilt, row-spacing, sun position)
- Direct irradiance on back of array (tilt, azimuth, Sun position (season, latitude))

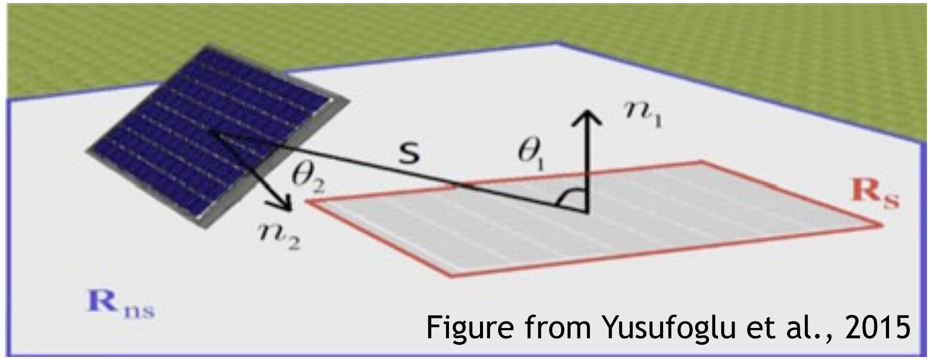
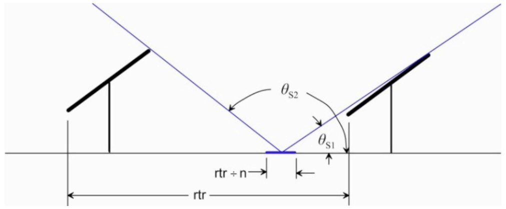


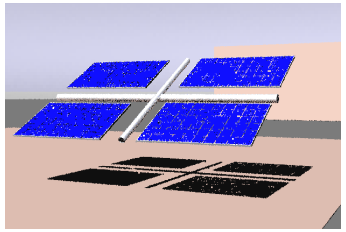

Figure from Yusufoglu et al., 2015

$R_{ns}$ is unshaded ground
$R_s$ is shaded ground
S is the distance from module/cell to shadow

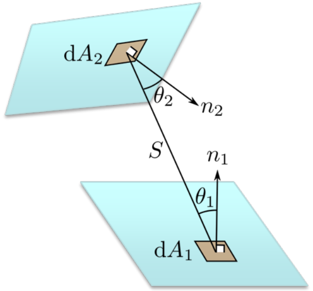
2D View Factor

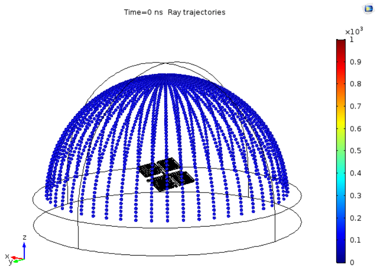



3D Ray Trace



3D View Factor

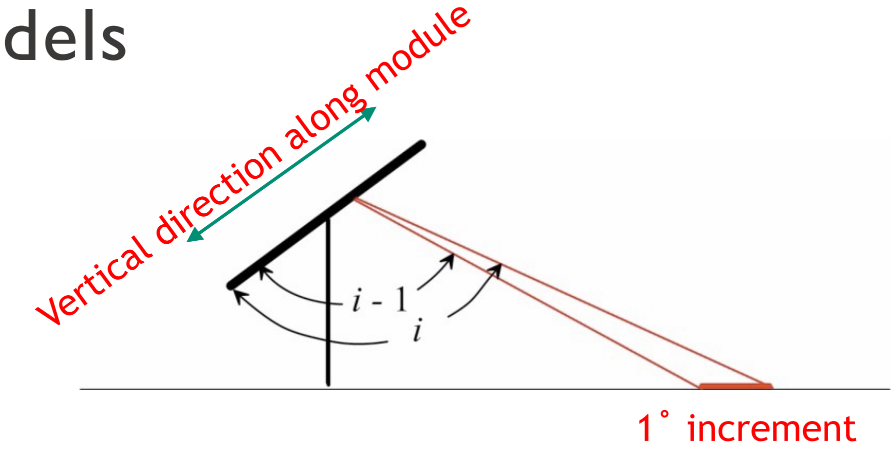


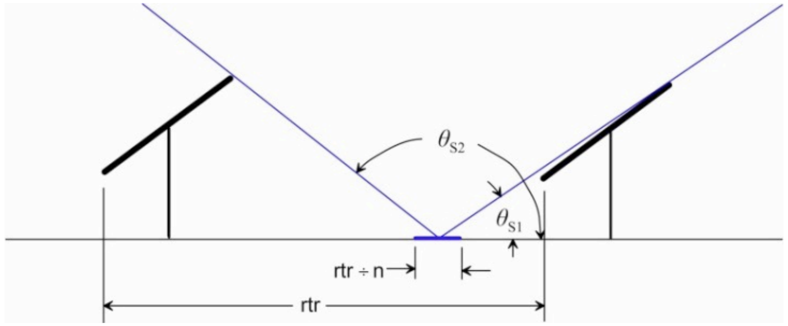



# View Factor Models

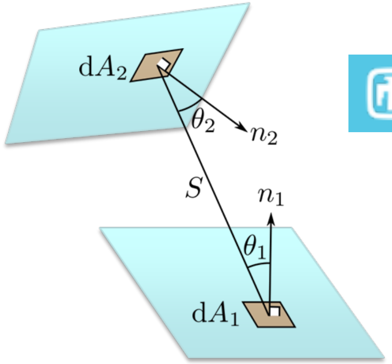
## 2D View Factor

- NREL model calculates backside irradiance for each row of cells and builds an irradiance profile along the "vertical" direction of the module or array.
- Backside irradiance at a point on the module is the sum of:
  - AOI corrected beam irradiance + $\sum_{i=1^\circ}^{180^\circ} VF_i F_i I_i$
    - ➢ $VF_i$ = view factor for each increment
    - ➢ $F_i$ = AOI correction
    - ➢ $I_i$ = Irradiance viewed by the i[th] increment




- Irradiance is either from sky diffuse, ground reflected, or reflected from other parts of the array (rows behind).
- PVsyst implements a similar approach.




## 3D View Factor

Sandia model is similar to 2D model except integration is performed over 2D ground grid and 3D objects.

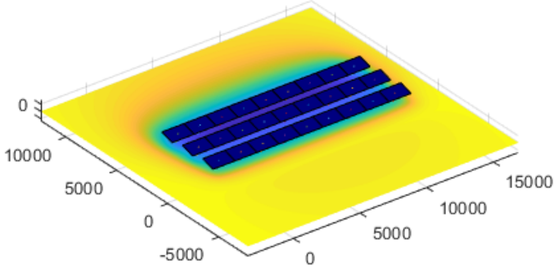
$$F_{1\to 2} = \frac{1}{A_1}\int_{A_1}\int_{A_2} \frac{\cos\theta_1 \cos\theta_2}{\pi s^2}\, \mathrm{d}A_2\, \mathrm{d}A_1$$

$$E_{back,k}(t) = E_{ground,k}(t) + E_{sky}(t) VF_{k\to sky} + E_{beam}(t)$$

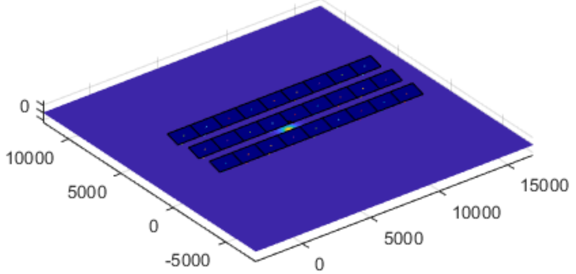
$$E_{ground,k}(t) = \sum_i \alpha_i G_i(t) VF_{i\to k}$$

- Backside irradiance is calculated for each 2D cell
- Ground irradiance is calculated on a 2D grid
- Other modules and structures cast shadows on ground but do not directly reflect light to cells.

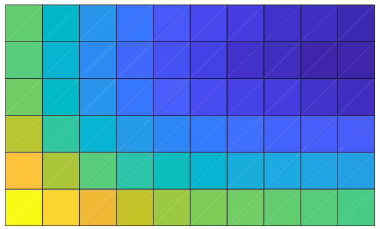
Ground to sky view factors




View factors for Row2 Pos5, Cell (1,1)




Backside irradiance map




Hansen, C. W., et al., 2017,. A Detailed Model of Rear-Side Irradiance for Bifacial PV Modules. 44th IEEE PVSC. Washington DC. SAND2017-6554 C.

Marion, B., et al., 2017. A Practical Irradiance Model for Bifacial PV Modules. 44th IEEE PVSC. Washington DC.

# 3D Ray Trace Model for Bifacial PV

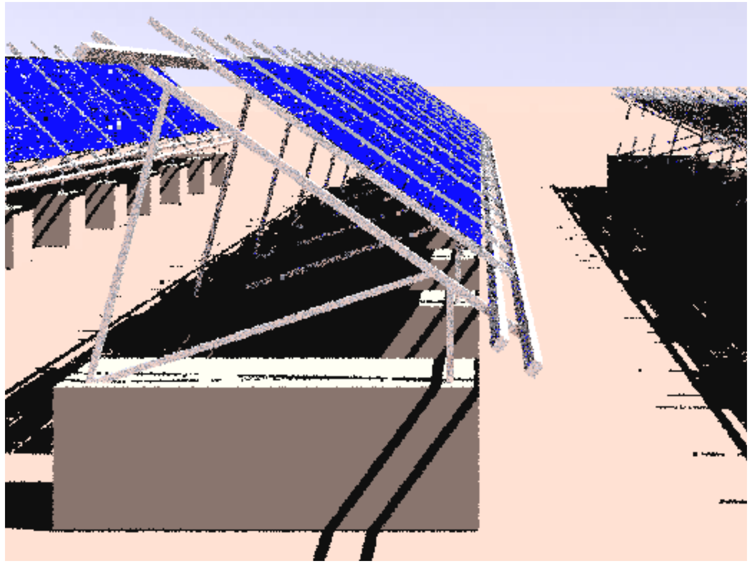
Based on RADIANCE (reverse ray tracing model developed at LBNL)

Can include complex objects (racking, ballast, equipment racks, etc.)

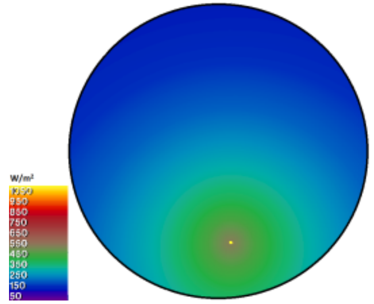
Computationally complex

- Run times are slow, model is stochastic

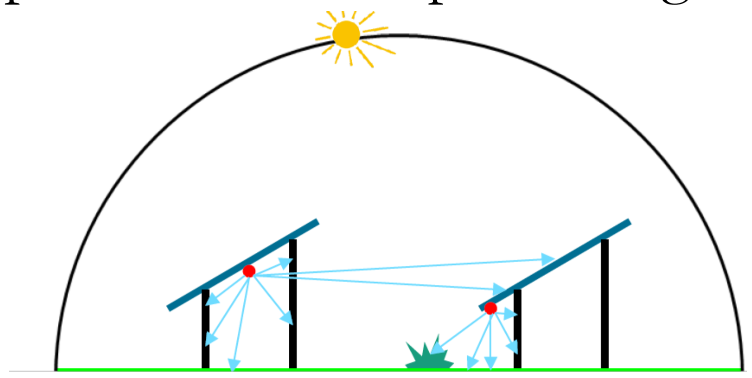
Each simulation is independent so the problems is perfect for multi processing on a cluster.



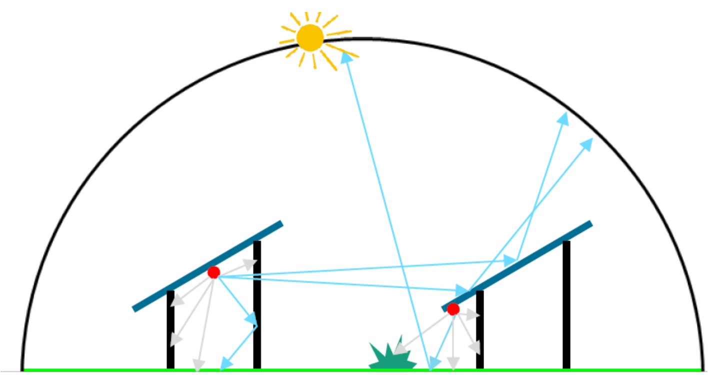
Example sky dome light source



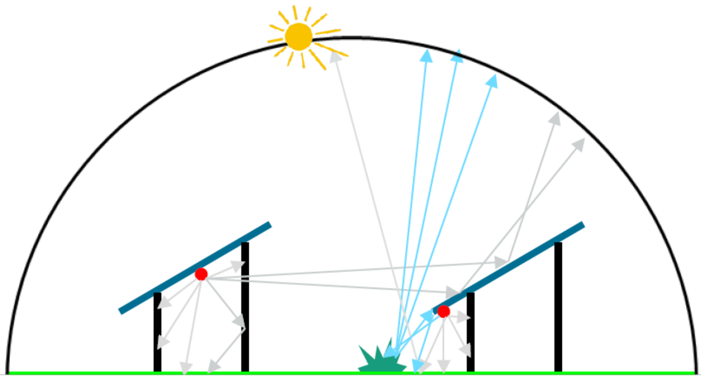
Single hourly Perez sky (W/m²)



1. Rays are traced in all directions from sensor points. The sky dome is a heterogeneous light source.



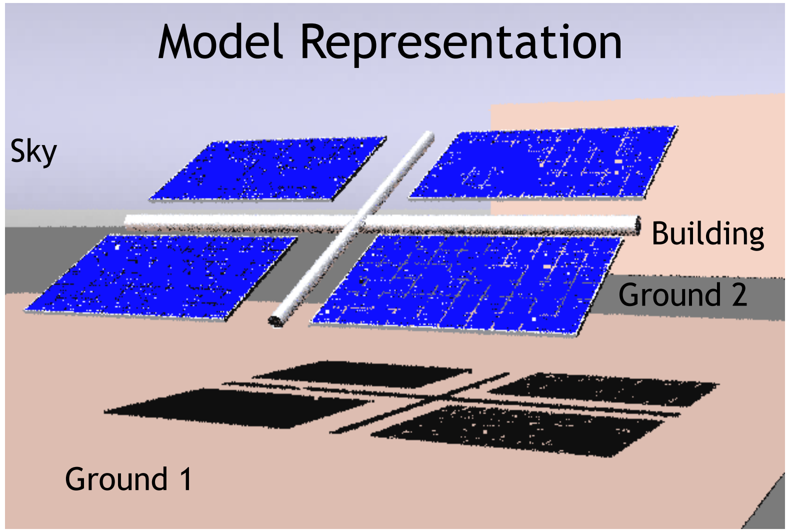
2. Rays bounce off surfaces. Specular and diffuse reflections are considered. Multiple bounces are allowed.



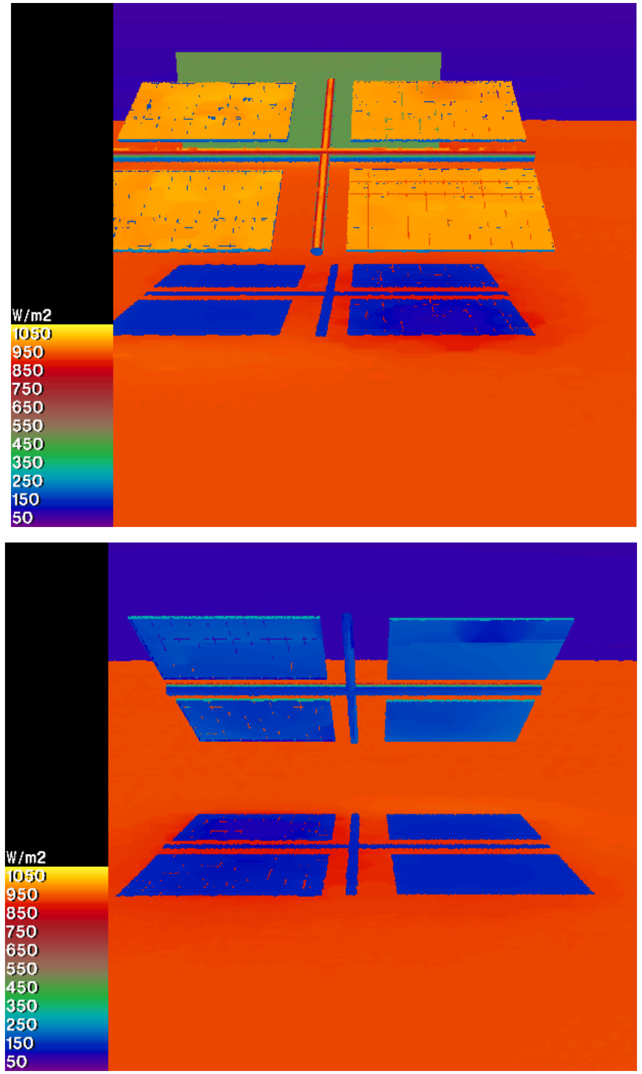
3. Light reaching sensor points is calculated by adding up all the rays that reach the sky and considering losses from absorption.

# Example Ray Trace Modeling Results

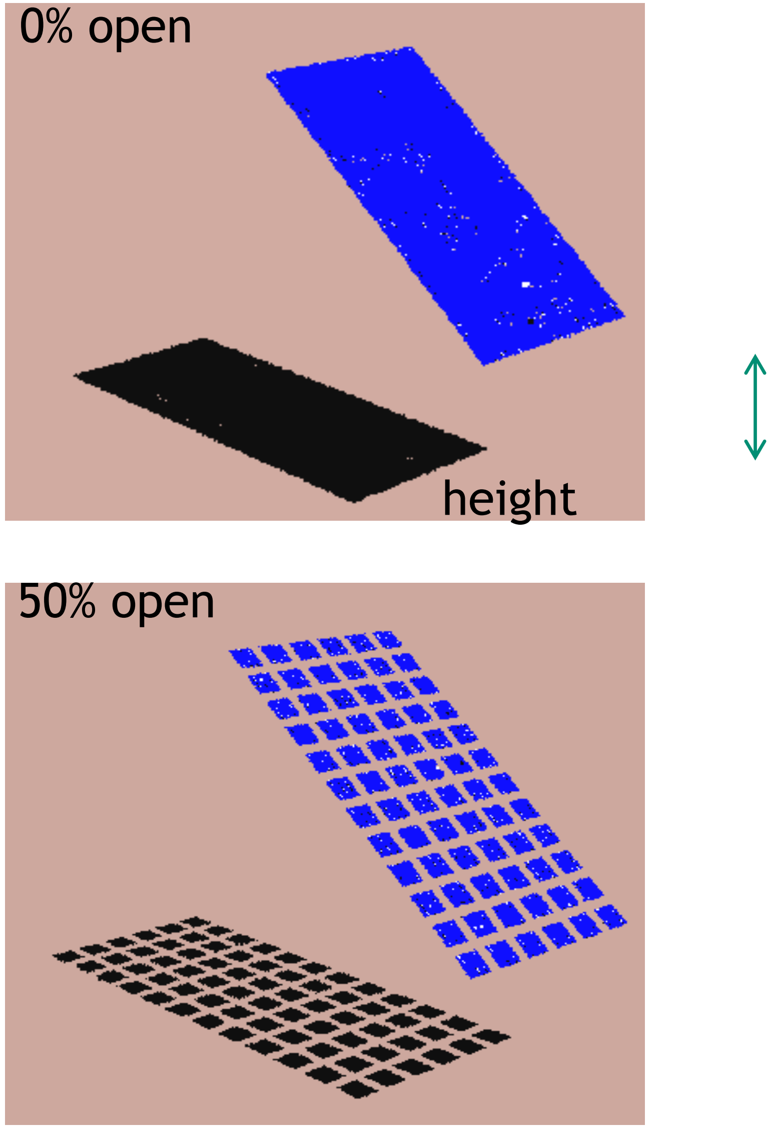
Real system

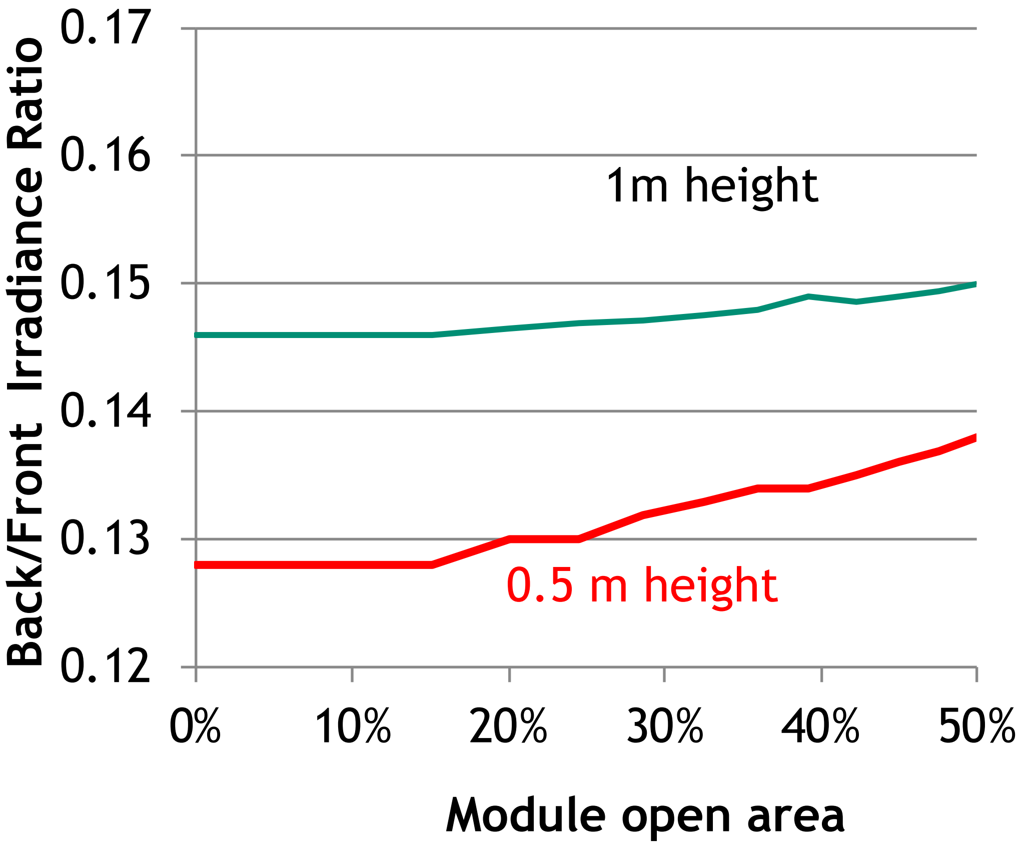



Irradiance Results



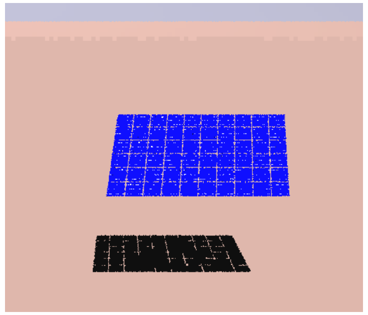
# Effect of height and cell spacing on back + front irradiance



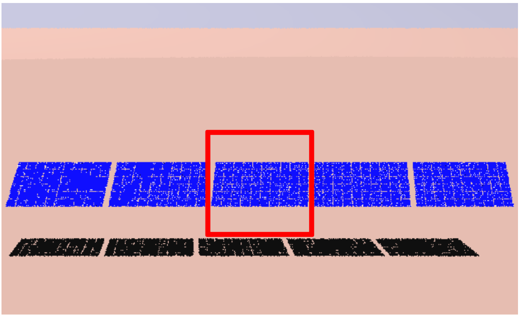




- Increasing height of module from the ground increases backside irradiance.
- Increasing space between cells increases backside irradiance, but at the expense of reducing active area, which is not economic unless it adds additional value (e.g., visual appeal).

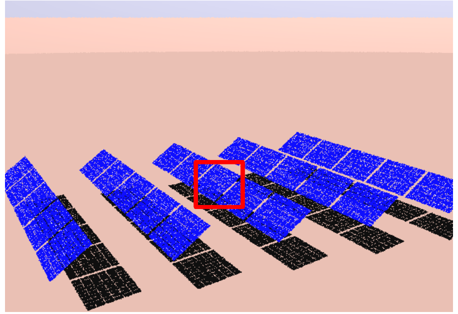
# Effect of system size



Single module

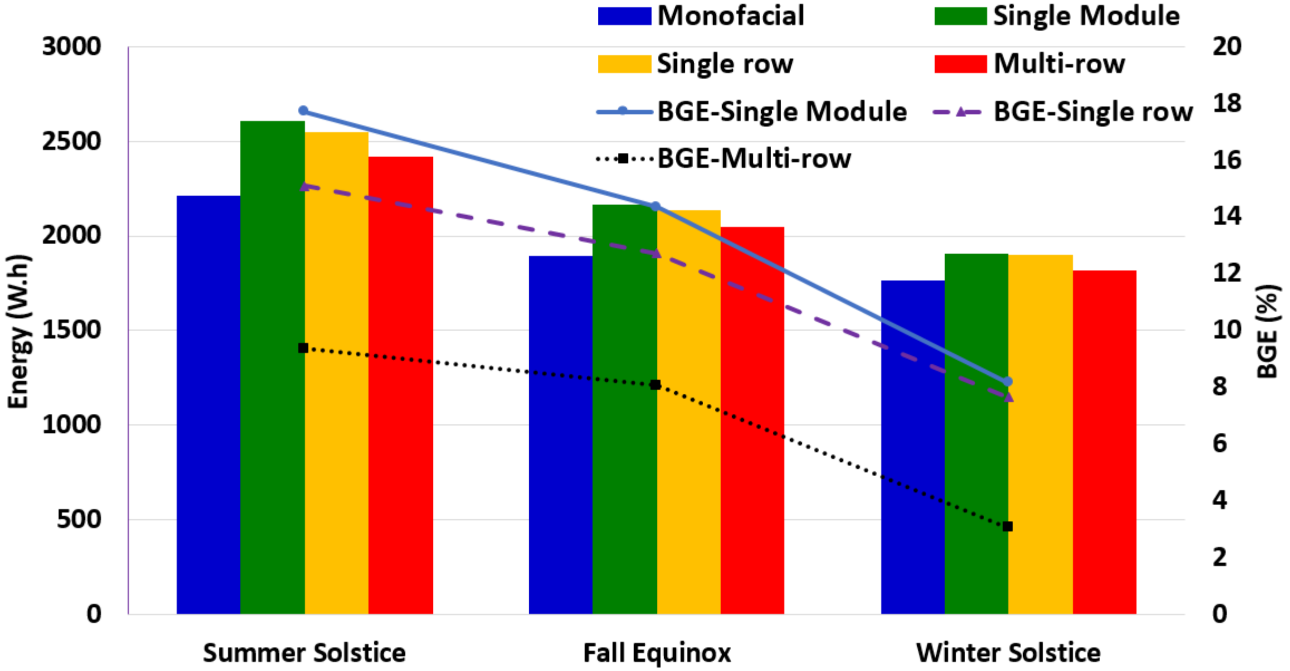


A row consisting of five modules



Five rows, each with five modules

Input Parameters
- Albedo = 0.21
- height = 1.5 m (lower edge)
- Tilt = optimal




## Bifacial Gain Results

| Module | Summer | Equinox | Winter |
|---|---|---|---|
| Single module | 18% | 14% | 8% |
| Single row | 15% | 12% | 7% |
| Multi-row | 9% | 8% | 3% |

Asgharzadeh, A. et al. 2018. “A Sensitivity Study of the Impact of Installation Parameters and System Configuration on the Performance of Bifacial PV Arrays.” IEEE Journal of Photovoltaics 8(3): 798-805.

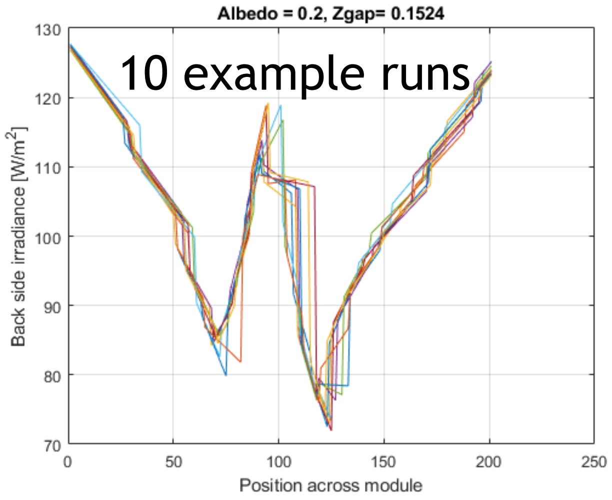
# Bifacial PV on Single Axis Trackers – Torque tube shading

Single axis trackers are typically either 1-up portrait or 2-up portrait.

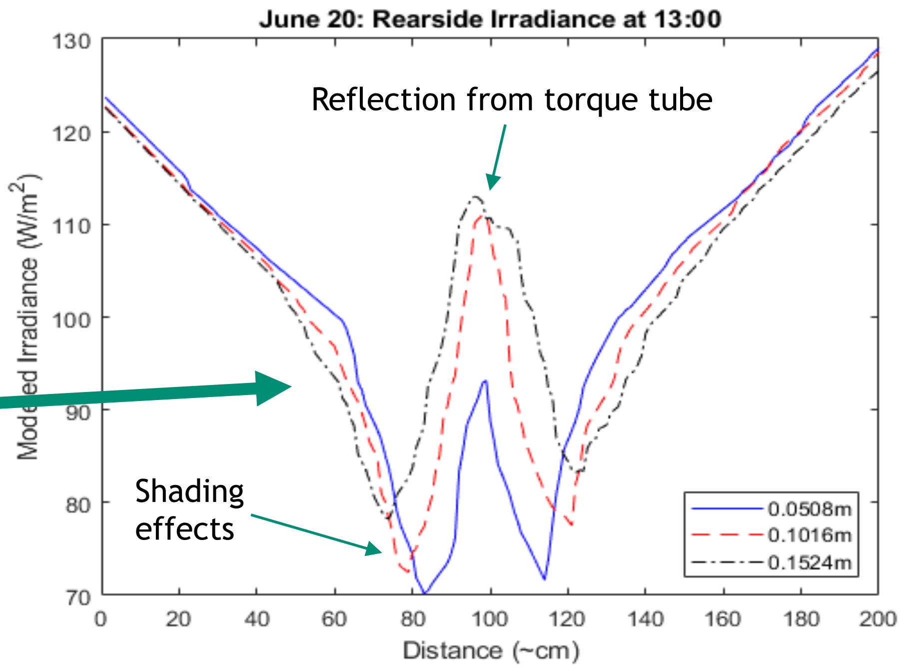
- 1-up experiences less wind load but has torque tube shading

Initial ray tracing calculations were run to test the effect of different torque tube gaps (distance between module and torque tube). Two rows of trackers were simulated.

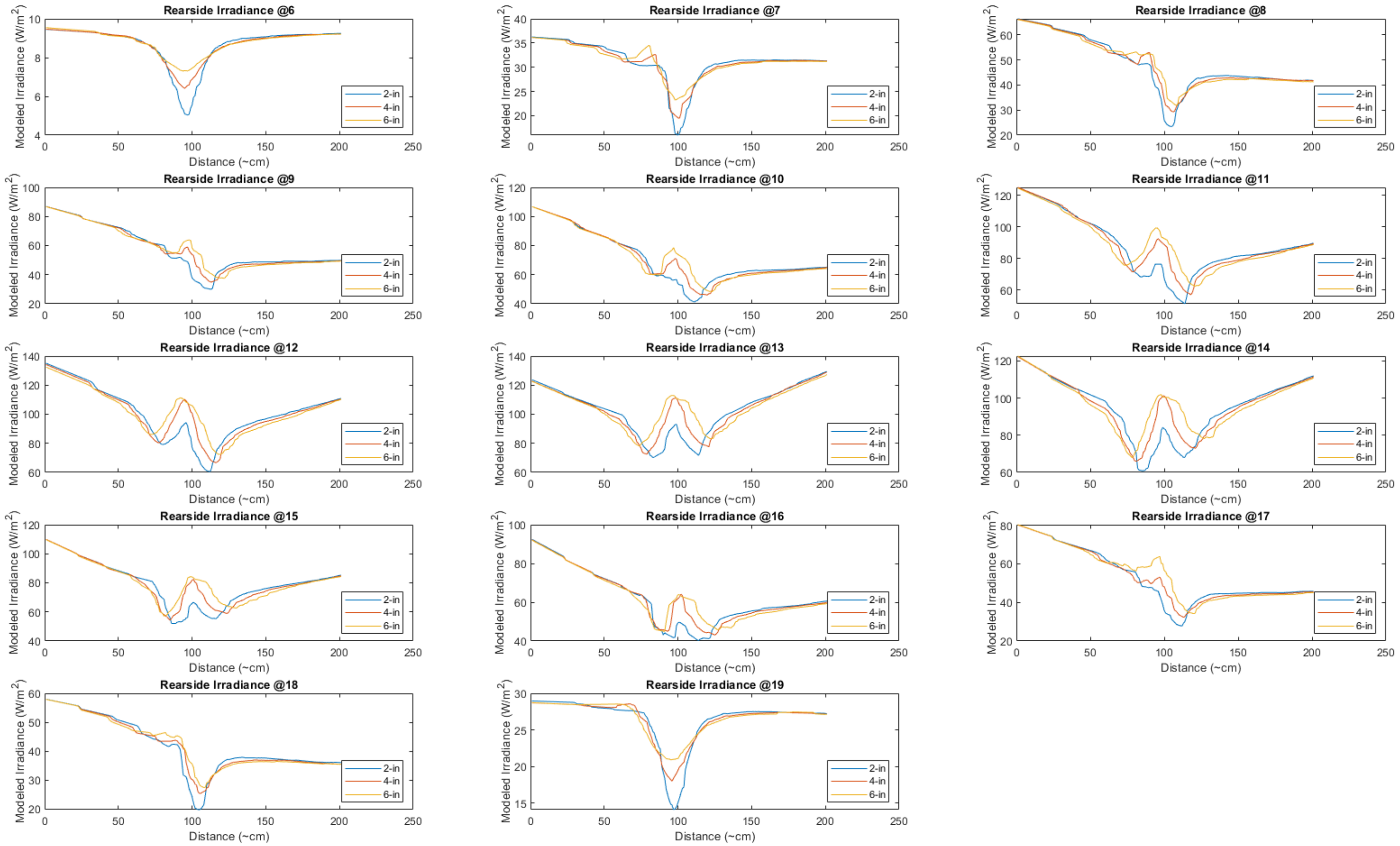
- Runs took several hours on a desktop machine.
- Only able to run single days at hourly intervals.
- Model is stochastic and several runs are averaged to obtain repeatable results.




Each profile is an average of 10 runs



# Model Results for a Single Clear Summer Day




Moving torque tube further from module increases irradiance directly behind but decreases irradiance further away.

# Sensitivity to Albedo and Torque Tube gap

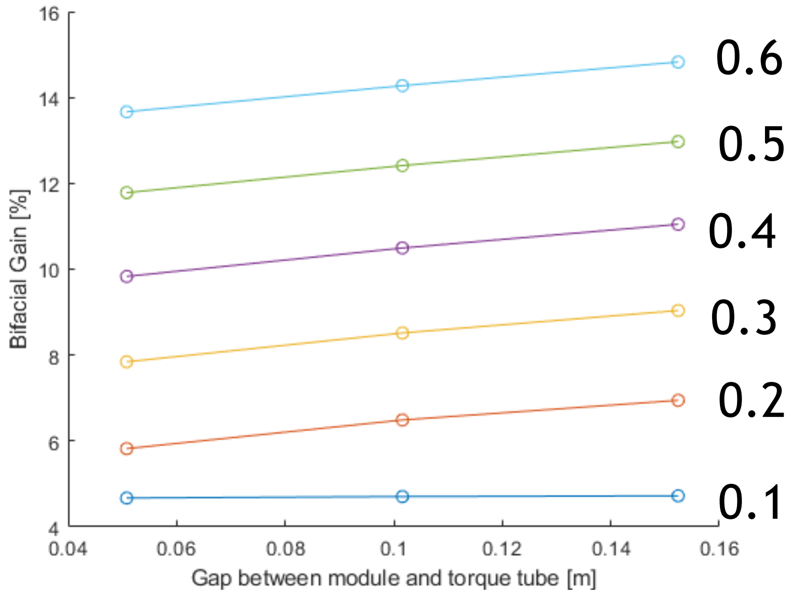
Bifacial gain in this example

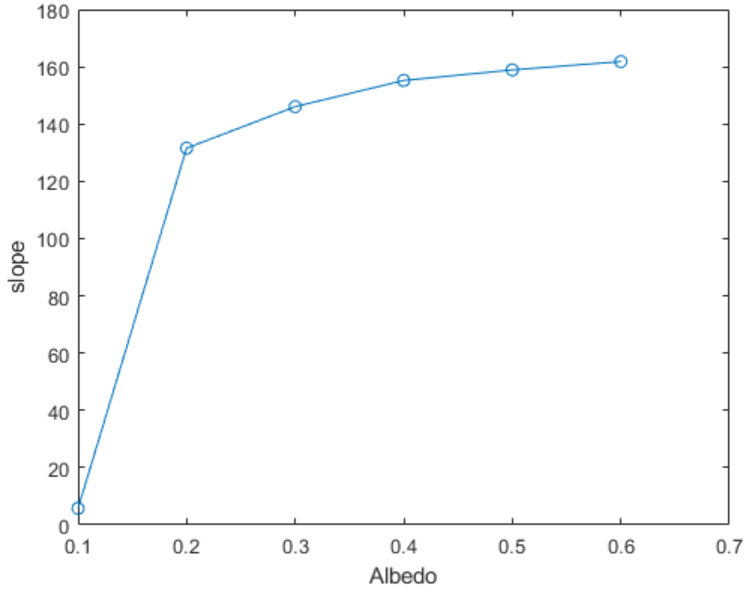
- Calculated assuming bifaciality = 100% and no mismatch
- Highest sensitivity is to albedo
- Low albedo (0.1) BG = ~4.5%
- High albedo (0.6) BG = ~14%

Effect of torque tube gap is small (unless mismatch is important)

- Changing the torque tube gap from 0.0508 m (2 inches) to 0.1524 m (4.5 inches) resulted in about 1% increase in BG.

*This simulation is limited to a single day



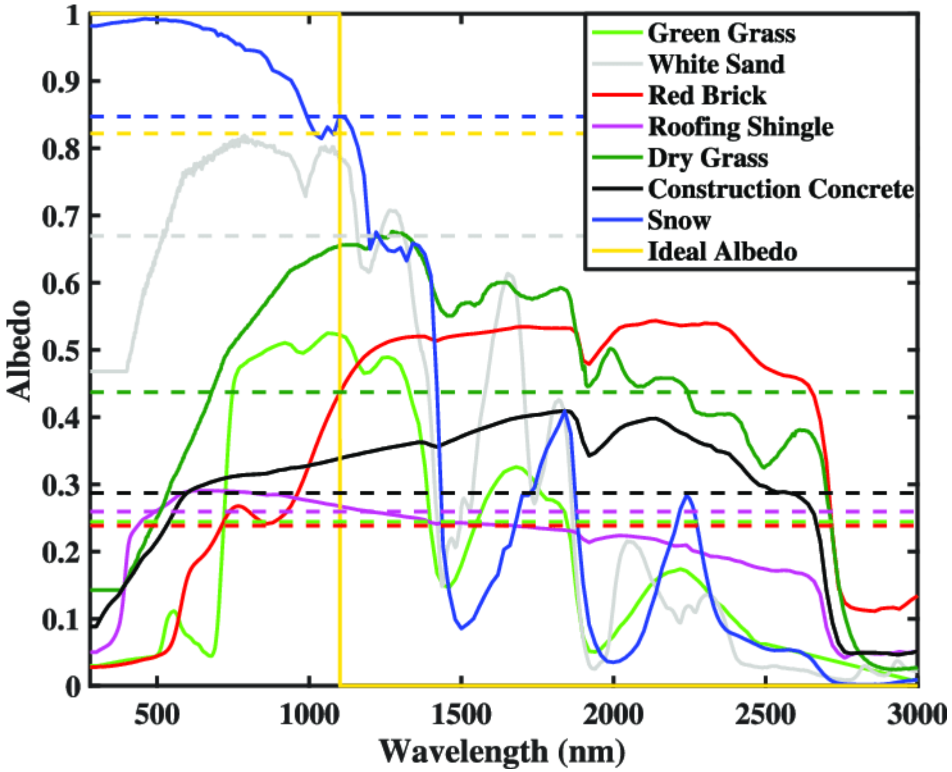
# Future Modeling Needs

Evaluation of small changes in module and/or system designs
- e.g., effect of partial shading from frame, mounting hardware, racking, etc.

Evaluation of performance over full year (subhourly)

Evaluation of spectral effects of backside irradiance

Optimization and sensitivity analyses
- What is the best design?




All of these require many simulations and a high level of detail

C. R. Russell, Thomas & Saive, Rebecca & Augusto, Andre & G. Bowden, Stuart & Atwater, Harry. (2017). The Influence of Spectral Albedo on Bifacial Solar Cells: A Theoretical and Experimental Study. IEEE Journal of Photovoltaics. PP. 1-8. 10.1109/JPHOTOV.2017.2756068.



# High Performance Computing

We are transferring the *bifacial_radiance* model to a high performance computing (HPC) environment.

- This has required some code changes to address "race conditions" (e.g., files being read by multiple processors at the same time). We are currently addressing these issues.

Our current goal is to run an entire annual simulation (e.g., 8760 hourly timesteps) in 5-10 minutes or less.

We plan to use DAKOTA to run sensitivity studies and optimizations.

DAKOTA also has the capability to generate surrogate, reduced order models from a collection of model outputs.

Questions include:

- How do design parameters effect annual bifacial PV performance in different locations (e.g., latitudes)?
- How much more energy might one produce by engineering the ground surface to be more reflective?
- Innovative system designs for various applications such as:
  - Fixed tilt, ground mount
  - Single axis tracking
  - Elevated parking structures
  - White flat commercial roofs
  - Hybrid designs?

# Takeaways

Bifacial PV is not a fad, modern cell designs are easily made bifacial, bifacial outperforms monofacial in open rack configurations.

Bifacial gain is a flawed metric but it can be useful. – Beware of excessive claims!

System size, design, and configuration for bifacial PV is very important

- A single bifacial PV module out in the open can have bifacial gains exceeding 40% while bifacial gains for a larger, multirow systems will likely be much lower.

The challenge of modeling the performance of bifacial PV lies in estimating the distribution of the backside irradiance.

- Two methods (view factor and ray-tracing) are used.
- Backside irradiance is non uniform – can result in current mismatch

Novel bifacial PV system designs are worth considering

- Vertical E-W deployments in high latitudes
- Carports / shade structures (height is good)
- Hybrid deployments (multiple orientations, mix of monofacial and bifacial?)
- Albedo enhancement

Computational requirements for such investigations will require high performance computing

- Sandia is working toward full numerical optimization using HPC.