Characterizing and modeling the performance of bifacial photovoltaic modules and systems

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PVPerformance MODELING COLLABORATIVE

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Team Acknowledgements

This work is a collaborative project between three institutions

- Sandia National Laboratories
  - Joshua Stein - PI
  - Cliff Hansen
  - Dan Riley
- National Renewable Energy Laboratory
  - Chris Deline – Co-PI
  - Bill Marion
  - Sarah MacAlpine
- University of Iowa
  - Prof. Fatima Toor
  - Amir Asgharzadeh (graduate student)

Factors Influencing Bifacial PV Performance

- Bifacial PV makes lots of promises. What is the reality?
  - Bifacial performance is affected by many more factors than monofacial PV performance. Our project aims to quantify these effects.
- Factors that affect irradiance on back (and front) of module
    - Sun position (latitude, season), Tilt and Azimuth
    - Height above ground
    - System size and configuration
    - Albedo
    - Obstructions and shadows, and system size (racking)
    - Snow and soiling factors
    - Others?
  - Factors that affect whether this light is converted to energy
    - Bifacial ratio (back/front module rating)
      - This varies from over 90% to much lower and depends on cell and module design.
    - Mismatch effects
    - Others?

3-Yr Bifacial Research Project

Collaborative project between Sandia, NREL and University of Iowa

Tasks:

1. Measure Outdoor Bifacial Performance

- Module scale
  - Adjustable rack IV curves (height, tilt, albedo, and backside shading effects)
  - Spatial variability in backside irradiance
  - Effects of backside obstructions and shading
  - Prism Solar RTC (tilt, orientation, and albedo effects)
  - Vertical bifacial modules at Turku University, Finland (latitude effects)
- String scale
  - Fixed tilt rack (tilt, system size, and mismatch effects)
  - Single axis tracker (investigate potential)
  - Two-axis tracker (investigate potential)
- System scale
  - String level monitoring on commercial rooftop system (validation data)

2. Develop Performance Models

- Ray tracing methods – Sensitivity studies
- View (Configuration) Factor methods

3. Support Rating Standards

- Support new bifacial rating standard being developed by IEC

Module-Scale Adjustable Rack

Holds four modules
- -2 bifacial
- -2 monofacial

Reference Cells
- -2 front facing
- -3 back facing

Multitracer
- -measures IV curves and module temps

Variabiles
- -Height
- -Tilt
- -Albedo

Module-Scale Adjustable Rack Results

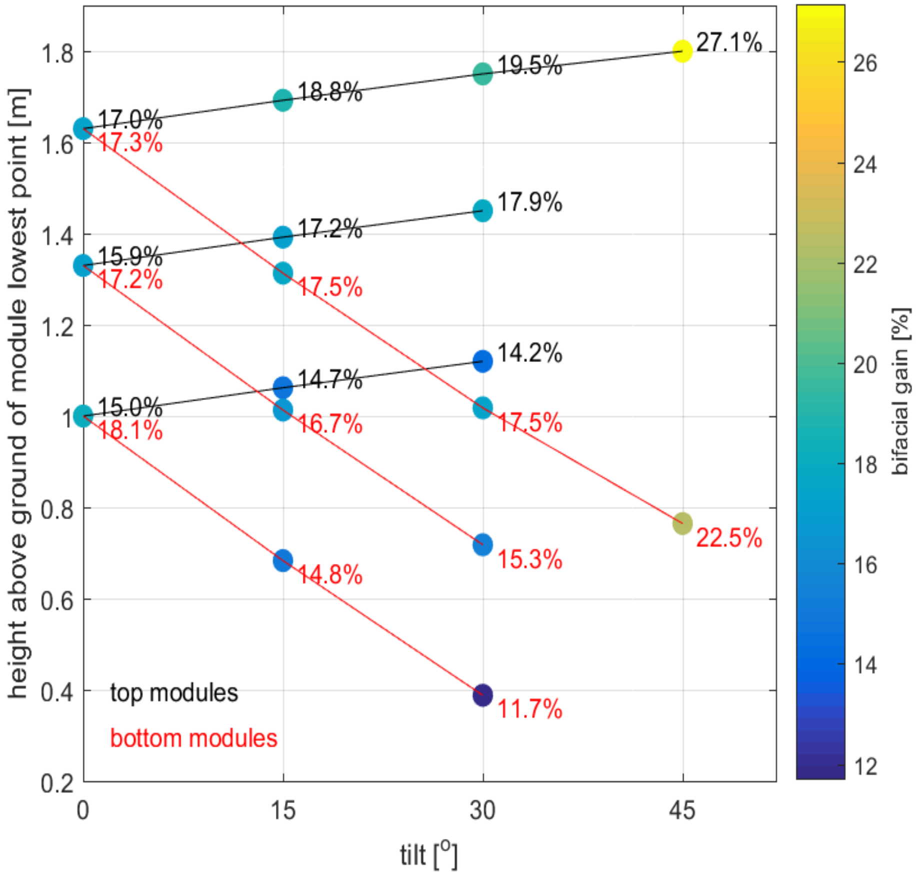
Initial Findings

- Bifacial gains increase as height of module increases.
- Bottom row module has highest bifacial gains, due to illuminated ground under and behind module.
- Bifacial gain seems to have a weak sensitivity to tilt angle.

Lit ground beneath bottom module

Bifacial Gain:

$$BG_i(t) = 100\% \times \left(\frac{P_{bifacial}(t) \;/\; Pmp_{bifacial}}{P_{monofacial}(t) \;/\; Pmp_{monofacial}} - 1 \right)$$

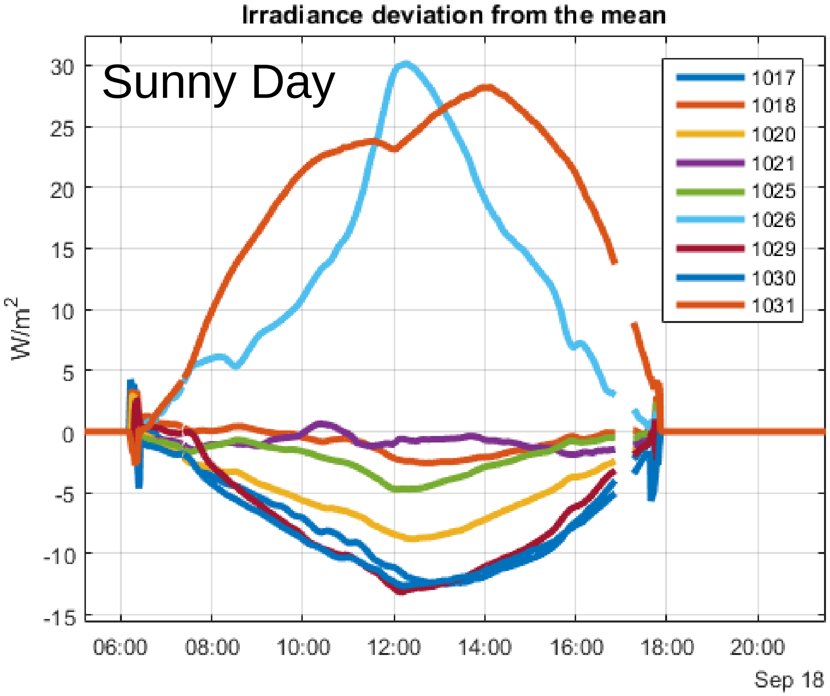


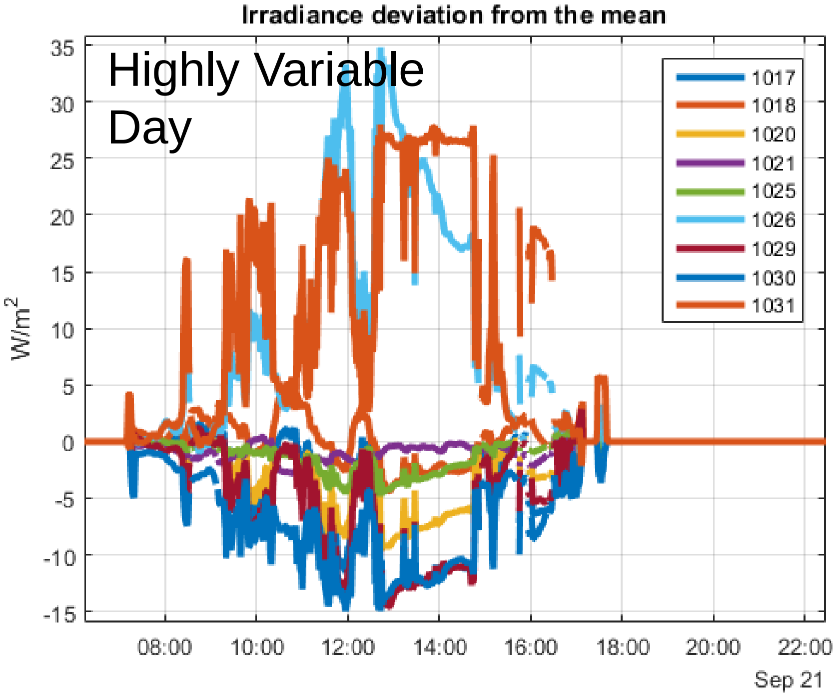
Backside Irradiance Mapping

- Measures 10 irradiances on the back side of a "module"
- "Module" can be moved and mounted anywhere to test different conditions
- Measurement cells calibrated to agree within 0.5%
- Data from the top mounting configuration shown on next slide

Backside Irradiance Mapping

Bottom cells exhibit higher irradiance values in this configuration





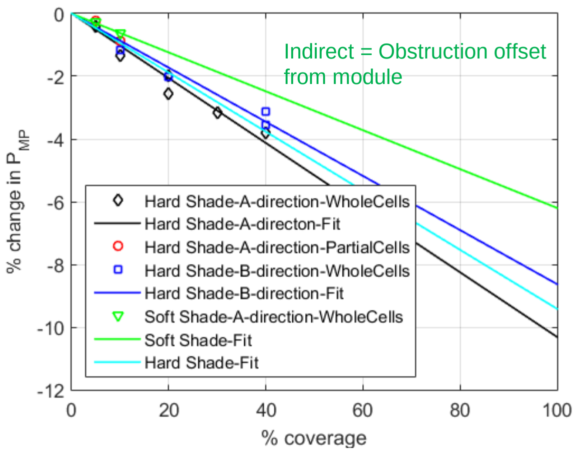
In this test configuration, irradiance on the backside differed by up to 42 W/m² on a sunny day

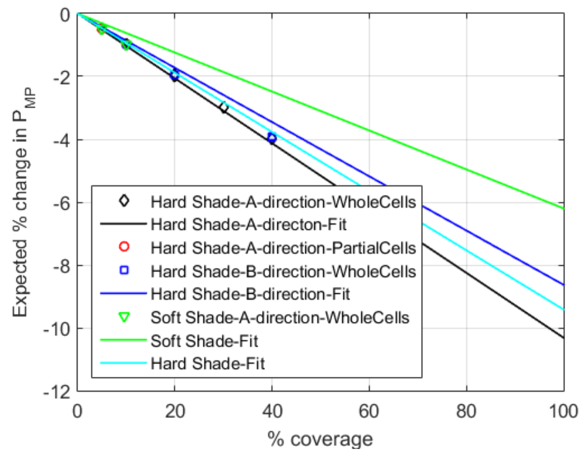
Effect of Backside Obstructions on Module Performance

We measured IV curves before and after applying backside obstructions from 5% to 40% in two directions (A & B).

Preliminary results show that the net effect of backside shading is generally linear with the percentage of coverage and back side irradiance.

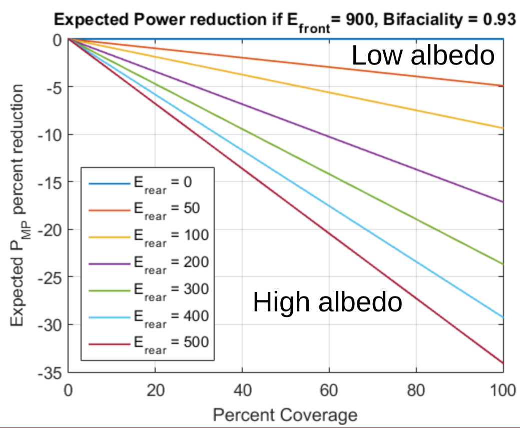
Example: 10% Backside Obstruction





A-direction: across cell strings

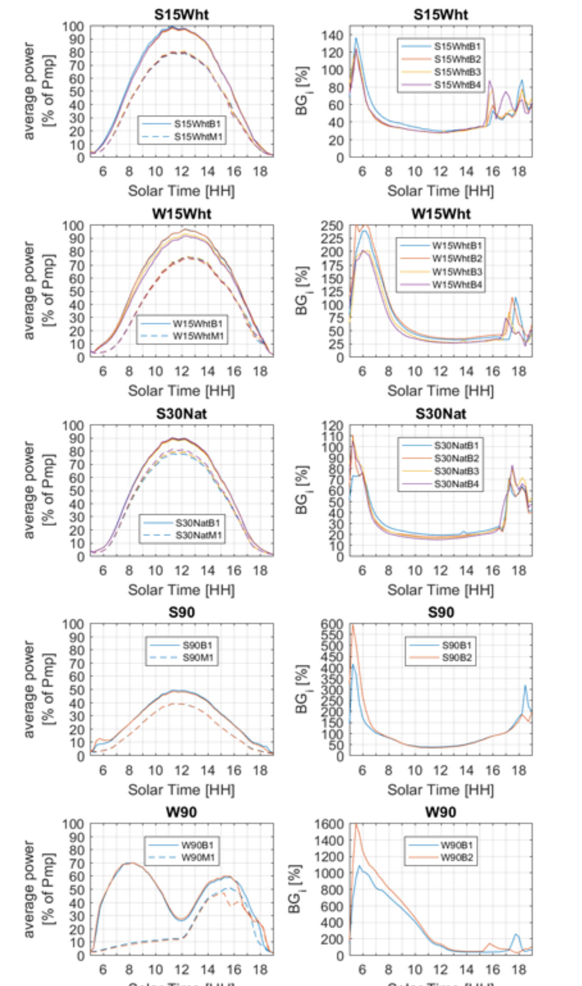
With 20% of backside covered, 2%-6% Pmp reduction expected. This needs to be validated.



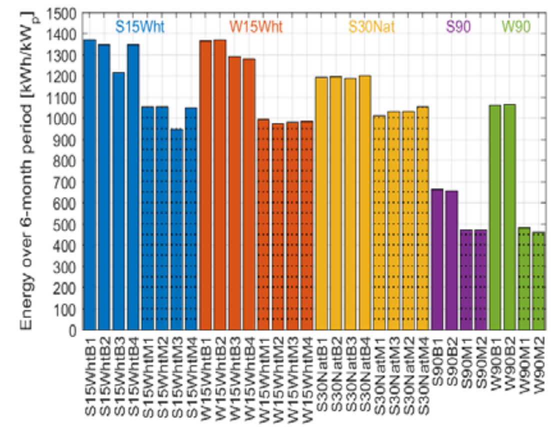
B-direction: with cell strings

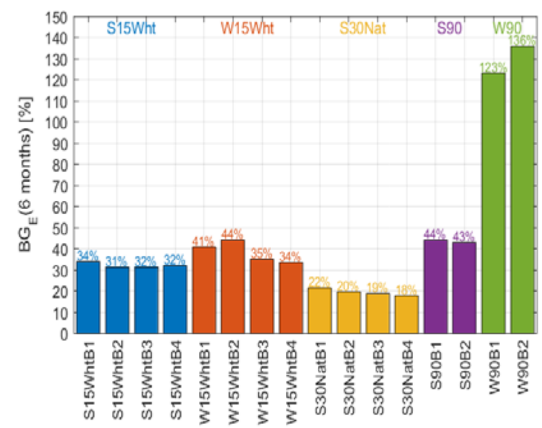
Prism Solar RTC System

Label	Orientation		Ground Surface
	Tilt	Azimuth	
S15Wht	15˚	180˚ (South)	White gravel
W15Wht	15˚	270˚ (West)	White gravel
S30Nat	30˚	180˚ (South)	Natural
S90	90˚	180˚ (South)	Natural
W90	90˚	270˚ (West)	Natural



- Five orientations
- Optimal racking (no backside shading)
- 6-month dataset (Feb-Aug 2016)
- Module-scale DC monitoring (I and V)
- Data corrected to front flash ratings
- Bifacial modules outperformed monofacial in all cases (energy).
- Bifacial power gains vary throughout the day.
- Bifacial energy gains ranged from 18%-136%
- W-facing vertical bifacial experienced bifacial energy gains over 100% likely due to cool morning and hotter afternoons.
- Bifacial advantages increase with non-optimal monofacial orientations.

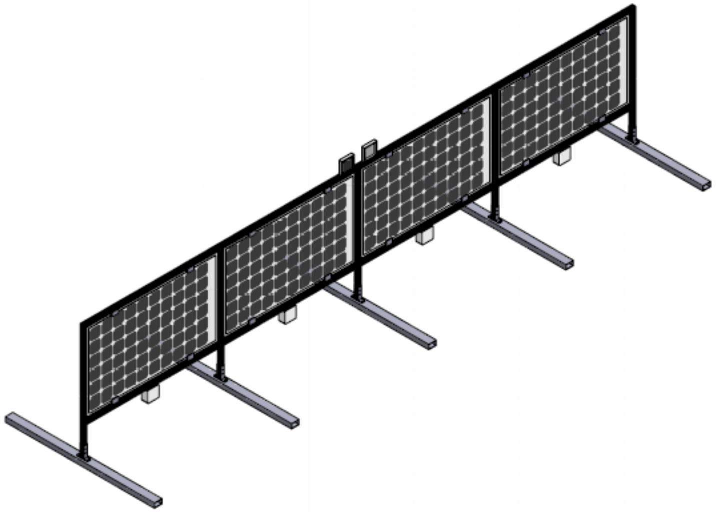




Vertical Bifacial in Finland

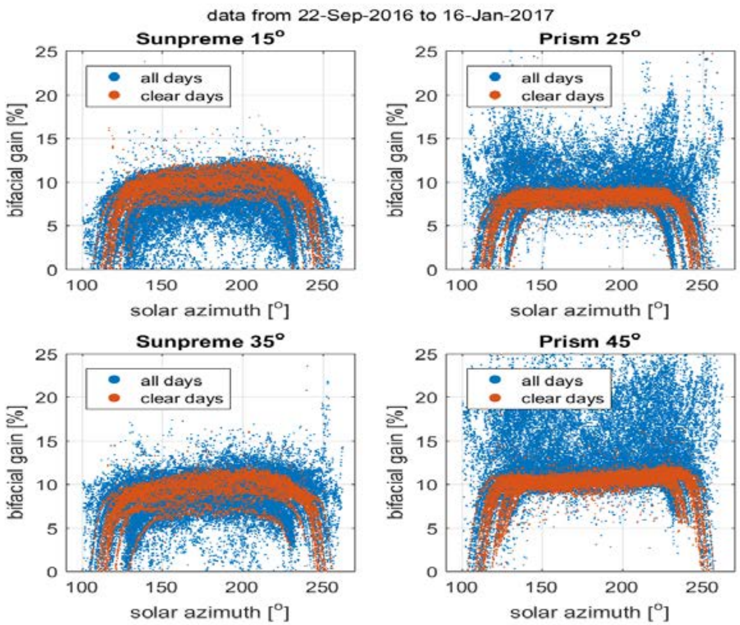
Sandia is partnering with Turku University of Applied Sciences in Finland to install vertical bifacial modules on rooftop.

- 60˚ N Latitude
- Individual modules will be monitored
- Reference cells on front and back
- Summer solstice sun rises and sets at 60˚ North and South of East and West, respectively.
- Vertical bifacial E-W should have significant benefits in Summer.
- Vertical orientation in winter with snow and low sun elevation should prove beneficial too.
- Contract placed. System installation expected before Summer solstice 2017.



Fixed Tilt String-Level Performance

- Four rows at 15˚, 25˚, 35˚,and 45˚ tilt.
- Each row has two strings of 8 modules (one monofacial and one bifacial)
- Modules are interspersed so rear side irradiance bias is minimized.
- Two types of bifacial modules are used:
  - Prism Solar (BG = 6%-10%+)
  - SunPreme performance is more variable (why is this?)
  - Lower gains in morning and afternoon may be caused by bifacial modules being shaded by the monofacial modules that stand off the rack due to thicker frames.



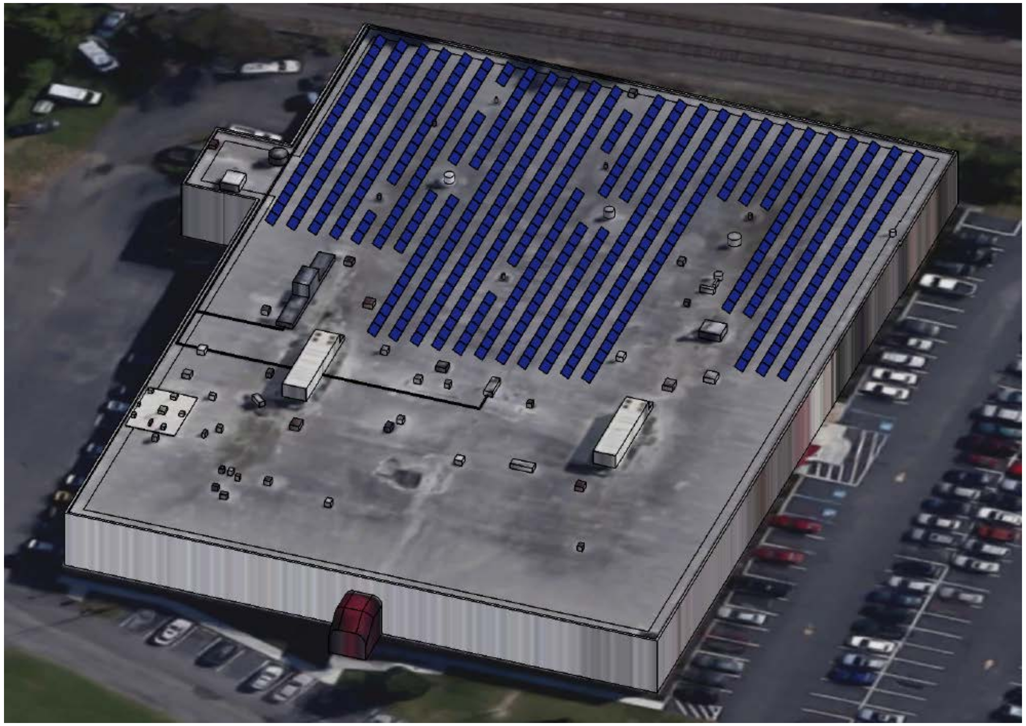
Fixed-tilt String-level Arrays

Stein, J. S., D. Riley, M. Lave, C. Deline and F. Toor (2017). Outdoor Field Performance from Bifacial Photovoltaic Modules and Systems. 44th IEEE PVSC. Washington, DC. Submitted.

Bifacial Single Axis Tracker (NM)

- Module and Inverters installed
  - String 1: Prism Solar
  - String 2: Sunpreme
  - String 3: TBD
  - String 4: TBD
- Inclinometers, front and back reference cells on each tracker
- Plan to have data flowing from systems in April.

Commercial Bifacial System



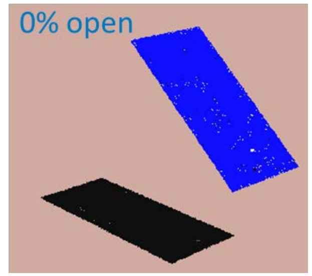
String level DC performance will be measured on four strings on this NY commercial rooftop bifacial system.

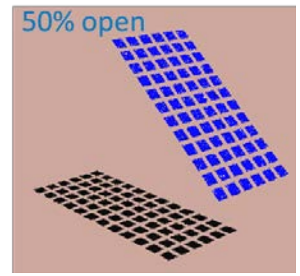
Modeling Sensitivity Studies

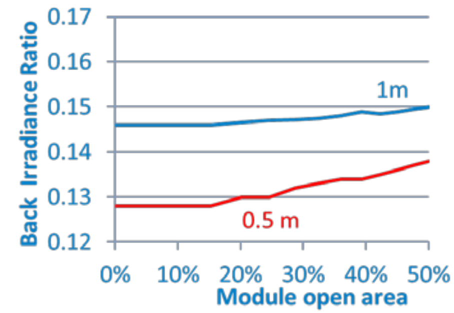
- Ray-Tracing model RADIANCE is being used by NREL and UIowa to infer backside irradiance sensitivity to several factors including:
  - Cell spacing in module
  - Height above ground
  - Module position in row
  - Number of rows
  - System size
  - Albedo

Modeling Sensitivity Studies (NREL)

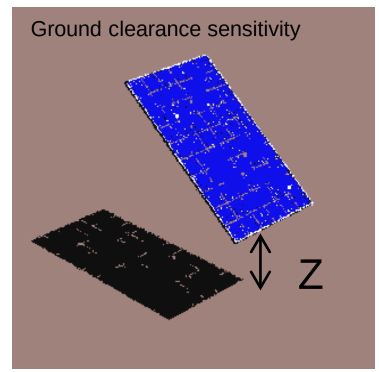
- Cell spacing impact
  - Slight effect

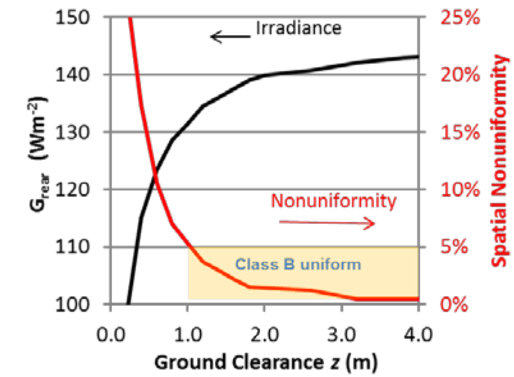




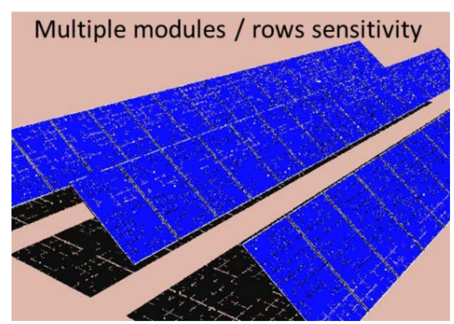


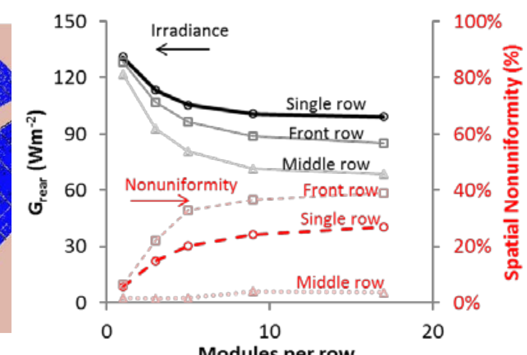
- Height above ground





- Effect of multiple rows and position in row





Deline, C., S. MacAlpine, B. Marion, F. Toor, A. Asgharzadeh and J. S. Stein (2017). "Assessment of Bifacial Photovoltaic Module Power Rating Methodologies – Inside and Out." Journal of Photovoltaics 7(2): 575-580.

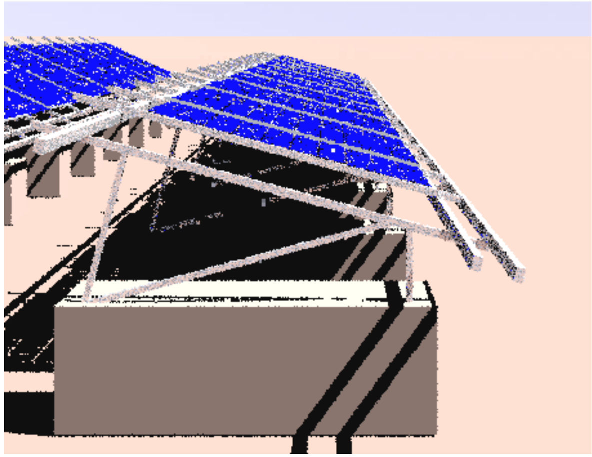
Modeling Sensitivity Studies (UIowa)

- Run 1:
  - They have build a 3D model of the fixed tilt bifacial test bed at Sandia.
  - The model was run for hourly intervals for single days using measured irradiance data
  - backside measured irradiance was compared to modeled
  - Several scenarios were run
    - Compare backside irradiance measurements and simulations
    - Determine effects of racking and ballast
- Run 2:
  - Investigate the effects of:
    - System size, albedo, height, and tilt

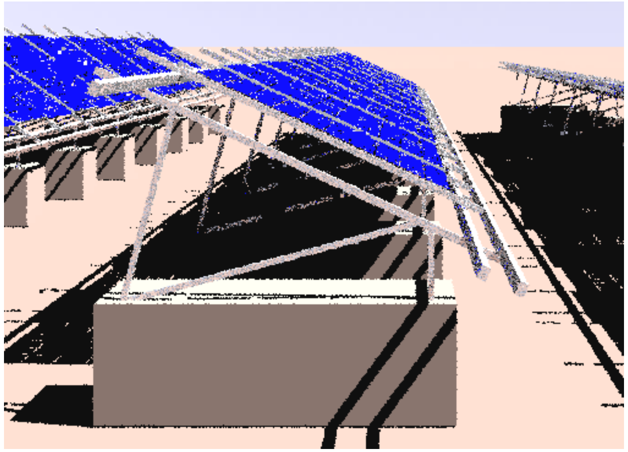
Fixed-tilt String-level Arrays

This work was performed by Amir Asgharzadeh and Fatima Toor (University of Iowa)

Modeling Sensitivity Studies (UIowa)



S15



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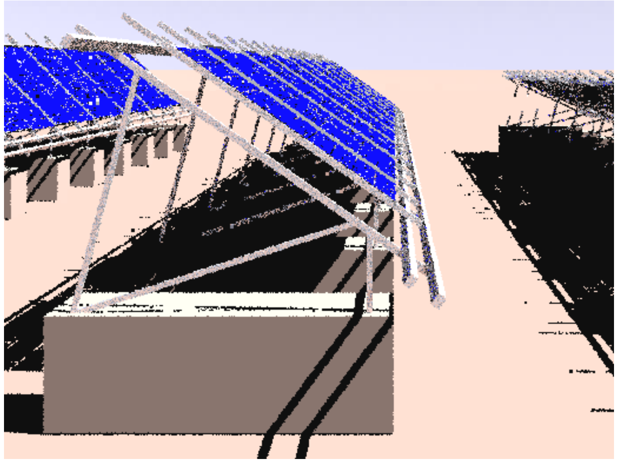

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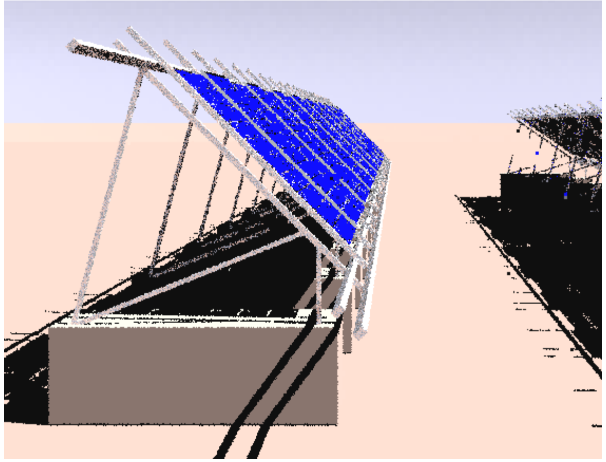

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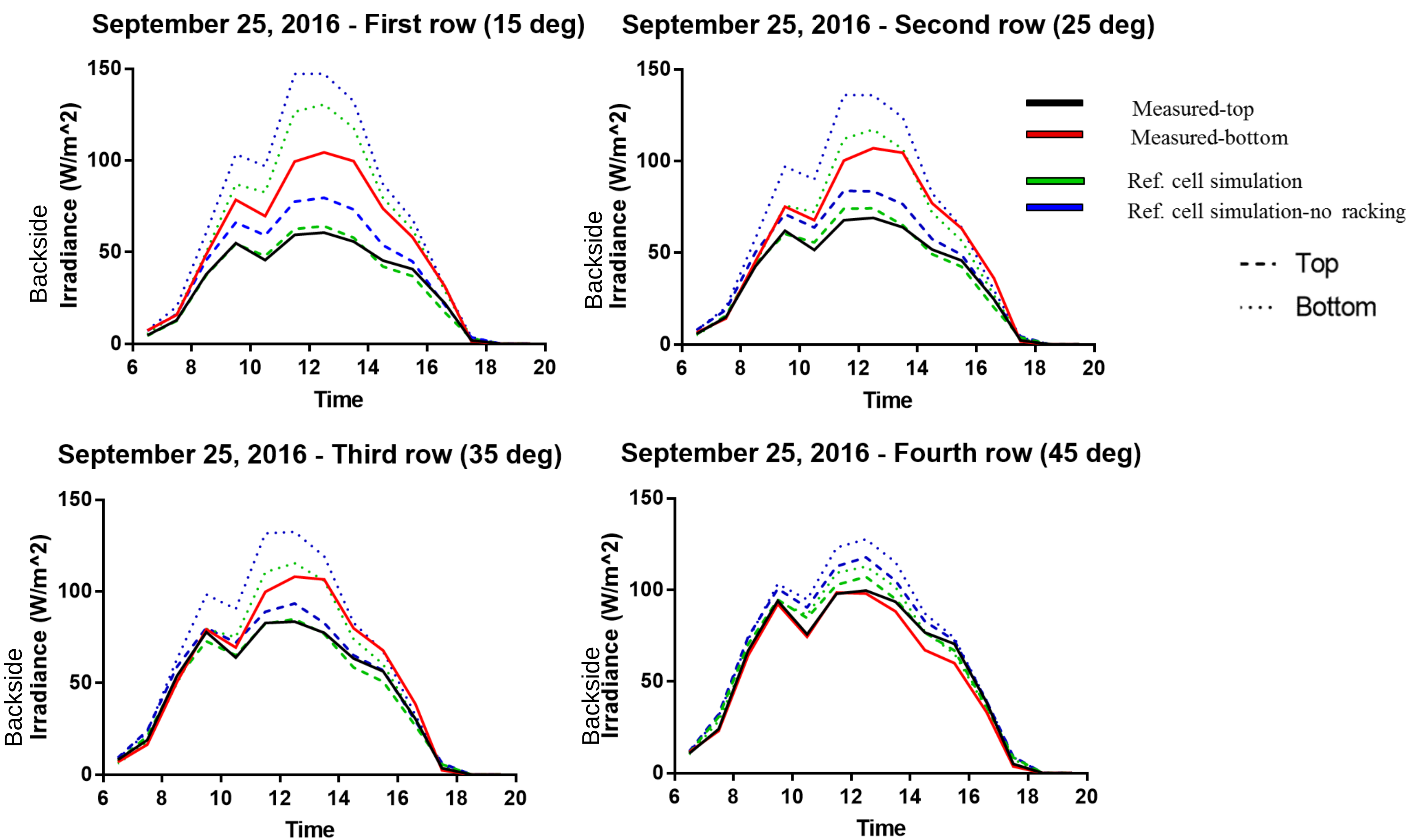
This work was performed by Amir Asgharzadeh and Fatima Toor (University of Iowa)

Modeling Sensitivity Studies (UIowa)

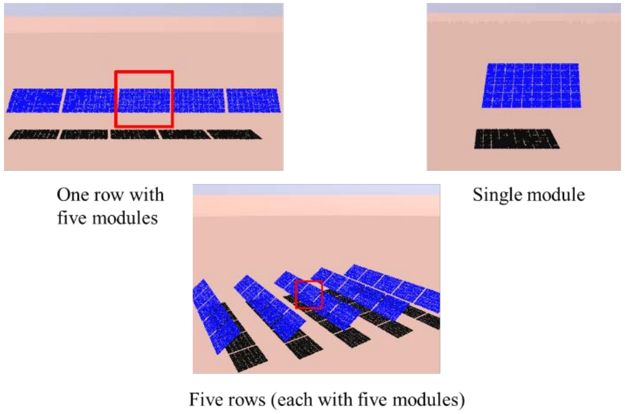


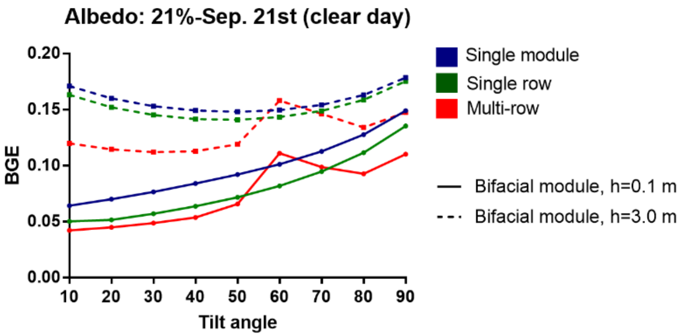
This work was performed by Amir Asgharzadeh and Fatima Toor (University of Iowa)

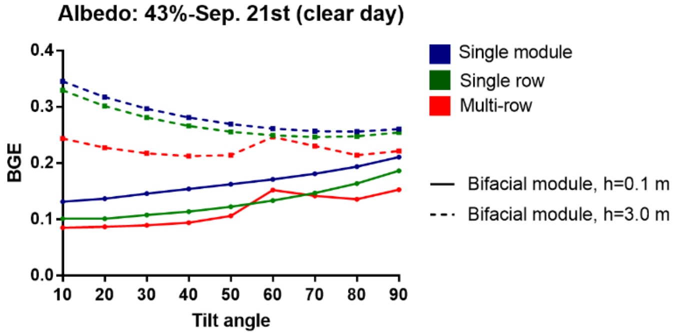
Modeling Sensitivity Studies (UIowa)

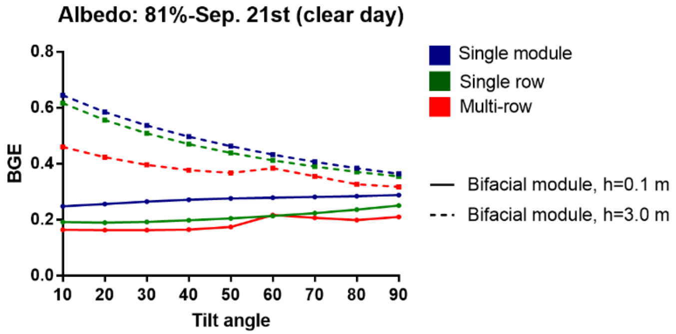
UIowa used RADIANCE to test the sensitivity of system size on bifacial performance gains.

- Computationally expensive (only six days were simulated)
- Simulated middle modules on three different arrays
- Varied tilt, height, and albedo for each array
- Results:
  - System size is important (color)
  - Height is important (line vs dashed)
  - Albedo is important (plot)
  - Tilt effect varies with albedo and height









This work was performed by Amir Asgharzadeh and Fatima Toor (University of Iowa)

Summary and Future Work

- Bifacial PV offers and delivers extra energy per m^2 of array.
- Bifacial gain varies as a complex function of sun position, tilt and azimuth angles, albedo, system size, and backside obstructions.
- Predictive models are making progress in representing these factors.
  - Detailed ray tracing methods appear to be able to represent these effects, however they are computationally expensive.
  - View factor methods, not discussed here, may be able work almost as well, and run faster (allowing 8760-hourly runs).
  - Development and validation continue with both approaches.
- Project goals for 2018 include:
  - Develop and validate predictive models that can evaluate system performance and LCOE. – Balance detail with speed of calculations
  - Publish design guidelines for bifacial PV systems.
  - Publish and compare bifacial performance for different applications.

Questions?

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