SAND2018-12390PE

PV Performance
What is the future?




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Nicosia, Cyprus

PRESENTED BY

Joshua S. Stein

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SAND2018-XXXX

Outline

- What is the future of PV?
- How might it change?
- What are the opportunities?

- Review of PV monitoring approach used by Sandia National Laboratories
- Soiling and Snow Stations
- Monitoring Example from Sandia
  - Bifacial PV systems on Single Axis Trackers
- Overview of the PV Performance Modeling Collaborative
  - Website
  - Open Source Software
  - Workshops

PV is a Disruptive Technology

Steven Sinofsky defines four "Stages of Disruptive Technologies"

1. ***Disruption of Incumbent***

   PV cells and modules offer "clean" and "free" energy but production costs are initially very high – Focus on small, off-grid systems & first adopters. PV's reliability "black eye" in the 1970's and early 1980's

2. ***Rapid Linear Evolution***

   Efficiencies rise, reliability and durability increases, production costs fall. Modules treated as a commodity.

3. ***Appealing Convergence***

   PV is cheapest form of electricity! Integration challenges remain (e.g., energy storage, market structure, demand response, etc.)

4. ***Complete Reimagination***

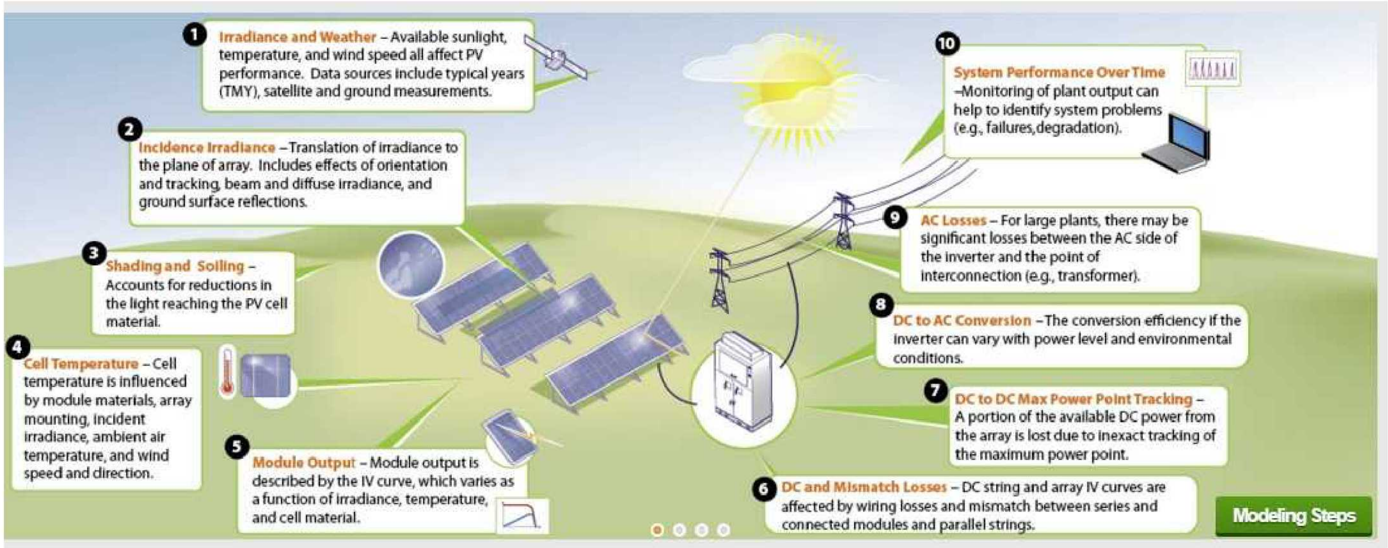
   Solar roofing (e.g., Tesla) and BIPV

   Solar Transportation (e.g., Toyota is aiming for: 70% of cars, 50 GW/yr. 8% GHG reduction) – ships, trains, etc.

   Solar roads, vertical bifacial, internal tracking (MOSAIC), adaptive shade response, conformable PV, lightweight, and much more beyond what we can now imagine…

Future PV products will have many different characteristics from today's modules. We need to be ready to characterize and model tomorrow's PV technologies.

Measuring and Modeling PV Performance



Factors that Affect PV Performance

- Irradiance (intensity, uniformity, spectrum, variability, reflection, soiling, albedo)
- Temperature (uniformity, effects of air temp, irradiance, wind, RH, etc.)
- IV Behavior (LID, linearity, metastability, mismatch)
- MPPT (string-module-cell level, DC/AC>1)
- System Performance over time (degradation, variability)

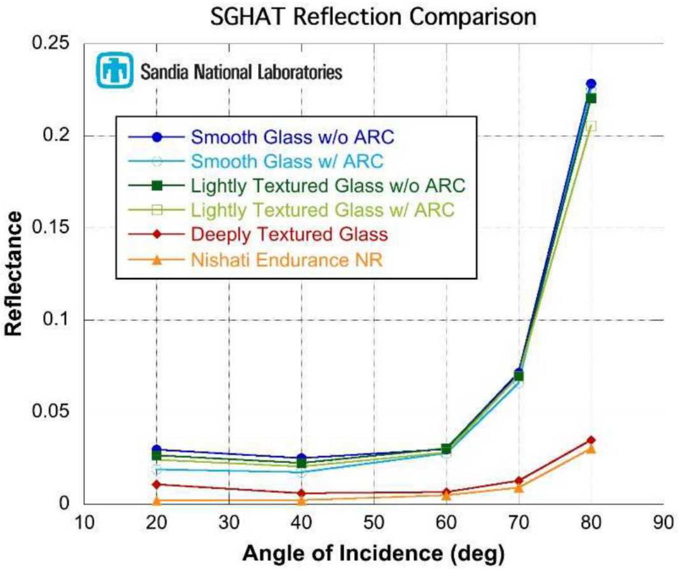
New PV technologies will require new ways of characterization and modeling.

Strategies for Improving PV Performance & Value

- **Increase effective irradiance**
  - Reduce reflection losses and soiling (coatings, texturing)*
  - Bifaciality*
  - Increase active area (e.g., shingled cells)
- **Decrease operating temperature**
  - "Spectral cooling": selective absorption and emission properties (up to 10°C temperature reduction possible)
  - Increasing thermal conductivity of backsheets*
- **Manage electrical mismatch**
  - Module and Sub-module power optimizers
- **Added value deployments**
  - PV + <u>*"blank"*</u> (e.g., Roofing, facades, agriculture, transportation, etc..
  - Features such as weight, flexibility, form factor, shade tolerance become important.
- **Increase lifetimes**
  - Can we build an affordable 50 yr module?
  - Need for new testing protocols

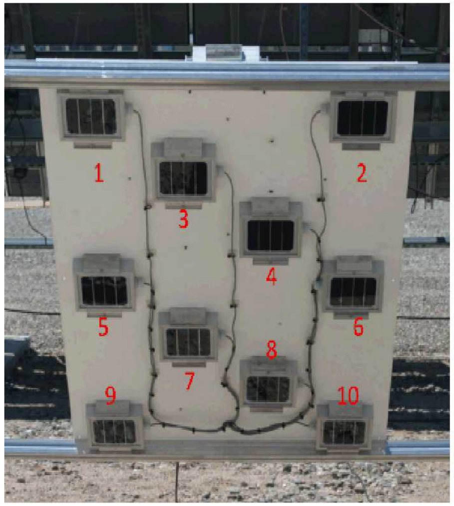
Reducing Reflections from PV (e.g. Nishati)

- Nishati makes rugged, glass-free solar panels designed for extreme environments (e.g. military deployments).
- They are working with Sandia (SBV Program) to evaluate reflective properties of design variations of their modules.
- Initial results show that reflections are significantly reduced compare with conventional modules with glass top-sheets.
- Such modules would be less visible and may be appropriate for installations near airports or in tactical environments.
- Can they last 20+ yrs?



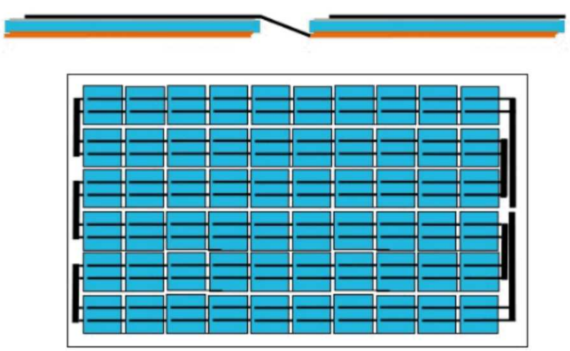
Bifacial Photovoltaics

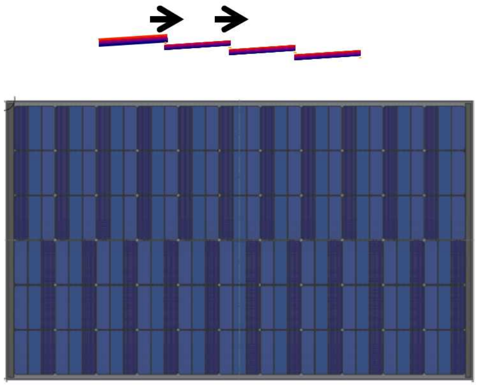
- Bifacial PV offers a means to increasing the output of PV systems by up to 10-20% with little additional costs (~3% cost increase for adding bifacial to 1-axis tracking (Source- PV magazine).
- Sandia and NREL project goal is to build and validate bifacial PV performance models, generate performance data, and develop rating standards.
- Our approach has been to deploy test systems, measure performance & backside irradiance, and develop prediction models.
    - Backside irradiance is affected shadows from modules, racking, and other objects.
    - Backside irradiance is spatially variable.
- Modeling has focused on ray-tracing and view factor approaches.
- Open-source models are available:
    - https://pvpmc.sandia.gov/pv-research/bifacial-pv-project/



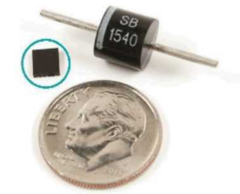
Increase Active Area: Shingled-cell PV Modules

- SunPower recently acquired SolarWorld Americas to build shingled P-Series modules in the US.
- Shingled modules interconnect shingled cells with conductive adhesives.
  - Maximizes the active area in the module
  - Eliminates solder bond cell-cell interconnections (common point of failure)
- These modules require certain changes to modeling assumptions, such as the angular response function, which is directional due to the cell stacking and can include shading effects.
- Conductive adhesives can affect series resistance.
- Are there different failure and degradation modes?





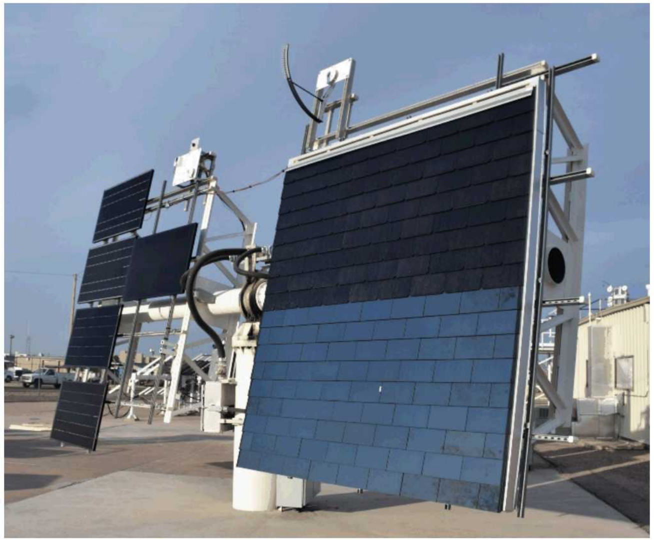
Reduce Electrical Mismatch

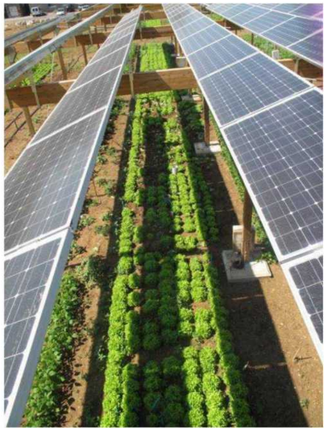


- Power optimizers allow modules (or cell strings) with different irradiance levels to be combined in series with minimal losses.
- Maxim Integrated is testing its optimizers at the Regional Test Centers
  - Allows for closer row spacing (higher GCRs)
- Future applications may include:
  - Bifacial modules
  - Curved or conformable arrays
  - Applications with partial shading

Added Value PV Deployments

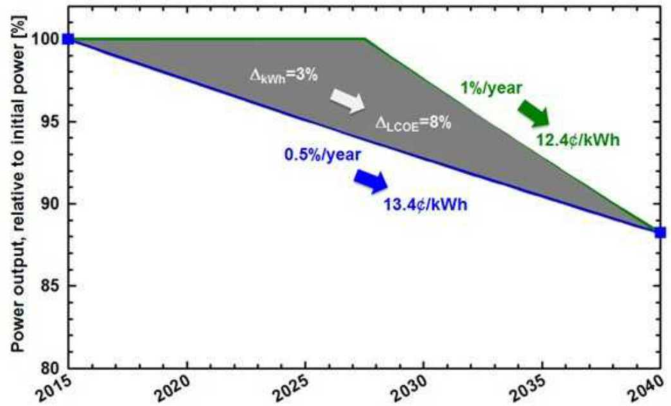
- PV modules that produce energy AND provide another value, such as …
  - Protect building from elements
    - Roof, windows, façades
  - Reduce evaporation on reservoirs
    - Floating PV
  - Allow more varied crops to be grown
  - Reduce fuel needs (remote grids, solar cars, ships
- **Value is more than energy**
  - Appearance, weight, physical properties are all important.



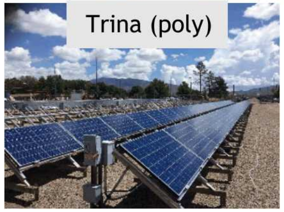


Increase PV Lifetime

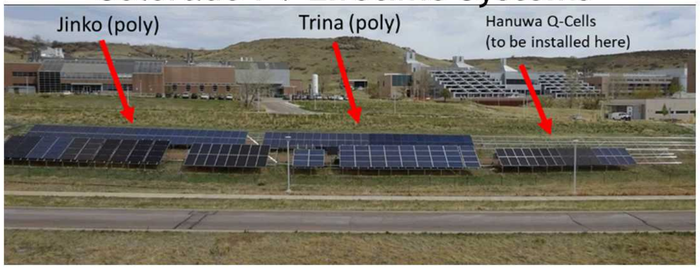
- Degradation rates and profiles affect LCOE.
- PV Lifetime Project
- Challenges include:
  - Keep out moisture
  - Minimize effects of thermal cycling & mechanical stress
- Possible solutions include:
  - Glass-glass modules
  - Eliminate junction box
  - Eliminate cables and connectors
  - Wireless charging technology?



New Mexico PV Lifetime Systems

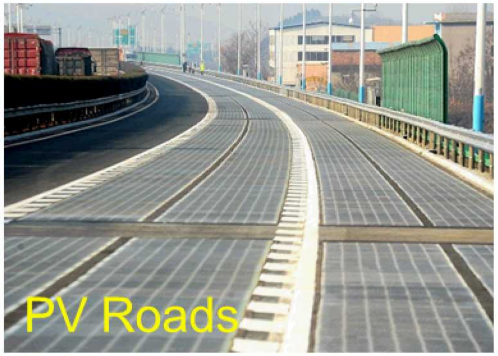


Colorado PV Lifetime Systems



Where are we headed?

- PV is a disruptive technology and is starting to be completely reimagined.
  - Early prototypes are always expensive but their multi-use value might be underestimated.
  - Refocusing from cost to value may open up new innovation opportunities.
  - New technology requires careful and accurate monitoring and analysis.



Monitoring PV Performance

PV performance depends on many factors

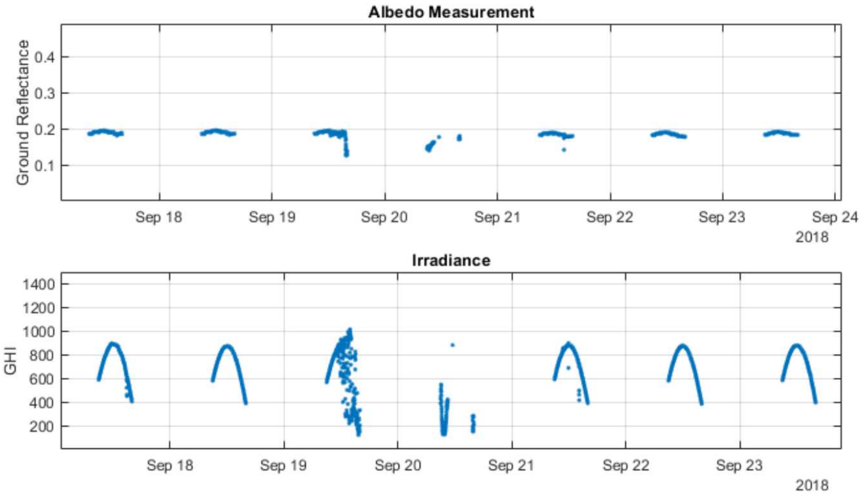
- Module and Cell characteristics
  - Cell performance (efficiency, low light behavior, temperature coef, etc.)
  - AR coatings
  - Cell sorting and mismatch
  - Diodes and connectors
- Effective Irradiance
  - Plane-of-Array
  - Spectral mismatch
  - Angular effects
- Cell temperature
  - Ambient temperature
  - POA irradiance
  - Wind speed, RH
  - Module construction
  - Mounting configuration

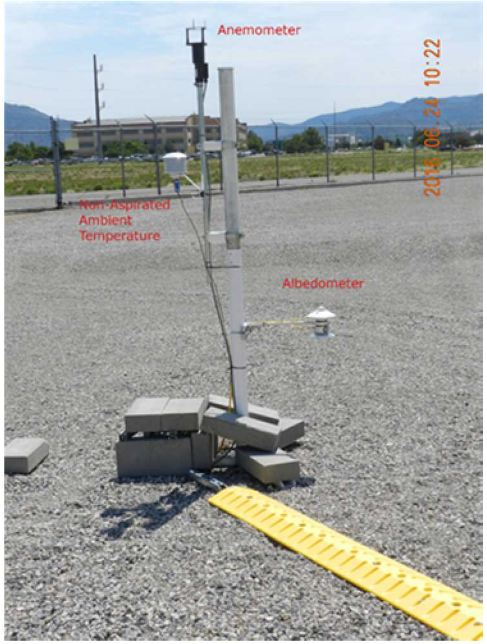
How and what to measure?

- Module and Cell characteristics
  - Module and cell IV characteristics at STC
  - Incident angle modifier
  - Temperature coefficients
- POA Irradiance
  - Pyranometer
  - Ref cell or module
  - Can also be calculated by transposition
- Module temperature
  - TC or RTD attached to back of module
- Electrical
  - Module or string IV curves
  - DC current and voltage
  - AC power (independent or inverter data)
- Technical issues
  - Isolation and filtering
  - Analogue to Digital
  - Sampling and averaging

Plane of Array Irradiance and Albedo

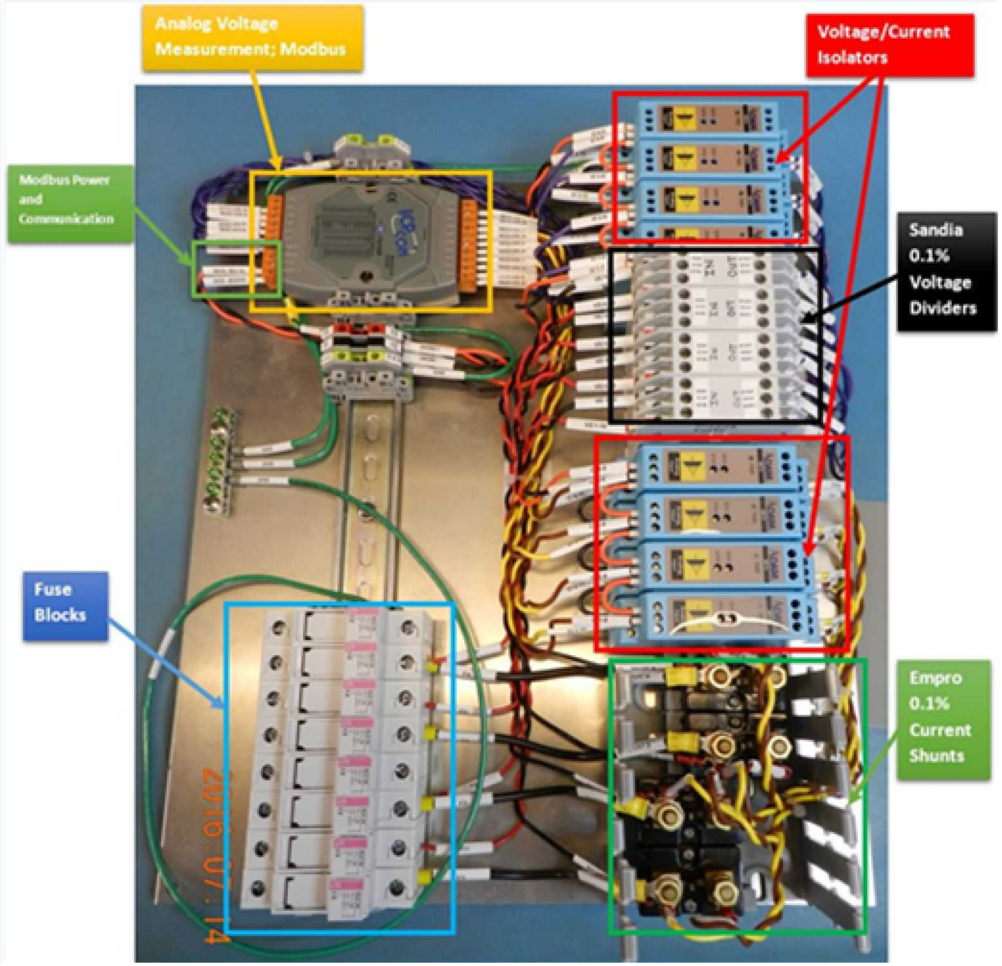
- We deploy two reference cells and one pyranometer at POA.
  - Pyranometer and one ref cell is cleaned twice a week.
  - Other ref cell is left to soil naturally.
- We measure albedo using two pyranometers, one facing up and one facing down.





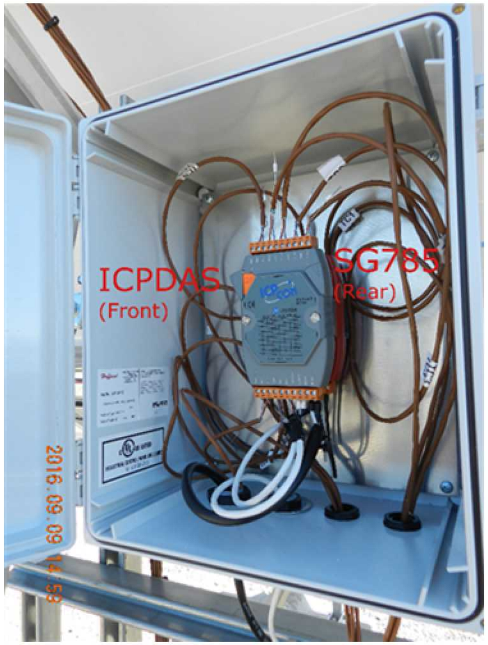
DC Current and Voltage Monitoring

- Current is read with Empro shunts calibrated to 0.1% accuracy
- Voltage measured with Sandia-designed voltage dividers
- Voltage and current measurements are isolated
  - Newer designs are using a floating power supply (wireless charging) for isolation.
- We use ICPDAS to perform analog to digital conversions and provide data via MODBUS.
  - Datalogger makes a data request



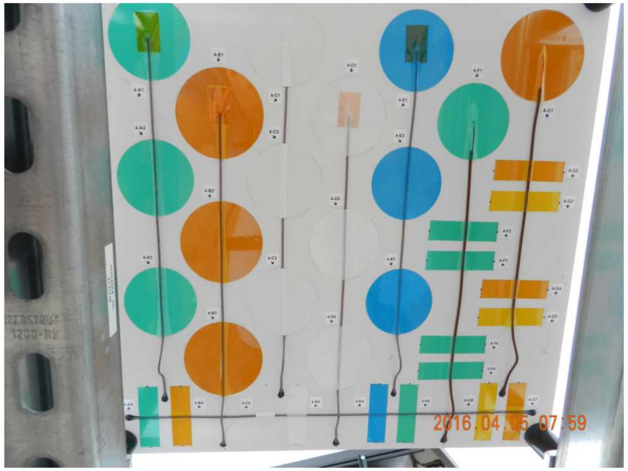
Module Temperature Measurements

- Module temperatures are measured with either thermocouples (T-type) or 4-wire RTDs (Pt 100Ω)
- ICPDAS is used to read the thermocouples
  - RTDs need different ICPDAS or Pordis makes a unit to read 8 RTDs.
- TC or RTD is attached to back of module
  - Different attachment solutions exist and are being field tested at Sandia.



- Measuring module temperature for bifacial modules is not standardized.
  - Do you place TC on back of cell and risk blocking light?
  - Do you place between cells and risk direct solar heating?

Sandia test of different TC Attachment Methods



Datalogger and Communications

- We typically use a Campbell Scientific CR1000 or CR6 (or CR1000X)
  - CR100 needs serial to MODBUS converter
    - CR6 speakes MODBUS
  - Battery backup ensures operation during power outages.
  - Datalonger is programed to request measurements every 5 sec that are rolled up into 1-min averages that are saved.
- We are testing new, low-cost logging hardware based on Raspberry Pi-based solutions.

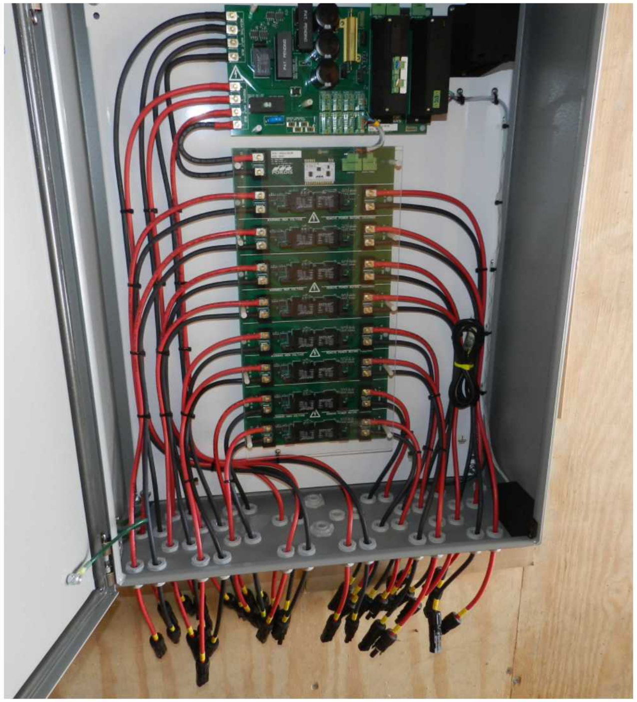
$40 board only

~$300 integrated system (UPS, 24V, DIN, MODBUS, RTC Watchdog)

Pordis 140A2 String IV Tracer and Switch Unit

- On many systems at Sandia we are measuring string-level IV curves on operating systems.
- Pordis 140A2 was jointly developed by Pordis and Sandia.
  - Designed for low cost: $0.012/W (100+ units)
  - Patented hybrid switch boards (each switches up to 8 strings) cleanly disconnect string from inverter, sweep an IV curve and then reconnect.
  - Capacitive IV sweep.
  - Up to three switch boards can be controlled with each controller. (up to 24 string/unit)
  - Control card based on BeagleBoneBlack with a GPS, RTC, and UPS.
  - Speaks with the CR1000 to share data tables.
    - Synchronization with other site measurements
  - Speaks MODBUS to the ICPDAS units for module temperatures, POA irradiance, etc.
  - Module level IV capability is being developed.
- Stratasence offers a module-level tracer
  - Inline connection, wireless communications
  - Transistor based loads
  - Company purchased by GroundWork Renewables

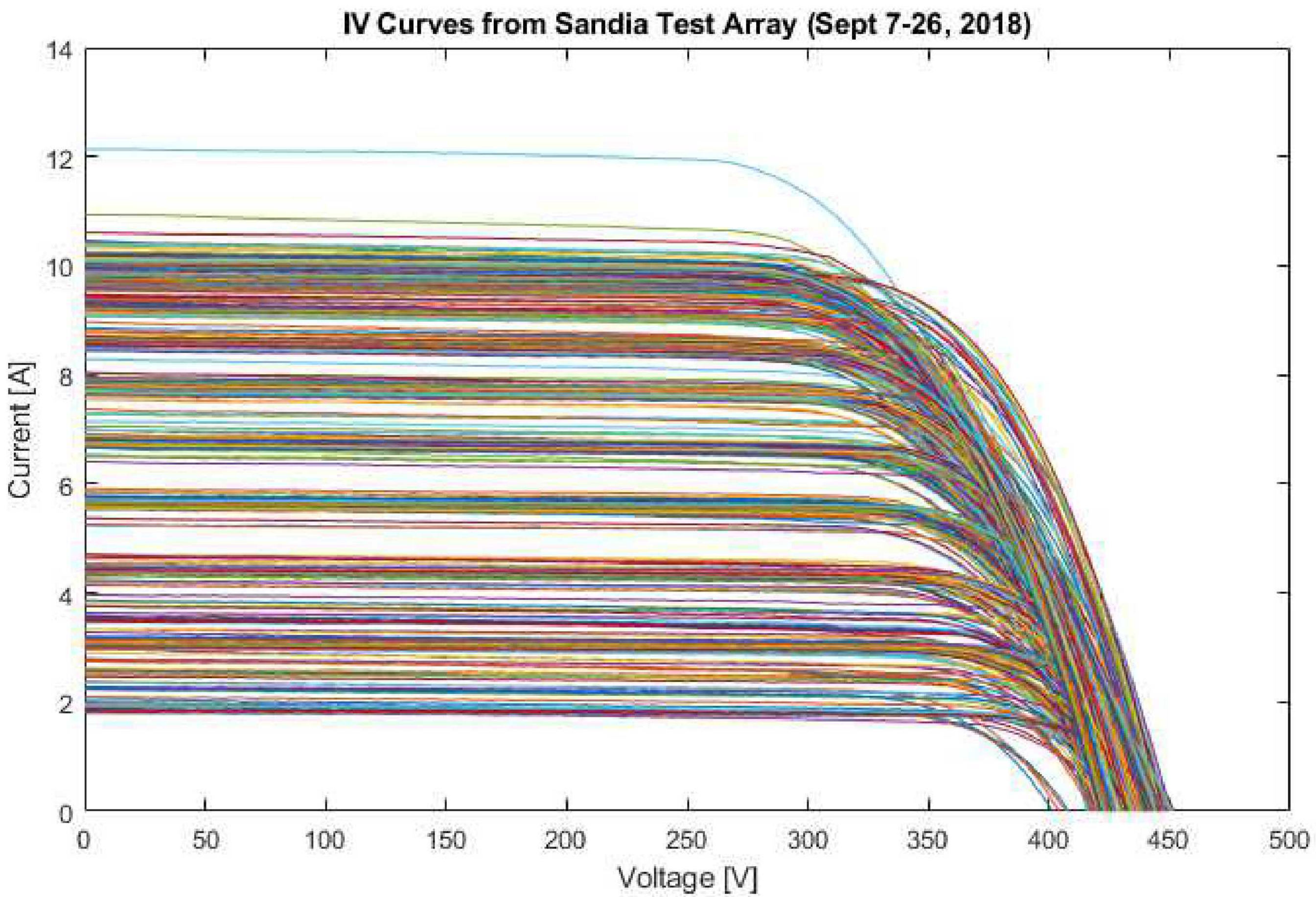
Pordis 140A2



Stratasense

Example IV Curves from Pordis Unit

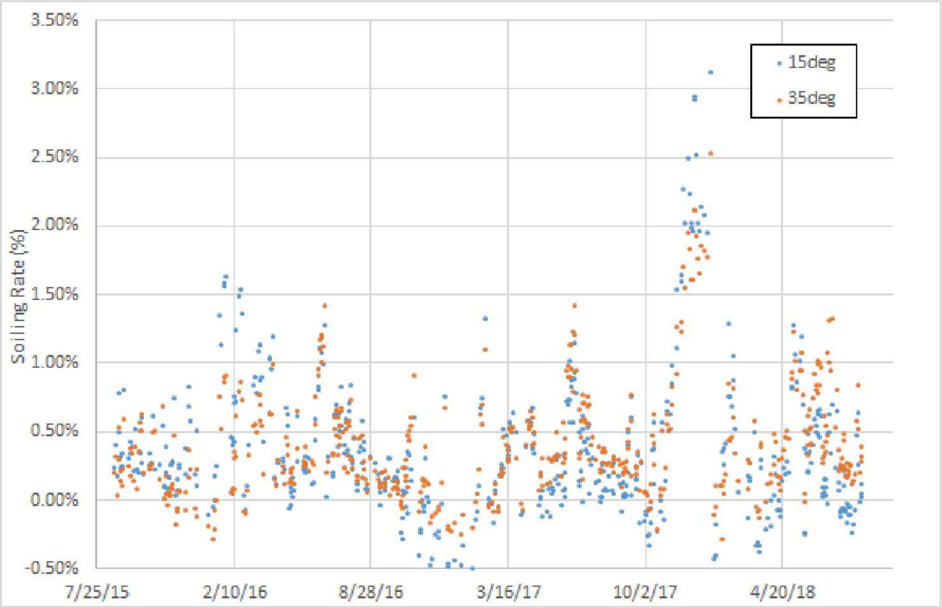
- Raw curves do not go through Isc
- We interpolate to Isc and Voc to clean up curves.



Soiling and Snow Stations

- Soiling stations are located in New Mexico, Florida, Colorado, Vermont.
  - 10 Split cells (each measuring Isc) are set at different tilt angles.
  - Bottom half of each cell is cleaned (twice a week)

- Snow station located in Vermont
  - Photos are automatically taken every 15 min
  - Isc of modules are monitored.



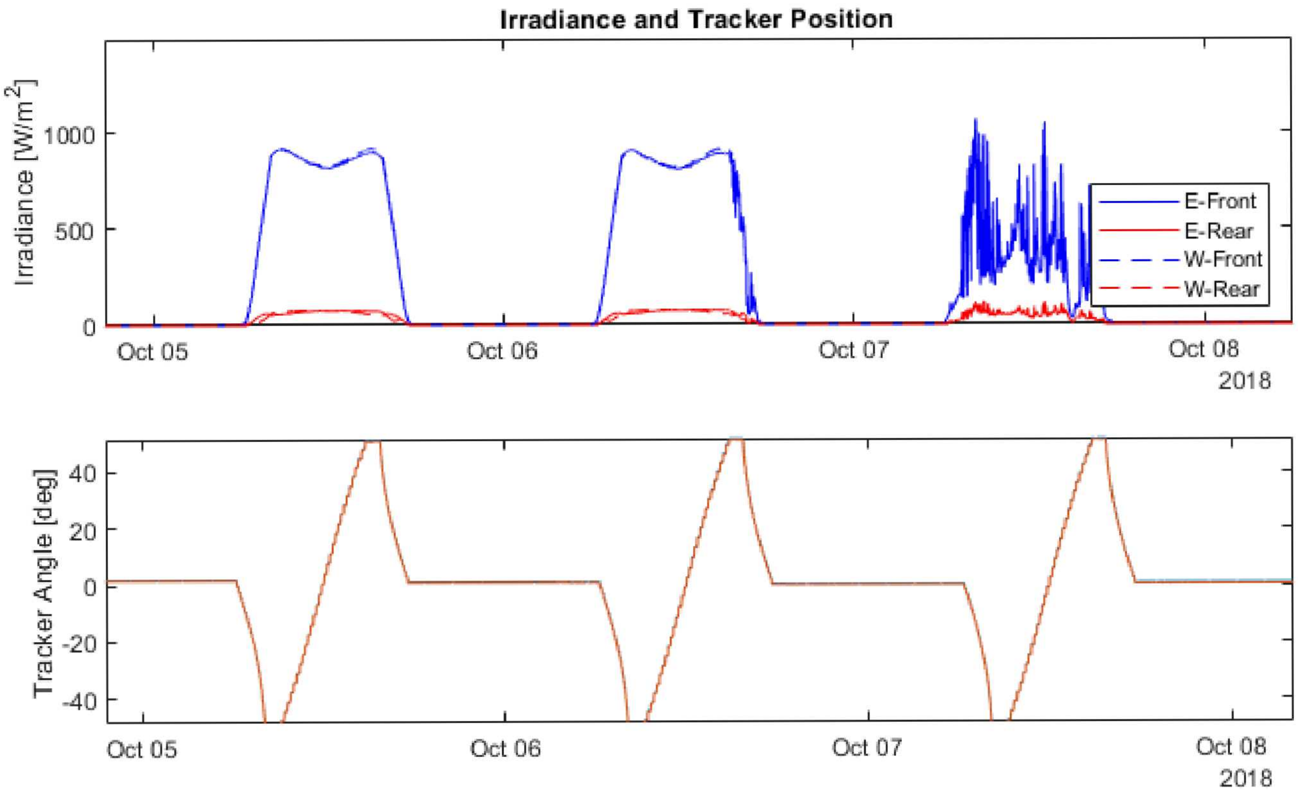
Example Performance Analysis of Bifacial PV on 1-Axis Trackers

System Description

- Two rows of single axis trackers in Albuquerque, NM USA
- Four module strings (2 monofacial, 2 bifacial)
- Measuring (using Raspberry Pi datalogger):
  - Front and rear POA irradiance with ref cells, albedo
  - DC string current and voltage
  - Module temperature (measured between cells to avoid shading)
  - Tracker angles

Irradiance and Tracker Angles

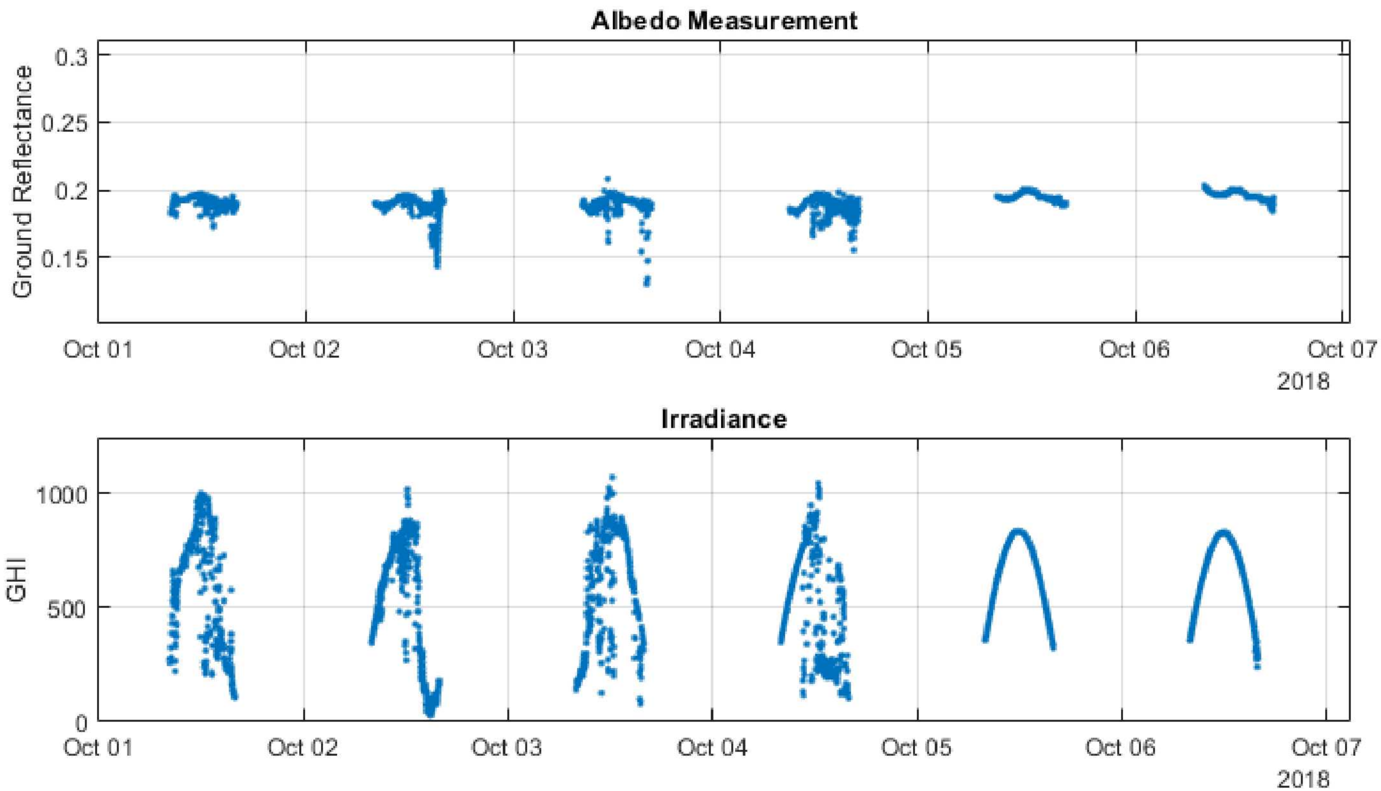
- Tracker uses backtracking to prevent sharing at start and end of the day



Albedo Measurement

Albedo varies between 0.15-0.2. Appears to be highest at midday

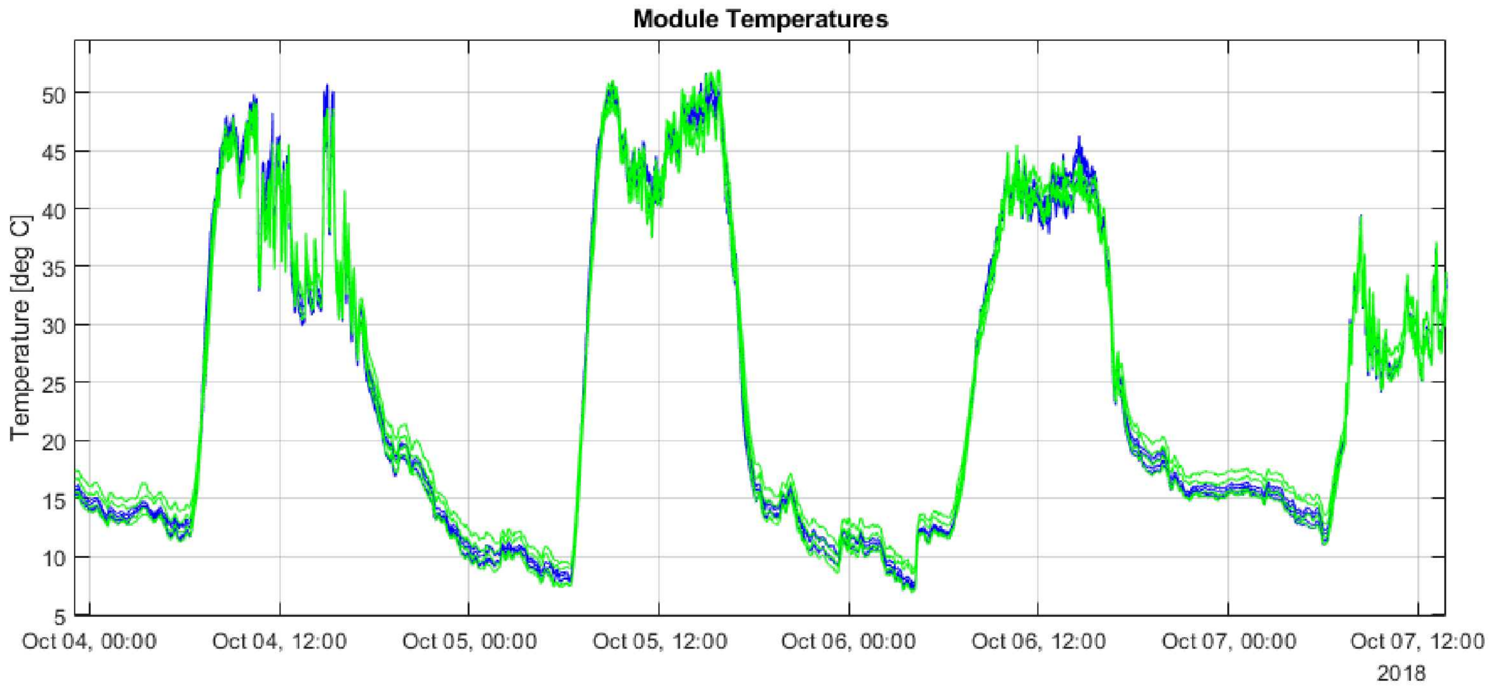
Varies more during partly cloudy conditions.



Module Temperatures

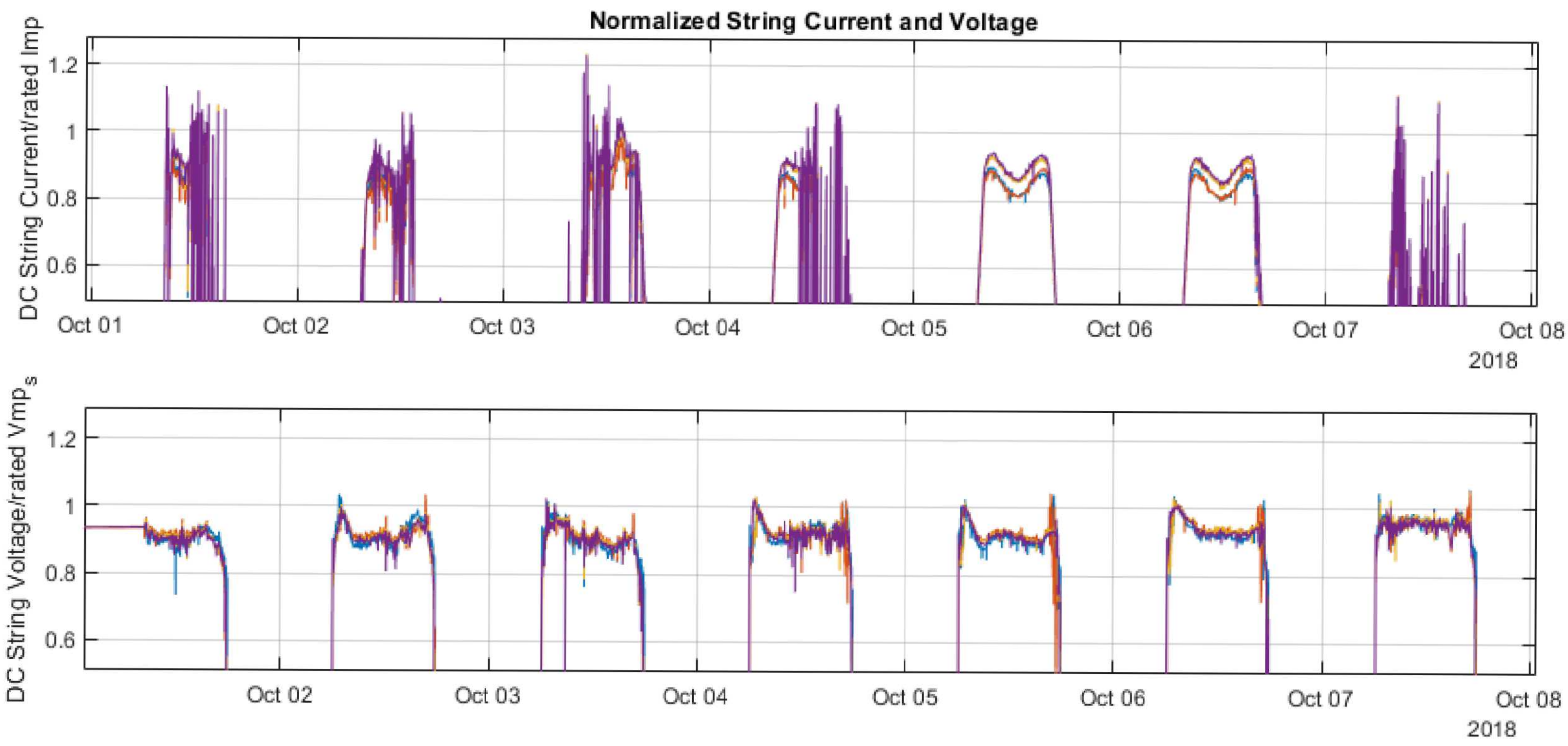
Green = bifacial, Blue = monofacial

No difference observed.



Normalized DC Current and Voltage

- Current is normalized by the module Imp @STC
- Voltage is normalized by the module Vmp@STC / number of modules in string

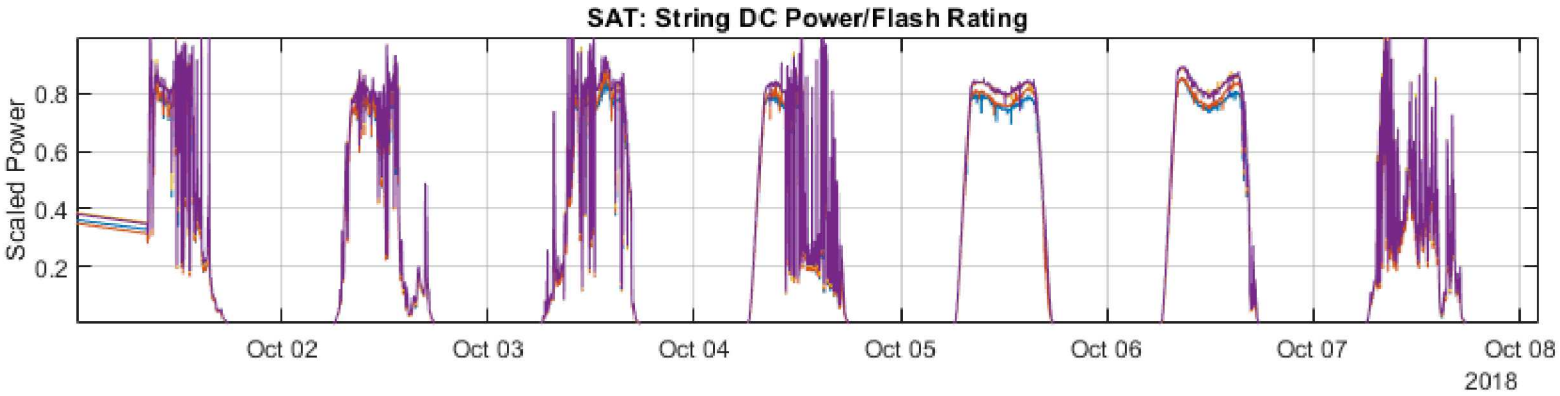


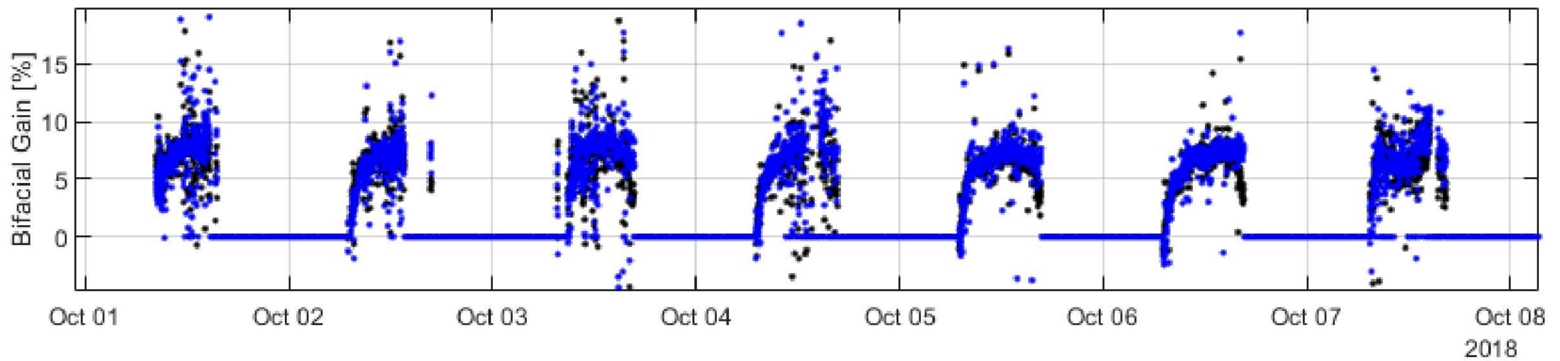
Scaled DC Power and Bifacial Gain

- Scaled DC Power = String power (energy)/DC rating/#module per string

$$BG = \left[\frac{\left(\frac{P_{bifi}}{P_{rat-b}} / n_{bifi} \right)}{\left(\frac{P_{mono}}{P_{rat-m}} / n_{mono} \right)} - 1 \right] * 100$$

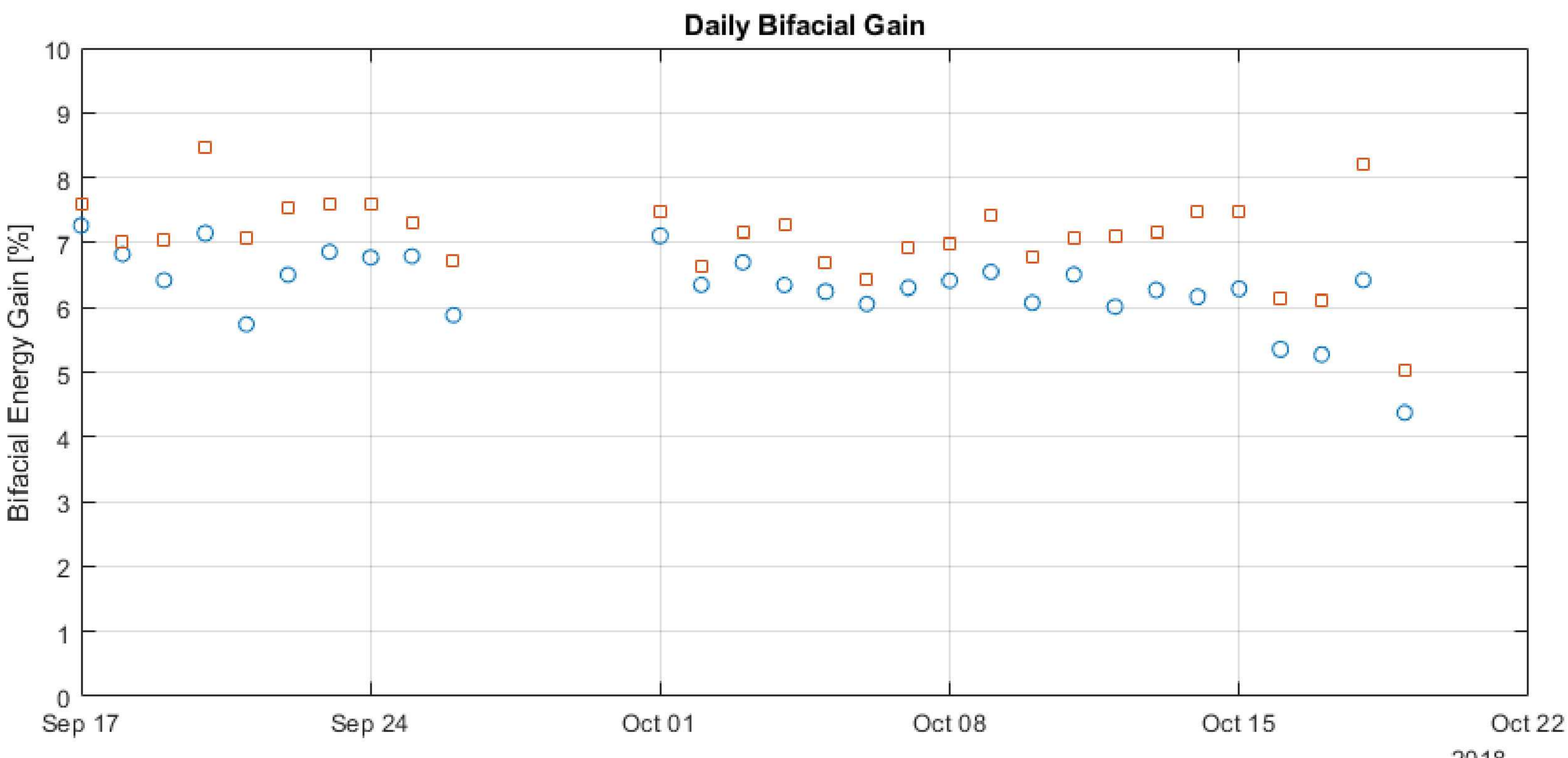
P_{bifi} = dc power measured on bifacial string
P_{mono} = dc power measured on monofacial reference string
$P_{rat\text{-}b}$ = frontside power flash rating of bifacial module
$P_{rat\text{-}m}$ = frontside flash power rating of monofacial reference string
n_{bifi} = number of module in bifacial string
n_{mono} = *number* of modules in monofacial string





Daily Bifacial Gain

- Daily bifacial gains are pretty consistent but vary by +/- 1-2%
  - Variation may be due to temperature, varying sky conditions, varying ground conditions, etc.
  - We are continuing to analyze this data to determine the cause of the variation.



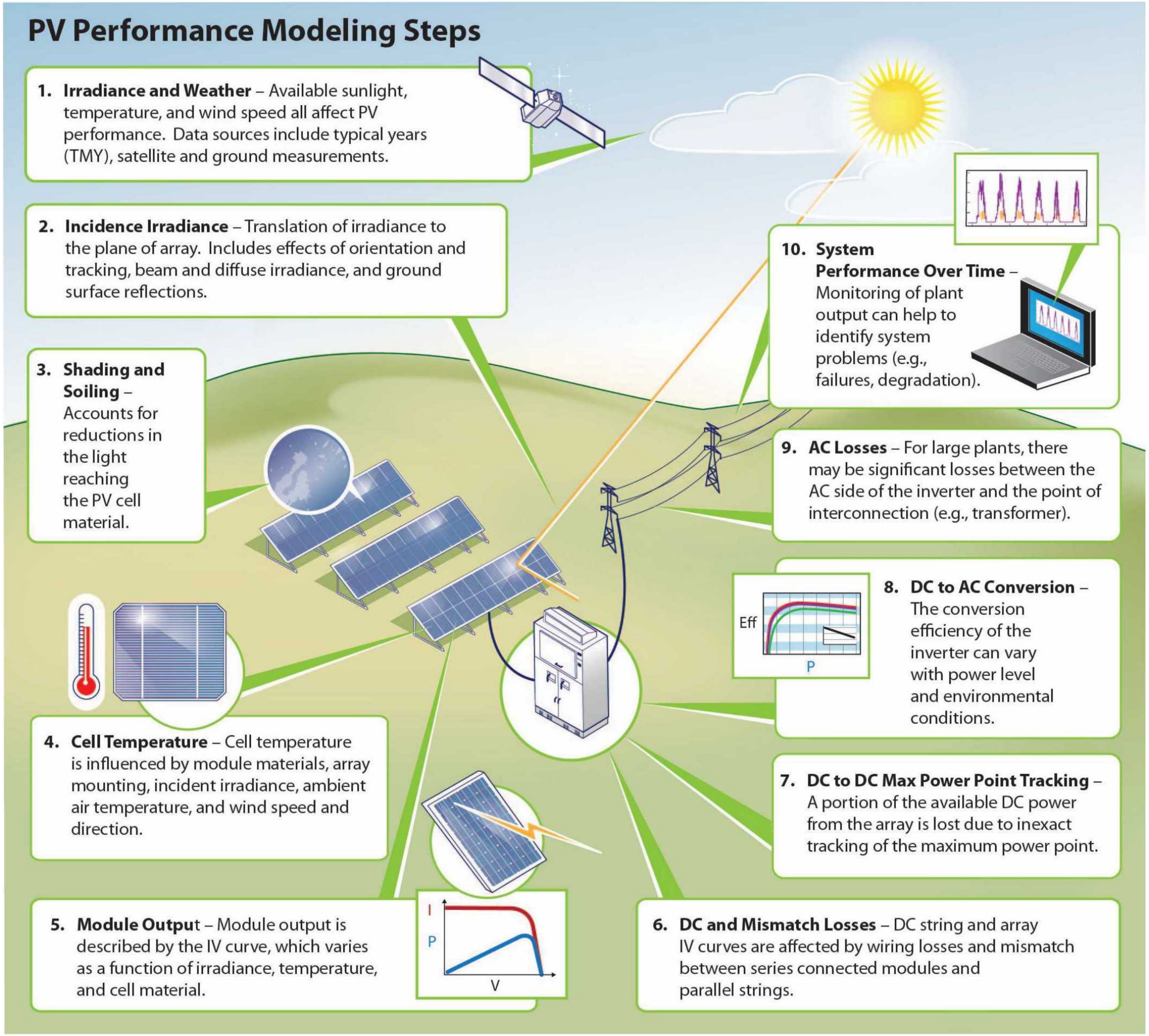
PV Performance Modeling Collaborative (PVPMC)

Founded in 2010 to foster better collaboration in PV Performance Modeling

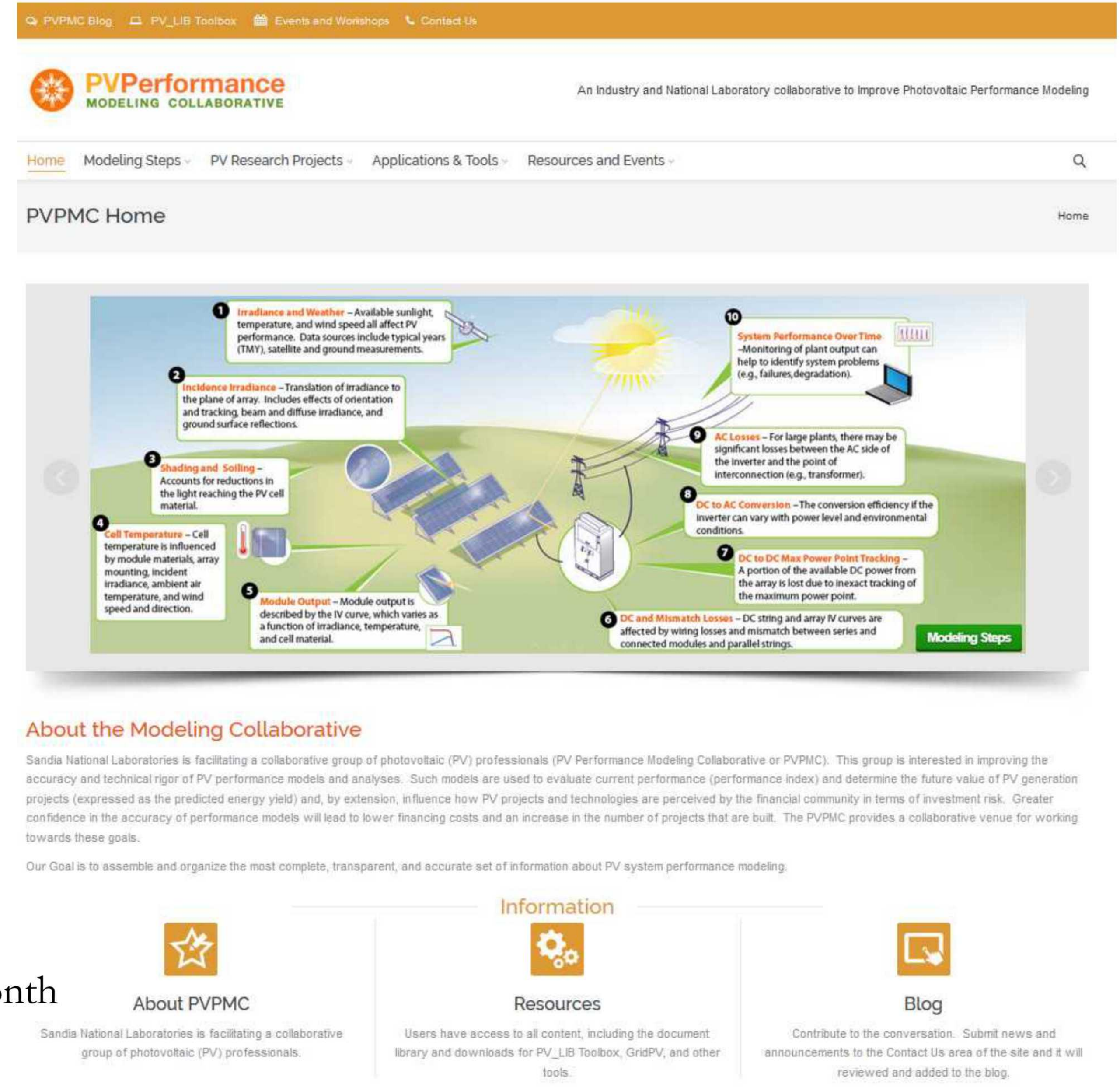
Three Pillars of Communication and Collaboration

1. **Website** (*PVPMC.sandia.gov*) (>10,000 visits per month)
   - Detailed Modeling Steps (~150 technical webpages)
   - Past workshop presentations (over 300 available for download*)
   - Document library, datasets, blog, events, …
2. **Open Source Software**
   - **PVLIB** - Modeling function libraries for Matlab and Python (50+ functions), BSD 3-clause licenses
   - **Wavelet Variability Model** – Matlab code for calculating geographic smoothing of PV plant power.
   - **GridPV** – Matlab code for analysis of distribution systems with PV
3. **Workshops**
   - Workshops held in US, Germany, Switzerland, and China
   - Planning is underway for:
     - 11^{th} PVPMC Workshop, Dec 4-7, 2018 in Weihai, China
     - 12^{th} PVPMC Workshop, May 14-16, 2019 in Albuquerque, NM

Introduction to PV Performance Modeling



Website: http://pvpmc.sandia.gov



10,000 to 15,000 visits per month

~200 web pages published

Example Model Description

Brief description

Equation support

Hyperlinking

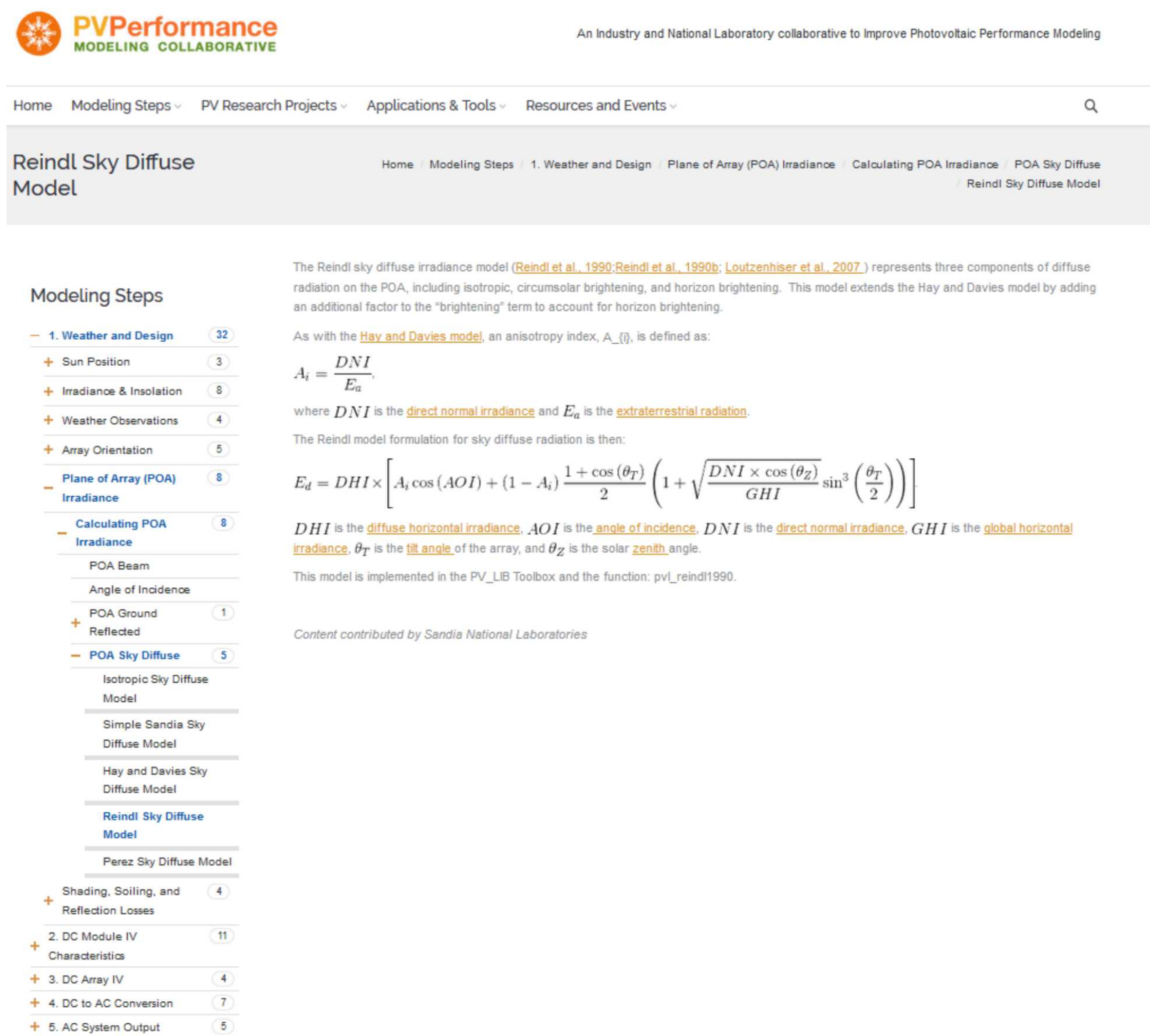
Link to PVLIB functions

References

Contributor info

We accept additional models and process descriptions

We host over 100 model descriptions



PVPerformance MODELING COLLABORATIVE

An Industry and National Laboratory collaborative to Improve Photovoltaic Performance Modeling

Home | Modeling Steps | PV Research Projects | Applications & Tools | Resources and Events

Reindl Sky Diffuse Model

Home / Modeling Steps / 1. Weather and Design / Plane of Array (POA) Irradiance / Calculating POA Irradiance / POA Sky Diffuse / Reindl Sky Diffuse Model

Modeling Steps

- 1. Weather and Design (32)
  - Sun Position (3)
  - Irradiance & Insolation (8)
  - Weather Observations (4)
  - Array Orientation (5)
  - Plane of Array (POA) Irradiance (8)
    - Calculating POA Irradiance (8)
      - POA Beam
      - Angle of Incidence
      - POA Ground Reflected (1)
      - POA Sky Diffuse (5)
        - Isotropic Sky Diffuse Model
        - Simple Sandia Sky Diffuse Model
        - Hay and Davies Sky Diffuse Model
        - Reindl Sky Diffuse Model
        - Perez Sky Diffuse Model
  - Shading, Soiling, and Reflection Losses (4)
- 2. DC Module IV Characteristics (11)
- 3. DC Array IV (4)
- 4. DC to AC Conversion (7)
- 5. AC System Output (5)

The Reindl sky diffuse irradiance model (Reindl et al., 1990;Reindl et al., 1990b; Loutzenhiser et al., 2007) represents three components of diffuse radiation on the POA, including isotropic, circumsolar brightening, and horizon brightening. This model extends the Hay and Davies model by adding an additional factor to the "brightening" term to account for horizon brightening.

As with the Hay and Davies model, an anisotropy index, A_{i}, is defined as:

$$A_i = \frac{DNI}{E_a},$$

where DNI is the direct normal irradiance and E_a is the extraterrestrial radiation.

The Reindl model formulation for sky diffuse radiation is then:

$$E_d = DHI \times \left[A_i \cos(AOI) + (1 - A_i) \frac{1 + \cos(\theta_T)}{2} \left(1 + \sqrt{\frac{DNI \times \cos(\theta_Z)}{GHI}} \sin^3\left(\frac{\theta_T}{2}\right) \right) \right]$$

DHI is the diffuse horizontal irradiance, AOI is the angle of incidence, DNI is the direct normal irradiance, GHI is the global horizontal irradiance, θ_T is the tilt angle of the array, and θ_Z is the solar zenith angle.

This model is implemented in the PV_LIB Toolbox and the function: pvl_reindl1990.

Content contributed by Sandia National Laboratories

2018 11th PV Performance Modeling Workshop (Dec 4-7, 2018) Weihai & Suzhou, China

- Dec 4-5: Technical workshop (Modeling and Monitoring) in Weihai (~$365)
- Optional PV manufacturing tours (fixed price (~$665) includes:
  - Dec 4-5 PVPMC Workshop in Weihai
  - Dec 5 (p.m.) Flight from Weihai to Shanghai – transport to Suzhou.
  - Dec 6-7: Guided tours to 3-4 PV manufacturing centers (TBD)
  - Hotel in Suzhou (2 nights)
  - Meals
  - Local transportation
  - PV Manufacturing Tutorial
- Optional Local tour add-on (~$725):
  - Dec 8: Local tour of cultural sites in Suzhou
- https://pvpmc.sandia.gov/resources-and-events/events/