NREL
NATIONAL RENEWABLE ENERGY LABORATORY

# Progress & Frontiers in PV Performance

Chris Deline, Nick DiOrio, Dirk Jordan, NREL

Fatima Toor, University of Iowa

September 12, 2016

Solar Power International 2016

Las Vegas, Nevada

**NREL/PR-5J00-67174**

SunShot
U.S. Department of Energy

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

# Outline

| | |
|---|---|
| 8:00 | Workshop introduction<br>Chris Deline (NREL) |
| 8:15 | SAM introduction and battery modeling<br>Nick DiOrio (NREL) |
| 9:15 | Bifacial modules and modeling<br>Fatima Toor (University of Iowa) |
| 10:00 | Break |
| 10:15 | Shade modeling and MLPE<br>Chris Deline (NREL) |
| 11:00 | Degradation rates<br>Dirk Jordan (NREL) |
| 11:30 | PVWatts updates and validation<br>Dirk Jordan (NREL) |

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

# System Advisor Model Introduction

Nick DiOrio

September 12, 2016
Solar Power International 2016

SunShot
U.S. Department of Energy

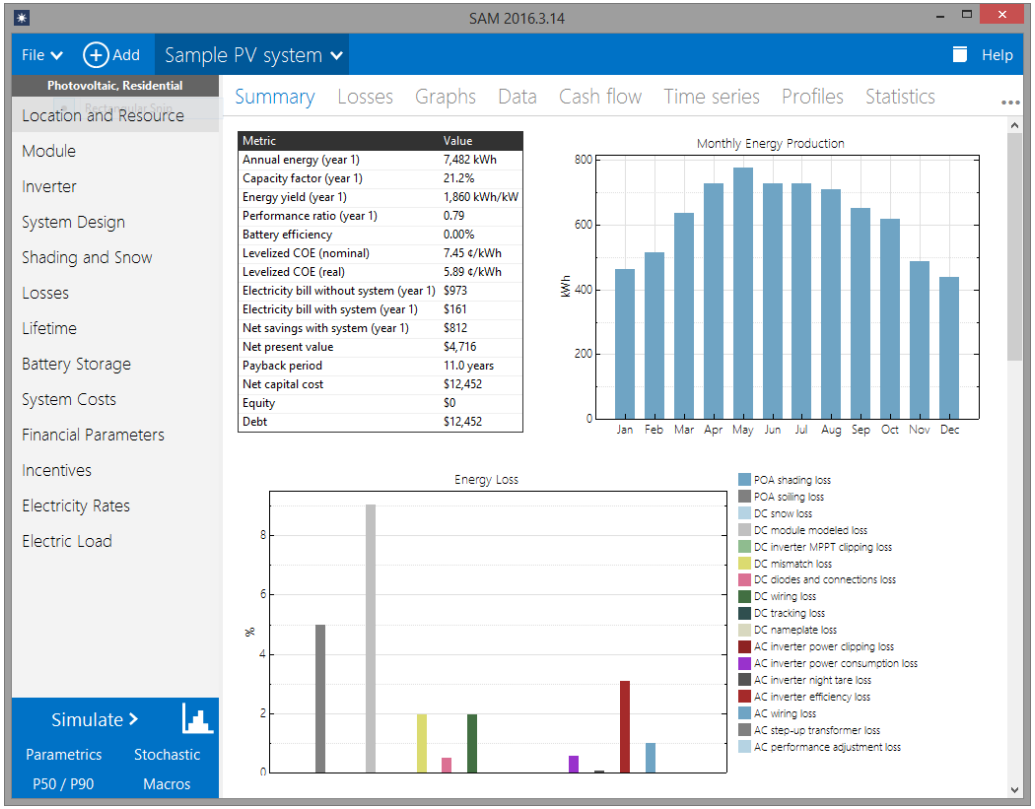
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

# Outline

- SAM Introduction
- Photovoltaic Model
- Battery Model

# System Advisor Model (SAM)

Free software that combines detailed performance and financial models to estimate the cost of energy for systems




http://sam.nrel.gov/download

## Technologies

Photovoltaics, detailed & PVWatts
Battery storage
Concentrating solar power
Wind
Geothermal
Biomass
Solar water heating

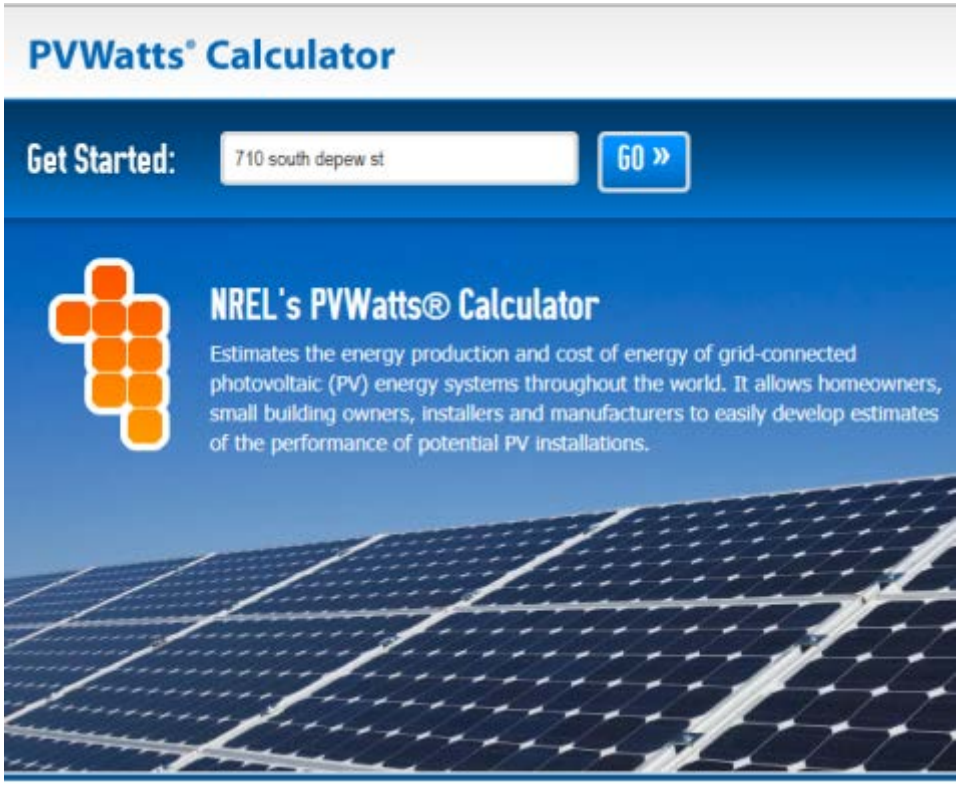
## Financials

Behind-the-meter
- residential
- commercial

Power purchase agreements
- single owner
- equity flips
- sale-leaseback

Simple LCOE calculator

# PVWatts or SAM?




*The SAM team maintains the PVWatts model, and it's included with SAM.

PVWatts

- Provides a simple performance and financial assessment for smaller-scale PV systems given an address, system design, and simple $/kWh electricity rate.

SAM

- Provides detailed performance assessment for small to utility scale systems
- Model complex shading and other losses.
- Can model detailed financial parameters, including complex utility rate tariffs, incentives.
- Models custom load profiles.
- Detailed outputs and visualization

# Questions you can answer with SAM

| Metric | Value |
|---|---|
| Annual energy (year 1) | 7,482 kWh |
| Capacity factor (year 1) | 21.2% |
| Energy yield (year 1) | 1,860 kWh/kW |
| Performance ratio (year 1) | 0.79 |
| Battery efficiency | 0.00% |
| Levelized COE (nominal) | 7.45 ¢/kWh |
| Levelized COE (real) | 5.89 ¢/kWh |
| Electricity bill without system (year 1) | $973 |
| Electricity bill with system (year 1) | $161 |
| Net savings with system (year 1) | $812 |
| Net present value | $4,716 |
| Payback period | 11.0 years |
| Net capital cost | $12,452 |
| Equity | $0 |
| Debt | $12,452 |

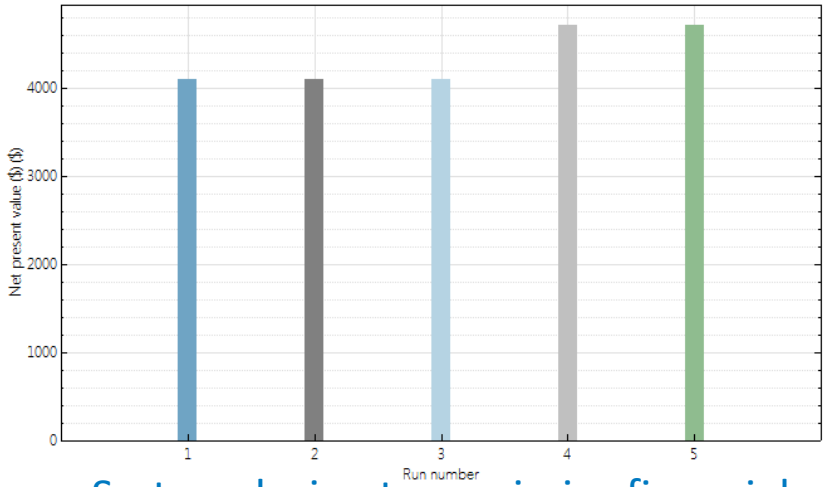
- Predicted technical and financial performance over project lifetime

Summary Losses Graphs Data Cash flow Time series Profiles Statistics

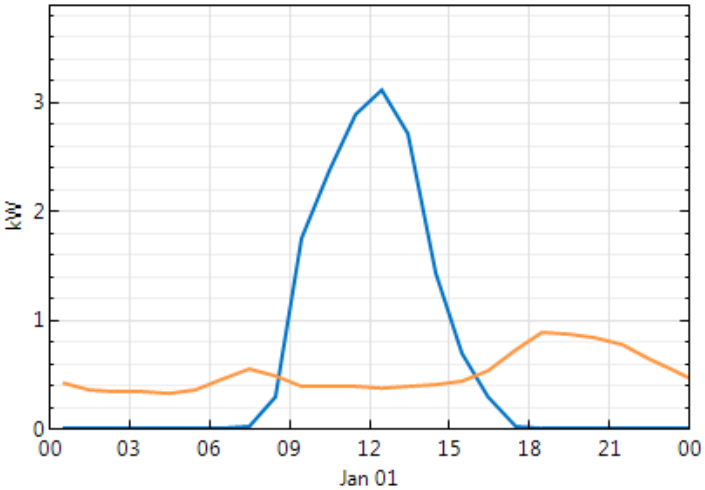
Copy to clipboard Save as CSV Send to Excel Send to Excel with Equations

| | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| PRODUCTION | | | | | | |
| Energy (kWh) | 0 | 7,482 | 7,444 | 7,407 | 7,370 | 7,333 |
| SAVINGS | | | | | | |
| Value of electricity savings ($) | 0 | 812 | 831 | 851 | 870 | 889 |
| OPERATING EXPENSES | | | | | | |
| O&M fixed expense ($) | 0 | 0 | 0 | 0 | 0 | 0 |
| O&M production-based expense ($) | 0 | 0 | 0 | 0 | 0 | 0 |
| O&M capacity-based expense ($) | 0 | 80 | 82 | 85 | 87 | 89 |
| Battery replacement cost ($) | 0 | 0 | 0 | 0 | 0 | 0 |
| Property tax expense ($) | 0 | 125 | 125 | 125 | 125 | 125 |
| Insurance expense ($) | 0 | 125 | 128 | 131 | 134 | 137 |
| Net salvage value ($) | 0 | 0 | 0 | 0 | 0 | 0 |
| Total operating expense ($) | 0 | 329 | 335 | 340 | 345 | 351 |
| Deductible expenses ($) | 0 | -125 | -125 | -125 | -125 | -125 |
| PROJECT DEBT | | | | | | |
| Debt balance ($) | 12,452 | 12,191 | 11,917 | 11,630 | 11,328 | 11,011 |
| Interest payment ($) | 0 | 623 | 610 | 596 | 581 | 566 |
| Principal payment ($) | 0 | 261 | 274 | 288 | 302 | 317 |
| Total P&I debt payment ($) | 0 | 884 | 884 | 884 | 884 | 884 |

- Detailed cash-flow financials




- System design to maximize financial return




- Time series behavior of system performance

# Detailed photovoltaic model

Irradiance
- Transposition using Isotropic, HDKR, or Perez
- Measured plane of array (POA) input

Shading
- Irregular obstruction shading from 3D scene
- Self-shading for regularly spaced rows
- External input from SunEye, Solar Pathfinder
- Snow cover loss model

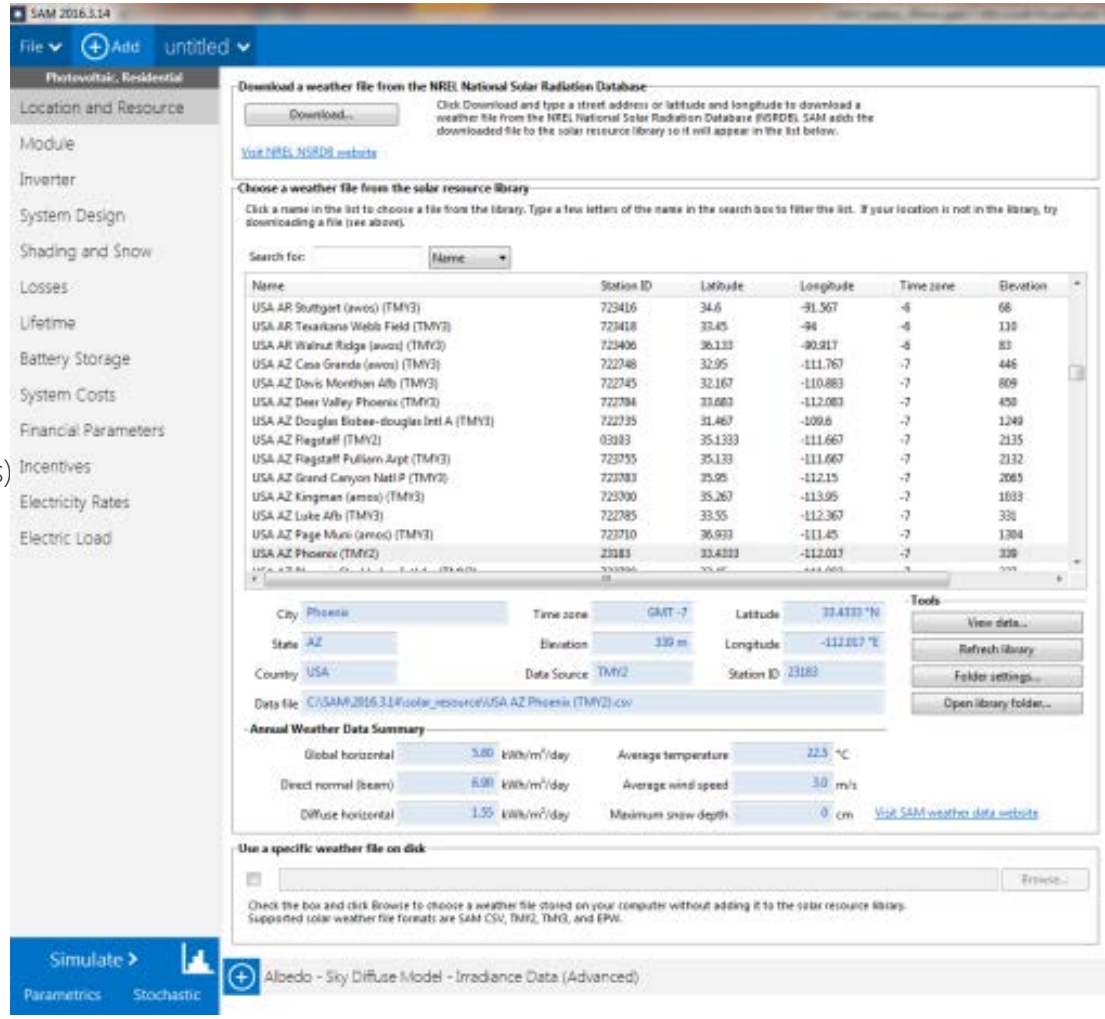
Module
- Simple efficiency model
- Single diode model (CEC database or datasheet)
- Extended single diode model (for IEC-61853 tests)
- Sandia PV Array Performance Model

Inverter
- Sandia/CEC grid-tied inverter model
- Datasheet part-load efficiency curve

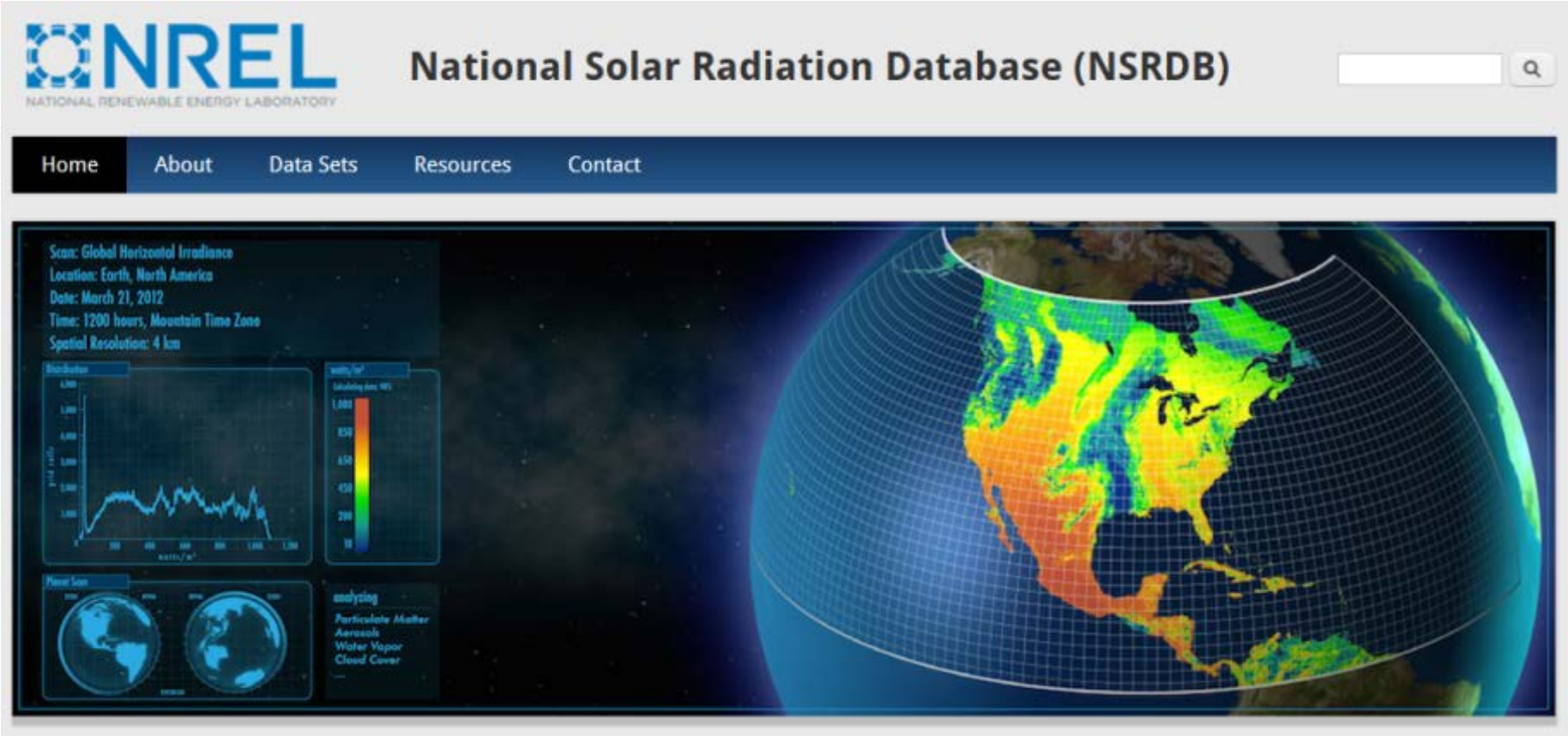
System
- Sizing wizard or electrical layout
- Multiple subarrays
- Fixed, 1 axis, backtracking, azimuth axis, 2 axis
- Battery storage

Degradation
- Extrapolated single year
- Lifetime simulation of all years

Simulation
- 1 minute to 1 hour time steps

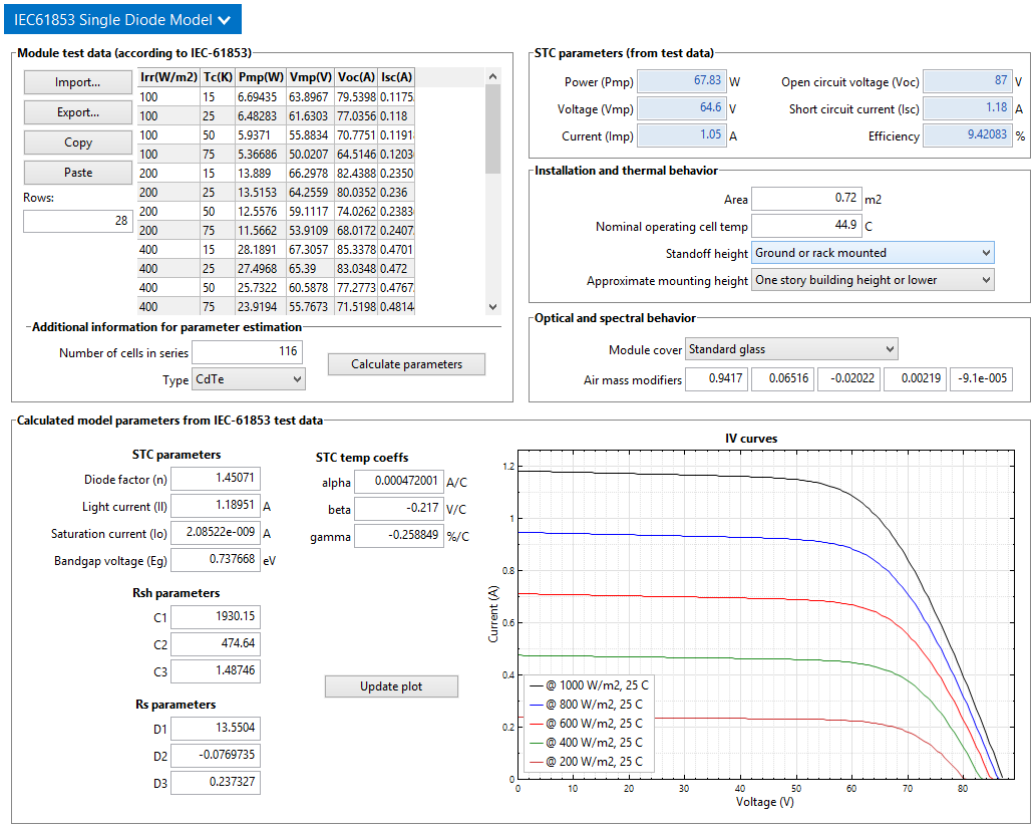


# Resource Data




- SAM allows selection from NREL NSRDB, TMY3, or input of a custom user defined weather file in an easy to use format.
- Multiple sources of data available: sam.nrel.gov/weather
- NSRDB – 4x4 km data at 30 minute resolution for North and Central America. 10x10 km hourly data for various countries in South Asia

# Module and Inverter Modeling




Can choose which performance model to use (Simple, CEC, Sandia, IEC-61853)

Select module and inverter from a database maintained by the California Energy Commission or specify your own parameters from a datasheet or part load curve.

Dobos, A.; MacAlpine, S. Procedure for Applying IEC-61853 Test Data to a Single Diode Model. Proc. IEEE 40th PVSC Conf. Denver CO, June, 2014

# System Design

Auto size the system or specify the module strings and inverters directly.

**System Sizing**

Specify desired array size

| | | |
|---|---|---|
| Desired array size | 4 | kWdc |
| DC to AC ratio | 1.10 | |

Specify modules and inverters

| | |
|---|---|
| Modules per string | 6 |
| Strings in parallel | 2 |
| Number of inverters | 1 |

**Configuration at Reference Conditions**

**Modules**

| | | |
|---|---|---|
| Nameplate capacity | 4.022 | kWdc |
| Number of modules | 12 | |
| Modules per string | 6 | |
| Strings in parallel | 2 | |
| Total module area | 19.6 | $m^2$ |
| String Voc | 407.4 | V |
| String Vmp | 343.8 | V |

**Inverters**

| | | |
|---|---|---|
| Total capacity | 4.000 | kWac |
| Total capacity | 4.186 | kWdc |
| Number of inverters | 1 | |
| Maximum DC voltage | 600.0 | Vdc |
| Minimum MPPT voltage | 250.0 | Vdc |
| Maximum MPPT voltage | 480.0 | Vdc |

Sizing messages (see Help for details):

Actual DC to AC ratio is 1.01.

Voltage and capacity ratings are at module reference conditions shown on the Module page.

Configure up to 4 sub-arrays, each with a specific:

- Tracking system
- Tilt
- Azimuth
- Ground Coverage Ratio
- Shading Table

# 3D shading calculator

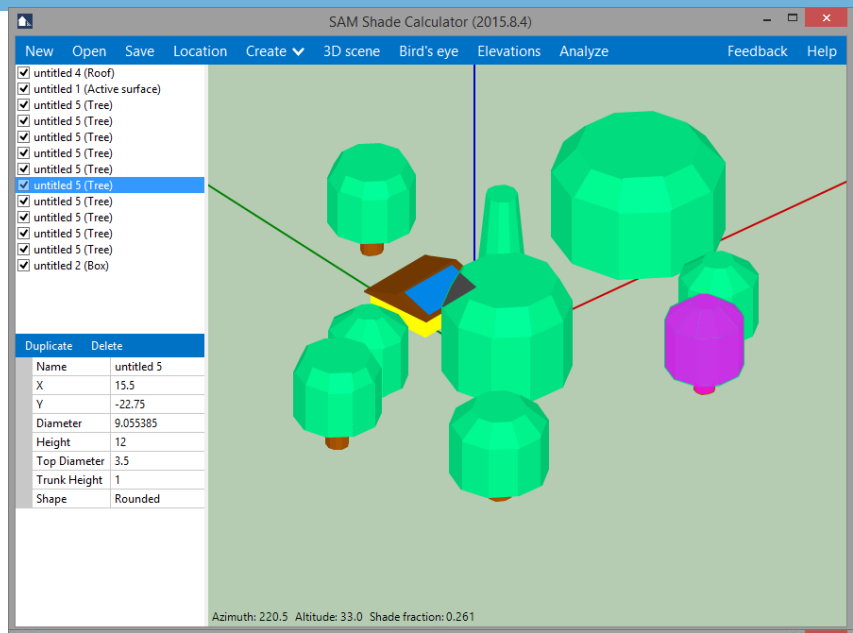
Calculates linear beam irradiance shading losses and sky diffuse view factor loss

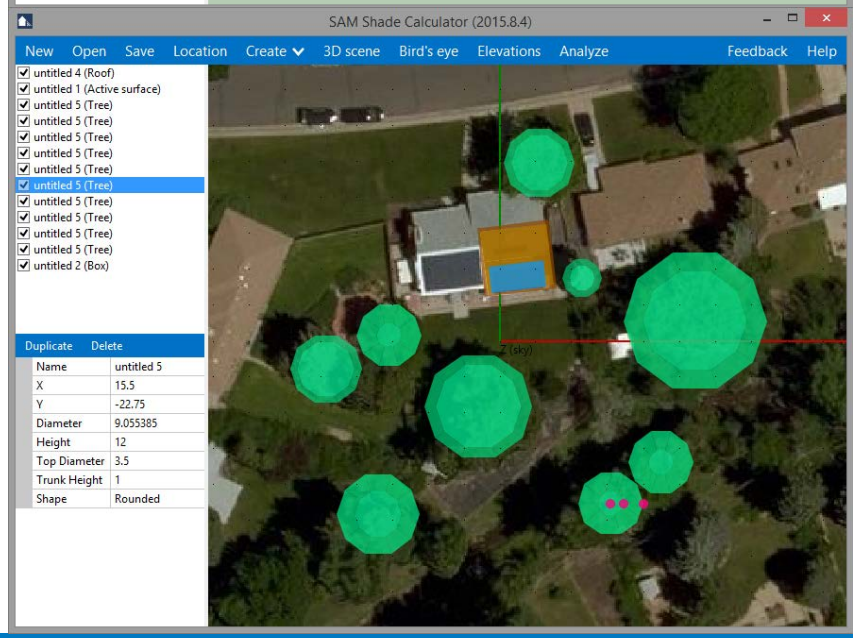
Imports 2D mapping underlays from online maps

Outputs are diurnal or hourly/subhourly time series linear shade loss percentages

You can group PV surfaces into subarrays and specify parallel strings

Scripting to automate panel layout and import/export geometry data



# Loss Modeling

- Irradiance Losses
  - Soiling
- DC Losses
  - Module mismatch
  - Wiring
  - Diodes and connections
- AC Losses
  - Wiring
  - Transformer

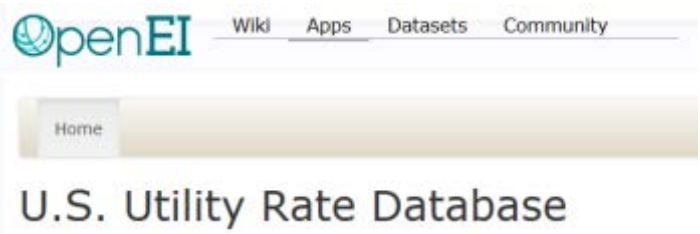
# Financial Modeling

Financial models:

| | |
|---|---|
| Residential (distributed)<br>Commercial (distributed) | • Specify electric load<br>• Specify utility rate structure |
| Third party ownership | • From perspective of off-taker (customer) |
| PPA single owner (utility)<br>PPA partnership flip with debt (utility)<br>PPA partnership flip without debt (utility)<br>PPA sale leaseback (utility) | • Utility scale systems with various ownership structures<br>• Power purchase agreements specify value of selling power to grid throughout the year |
| LCOE calculator (FCR method) | • Non cash-flow based fixed-charge rate method for calculating LCOE.<br>• Best for market level (not project level) analysis. |
| No financial model | • If you are only interested in system performance, not financial performance |

All financial calculations generally require some information about system costs, loans, taxes, inflation rates, discount rates, depreciation, and other relevant parameters, depending on the model

# Complex Utility Rate Tariffs




**Weekday**

| | 12am | 1am | 2am | 3am | 4am | 5am | 6am | 7am | 8am | 9am | 10am | 11am | 12pm | 1pm | 2pm | 3pm | 4pm | 5pm | 6pm | 7pm | 8pm | 9pm | 10pm | 11pm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 |
| Feb | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 |
| Mar | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 |
| Apr | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 |
| May | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 |
| Jun | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 |
| Jul | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 |
| Aug | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 |
| Sep | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 |
| Oct | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 |
| Nov | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 |
| Dec | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 |

**Rate Structure for Energy Rates**

Import...
Export...
Copy
Paste

| Period | Tier | Max. Usage | Max. Usage Units | Buy ($/kWh) | Sell ($/kWh) |
|---|---|---|---|---|---|
| 1 | 1 | 1e+038 | kWh | 0.26687 | 0.26687 |
| 2 | 1 | 1e+038 | kWh | 0.08328 | 0.08328 |
| 3 | 1 | 1e+038 | kWh | 0.22057 | 0.22057 |
| 4 | 1 | 1e+038 | kWh | 0.08326 | 0.08326 |

Number of entries: 4

## Utility Rate Database

- Tool in SAM to download and automatically populate complex inputs from utility rate database.
- http://en.openei.org/apps/USURDB/

## Modeling

- Time-of-use energy and demand charges with ability to model usage tiers.
- Monthly demand charges
- Multiple metering and rollover options
- Convenient output of energy/demand charges by month, period, tier, etc.

# Validation Studies

**Validation of Multiple Tools for Flat Plate Photovoltaic Modeling Against Measured Data**

Janine Freeman, Jonathan Whitmore, Nate Blair, and Aron P. Dobos

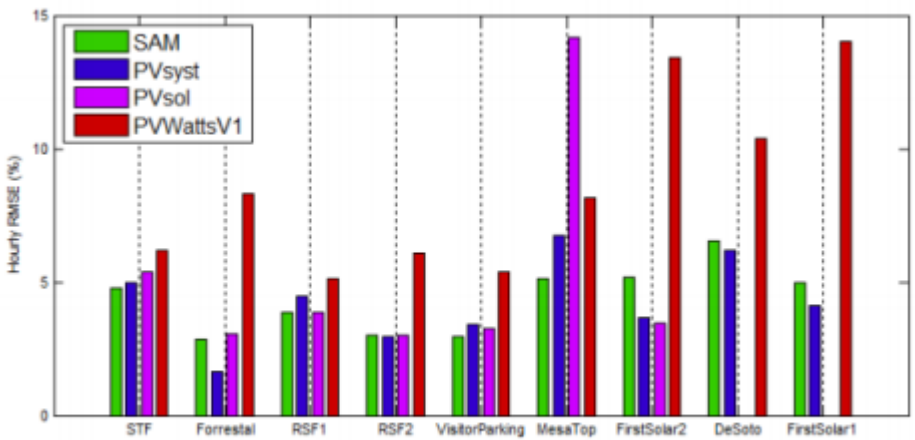



**Figure 3. Normalized hourly RMSE of each tool, sorted in order of system size [1]**

## Photovoltaic Modeling

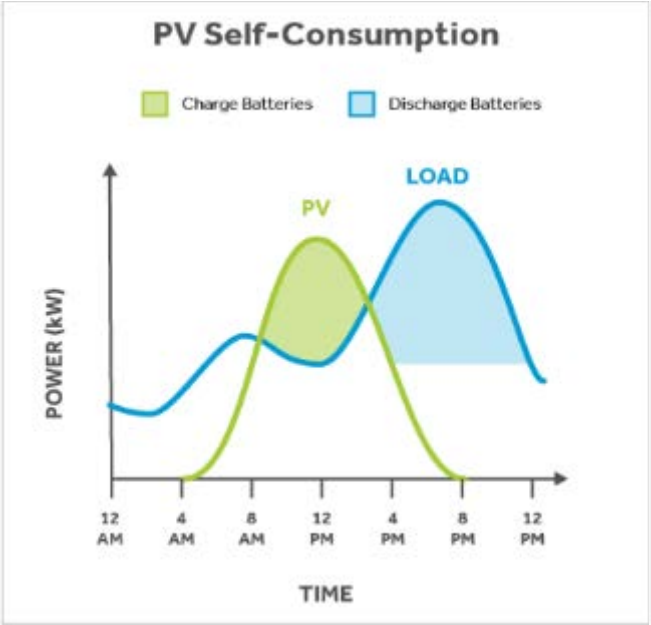
- Comparisons of SAM and other tools to measured performance data:
- Most recent study concluded SAM annual errors within +/- 8% of measured data
- https://sam.nrel.gov/case-studies

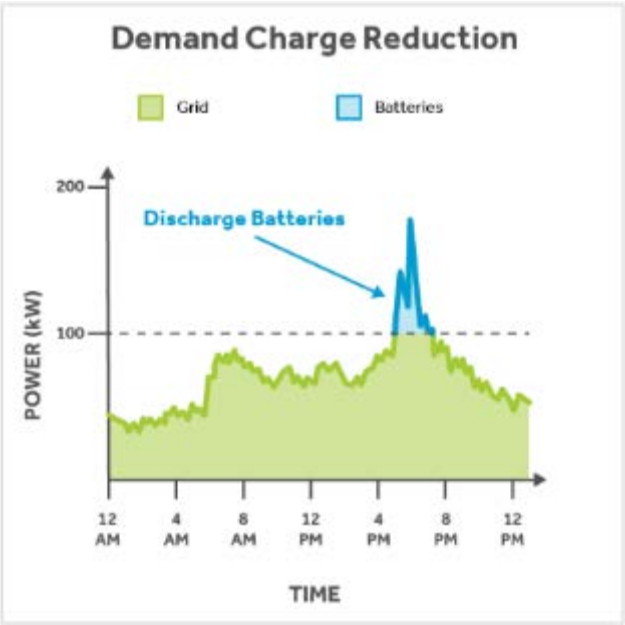
## Upcoming Validation

- Comparison of SAM and other tools 3D shading calculations against SunEye measurements.
- Preliminary results suggest potentially large differences between tools

# SAM Battery Model

# Motivation for behind-the-meter storage






Images from: http://www.aquionenergy.com/

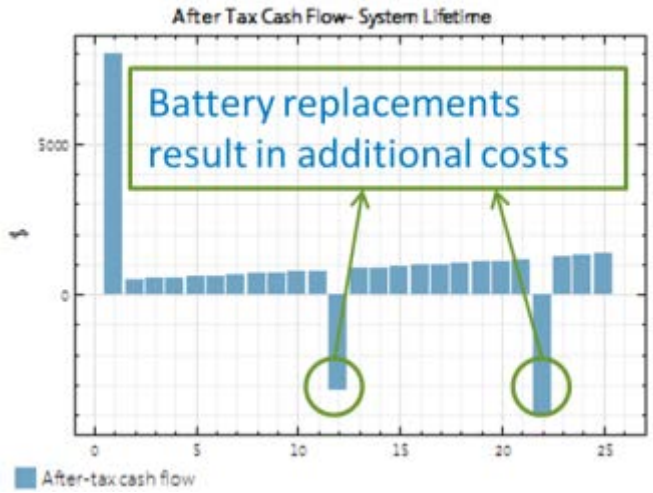
- Batteries charged primarily from PV eligible for Federal ITC subject to 75% cliff
- End of NEM in some states

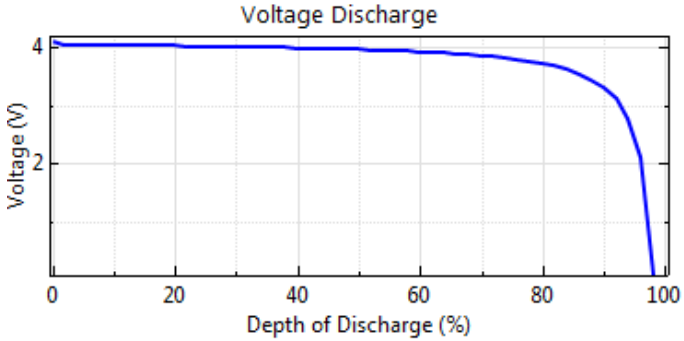
- Residential and commercial utility rate structures with high TOU charges.
- Charge when rate is low, discharge when rate is high

- Commercial utility structures can have very high TOU demand charges.

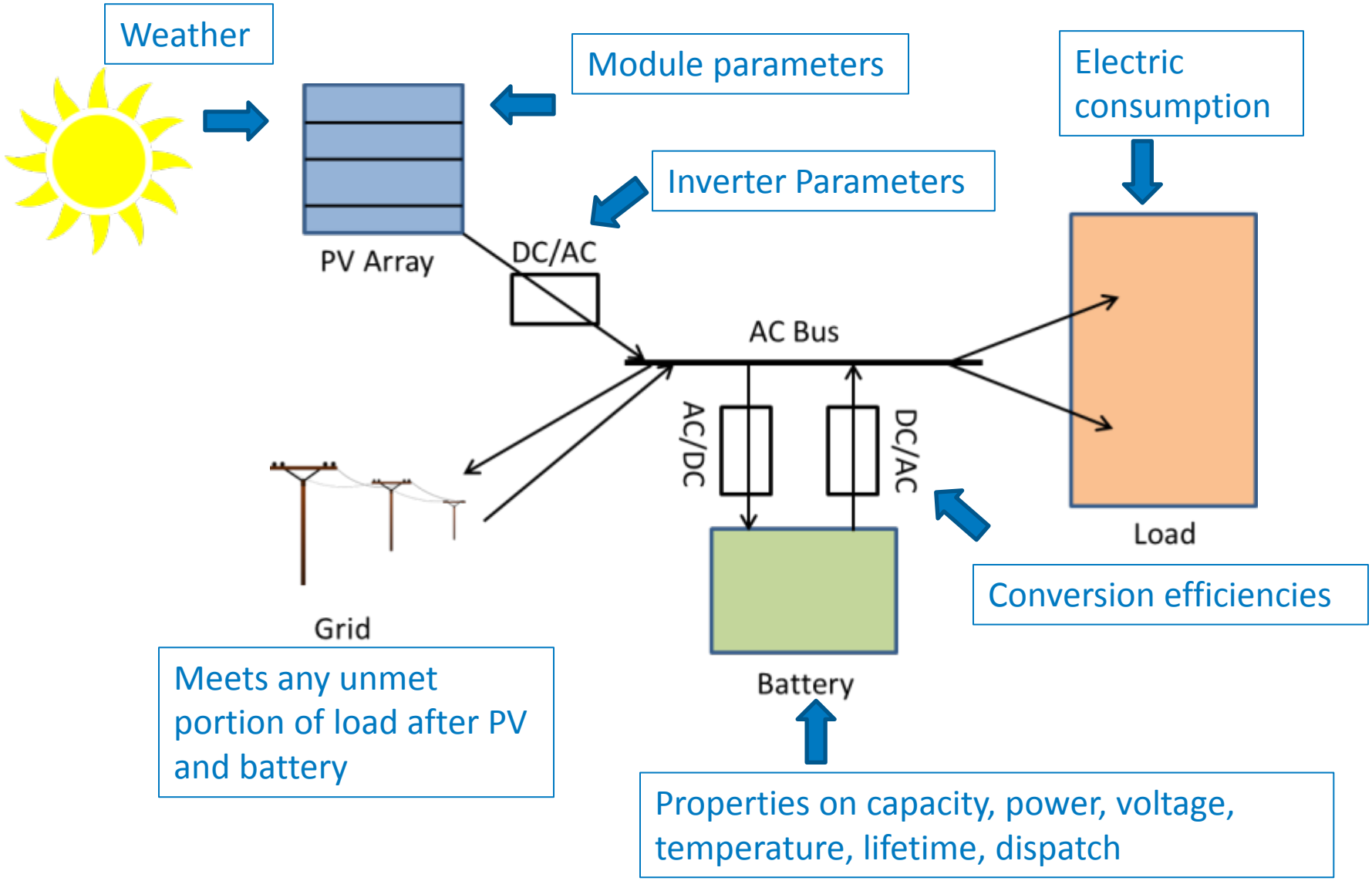
# Model Overview

- Techno-economic model for residential, commercial, and third-party ownership systems
  - Lead acid & lithium ion battery chemistries
  - System lifetime analysis including battery replacement costs
  - Models for terminal voltage, capacity, temperature
  - Multiple dispatch controllers available



# Modeled Configuration



# Implementation in SAM

SAM 2016.3.14

Choose a performance model, and then choose from the available financial models.

- Photovoltaic (detailed)
- Photovoltaic (PVWatts)
- High concentration PV
- Wind
- Biomass combustion
- Geothermal
- Solar water heating
- Generic system
- CSP parabolic trough (physical)
- CSP parabolic trough (empirical)
- CSP power tower molten salt
- CSP power tower direct steam
- CSP linear Fresnel molten salt
- CSP linear Fresnel direct steam
- CSP dish Stirling
- CSP generic model
- CSP Integrated Solar Combined Cycle

- Residential (distributed)
- Commercial (distributed)
- Third party ownership
- PPA single owner (utility)
- PPA partnership flip with debt (utility)
- PPA partnership flip without debt (utility)
- PPA sale leaseback (utility)
- LCOE calculator (FCR method)
- No financial model

Help | OK | Cancel

SAM 2016.3.14

File | Add | Commercial Battery

Photovoltaic, Commercial

- Location and Resource
- Module
- Inverter
- System Design
- Shading and Snow
- Losses
- Lifetime
- Battery Storage
- System Costs
- Financial Parameters
- Incentives
- Electricity Rates
- Electric Load

Enable Battery

**Battery Bank Sizing**

Specify desired bank size | Specify cells

Desired bank capacity 3 kWh | Number of cells in series

Desired bank voltage 12 V | Number of strings in parallel

**Chemistry**

Battery type: Lithium Ion: Nickel Manganese Cobalt Oxide (NMC)

**Voltage Properties**

Cell nominal voltage 3.6 V | Internal resistance 0.1 Ohm

C-rate of discharge curve 0.2

Fully charged cell voltage 4.1 V

Exponential zone cell voltage 4.05 V

Nominal zone cell voltage 3.4 V

Charge removed at exponential point 1.78 %

Charge removed at nominal point 88.9 %

**Current and Capacity**

Cell capacity 2.25 Ah | Max C-rate of charge

Max C-rate of discharge

**Computed Properties**

Nominal bank capacity 3.0132 kWh | Maximum power 3.0

Nominal bank voltage 14.4 V | Time at maximum power

Cells in series 4 | Maximum charge current 20

Strings in parallel 93 | Maximum discharge current 20

**Power Converters**

AC to DC conversion efficiency 99 %

# Battery Financials

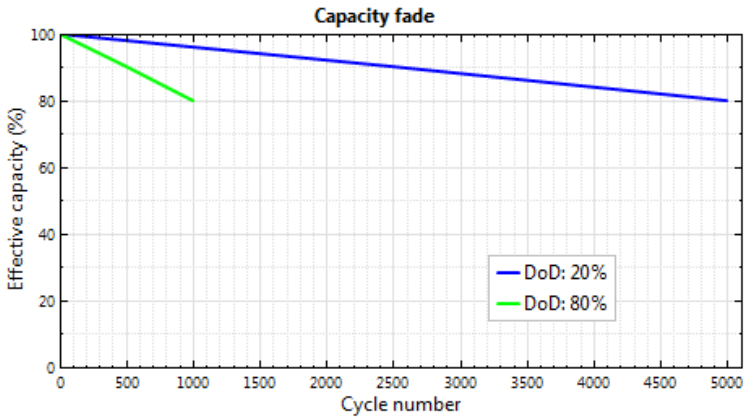
- **Lifetime**

PV simulation over analysis period

**PV Array Performance Degradation**

Module degradation rate 0 %/year

Applies to the array's hourly DC output.




Battery capacity fades with cycling, depends on depth-of-discharge

- **System Costs**

**Direct Capital Costs**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Module | 928 | units | 0.2 | kWdc/unit | 199.8 | kWdc | 0.71 | $/Wdc |
| Inverter | 5 | units | 36.0 | kWac/unit | 180.0 | kWac | 0.21 | $/Wdc |
| | | | | Battery bank | 3.0 | kWh dc | 600.00 | $/kWh dc |

- **Battery Bank Replacement (Battery Storage page)**

**Battery Bank Replacement**

- No replacements
- Replace at specified capacity
- Replace at specified schedule

Battery bank replacement threshold 20 % capacity

Battery bank replacement schedule Edit data...

Battery bank replacement cost 600 $/kWh

Battery cost escalation above inflation 0 % %/year

SAM applies both inflation and escalation to the first year cost to calculate out-year costs. See Help for details.

# Battery Dispatch

**Storage Dispatch Controller**

**Choose Dispatch Model**

- ○ Peak shaving: 1-day look ahead
- ○ Peak shaving: 1-day look behind
- ○ Automated grid power target
- ◉ Manual dispatch

**Charge Limits and Priority**

| | | |
|---|---|---|
| Minimum state of charge | 30 | % |
| Maximum state of charge | 95 | % |
| Minimum time at charge state | 10 | min |

**Automated Grid Power Target Model**

Enter single or monthly powers

| | | |
|---|---|---|
| Single or monthly | Edit values... | kW |
| Time series | Edit data... | kW |

**Manual Dispatch Model**

| | Charge from PV | Charge from grid Allow | Charge from grid % capacity | Discharge Allow | Discharge % capacity |
|---|---|---|---|---|---|
| Period 1: | ☑ | ☐ | 25 | ☐ | 25 |
| Period 2: | ☑ | ☑ | 25 | ☐ | 25 |
| Period 3: | ☑ | ☐ | 25 | ☑ | 25 |
| Period 4: | ☐ | ☐ | 25 | ☐ | 25 |
| Period 5: | ☐ | ☐ | 25 | ☐ | 25 |
| Period 6: | ☐ | ☐ | 25 | ☐ | 25 |

To activate the manual dispatch model, choose Manual Dispatch under "Choose Dispatch Model" above. These inputs are inactive for the automated dispatch options.

The manual dispatch model aims to minimize purchases from the grid. It first tries to meet load with PV, then battery, then grid. Choose whether PV should meet the load or charge the battery below. Use the timing controls to constrain the battery controller. See help for details.

- ◉ PV meets load before charging battery
- ○ PV charges battery before meeting load

**Weekday**

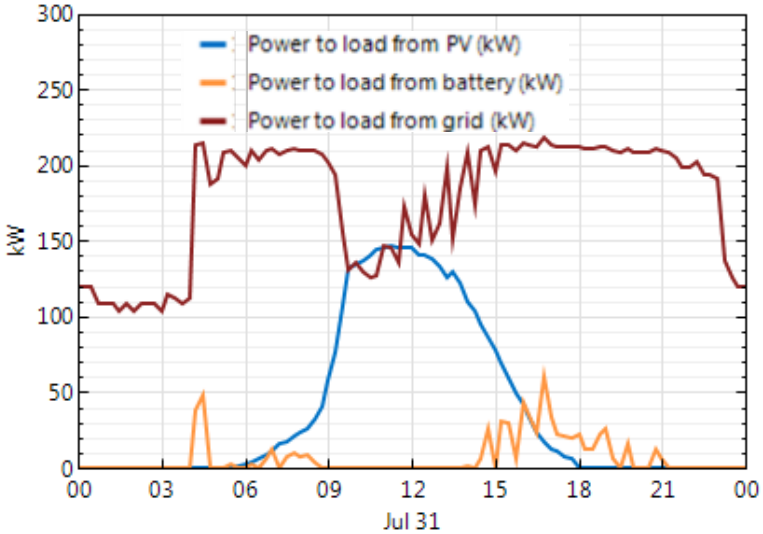
| | 12am | 1am | 2am | 3am | 4am | 5am | 6am | 7am | 8am | 9am | 10am | 11am | 12pm | 1pm | 2pm | 3pm | 4pm | 5pm | 6pm | 7pm | 8pm | 9pm | 10pm | 11pm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 1 | 1 | 1 | 1 |
| Feb | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 1 | 1 | 1 | 1 |
| Mar | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 1 | 1 | 1 | 1 |
| Apr | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 1 | 1 | 1 | 1 |
| May | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 1 | 1 | 1 | 1 |
| Jun | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 1 | 1 | 1 | 1 |
| Jul | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 1 | 1 | 1 | 1 |
| Aug | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 1 | 1 | 1 | 1 |
| Sep | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 1 | 1 | 1 | 1 |
| Oct | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 1 | 1 | 1 | 1 |
| Nov | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 1 | 1 | 1 | 1 |
| Dec | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 1 | 1 | 1 | 1 |

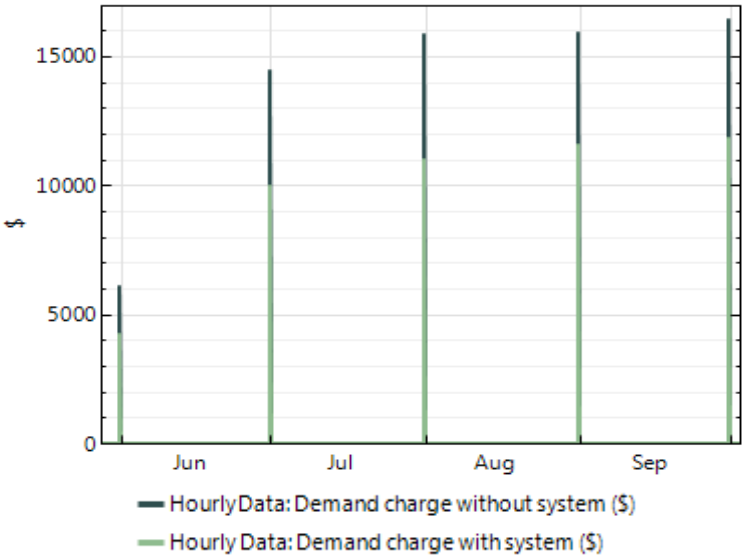
**Weekend**

| | 12am | 1am | 2am | 3am | 4am | 5am | 6am | 7am | 8am | 9am | 10am | 11am | 12pm | 1pm | 2pm | 3pm | 4pm | 5pm | 6pm | 7pm | 8pm | 9pm | 10pm | 11pm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Feb | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Mar | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Apr | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| May | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Jun | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Jul | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Aug | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Sep | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Oct | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Nov | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Dec | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

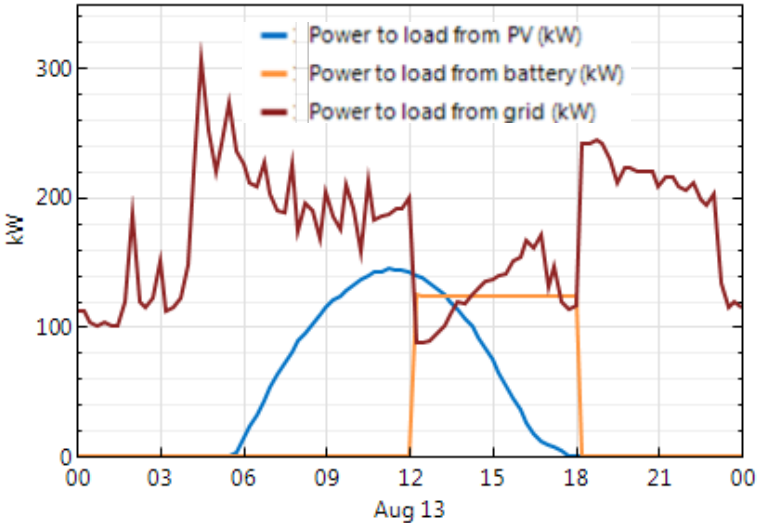
# Dispatch Visualization

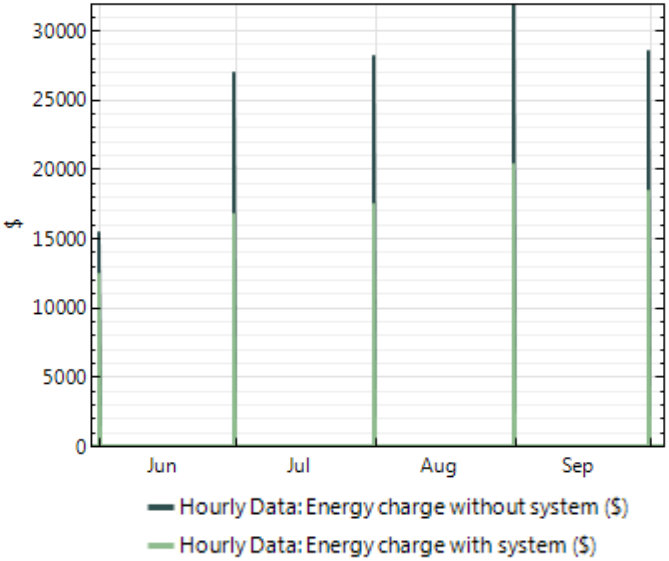
## Peak shaving for demand charge reduction




## Manual dispatch for energy arbitrage



# Example Case Study

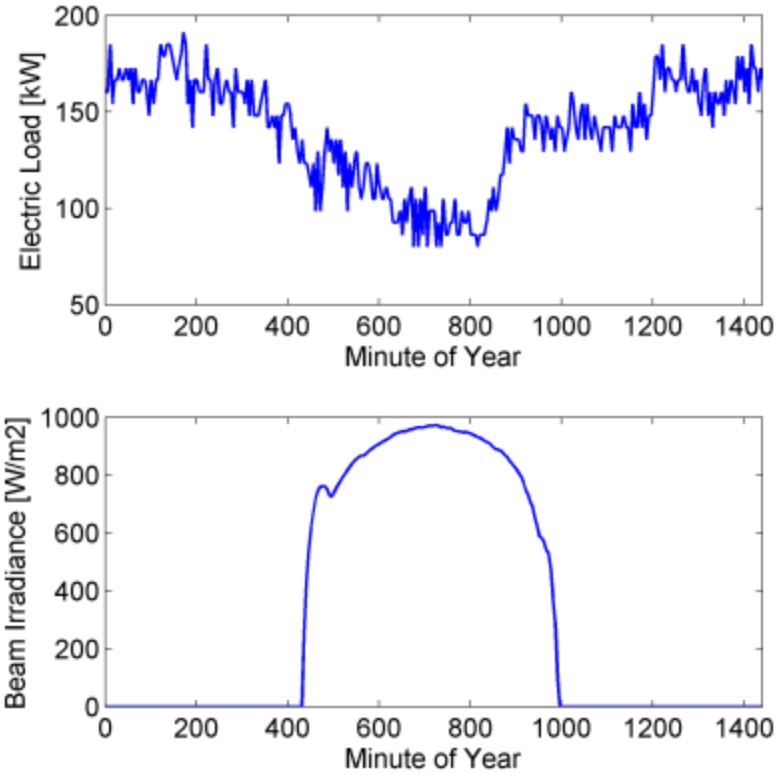
- Evaluate economics of installing PV-coupled battery system for demand-charge reduction:
  - Los Angeles, CA
  - 27,625 $ft^2$ grocery store with 247 kW peak load
  - Southern California Edison TOU-GS-2 Option B

Image from SCE TOU-GS-2 Option B datasheet

# Simulation Data

- One-minute weather data taken from NREL's Measurement & Instrumentation Data Center network, location in Los Angeles.
- Five-minute electric load data obtained from EnerNOC's free online database for commercial facilities.
- Assumed California's SGIP applied

January 1st, 2012



# Lithium Ion Battery System

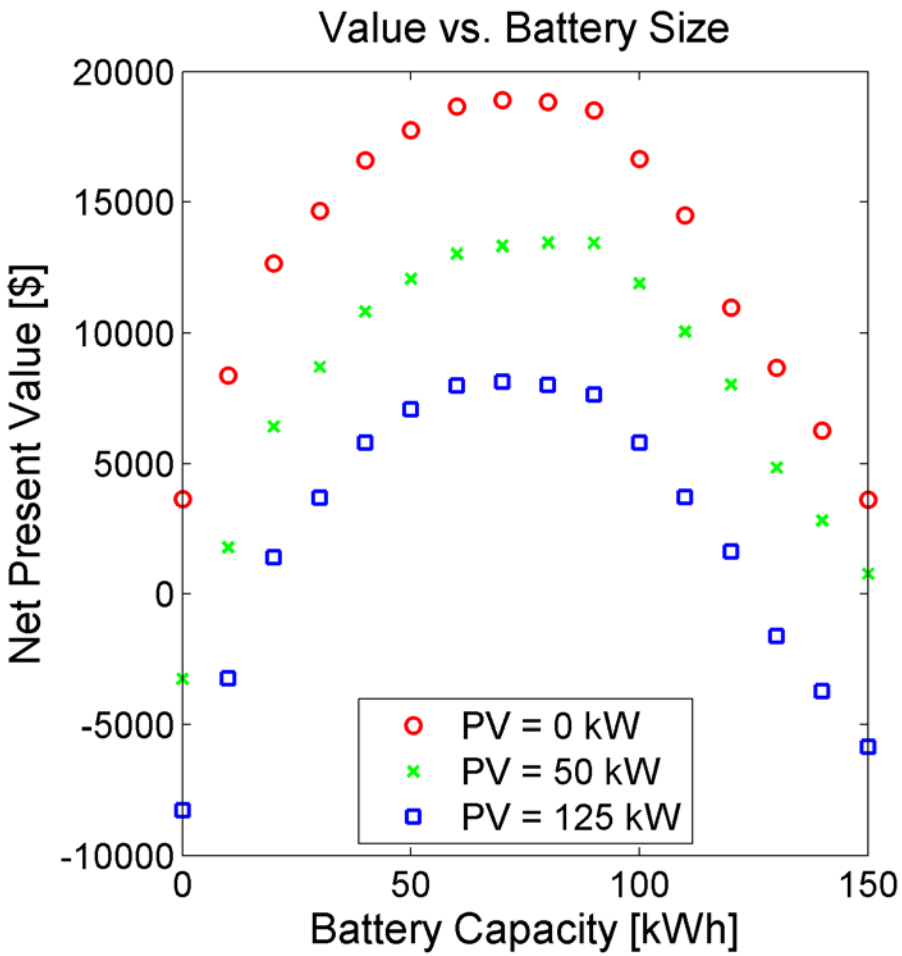
- Model battery similar to Tesla Powerwall
  - Lithium-ion nickel manganese cobalt
  - Assumed can cycle full 7 kWh down to 30% of state-of-charge, for a full capacity of 10 kWh.
  - Price given as ~$300/kWh before balance of system costs.
  - Assumed lifetime of 10-15 years before degrading to 70% of original capacity

**Table 3: Tesla Powerwall Specifications [13]**

| Property | Value |
|---|---|
| Price | $3000 |
| Capacity | 7 kWh |
| Power | 2.0 kW continuous, 3.3 kW peak |
| Efficiency | 92% |
| Voltage | 350 – 450 V |
| Current | 5.8 A nominal, 8.6 A peak |
| Weight | 100 kg |
| Dimensions | 1300 mm x 860 mm x 180 mm |

Image from teslamotors.com/powerwall

# Parametric sizing results

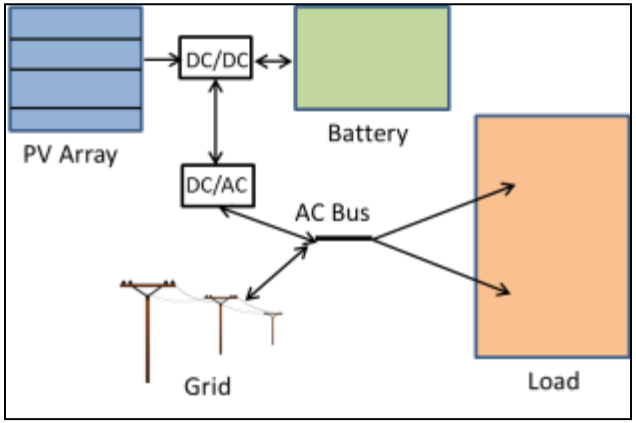



- NPV maximized for no PV system, battery bank capacity of 70 kWh
- Illustrates simulation-based method to approximate 'optimal' sizing.

# Upcoming features

- Additional system configurations
- Additional battery chemistries
- Battery systems for PPA financial models
- Continued improvement of dispatch controllers
- Improved lifetime modeling for some battery chemistries

DC-connected battery




Flow batteries

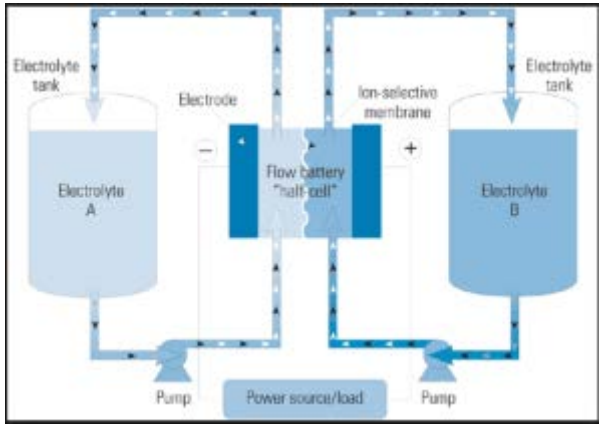



Image from tantaline.com

# Battery summary

- Battery model adds on to SAM's powerful PV and inverter modeling capabilities to evaluate behind-the-meter storage systems.
- Can answer questions like:
  - What sizes of battery/PV system will provide value over the system lifetime?
  - How will battery replacement costs affect economic viability?
  - How does the dispatch strategy affect bill savings?

# Questions?

- Resources:
  - **https://sam.nrel.gov/learning**
  - **https://sam.nrel.gov/videos**
  - **https://sam.nrel.gov/webinars**
- Reports available
  - Economic Analysis Case Studies of Battery Energy Storage with SAM
    - **http://www.nrel.gov/docs/fy16osti/64987.pdf**
  - Technoeconomic Modeling of Battery Energy Storage in SAM
    - **http://www.nrel.gov/docs/fy15osti/64641.pdf**

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory

www.nrel.gov

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

# Bifacial PV Review

**Fatima Toor, Ph.D.**
Assistant Professor
Photonics Research Group
Departments of Electrical and Computer Engineering
University of Iowa, Iowa City, IA
https://research.engineering.uiowa.edu/ftoor/

# Agenda

- DOE SuNLaMP Project
- Introduction to Bifacial Photovoltaics
- Bifacial PV cost analysis and SunShot goals
- Bifacial Solar Cell Designs
- Field Results of Bifacial PV Gain (Various Studies)
- Analysis of Backside Irradiance
- Characterization of Bifacial Modules
- PV System Modeling using PVLIB

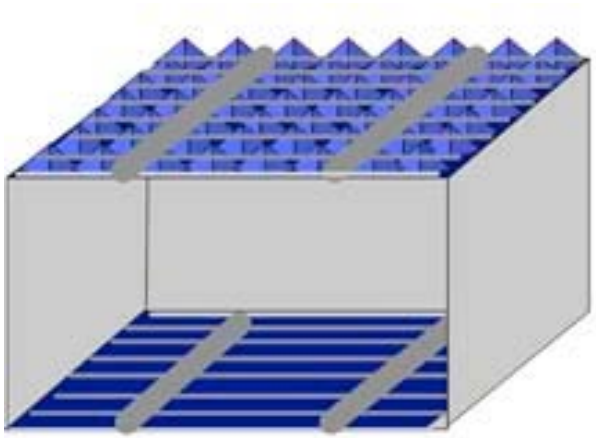
# Collaborators of the DOE SuNLaMP Project

- Sunshot National Laboratory Multilayer Partnership (SuNLaMP) project on bifacial photovoltaic (PV)

# Agenda

- DOE SuNLaMP Project
- Introduction to Bifacial Photovoltaics
- Bifacial PV cost analysis and SunShot goals
- Bifacial Solar Cell Designs
- Field Results of Bifacial PV Gain (Various Studies)
- Analysis of Backside Irradiance
- Characterization of Bifacial Modules
- PV System Modeling using PVLIB

# Bifacial Photovoltaic (PV) Cells



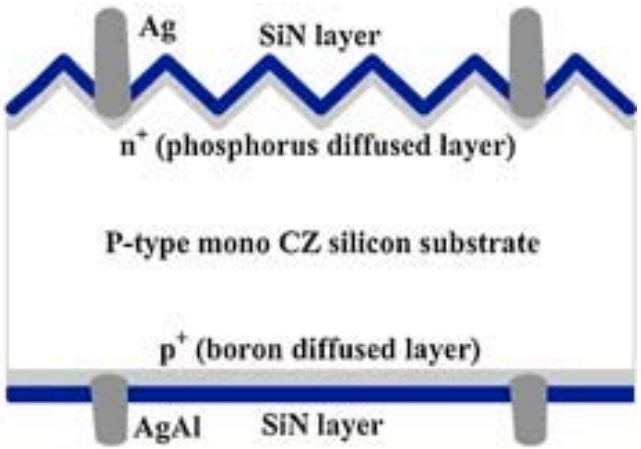
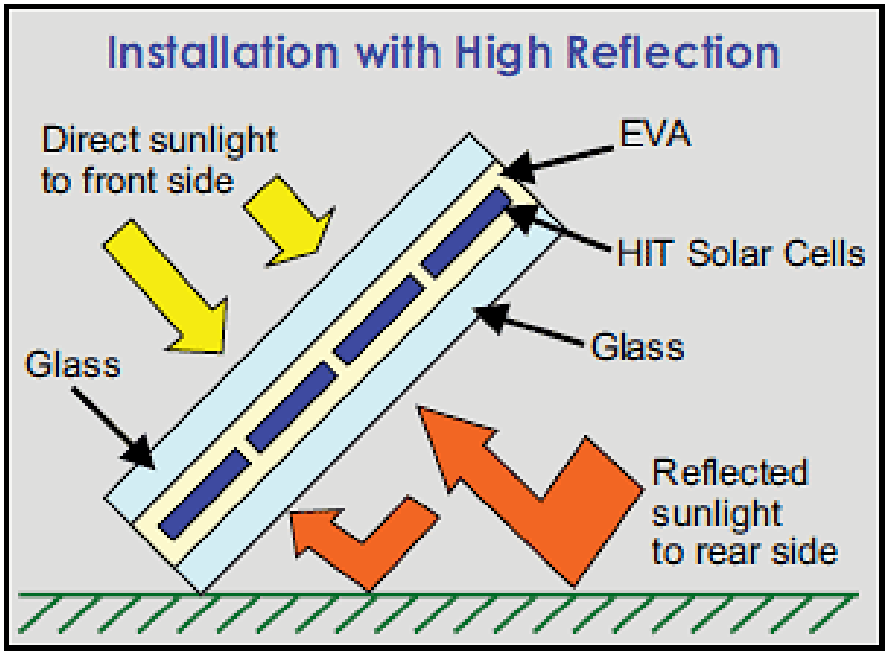



*Image Source: "High efficiency screen printed bifacial solar cells on monocrystalline CZ silicon"* Prog. Photovolt. Res. Appl. (2011) **19**:275-279

# Bifacial Solar Modules



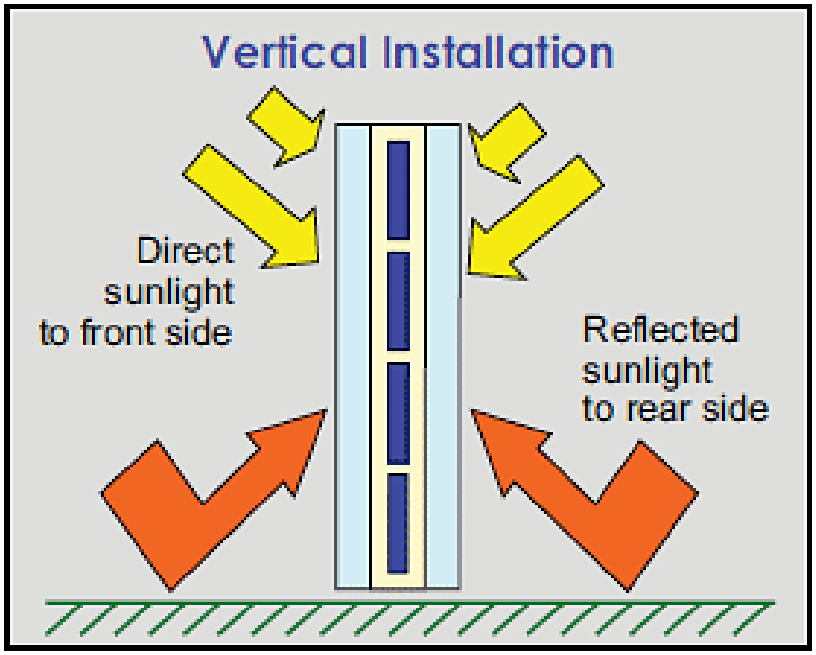
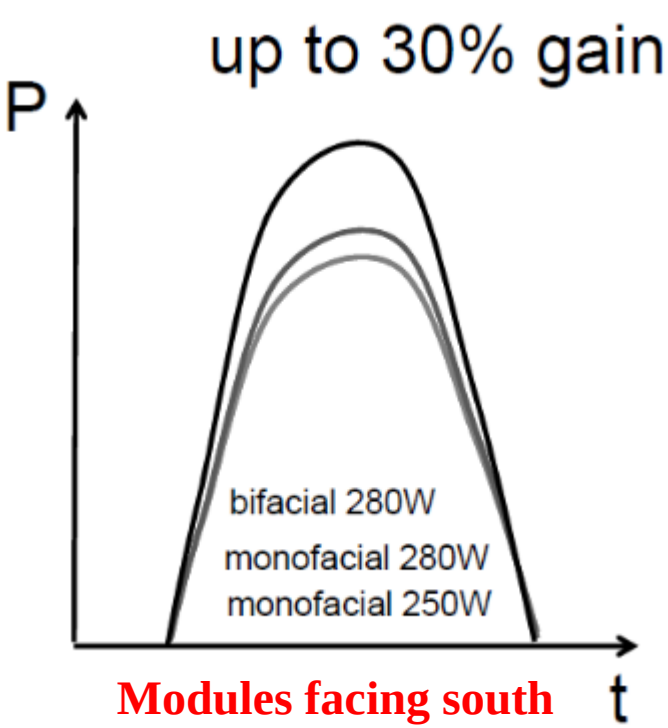




*Image Source: Sanyo Energy Corporation via Solar Electric Supply*

# Daily Energy Production of Bifacial versus Monofacial Modules




**Modules facing south**

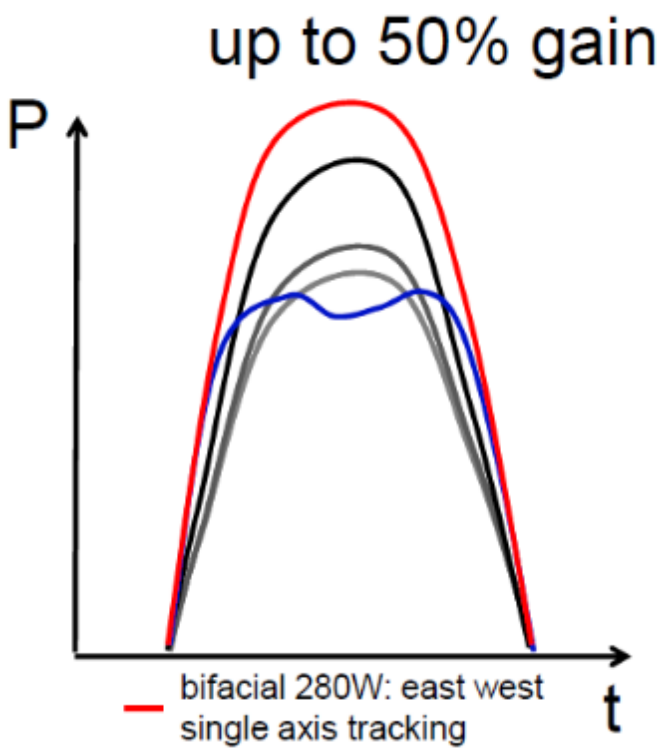



*Image Source: Radovan Kopecek, ISC Konstanz, 2015 bifi PV Workshop*

# Bifacial gain values from literature

THE UNIVERSITY OF IOWA

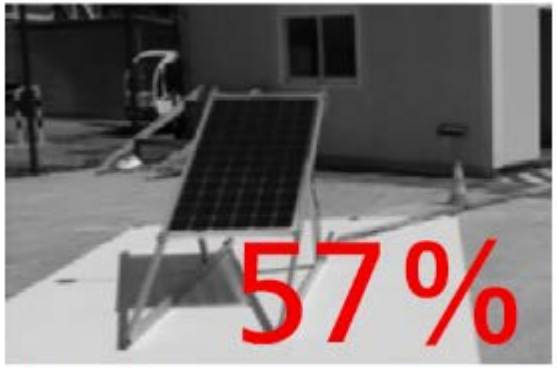
Some bifacial gain values from literature (mainly experimental / test systems):

bSolar 2014

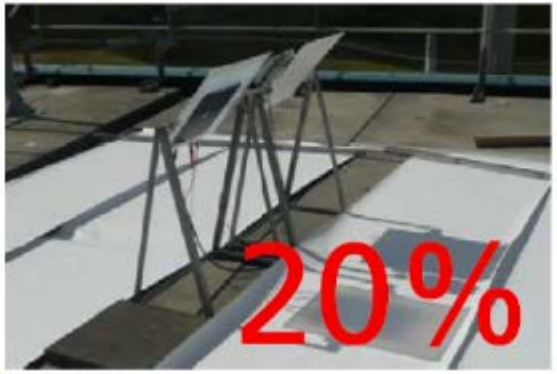
bSolar 2014

Sanyo 2009

ISC Konstanz 2014




EdF R&D 2014




ECN 2014

*Image Source: Christian Reise et al., Fraunhofer ISE, 2015 PV Performance Modeling and Monitoring Workshop*

# Examples of Bifacial PV Installations

*Image Source: Tokyo Solar Building Materials Corp. and Applied Energy Technologies (AET)*

# Bifacial PV History

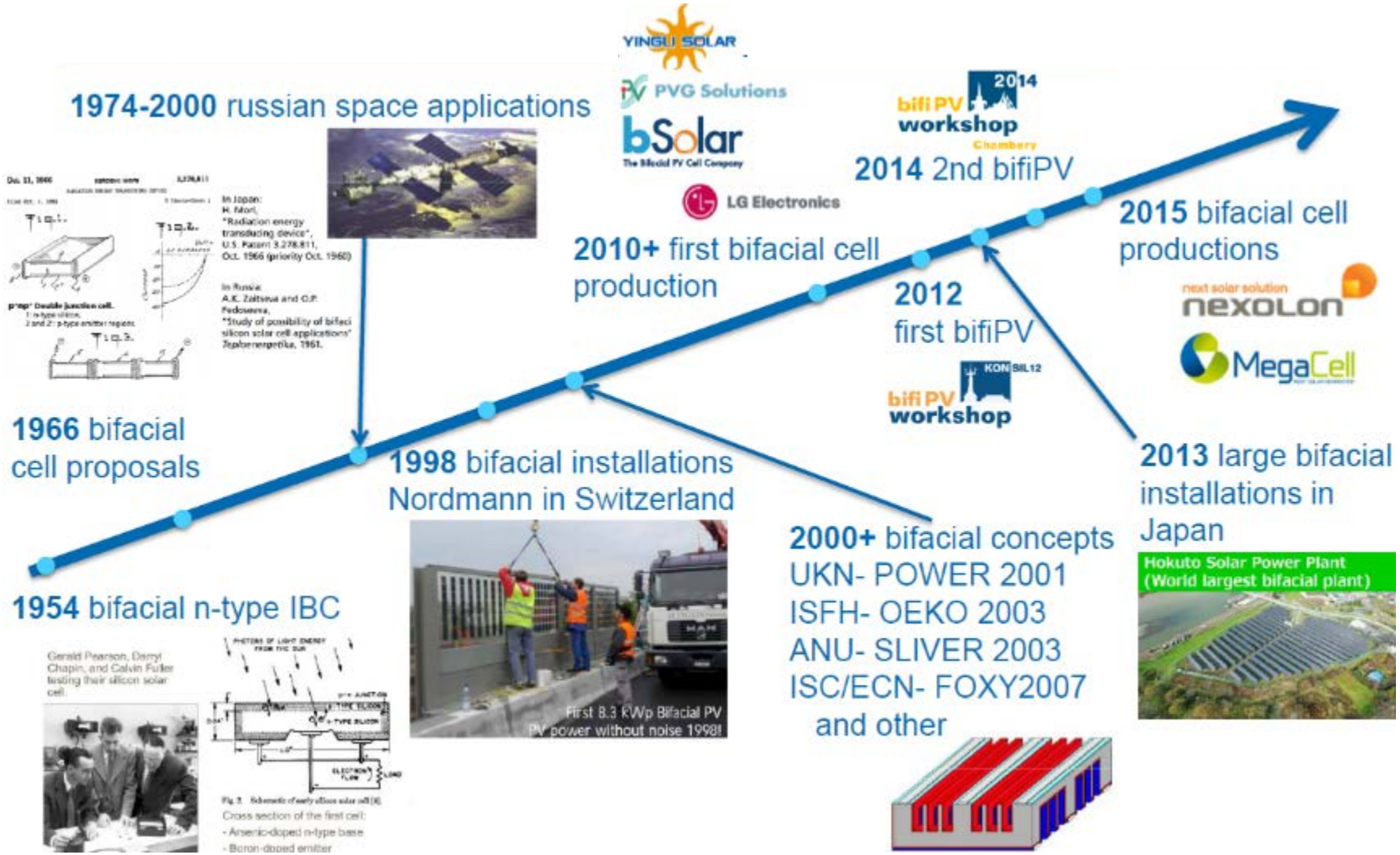



*Image Source: Radovan Kopecek, ISC Konstanz, 2015 bifi PV Workshop*

# The largest Bifacial PV Installation (2015)

THE UNIVERSITY OF IOWA

**1.25MW Solar Plant Starts Operation With Bifacial Panels**

"Asahikawa Hokuto Solar Power Plant," a 1.25MW solar plant using bifacial solar panels (source: Nishiyama Sakata Denki)

# Agenda

- DOE SuNLaMP Project
- Introduction to Bifacial Photovoltaics
- Bifacial PV cost analysis and SunShot goals
- Bifacial Solar Cell Designs
- Field Results of Bifacial PV Gain (Various Studies)
- Analysis of Backside Irradiance
- Characterization of Bifacial Modules
- PV System Modeling using PVLIB

# Bifacial x-Si Modules will Beat the Efficiency and Cost Targets Needed for $1/W System Price

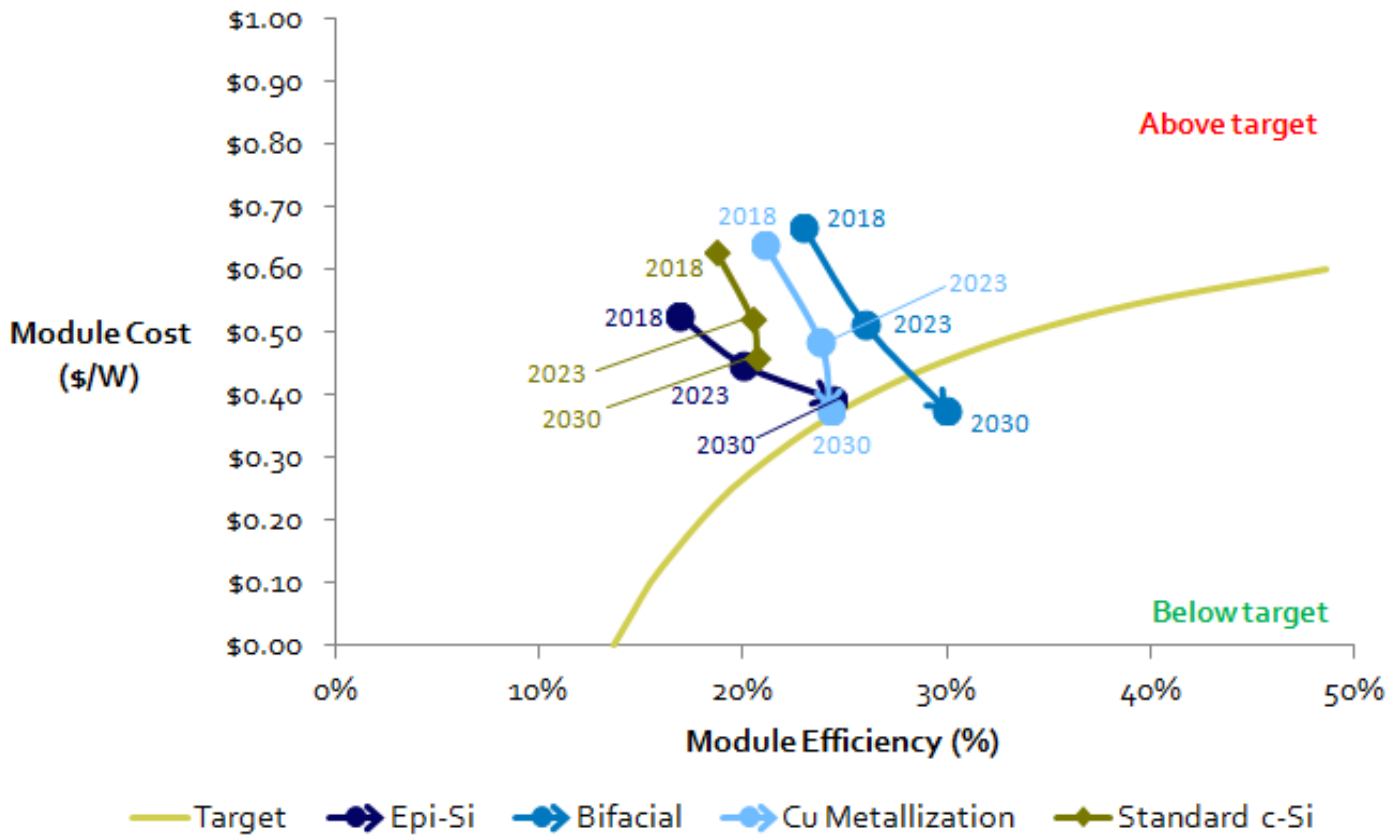



*Image Source: Toor et al., 2013 Lux Research Report, "Continuing Education: Going back to school for PV Innovation"*

# Cost of Ownership (CoO) of 60-cell modules

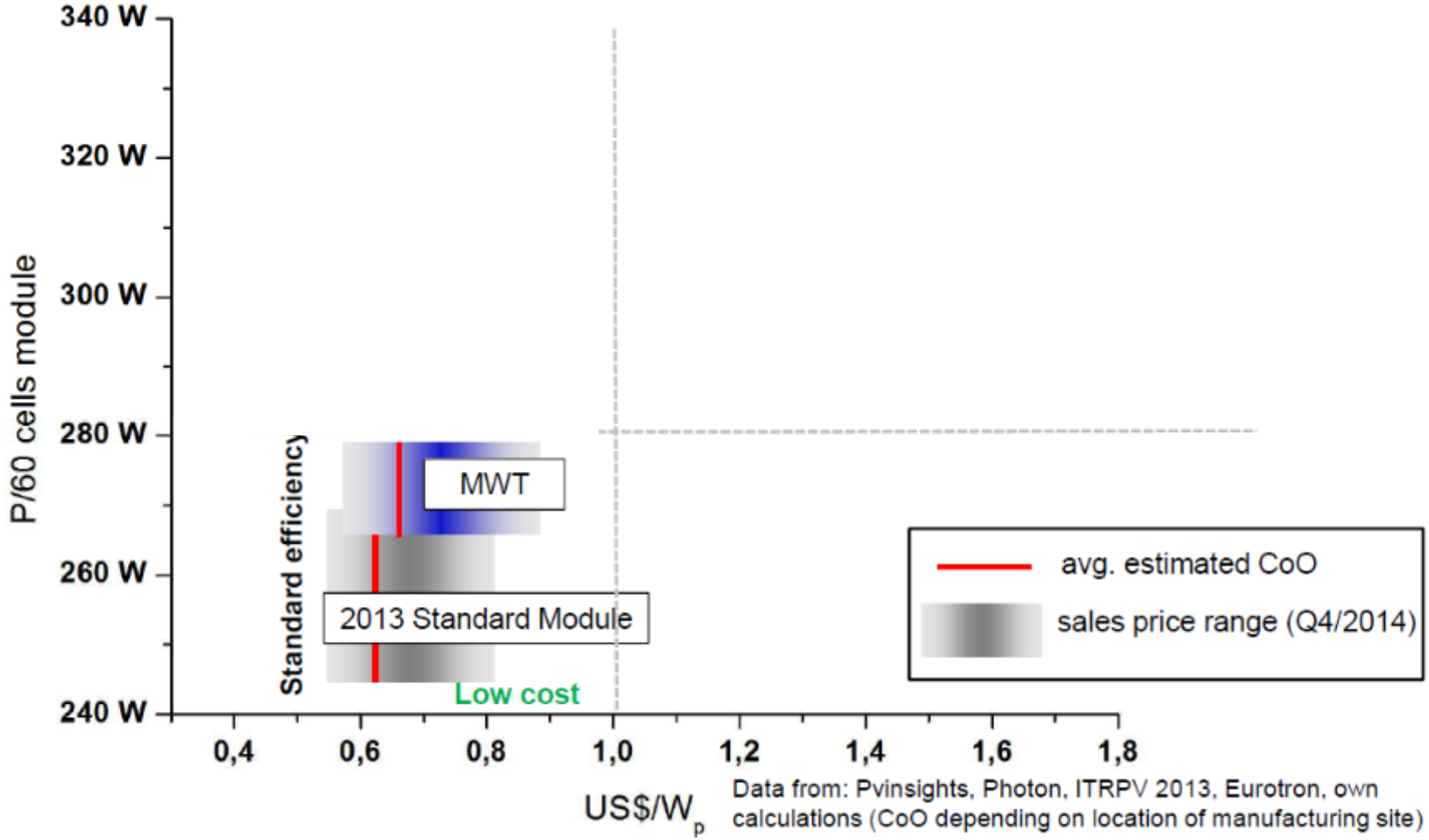



*Image Source: Radovan Kopecek, ISC Konstanz, 2015 bifi PV Workshop*

# Balance of Systems (BoS) Costs

THE UNIVERSITY OF IOWA

*Bifacial Bison module with 290W front side Pmpp can produce the same kWh/kWp as a monofacial module with 350 W Pmpp (20% Albedo)*

*Image Source: Radovan Kopecek, ISC Konstanz, 2014 bifi PV Workshop*

# Agenda

- DOE SuNLaMP Project
- Introduction to Bifacial Photovoltaics
- Bifacial PV cost analysis and SunShot goals
- Bifacial Solar Cell Designs
- Field Results of Bifacial PV Gain (Various Studies)
- Analysis of Backside Irradiance
- Characterization of Bifacial Modules
- PV System Modeling using PVLIB

# Examples of Bifacial Solar Cell Designs

*Image Source: Meyer Burger, 2014 bifi PV Workshop*

# n-type bifacial cell manufacturers

THE UNIVERSITY OF IOWA

| Company/Institute | Country | Name | Bifacial cell structure | Technology | Efficiency [%] | Reference |
|---|---|---|---|---|---|---|
| Yingli | China | PANDA | H-pattern | Diffused, SP | 19.5 | [7] |
| ECN | Netherlands | n-Pasha | H-pattern | Diffused, SP | 20 | [8] |
| INES | France | NN | H-pattern | Diffused, SP | 20 | [9] |
| ISC Konstanz | Germany | BiSoN | H-pattern | Diffused, SP | 20 | [10] |
| PVG Solutions | Japan | NN | H-pattern | Diffused, SP | 20 | [11] |
| Suniva | USA | NN | H-pattern | Implanted, SP | 20 | [12] |
| LG Electronics | Korea | Neon | H-pattern | Implanted, SP | 20.5 | [13] |
| Bosch Solar | Germany | iBiN | H-pattern | Implanted, SP | 20.5 | [14] |
| Hareon | China | NN | IBC | Diffused, SP | 20 | [15] |
| Samsung | Korea | NN | IBC | Implanted, SP (metal glass) | 20.5 | [16] |
| ISC Konstanz | Germany | ZEBRA | IBC | Diffused, SP | 21 | [17] |

**Table 1. Diffused and ion-implanted 6″ industrial n-type solar cells from different companies/institutes with screen-printed (SP) metallization and with two different geometries, both having a bifacial characteristic. (Efficiency values are rounded to 0.5% abs., as different measuring conditions were applied.)**

R. Kopecek and J. Libal, PV international, September 2013

Photovoltaics International

# n-type wafer and solar cell producers

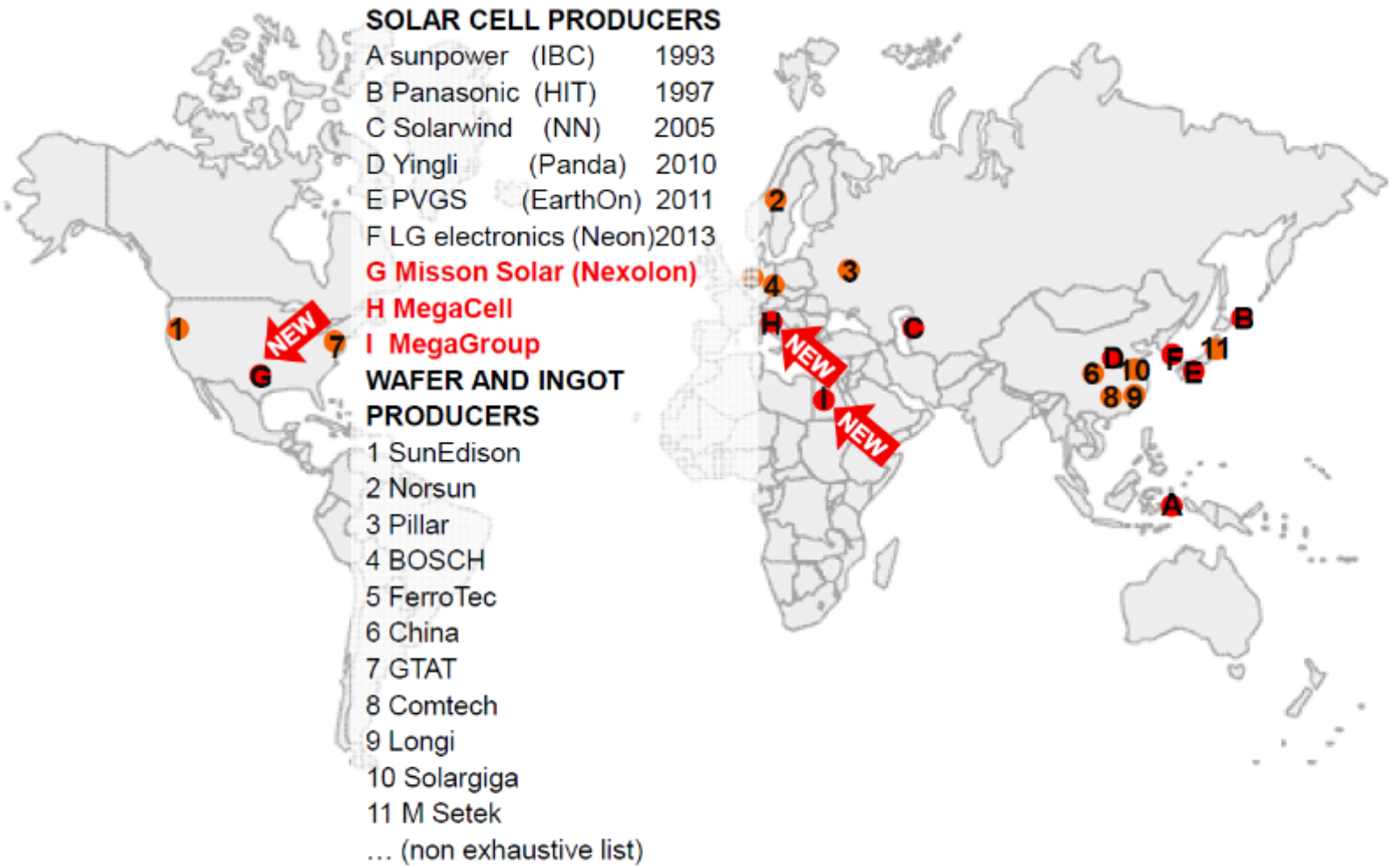



*Image Source: Radovan Kopecek, ISC Konstanz, 2015 bifi PV Workshop*

# Agenda

- DOE SuNLaMP Project
- Introduction to Bifacial Photovoltaics
- Bifacial PV cost analysis and SunShot goals
- Bifacial Solar Cell Designs
- Field Results of Bifacial PV Gain (Various Studies)
- Analysis of Backside Irradiance
- Characterization of Bifacial Modules
- PV System Modeling using PVLIB

# Bifacial Gain based on Albedo

**Bifacial gain = Energy yield of rear (kWh)/Energy yield of front only (kWh)**

| surface | albedo [%] |
|---|---|
| water | 8 |
| dry dark soil | 13 |
| grass | 17-28 |
| dry sand | 35 |
| dune sand | 37 |
| old snow | 40-70 |
| reflective roof coatings | 80-90 |
| fresh snow | 75-95 |

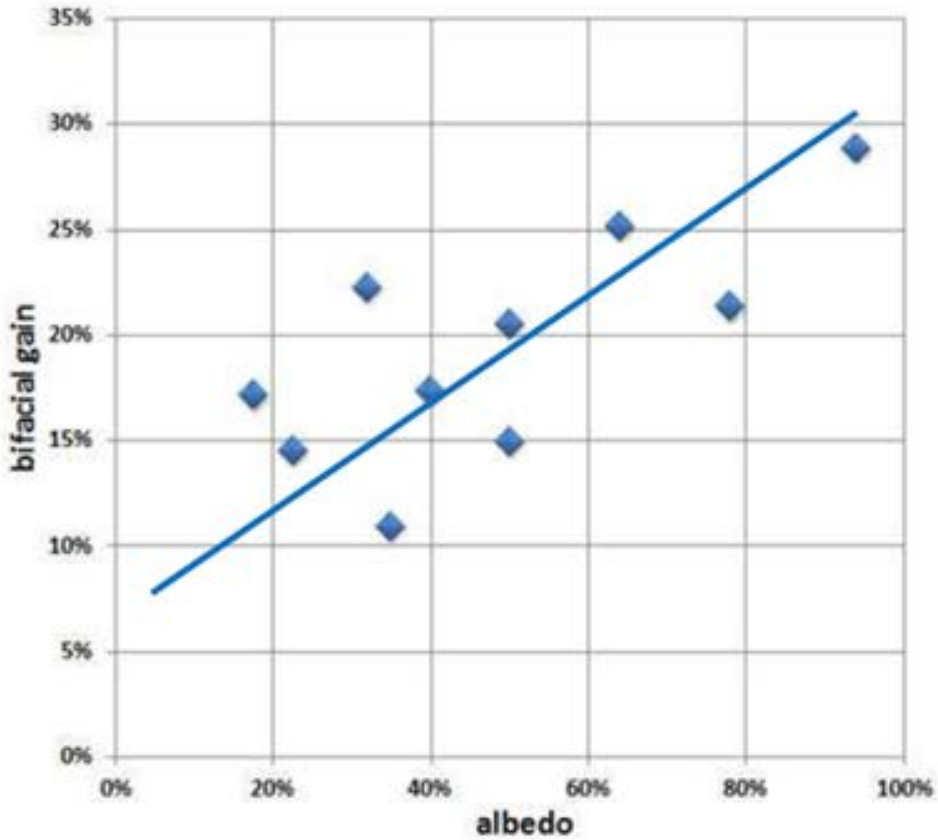
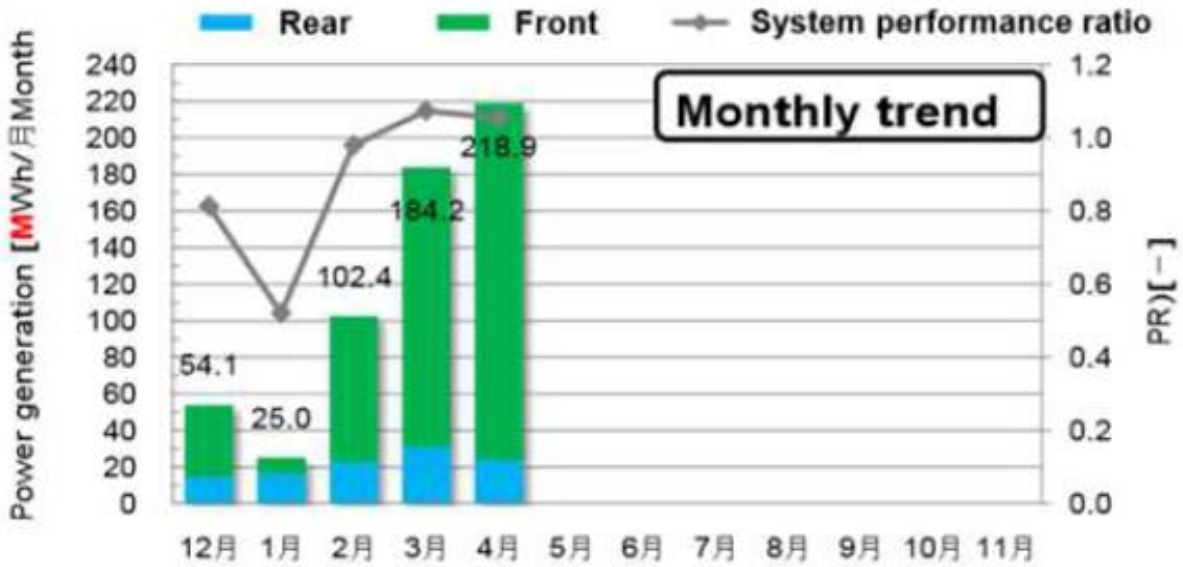



*Image Source: Radovan Kopecek, ISC Konstanz, 2015 bifi PV Workshop*

# Bifacial gain in the largest bifacial PV installation ~ 10% to 20%




PVGS, bifiPV workshop, 2014

# Bifacial gain for a range of tilt angles, heights, and albedo values

THE UNIVERSITY OF IOWA

| Test Condition | Tilt Angle Θ (deg.) | Min Height h (m) | Albedo α (%) | Azimuth Φ (deg) | Bifacial Gain (%) |
|---|---|---|---|---|---|
| 1 | 30 | 0.63 | 10% | 180 | 18% |
| 2 | 30 | 0.76 | 77% | 180 | 37% |
| 3 | 30 | 0.2 | 77% | 180 | 27% |
| 4 | 20 | 0.2 | 70% | 180 | 18% |
| 5 | 20 | 0.2 | 68% | 180 | 20% |
| 6 | 20 | 0.2 | 22% | 180 | 12% |
| 7 | 10 | 0.3 | 75% | 180 | 18% |

*Image Source: Jose Castillo-Aguilella, Prism Solar, 2015 PV Performance Modeling and Monitoring Workshop*

# Outdoor test results of mini-modules

THE UNIVERSITY OF IOWA

**One day yield comparisons (bifacial versus monofacial):**

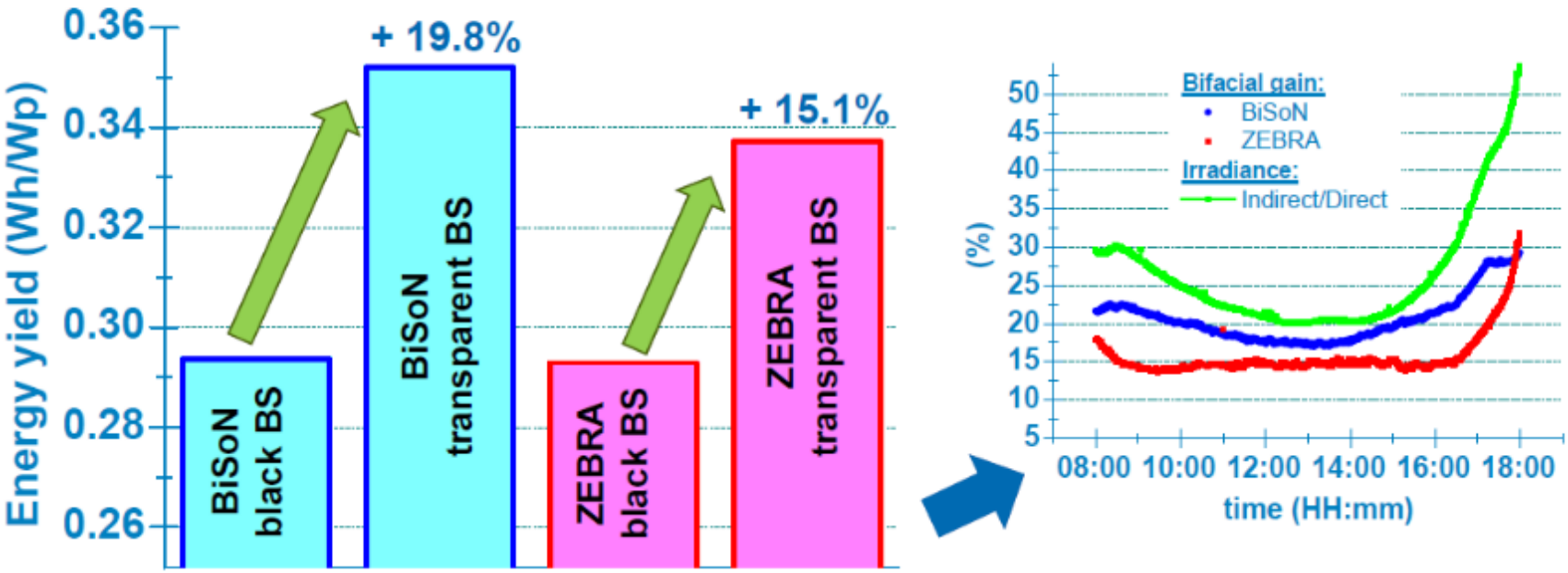
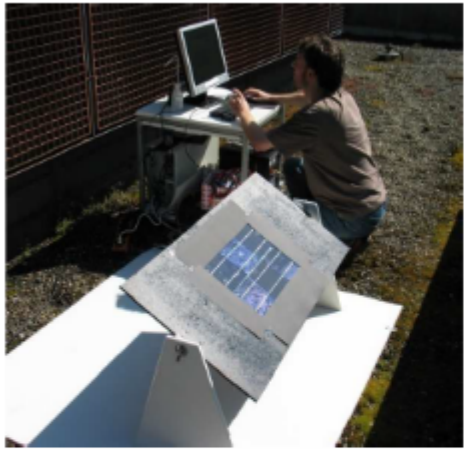
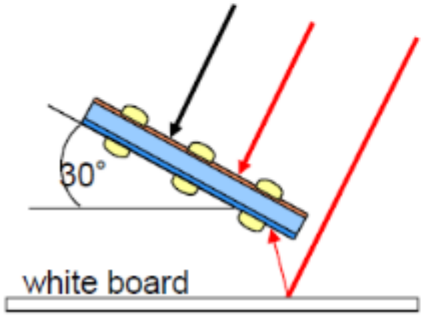



*Image Source: Radovan Kopecek, ISC Konstanz, 2014 bifi PV Workshop*

# Bifacial module gain when installed at latitude tilt facing south





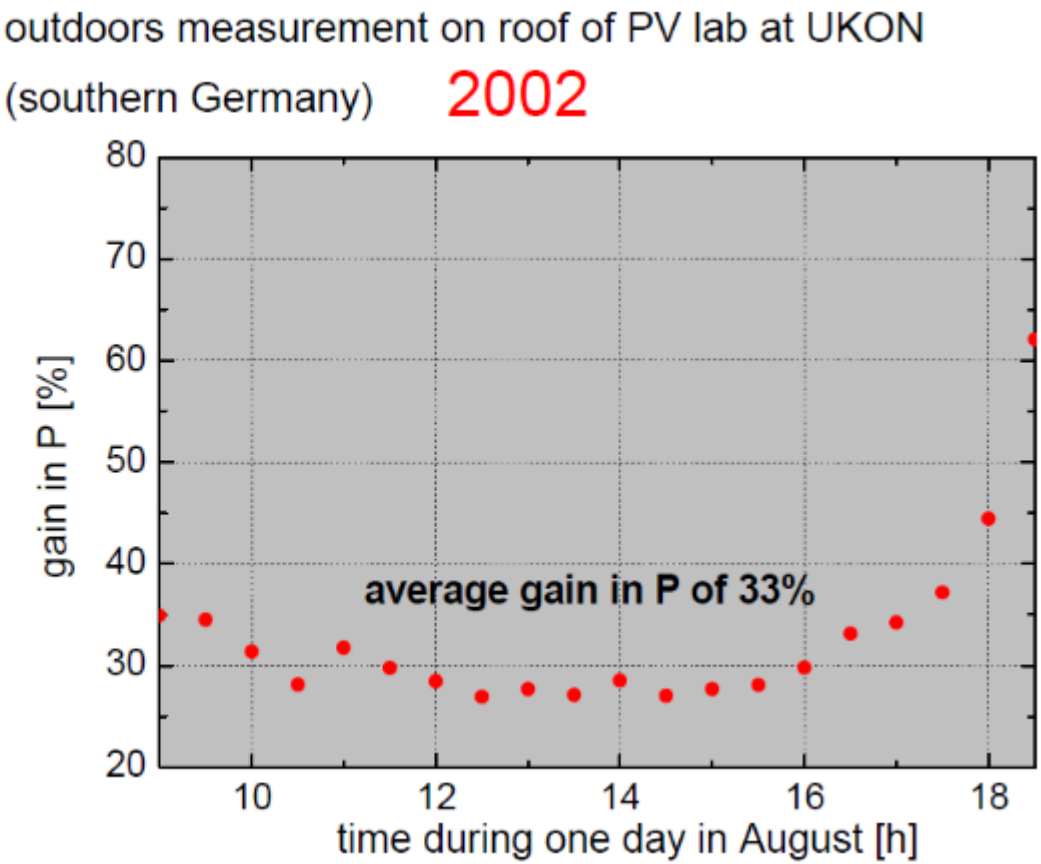
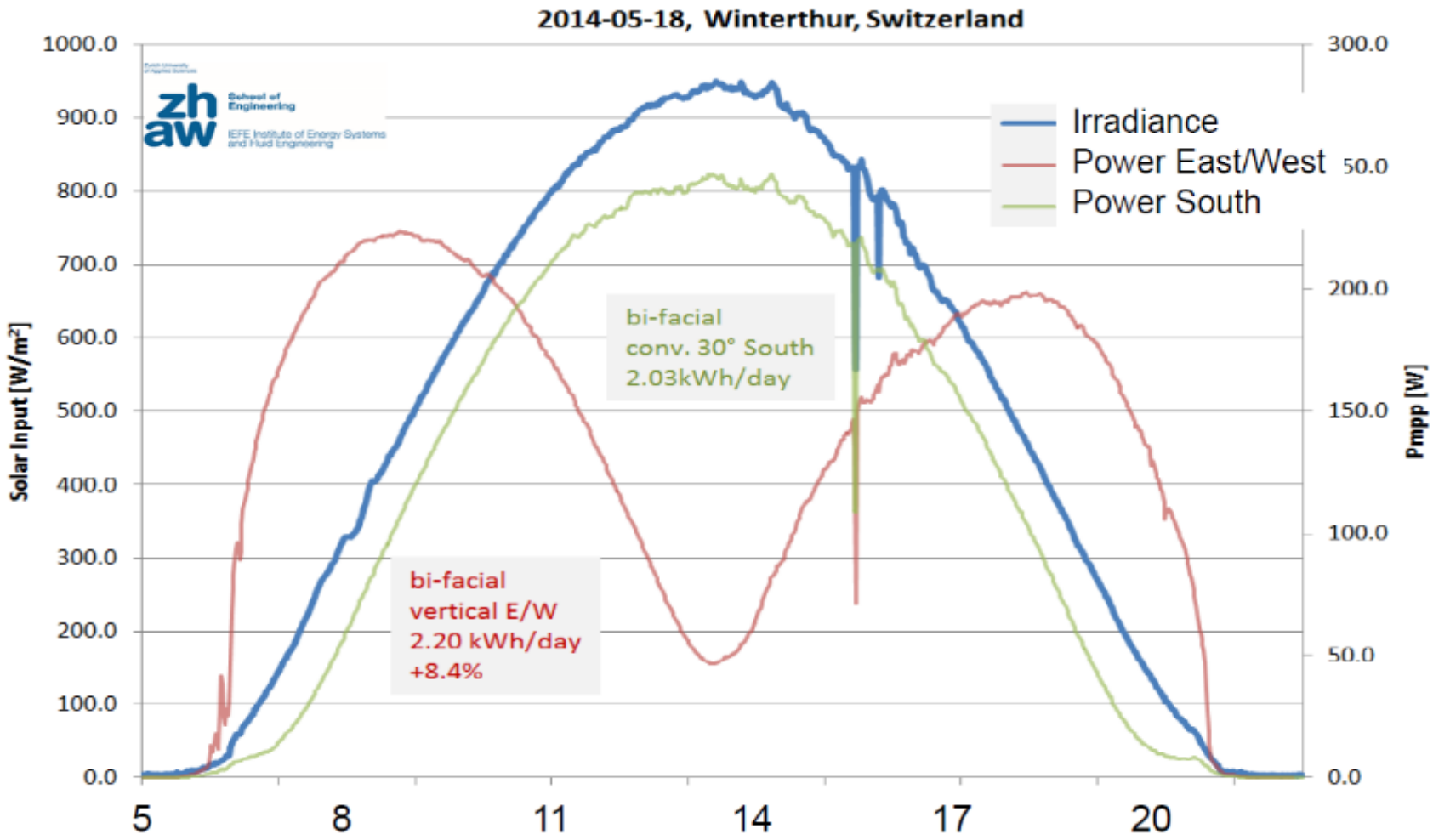




*Image Source: Radovan Kopecek, ISC Konstanz, 2013*

# Comparison of bifacial gain: vertical east/west versus 30º tilt south



# Bifacial gain in El Gouna, Egypt

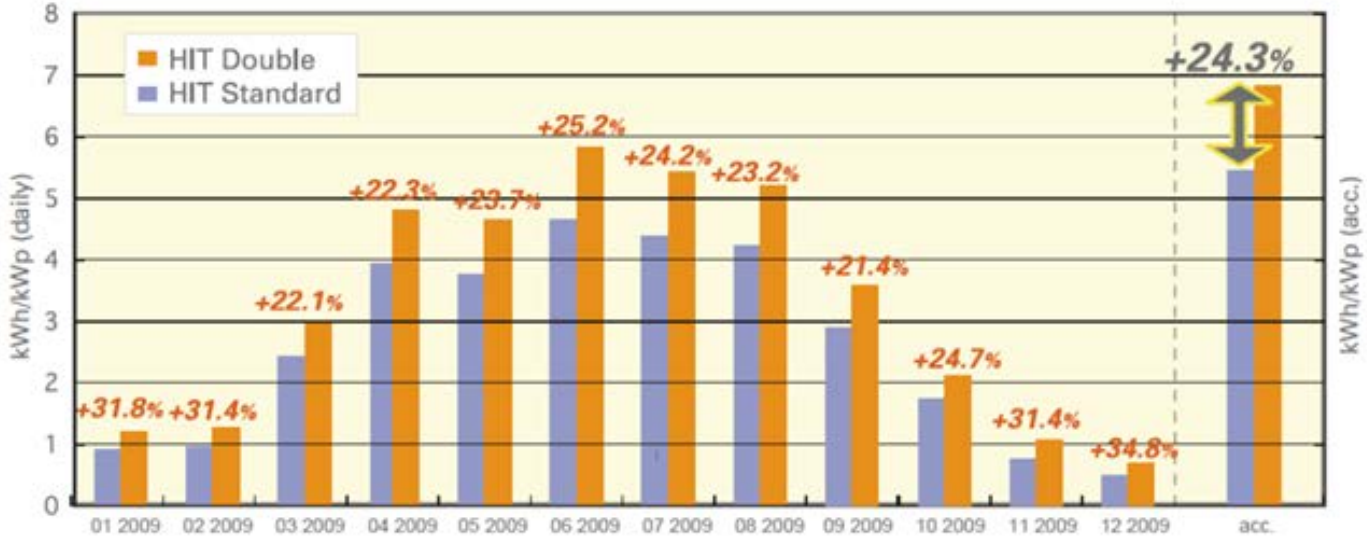
THE UNIVERSITY OF IOWA

- Outdoor test results from ISC site El Gouna, Egypt

- Monofacial Reference Module: Standard technology, STC Power 256W
- Bifaciality gain in energy yield (Wh/Wp): 14.3%
- Instantaneous peak power of 313 W at irradiance of 1214 W/m2

*Image Source: Apollon Solar, 2015 bifi PV Workshop*

# Bifacial gain in Sanyo HIT bifacial modules




Field installation in Germany, Albedo 64%, Sanyo HIT-DNKHE1: 70% back-to-front efficiency, Sanyo data sheet 04/2010

Sanyo bifacial: 24% more energy yield compared to own standard module.

→ **Need to define Pmax evaluation for energy yield prediction and for economical evaluation of the bifacial modules.**

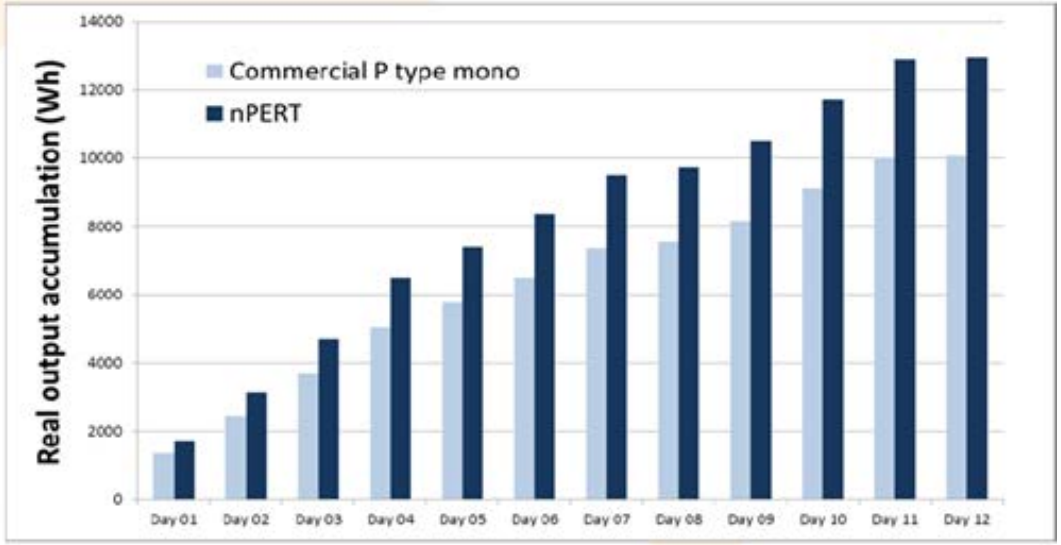
*Image Source: N. Ferretti, Photovoltaik-Institut, 2014 bifi PV Workshop*

# Bifacial gain as a function of albedo

Height=55 cm
Angle= 30°
Area background: 7m x 5m

# Bifacial gain in n-PERT bifacial modules

p-mono reference module (246W)




- ~30% output gain for nPERT bifacial module (60 cells): **320W effective output** as compared with p-mono reference module.

*Image Source: P.T. Hsieh, Motech, 2014 bifi PV Workshop*

# Bifacial gain as a function of time of day

- Higher PR gain in morning and evening (standard installation)

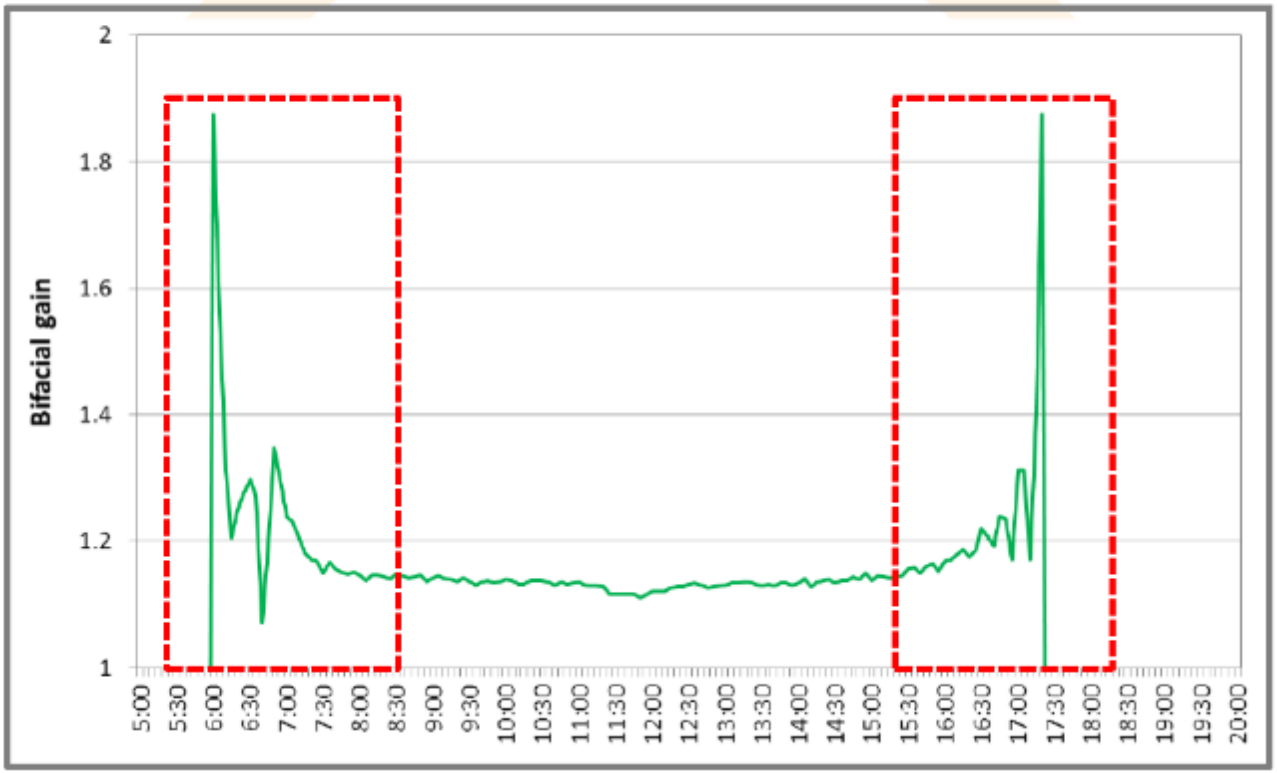
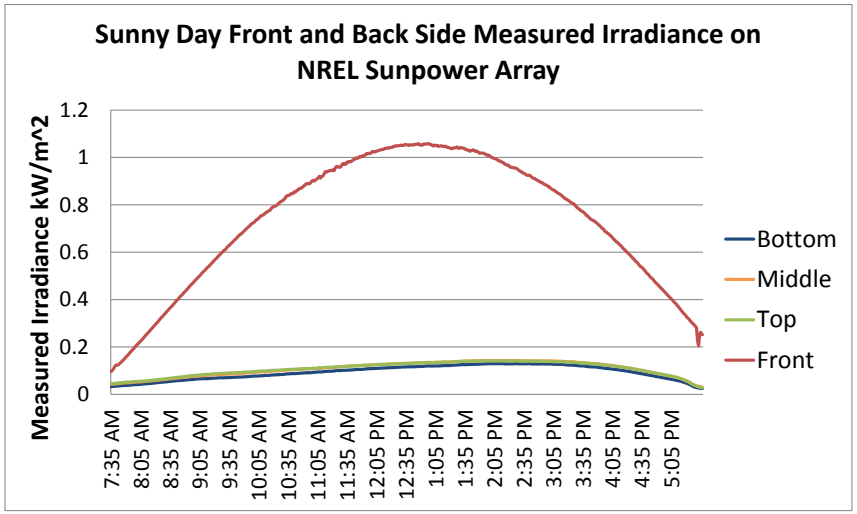


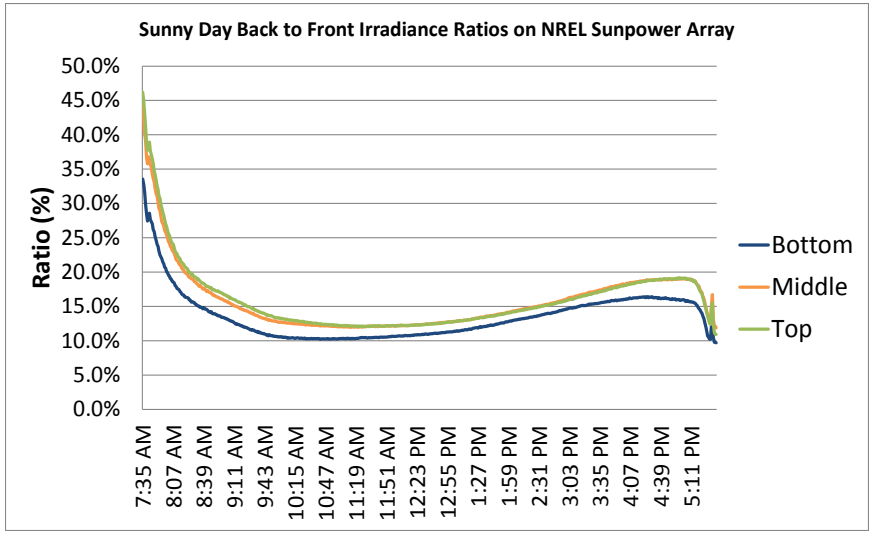

*Image Source: P.T. Hsieh, Motech, 2014 bifi PV Workshop*

# Agenda

- DOE SuNLaMP Project
- Introduction to Bifacial Photovoltaics
- Bifacial PV cost analysis and SunShot goals
- Bifacial Solar Cell Designs
- Field Results of Bifacial PV Gain (Various Studies)
- Analysis of Backside Irradiance
- Characterization of Bifacial Modules
- PV System Modeling using PVLIB

# Array Over Concrete: Backside Irradiance

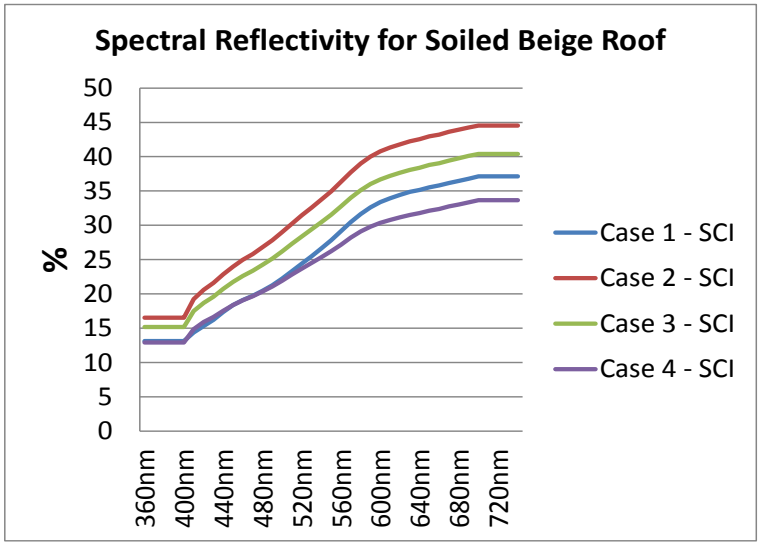


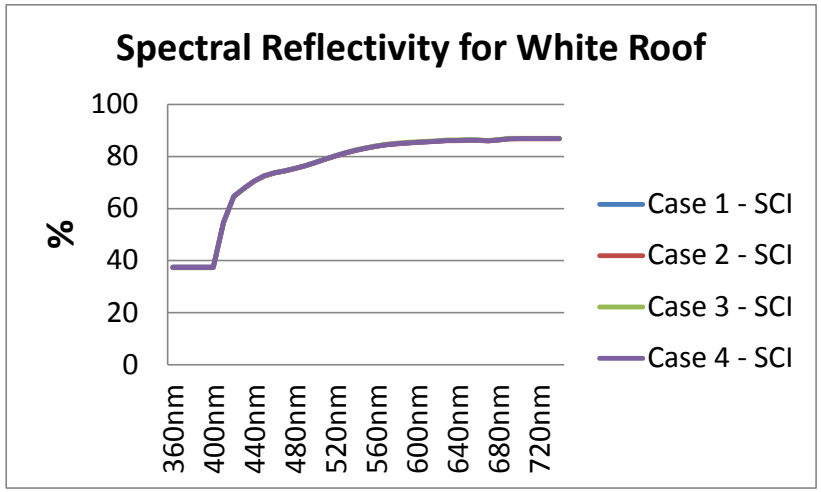




**10-20% back side irradiance gain during peak sun hours**

*Image Source: Chris Deline et al., NREL, 2016*

# Rooftop Measured Reflectance



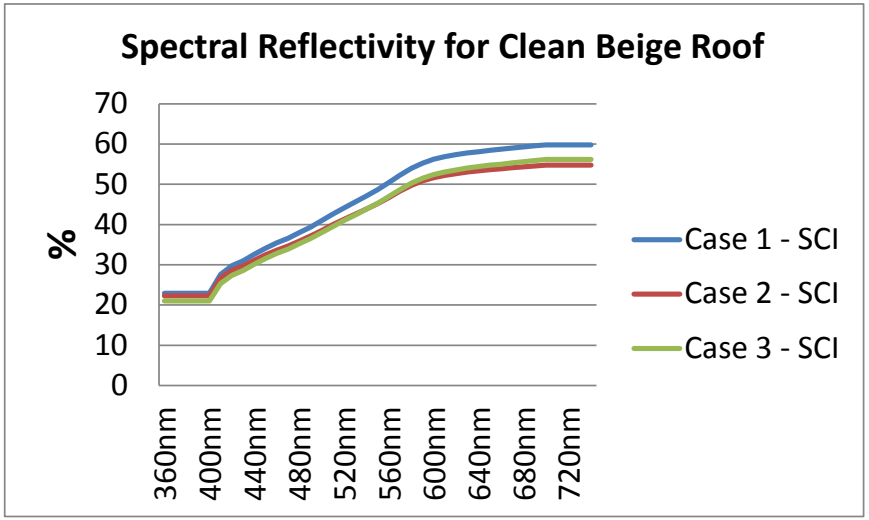
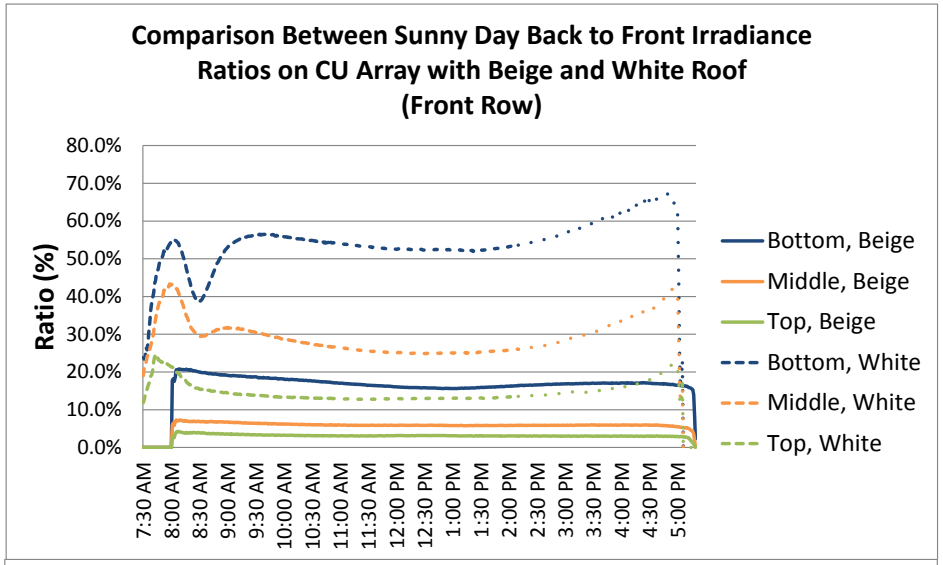
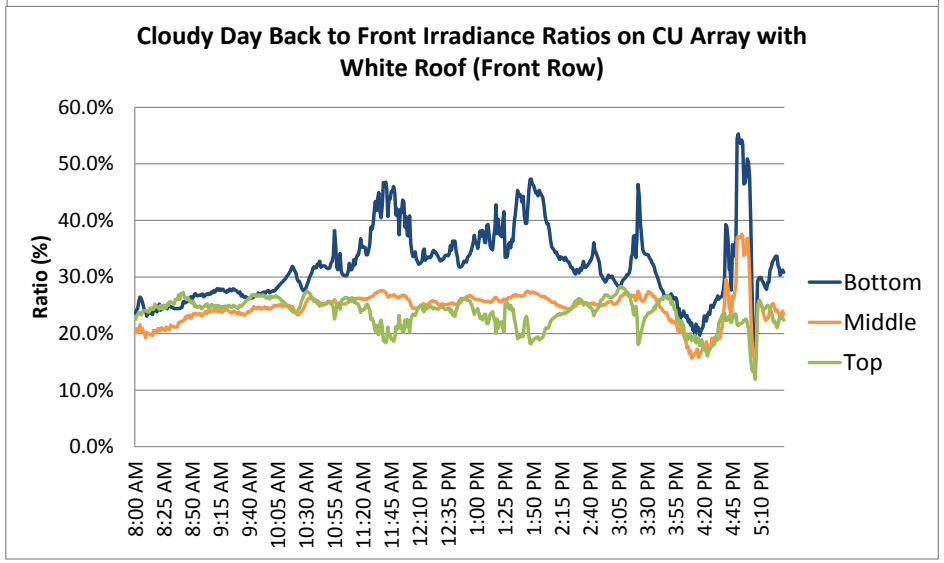




*Image Source: Chris Deline et al., NREL, 2016*

# Rooftop Array

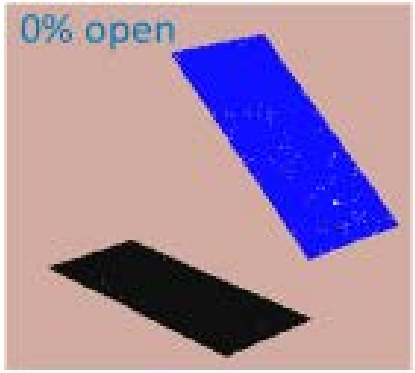


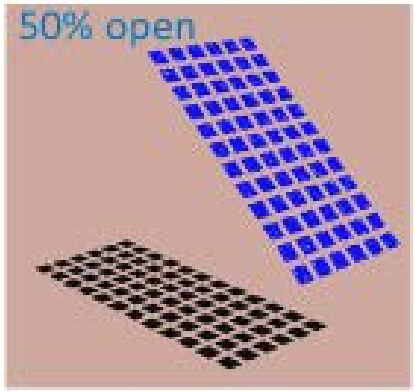




- Front row: beige roof: 5-20% gains, white roof: 15-55% gains
- Other rows: 2-9% gains (white roof approximately 2x of beige roof)
- Remember, these modules are opaque!

*Image Source: Chris Deline et al., NREL, 2016*

# Cell spacing impact

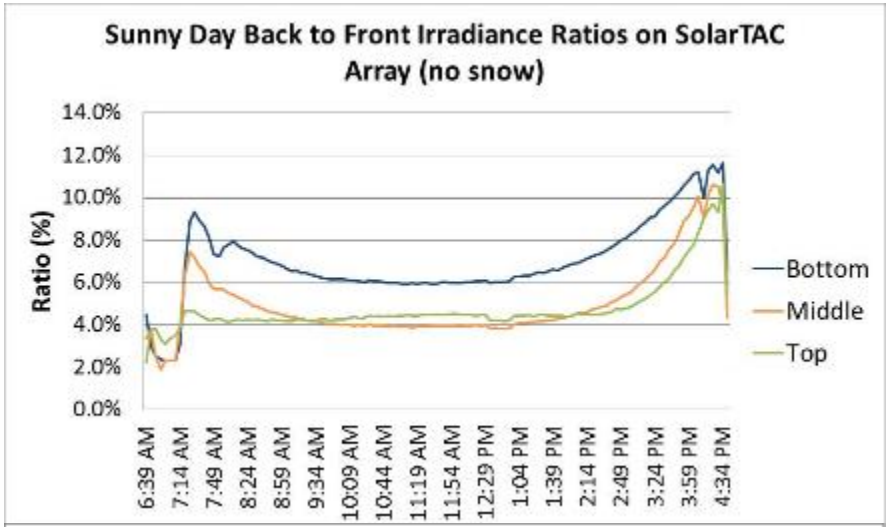


*Little impact on backside resource from a more transparent module

*Image Source: Chris Deline et al., NREL, 2016*

# Snow impact on ground mount array



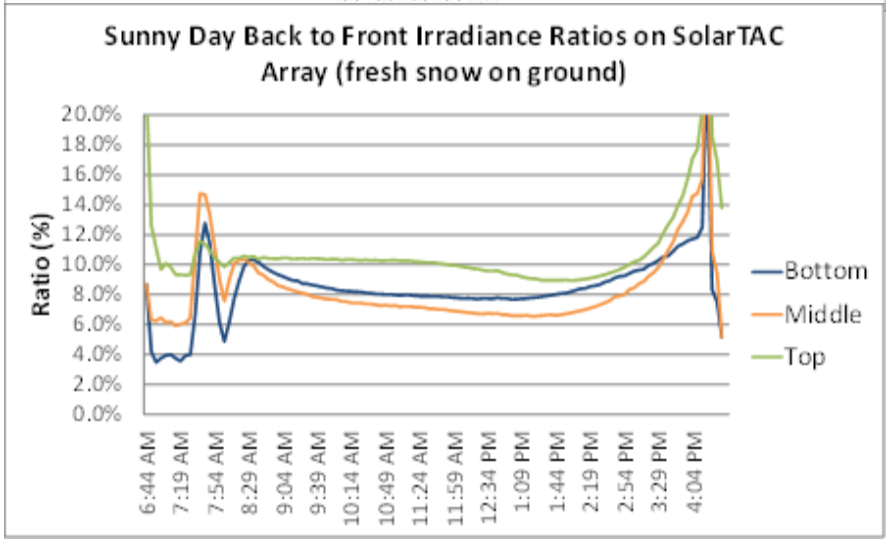




*Image Source: Chris Deline et al., NREL, 2016*

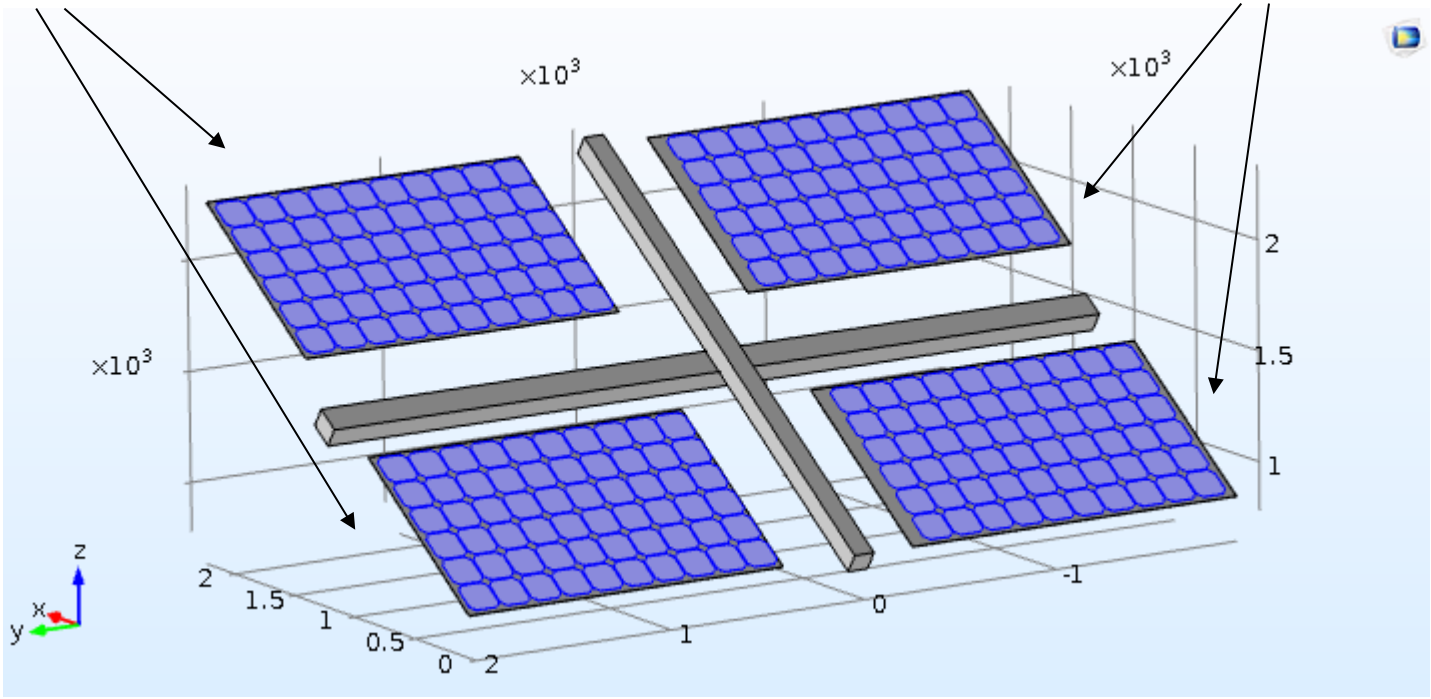
**4-6% gain without snow;**
**7-10% with snow**

# 4 module array simulation

- 4 module array was simulated according to spec

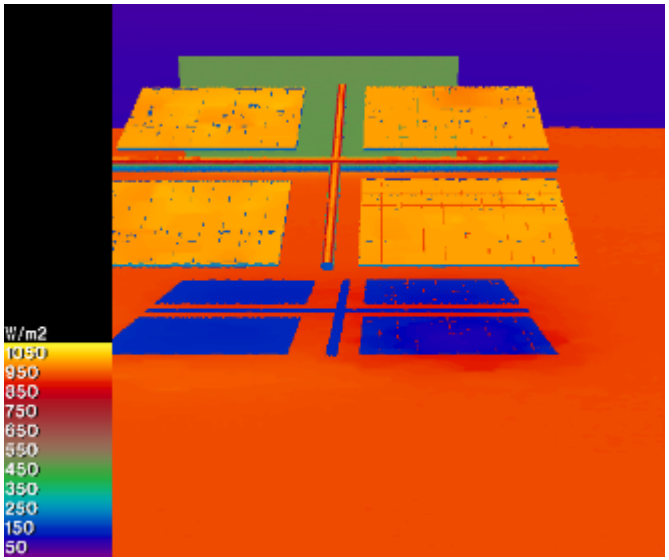
**Suniva 60 cell monofacial modules**

**Prism 60 cell bifacial modules**



# 4 module array simulation

**Front, back irradiance scans**



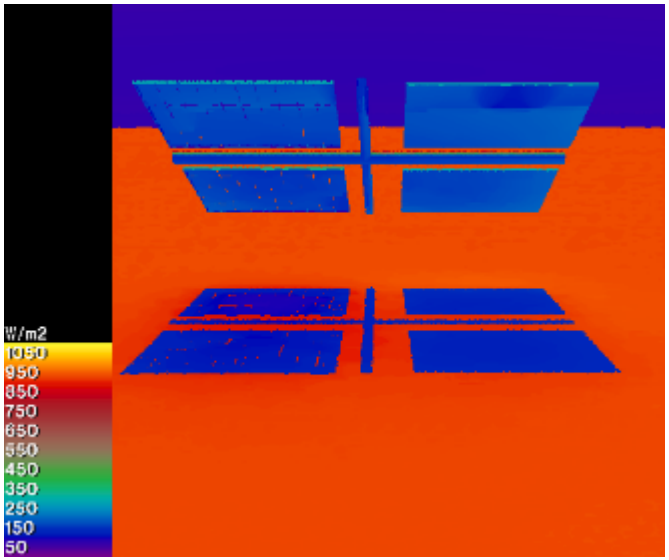




*Image Source: Chris Deline et al., NREL, 2016*

# Investigate Backside Irradiance

- For a bifacial power rating standard to gain acceptance with monofacial manufacturers, the backside resource needs to be consistent with the existing power rating standard (IEC 60904-3)
- Existing resource definition:
  - 900 W/m$^2$ DNI
  - 100 W/m$^2$ diffuse
  - Light soil albedo ($R$ = 0.21)
  - AM 1.5 spectrum
  - 37 tilt, ground clearance undef.

**60904-3 deployment case**

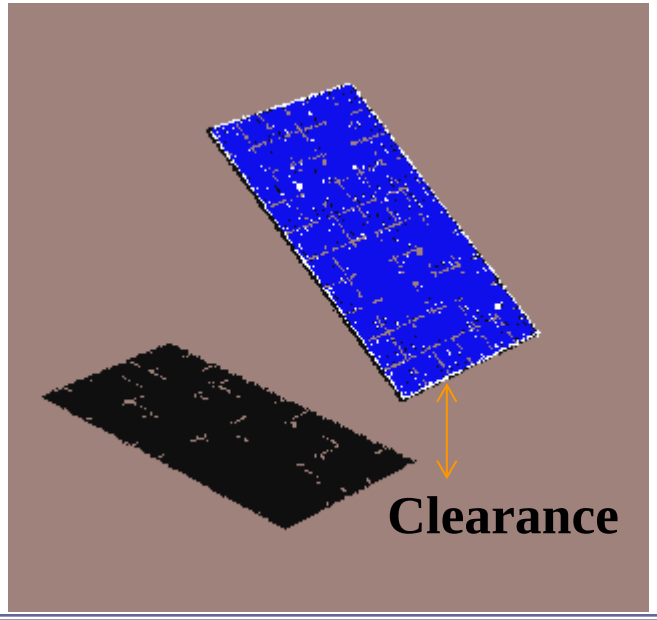



*Image Source: Chris Deline et al., NREL, 2016*

# Back Irradiance Simulation- height sensitivity

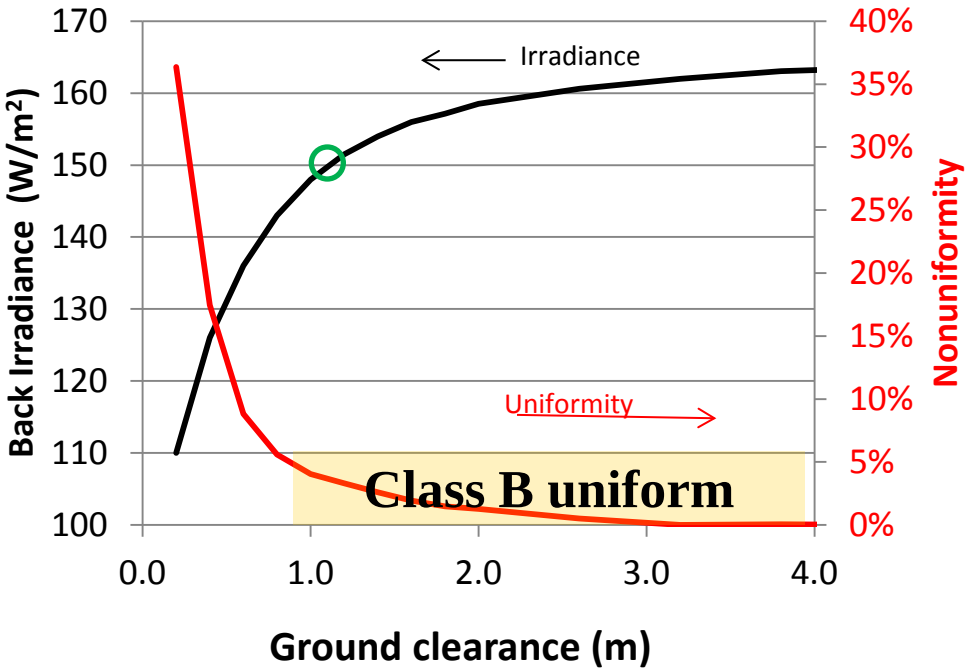
THE UNIVERSITY OF IOWA

Single module under 60904-3 conditions

Adjust ground clearance to see impact on avg. back irradiance

Resulting back irradiance avg.:

- 150 W/m$^2$ at 1 m height
- <5% spatial uniformity (class B) above 1m. $(Irr_{max} - Irr_{min})/Irr_{avg}$
- Suggested reference resource:
  - 150 W/m$^2$
  - AM1.5 spectrum for simplicity




C. Deline et al., "Evaluation and Field Assessment of Bifacial Photovoltaic Module Power Rating Methodologies", 2016 PVSC (not yet published)

# Agenda

- DOE SuNLaMP Project
- Introduction to Bifacial Photovoltaics
- Bifacial PV cost analysis and SunShot goals
- Bifacial Solar Cell Designs
- Field Results of Bifacial PV Gain (Various Studies)
- Analysis of Backside Irradiance
- Characterization of Bifacial Modules
- PV System Modeling using PVLIB

# Indoor & Outdoor measurement comparison: Design of Experiments (Example with $BiFi_{Isc}$ = 50%)

THE UNIVERSITY OF IOWA

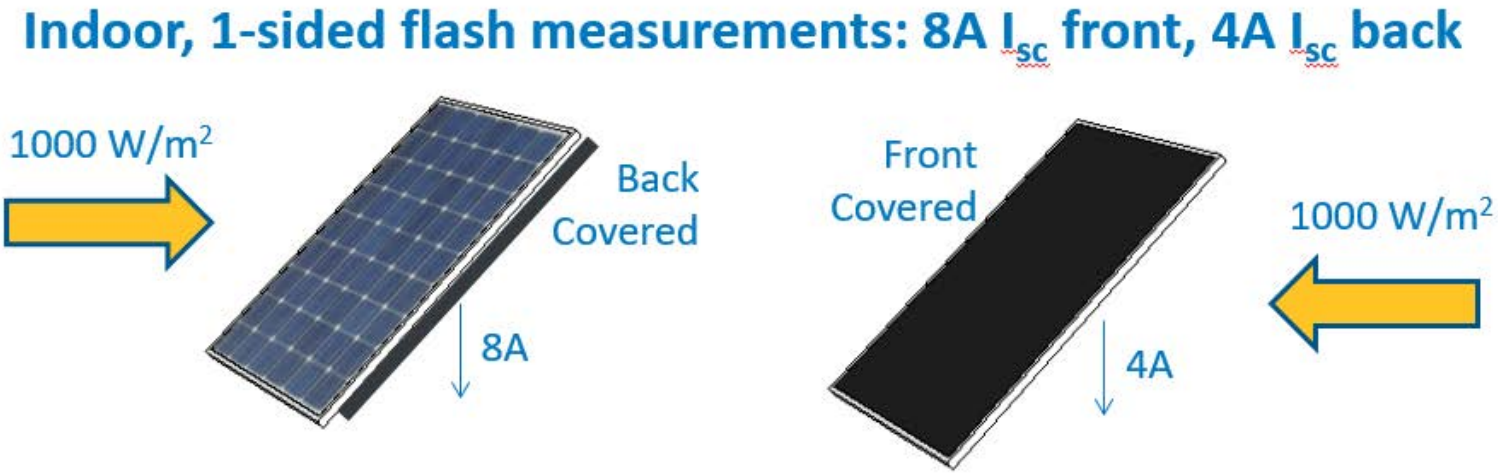



*Image Source: Chris Deline et al., NREL, 2016*

# “New bifacial history” and future

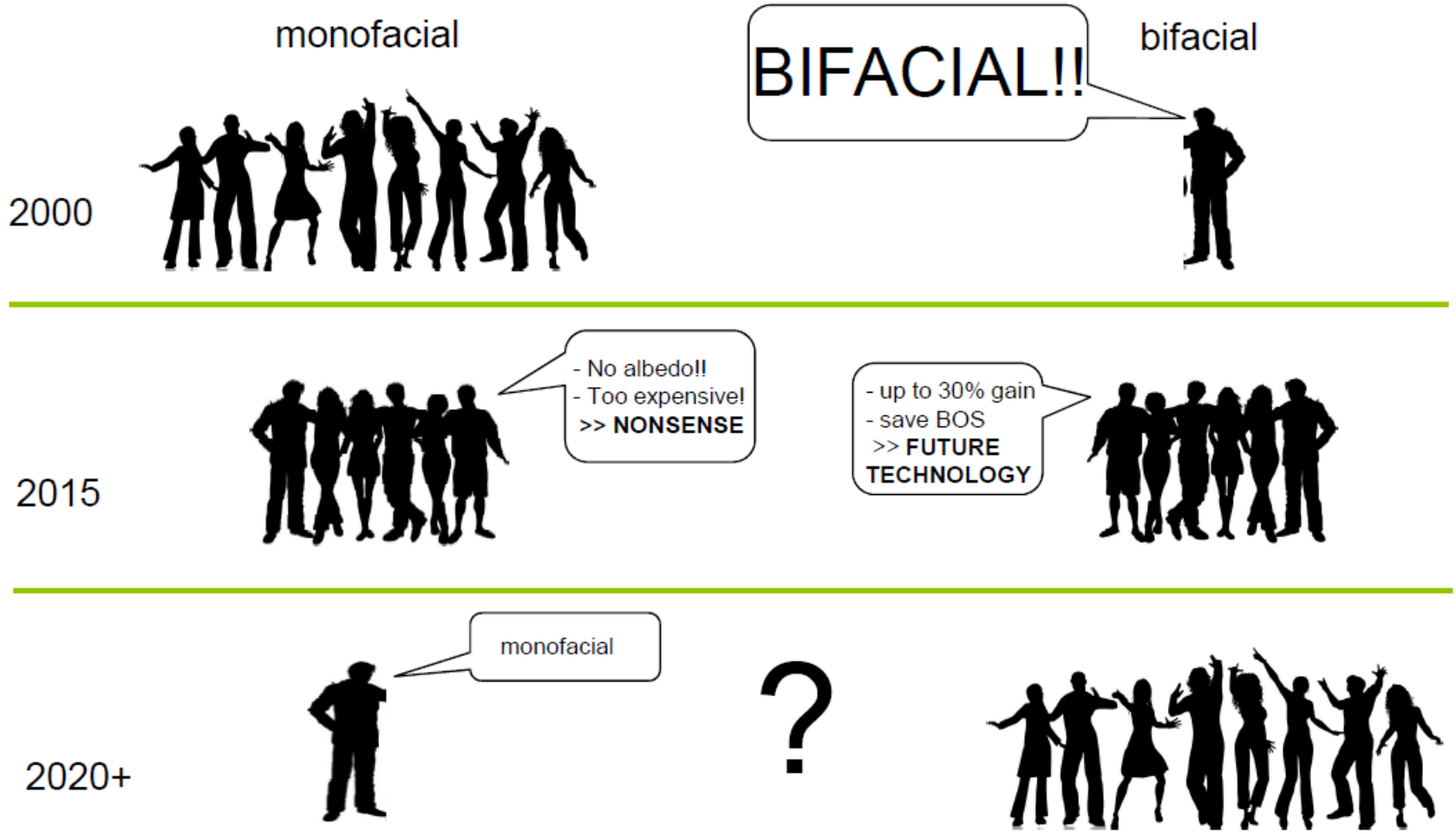



*Image Source: Radovan Kopecek, ISC Konstanz, 2015*

# Agenda

- DOE SuNLaMP Project
- Introduction to Bifacial Photovoltaics
- Bifacial PV cost analysis and SunShot goals
- Bifacial Solar Cell Designs
- Field Results of Bifacial PV Gain (Various Studies)
- Analysis of Backside Irradiance
- Characterization of Bifacial Modules
- PV System Modeling using PVLIB

*Exceptional service in the national interest*

Sandia National Laboratories

PVPerformance MODELING COLLABORATIVE

# Modeling the Performance of Photovoltaic Systems using the Open Source PVLIB Toolbox in Matlab and Python

Joshua S. Stein, Ph.D.

Sandia National Laboratories, Albuquerque, NM

U.S. DEPARTMENT OF ENERGY NNSA

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

# Why Model PV Performance?

To answer three types of questions:

1. How much energy will a PV system produce over its lifetime?
   - 100% of financial investment is made before any energy is produced.
2. What PV technologies will work best at my site?
   - Module technology (c-Si, CIGS, Cd-Te, etc.)
   - Inverter technology
   - Design factors (tilt, azimuth, row spacing, tracking vs. fixed tilt)
3. Is my PV system operating as expected?
   - What do I compare my measured performance to?

# Two Versions

## PVLIB Matlab

- Integrates with Matlab environment (help, search)
- Extensively tested by Sandia National Laboratories
- No extra toolboxes required

- Requires Matlab license ($$)
- Not fully integrated into GitHub (yet)
- Updates have been slow to be released.
- No formal way report/fix bugs except for email.

## PVLIB Python

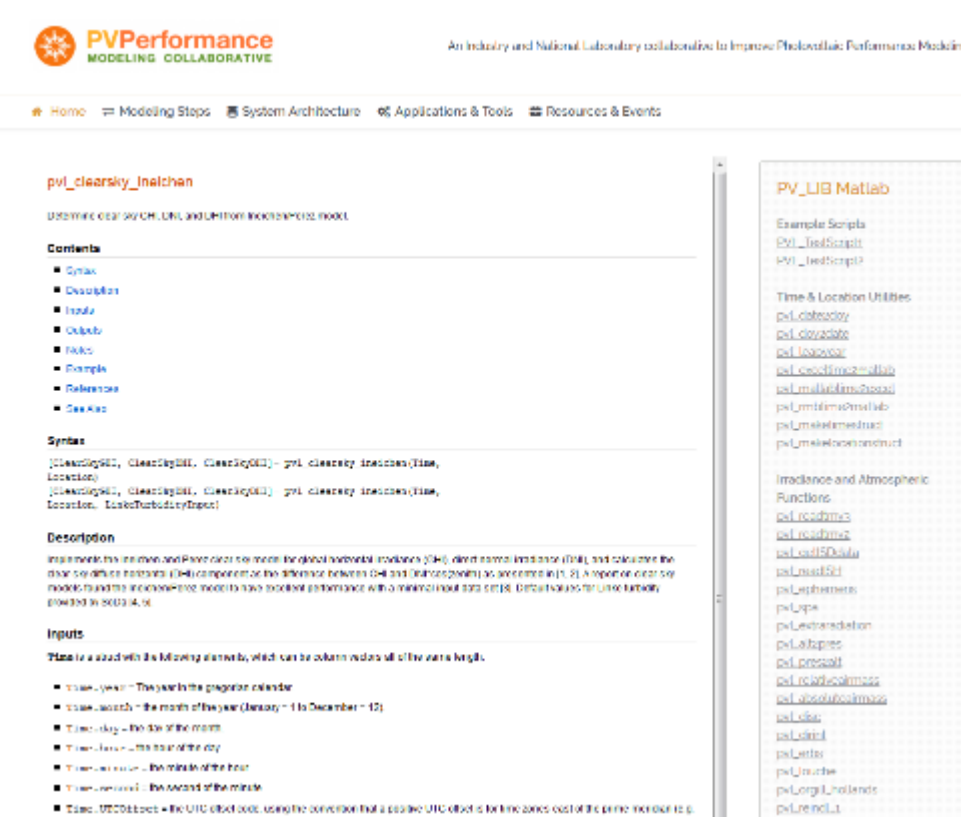
- Free
- Can be integrated with a huge ecosystem of Python libraries
- Comprehensive unit tests
- A real Python library, not just a wrapper with awkward syntax
- High-level features that do not (yet?) exist in PVLIB MATLAB
- A growing community on GitHub

- Getting started with Python, NumPy, SciPy can be challenging
- Not as many functions as PVLIB MATLAB

# PVLIB Documentation

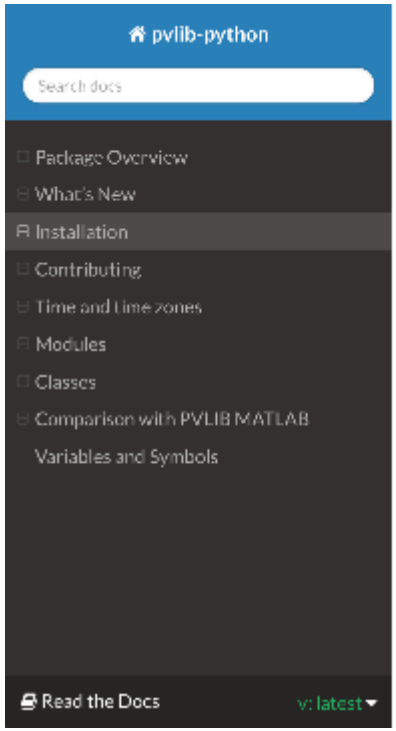
## Matlab

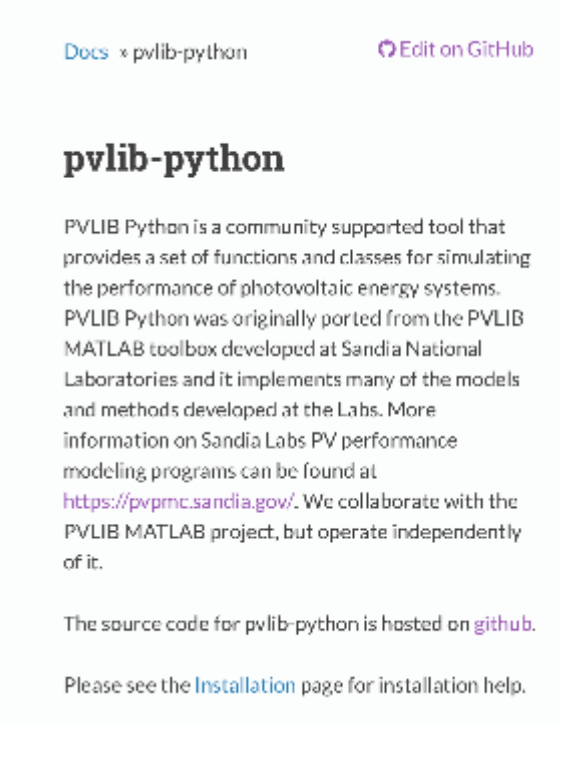
pvpmc.sandia.gov/applications/pv_lib-toolbox/




## Python

pvlib-python.readthedocs.io



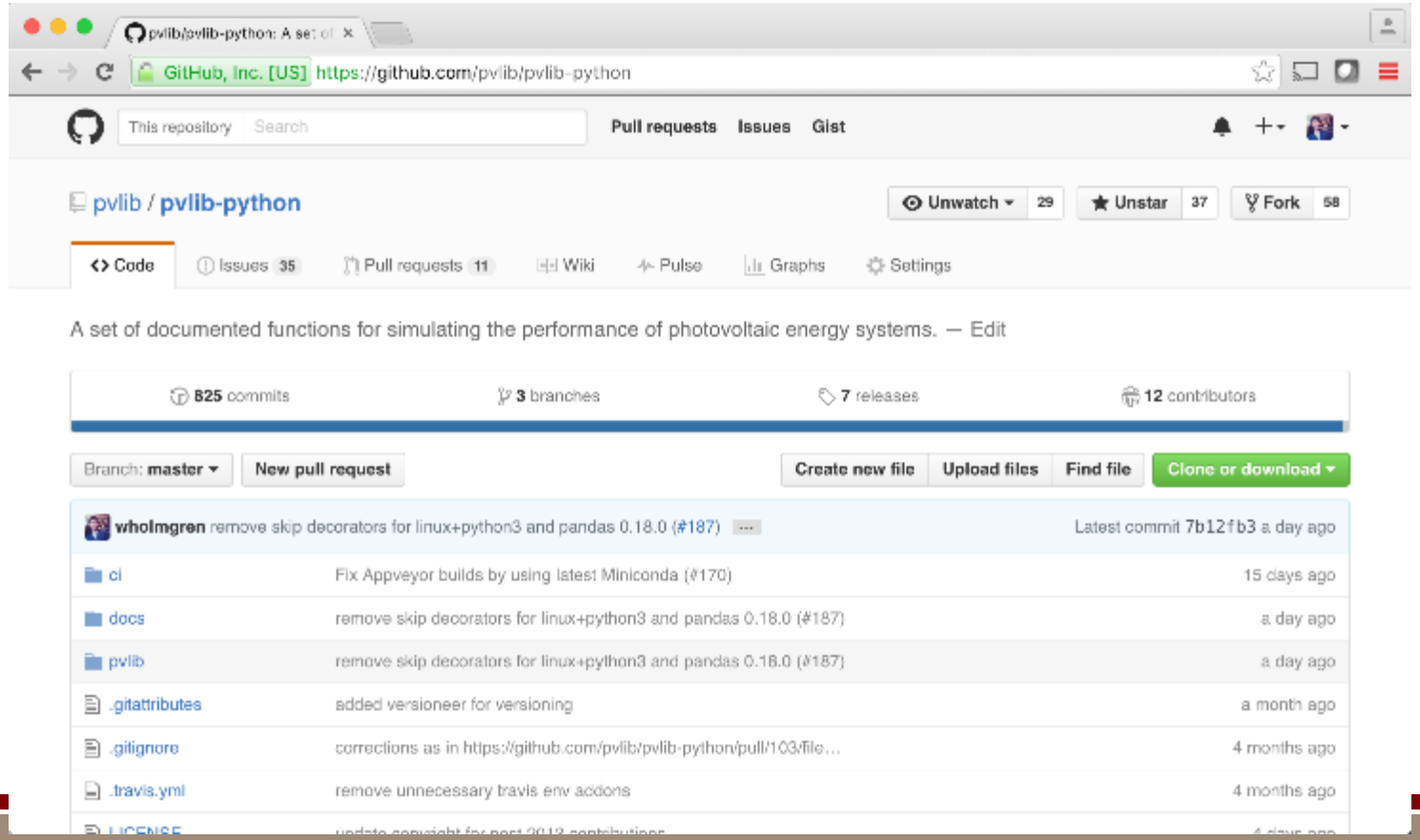



# PVLIB on GitHub

github.com/pvlib/pvlib-python

github.com/sandialabs/MATLAB_PV_LIB

Please go here!



# A bit of History

- Matlab version started as an internal tool at Sandia in 2010-2011 developed to help standardize analyses across the PV group.
  - PVLIB Version 1.0 – May 2012 – 29 functions
  - PVLIB Version 1.1 – Jan 2013 – 38 functions
  - PVILB Version 1.2 – Dec 2014 – 44 functions
  - PVLIB Version 1.3 – Dec 2015 – 59 functions
- Python version was initially developed from 2013-2014 by Rob Andrews under contract from Sandia.
- 2015 Python PVLIB converted to Open Source GitHub project largely managed by Will Holmgren at University of Arizona.

- Download links available on PVPMC website:
  - https://pvpmc.sandia.gov click on Applications and Tools link

PVPerformance
MODELING COLLABORATIVE

An Industry and National Laboratory collaborative to Improve Photovoltaic Performance Modeling

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

# Applications & Tools

Home > Applications & Tools

This area of the website explore various tools, datasets, and applications that relate to PV Performance Modeling.

- PV_LIB Toolbox – PV performance modeling functions available in Matlab and Python
- GridPV Toolbox – A tool for modeling power flow and voltage patterns on distribution feeders with PV
- PV Variability Datasets – A collection of high frequency (1 -30 sec) irradiance data samples across the US
- Wavelet Variability Model – A model for estimating the variability in PV plant output based in point sensors of irradiance and PV plant geometry.
- Summary of Data Needs – This page provides a summary of the data needs for running and validating a performance model.

PVPerformance
MODELING COLLABORATIVE

An Industry and National Laboratory collaborative to Improve Photovoltaic Performance Modeling

Home | Modeling Steps | System Architecture | Applications & Tools | Resources & Events

## PV_LIB Toolbox for Matlab Function Documentation and Help

We provide here a collection of online help pages identical to what is provided in the PV_LIB Toolbox for Matlab download (see \html folder). We are providing them here for users who might not have Matlab installed or may prefer to use this online version. Click the links to the right to view the documentation for each function.

### PV_LIB Matlab

**Example Scripts**
PVL_TestScript1
PVL_TestScript2

**Time & Location Utilities**
pvl_date2doy
pvl_doy2date
pvl_leapyear
pvl_exceltime2matlab
pvl_matlabtime2excel
pvl_rmbtime2matlab
pvl_maketimestruct
pvl_makelocationstruct

**Irradiance and Atmospheric Functions**
pvl_readtmy3
pvl_readtmy2
pvl_getISDdata
pvl_readISH
pvl_ephemeris
pvl_spa
pvl_extraradiation
pvl_alt2pres
pvl_pres2alt
pvl_relativeairmass
pvl_absoluteairmass
pvl_disc
pvl_dirint
pvl_erbs
pvl_louche
pvl_orgill_hollands
pvl_reindl_1
pvl_reindl_2
pvl_clearsky_haurwitz
pvl_clearsky_ineichen

# PVL_TestScript1

Example script to demonstrate the modeling of a PV system

This script demonstrates how to use the PV_Lib Toolbox to model the power output of a fixed-tilt photovoltaic array in Albuquerque, New Mexico, USA. The script uses irradiance and weather data that is read in from a Typical Meteorological Year 3 (TMY3) formatted file that contains one year of hourly-averaged data.

## Contents


- PV_LIB Functions used in this example
- **Step 0: Define PV System**
- 0.1 Define the PV module
- 0.2 Define the Inverter
- 0.3 Define the Array configuration
- 0.4 Define Additional Array Parameters
- **Step 1: Read in Irradiance and Weather**
- 1.1 Define Time and Irradiance Variabiles
- 1.2 Define the Site Location
- 1.3 Calculate Sun Position
- 1.4 Calculate Air Mass
- **Step 2: Calculate Incident Radiation**
- 2.1 Calculate Solar Angle of Incidence
- 2.2 Calculate Beam Radiation Component on Array
- 2.3 Calculate SkyDiffuse Radiation Component on Array
- 2.4 Calculate Ground Reflected Radiation Component on Array
- **Step 3 Shading and Soiling**
- **Step 4: Calculate Cell Temperature**
- **Step 5: Calculate Module/Array IV Performance**
- **Step 6: DC and Mismatch Losses**
- **Step 7: DC to DC Max Power Point Tracking**
- **Step 8: DC to AC Conversion**


## PV_LIB Functions used in this example

- `pvl_sapmmoduledb`
- `pvl_snlinverterdb`
- `pvl_readtmy3`
- `pvl_maketimestruct`
- `pvl_makelocationstruct`
- `pvl_ephemeris`
- `pvl_absoluteairmass`
- `pvl_relativeairmass`
- `pvl_getaoi`
- `pvl_kingdiffuse`
- `pvl_grounddiffuse`
- `pvl_sapmcelltemp`
- `pvl_sapm`
- `pvl_snlinverter`

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

# Modeling of Partially Shaded PV Systems

Chris Deline

September 12, 2016
Solar Power International 2016

SunShot
U.S. Department of Energy

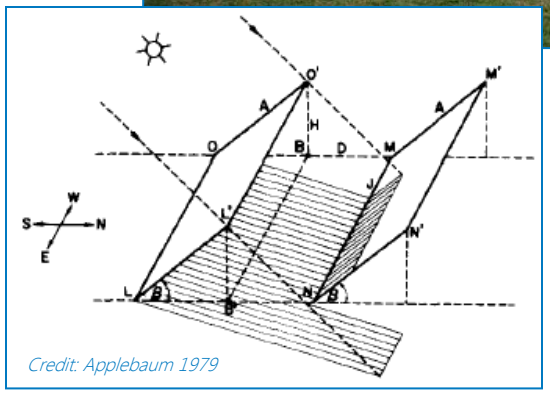
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

# Shading on PV systems

## Shading and mismatch occur on all types of PV systems

- Nearby obstructions like trees and telephone poles
- Horizon shading (mountains, buildings)
- Self-shading from adjacent rows
- Dirt, snow, bird droppings, etc.

Some types of shading are easier to quantify and model than others.

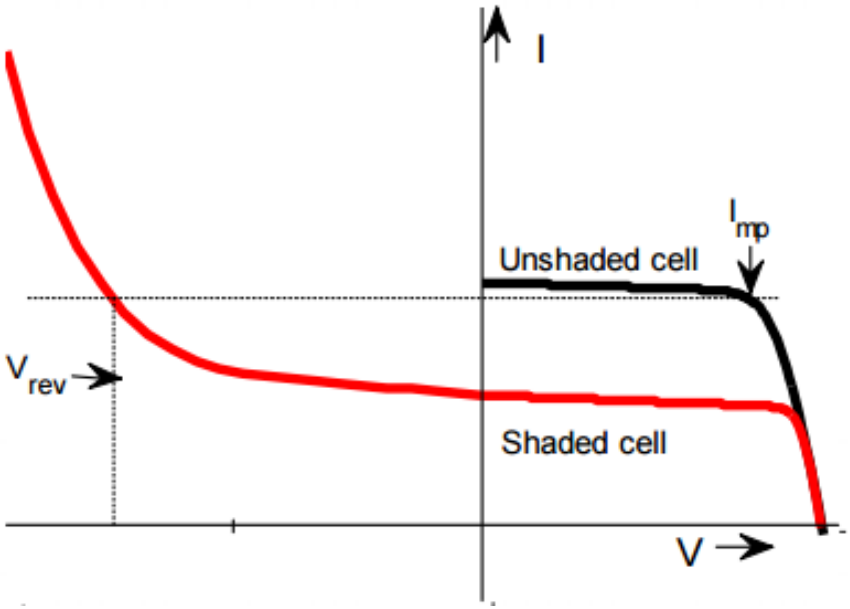



*1: Lakewood, CO. 2: Arlington, VA*

# Mismatch loss and hotspot in PV

Shade / orientation mismatch leads to power loss from reduced irradiance (non-recoverable) and panel mismatch (recoverable)

The better the peak-power tracking (MPPT) granularity, the higher the recoverable power



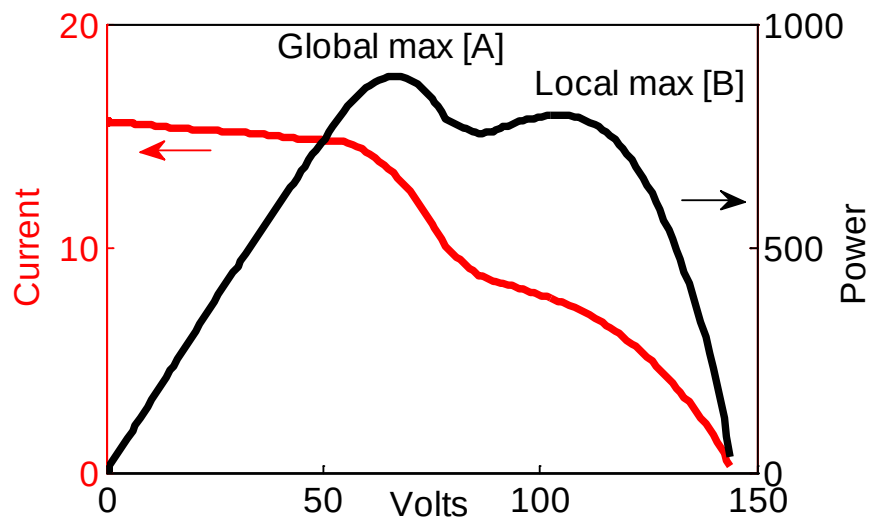

Mismatched panels / cells in a series string can result in reverse bias and HOTSPOT.

C. Deline, B. Marion, J. Granata, S. Gonzalez. *A Performance and Economic Analysis of Distributed Power Electronics in Photovoltaic Systems*. NREL Report No. TP-5200-50003. Golden, CO: National Renewable Energy Laboratory, December

# Mismatch loss and hotspot in PV

Shade / orientation mismatch leads to power loss from reduced irradiance (non-recoverable) and panel mismatch (recoverable)

The better the peak-power tracking (MPPT) granularity, the higher the recoverable power

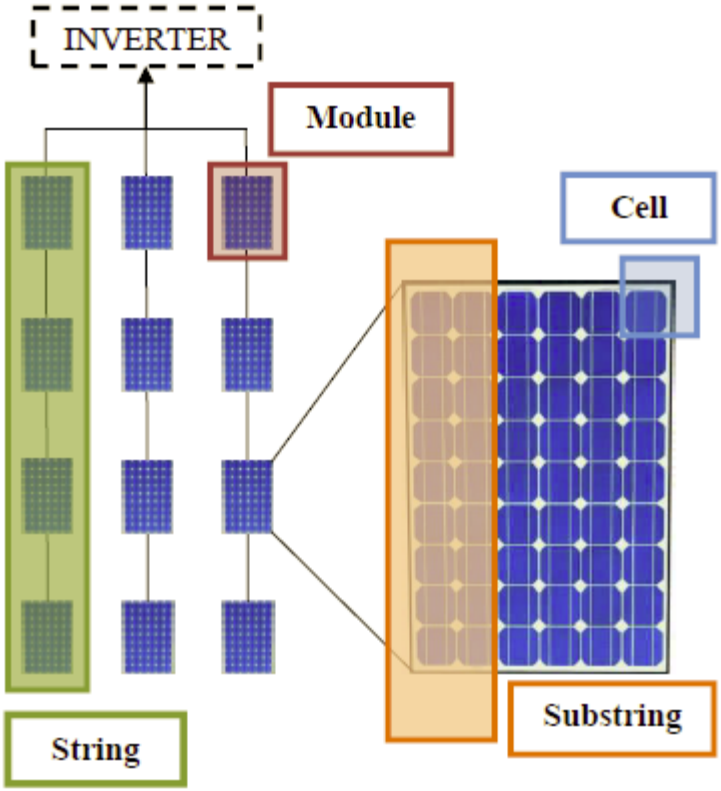



Distributed MPPT allows partially shaded modules to operate at their independent max-power point

C. Deline, B. Marion, J. Granata, S. Gonzalez. *A Performance and Economic Analysis of Distributed Power Electronics in Photovoltaic Systems*. NREL Report No. TP-5200-50003. Golden, CO: National Renewable Energy Laboratory, December

# Overview of Distributed MPPT

## Finer peak-power tracking granularity leads to reduced mismatch



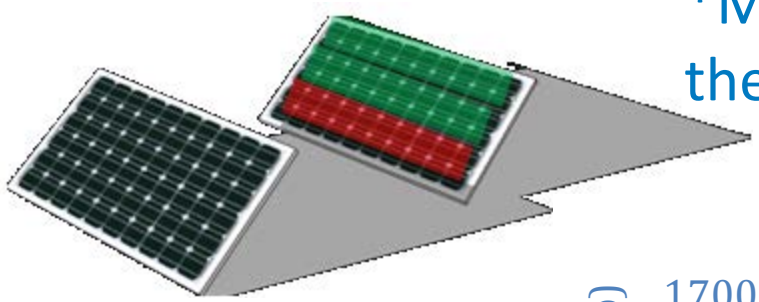

**Annual performance improvement under heavy shade**

| +2% | +8% | +9% | +12% |
|---|---|---|---|
| String | Module | Submodule | Cell |

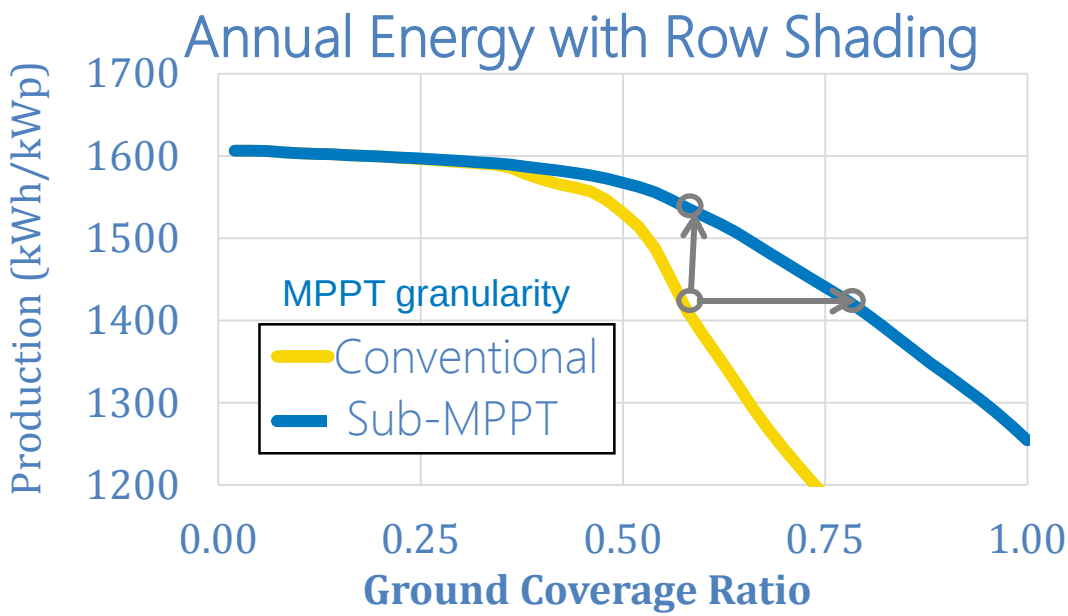
**MPPT Granularity**

S.M. MacAlpine, M.J.Brandemuehl, R.W.Erickson, "Potential for power recovery: simulated use of distributed power converters at various levels in partially shaded photovoltaic arrays," in Proc. PVSEC 2011.

# Sub-module converters in Close-packed arrays



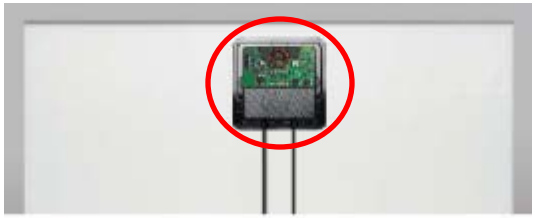
*Mismatch occurs **within** the module

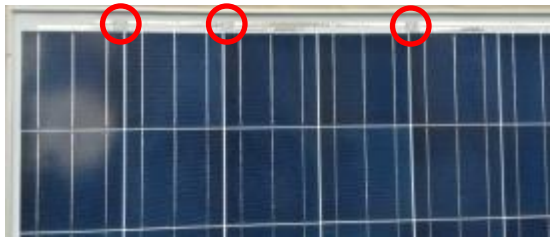


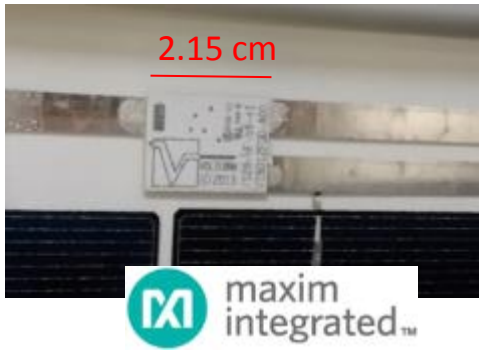

Sub-module converters inside the PV module (3-6 per module) enables 10-20% closer row spacing

C. Deline et al., "Evaluation of Maxim Module-Integrated Electronics at the DOE Regional Test Centers", 40th IEEE Photovoltaic Specialists Conference, Denver, CO, 2014

# Examples of Distributed MPPT products








Frame - attached

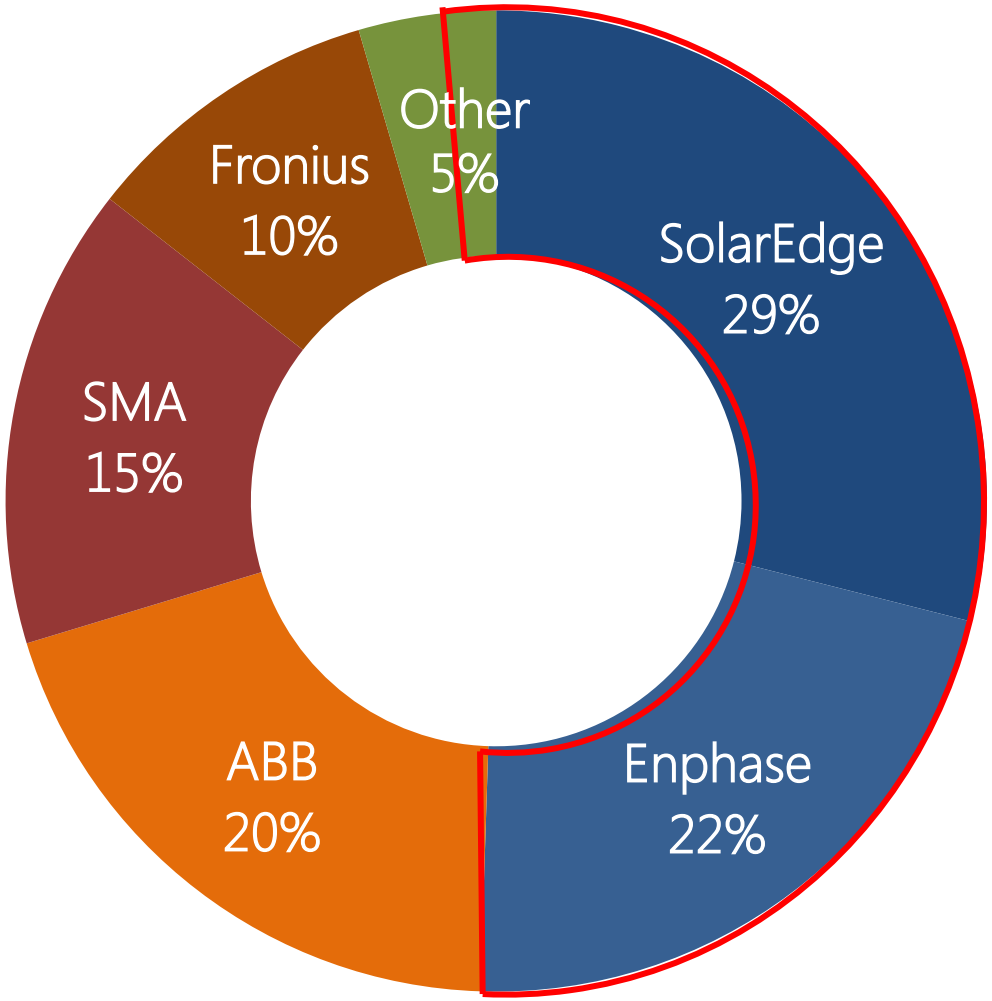
J-box embedded

Laminate embedded

Credit: Enphase Energy, Tigo Energy, Maxim Integrated

# US Single-Phase Inverter Market (2015)

Module-level solutions are 53% of the US single-phase market share




Source: GTM Research, Global PV Inverter and MLPE Landscape, June 2016

# Distributed MPPT pro/con

Pro:

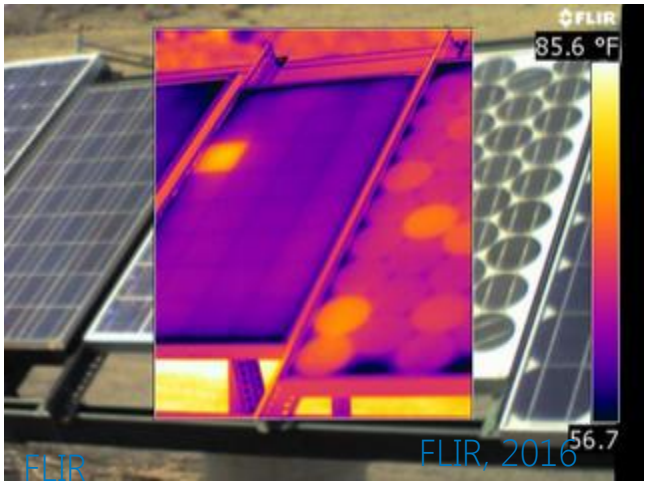
- Flexibility of design
- Safety
- Data monitoring
- Shade / orientation performance
- Redundancy

Con:

- Cost
- Efficiency (maybe)
- More potential points of failure
- O&M concerns

# PV Power Electronics for Safety

- DC Arc Fault detection
- Battery management
- Ground Fault detection
- Reduced Hotspot susceptibility

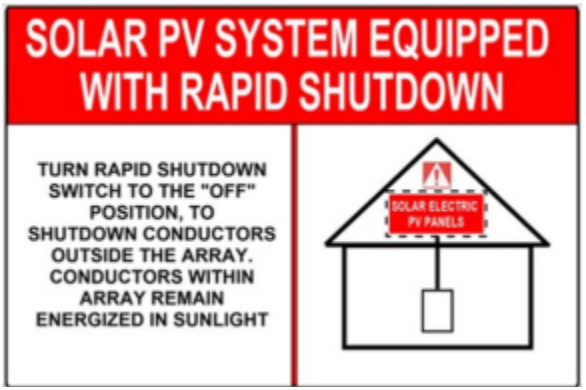


# Electric code updates for Firefighter Safety

Greg Ball: Rooftop PV and Firefighter Safety, 2016 PVSC

# NEC 690.12 (2014) "Rapid Shutdown"

Code requires rooftop PV conductors greater than 10' from the array to be de-energized in event of emergency




## Compliance options:

Remote relays

Roof-mounted inverters

Microinverters and Power Optimizers

Credit: Midnite Solar, SMA, Tigo

# NEC 690.12 (2017) 2nd draft

Next revision requires control inside array:

- 80 V maximum within 30 seconds

- Other allowances for reduced shock hazard, non-conductive construction

## Compliance options:

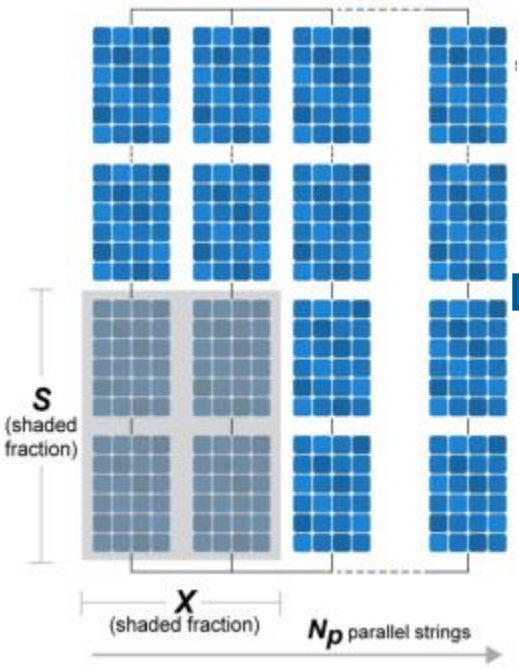
Remote relays

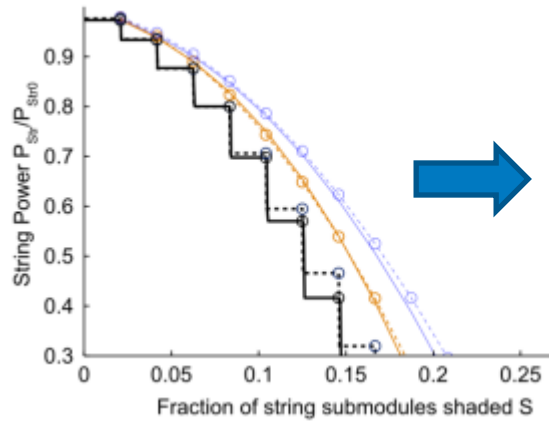
Roof-mounted inverters

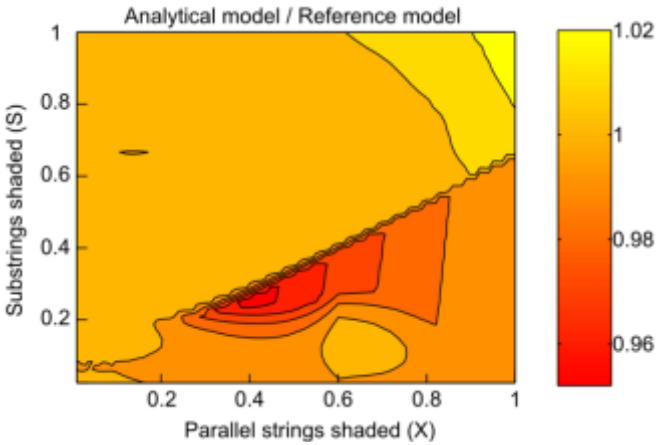
Microinverters and Power Optimizers

Credit: Midnite Solar, SMA, Tigo

# Overview of inter-row shading model






## Partial Shading definition

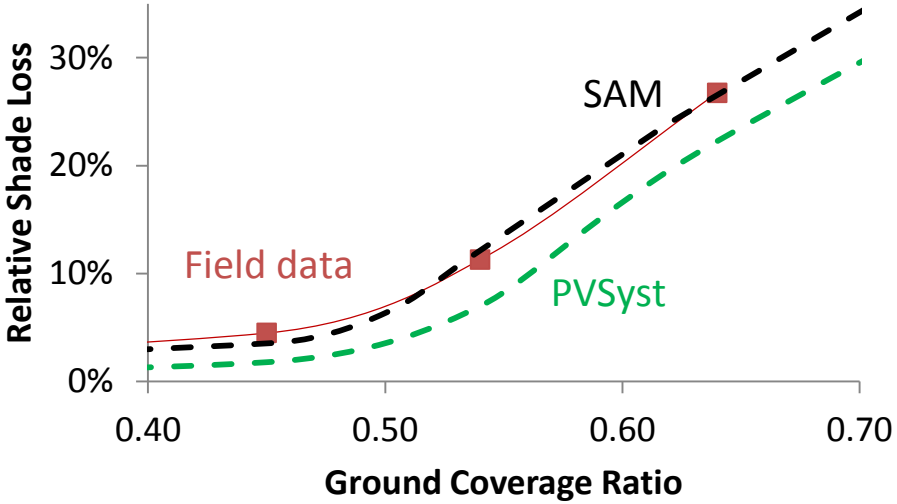
## Empirical Model

## Model validation < 6% error

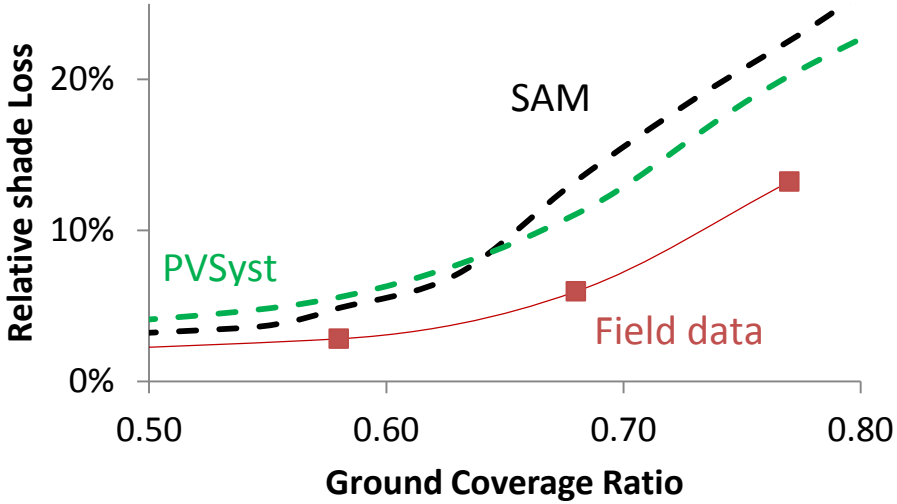
*C. Deline et al., "A simplified model of uniform shading in large photovoltaic arrays," Solar Energy 2013

# Comparison with Field Data and PVSyst

1x Portrait




2x Landscape




Calculated shade losses in SAM and PVSyst are within 2%-5% (absolute)

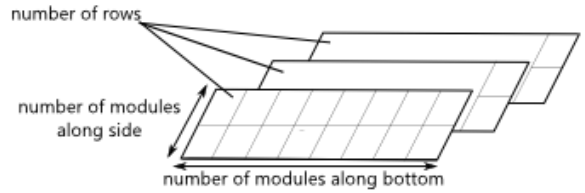
# Using inter-row shading in SAM (live demo)

- Location and Resource
- Module
- Inverter
- System Design
- Shading and Snow
- Losses
- Lifetime
- Battery Storage
- System Costs
- Financial Parameters
- Incentives
- Electricity Rates
- Electric Load

**Array Dimensions for Self Shading and Snow Losses**

The product of number of modules along side and bottom should be equal to the number of modules in subarray.

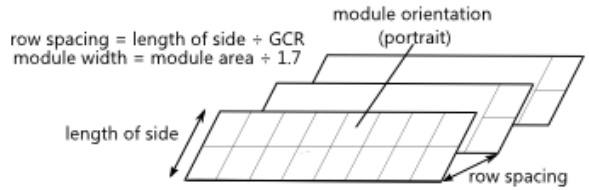
| | | | | |
|---|---|---|---|---|
| Number of modules along side of row | 1 | 2 | 2 | 2 |
| Number of modules along bottom of row | 12 | 9 | 9 | 9 |
| Number of rows | 53 | 0 | 0 | 0 |
| Modules in subarray from System Design page | 636 | 0 | 0 | 0 |




**Self Shading for Fixed Subarrays and One-axis Trackers**

Self shading is shading of modules in the array by modules in a neighboring row.

| | | | | |
|---|---|---|---|---|
| Self shading type | Standard (Non-line | None | None | None |
| Module orientation | Portrait | Portrait | Portrait | Portrait |
| Length of side (m) | 1.7 | 3.4 | 3.4 | 3.4 |
| GCR from System Design page | 0.3 | 0.3 | 0.3 | 0.3 |
| Row spacing estimate (m) | 5.66667 | 11.3333 | 11.3333 | 11.3333 |




Module area 1.6310 $m^2$

# 3D shading calculator

Calculates beam irradiance shading losses and sky diffuse view factor loss

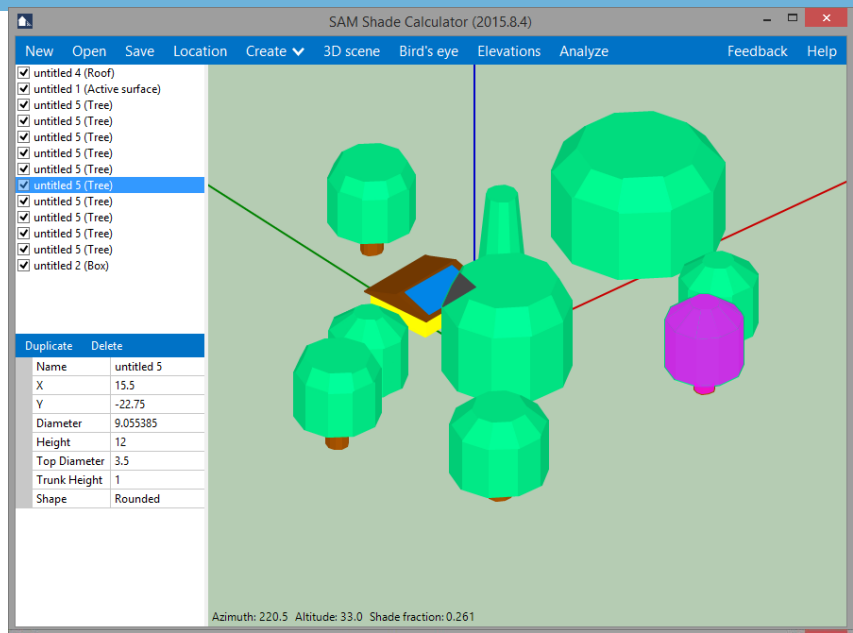
Imports 2D mapping underlays from online maps

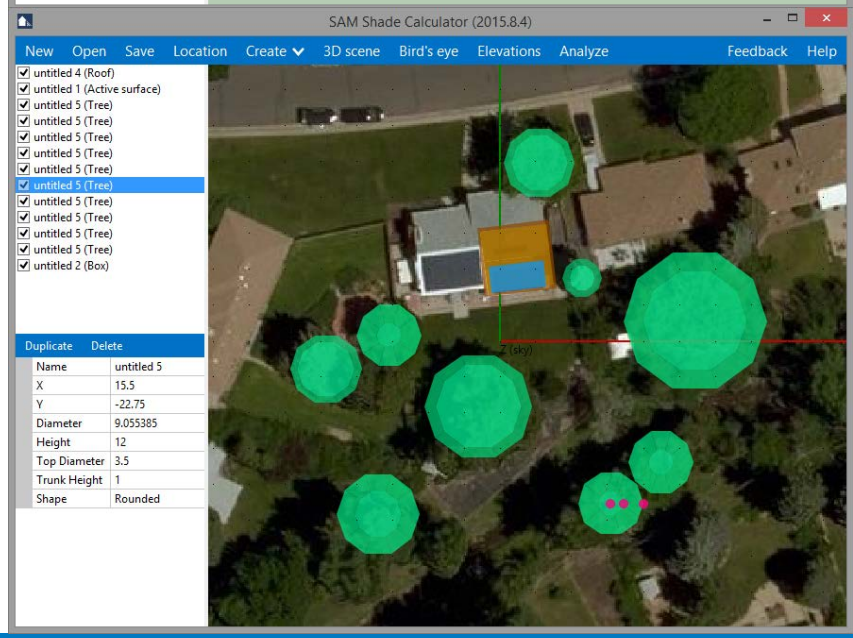
Outputs are diurnal or hourly/subhourly time series linear shade loss percentages

You can group PV surfaces into subarrays and specify parallel strings

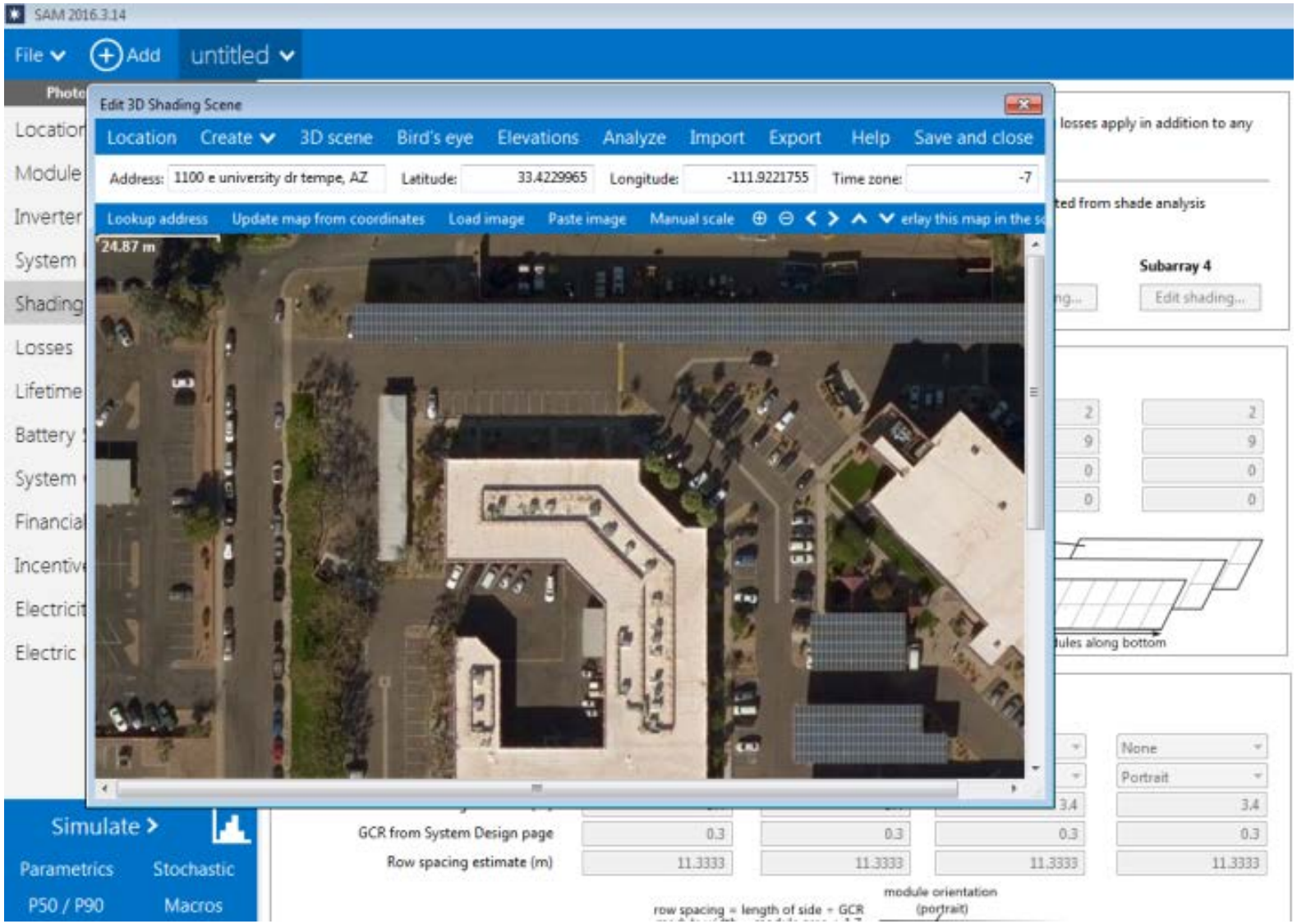
Non-linear shade response of **string inverters** uses shade database (see MacAlpine, Deline: IEEE PVSC 2015)

Linear response of **microinverters / optimizers** uses linear model.



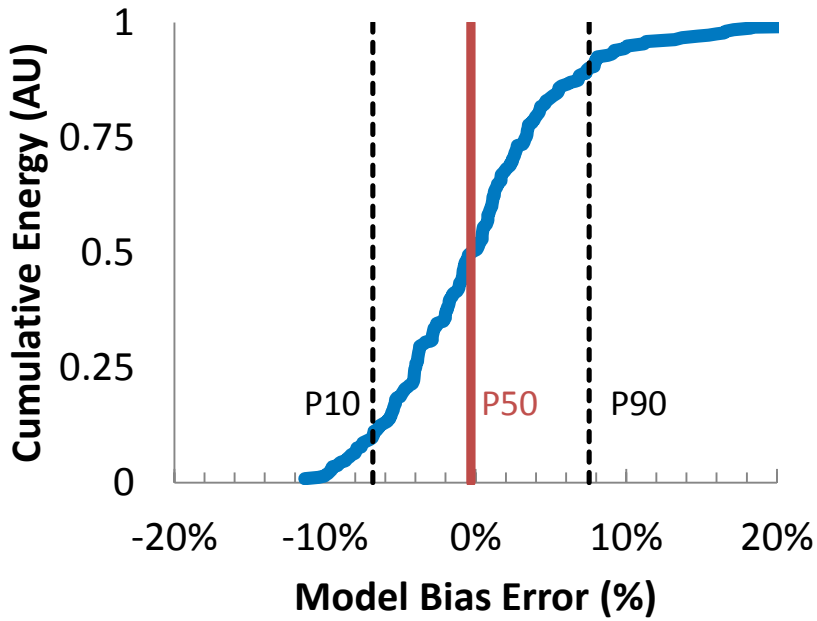



# Using 3D shading in SAM (live demo)

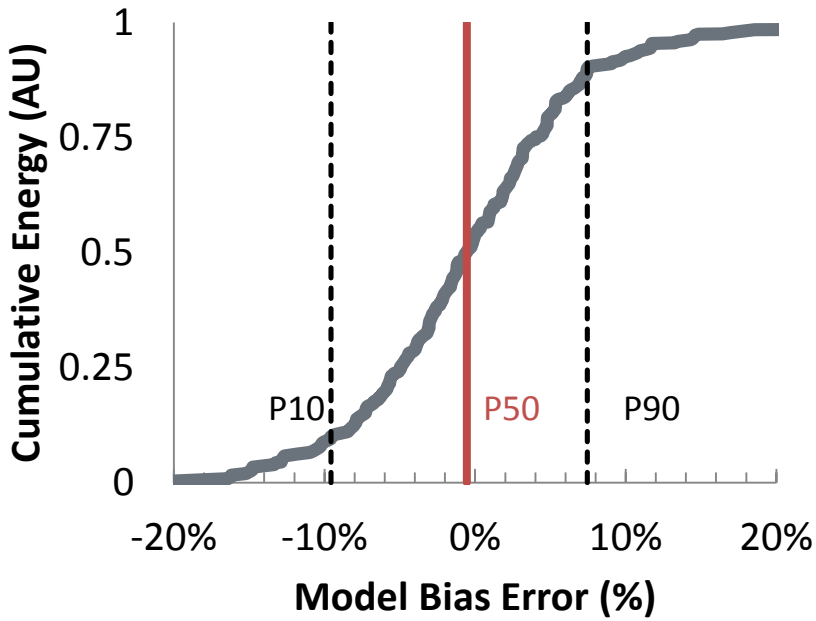


# 3D shading tool comparison with field data

Microinverter Model (linear)




String Inverter Database (nonlinear)




S. MacAlpine, C. Deline "Measured and Estimated Performance of a Fleet of Shaded PV Systems with String- and Module-level Inverters", Unpublished

# Thank You!

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory

www.nrel.gov

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

# Degradation (Rates) Curves

## Solar Power International

Las Vegas, NV

Dirk Jordan, Tim Silverman, Sarah Kurtz

9/12/2016

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

# Outline

- Economic & technical motivation
- Literature degradation & methodologies
- Climate
- Module ↔ System
- Non-linearities & degradation modes

# Why degradation (rates, curves, modes) matter

Degradation

Economic

Technical

$$$

Energy output prediction
Warranty default
Significant impact on LCOE

Chamber tests

Correlation

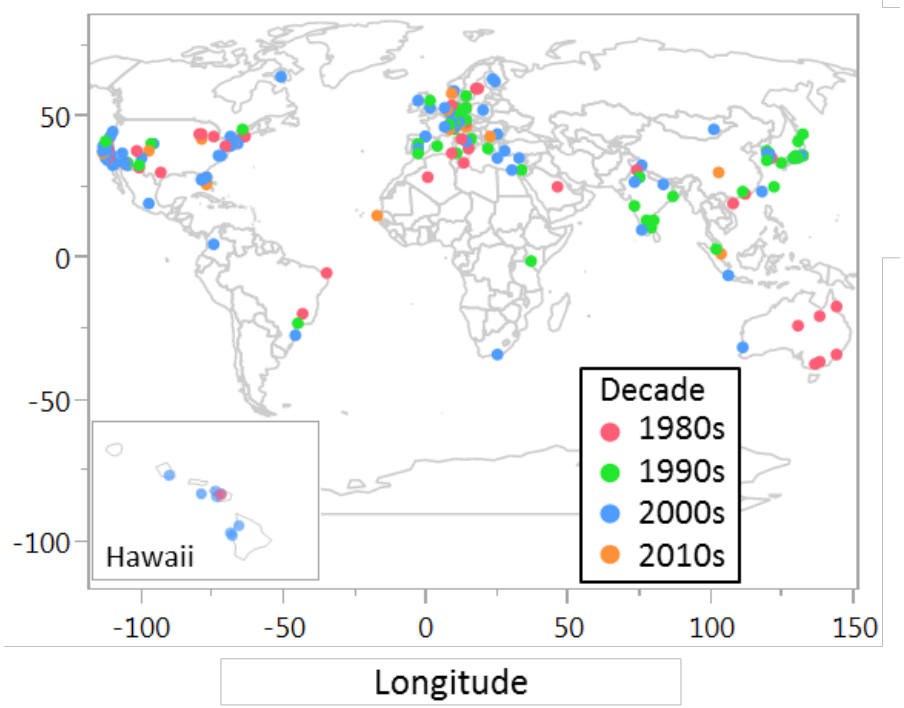
Field tests

Low cost & Lifetime prediction

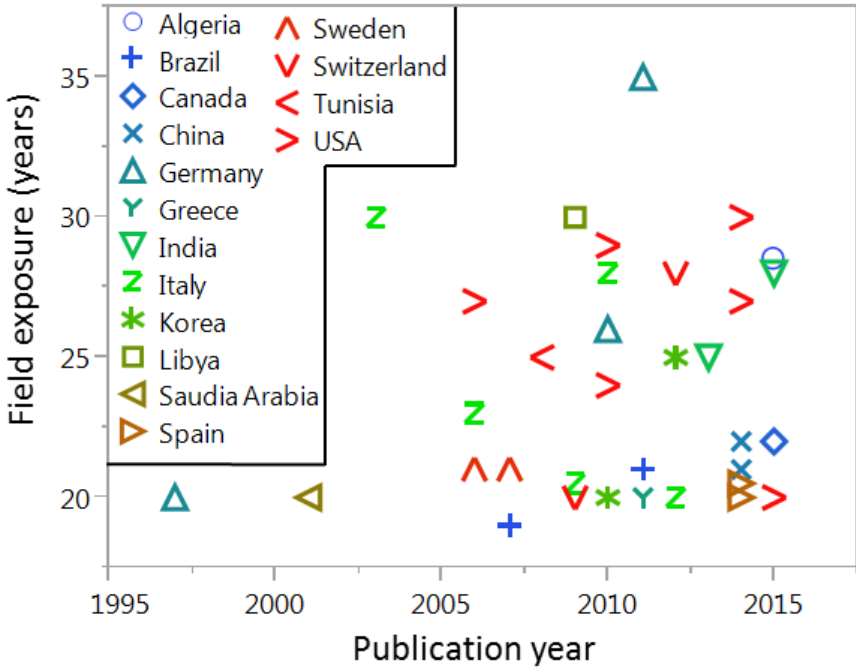
- Economic & technical motivation
- Literature degradation & methodologies
- Climate
- Module ↔ System
- Non-linearities & degradation modes

# > 30 system studies of 20+ years field exposure

Geographic distribution of degradation rates ($R_d$)




Studies of systems > 20+ years in field

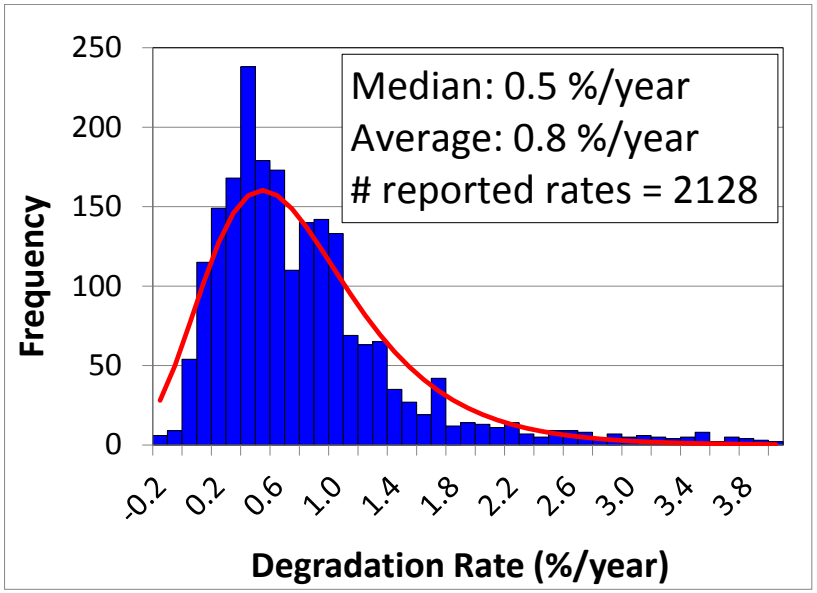



Increased interest in recent years in long-term performance & degradation

# Sampling bias is present – representative of the population?

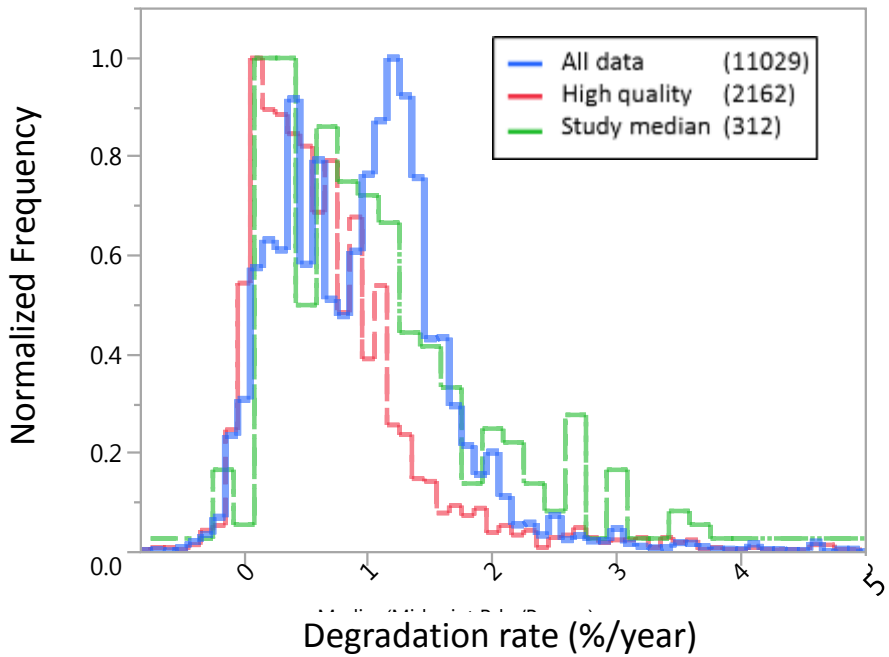
Literature survey

2011




Jordan et al., "Degradation Rates – An Analytical Review", Progress in PV, 2011

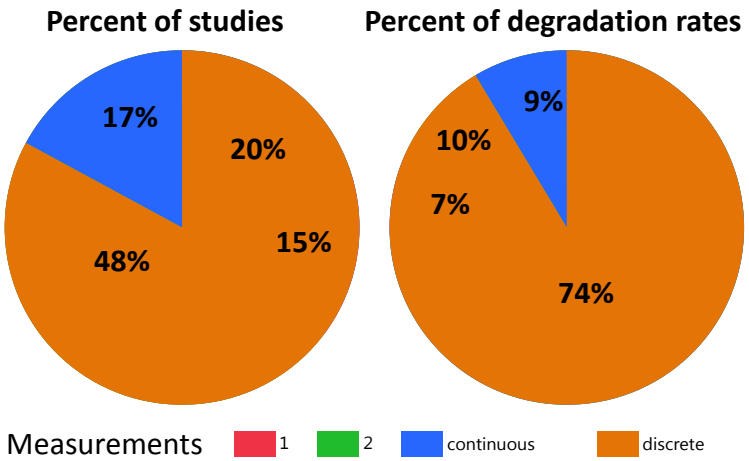
2016



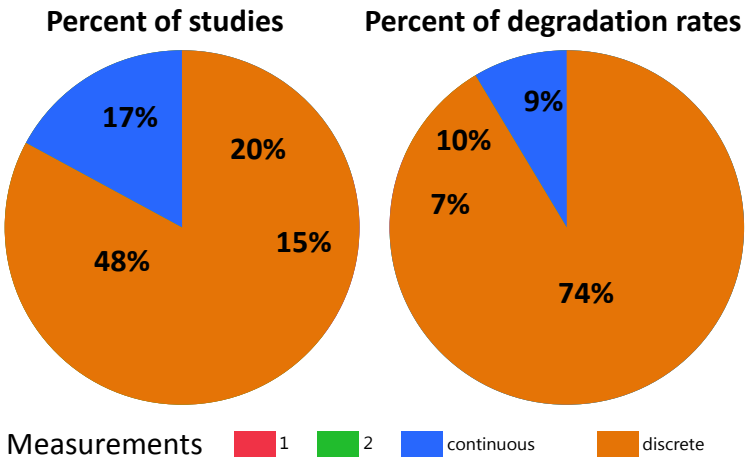

Jordan et al., "Compendium of photovoltaic degradation rates", Progress in PV, 2016

- Few studies with > 1000 modules
- Aggregated distribution is dominated by particular module, system, mounting, method etc.
- Counteract overrepresentation → analyze in different ways
- Median per study & system → second peak disappears
- High quality data (multiple measurements, calibrations etc.) → second peak disappears

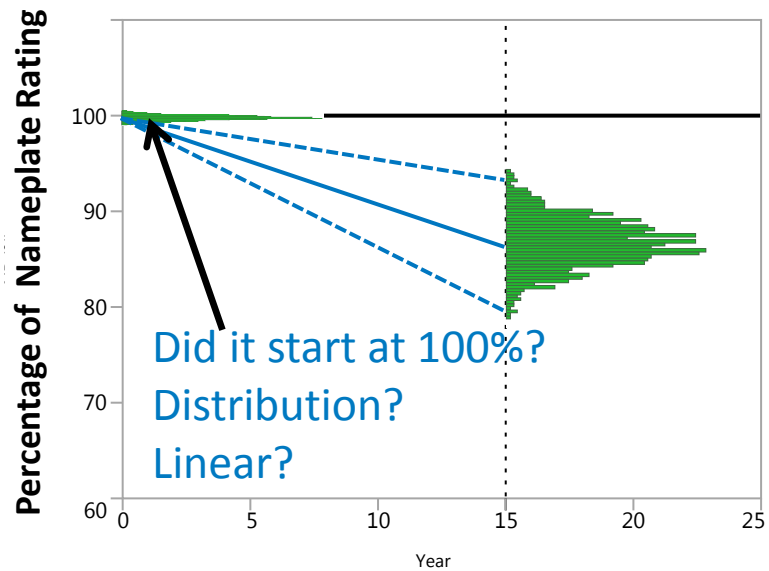
# Majority of $R_d$ are determined by single measurement.



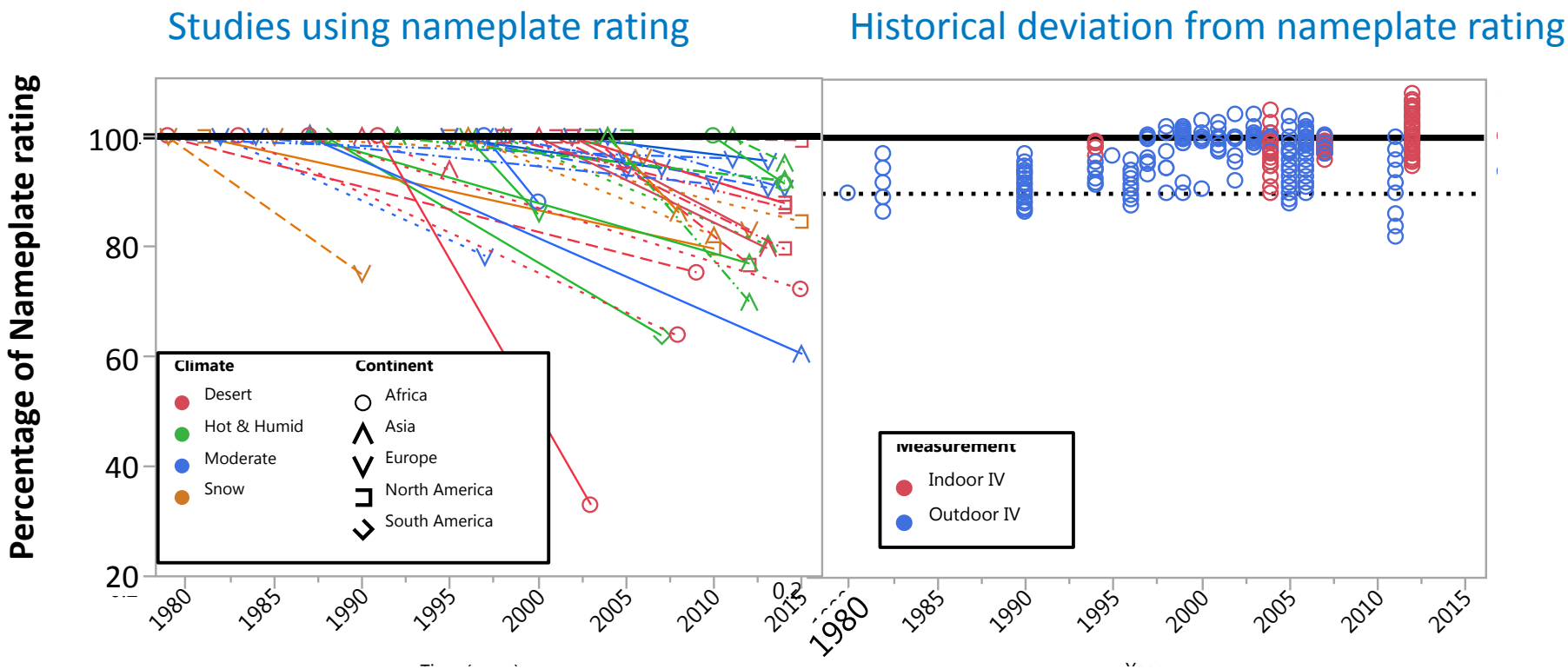
# Majority of $R_d$ are determined by single measurement.




How are $R_d$ determined with 1 measurement?



# $R_D$ using nameplate rating may have significant error.

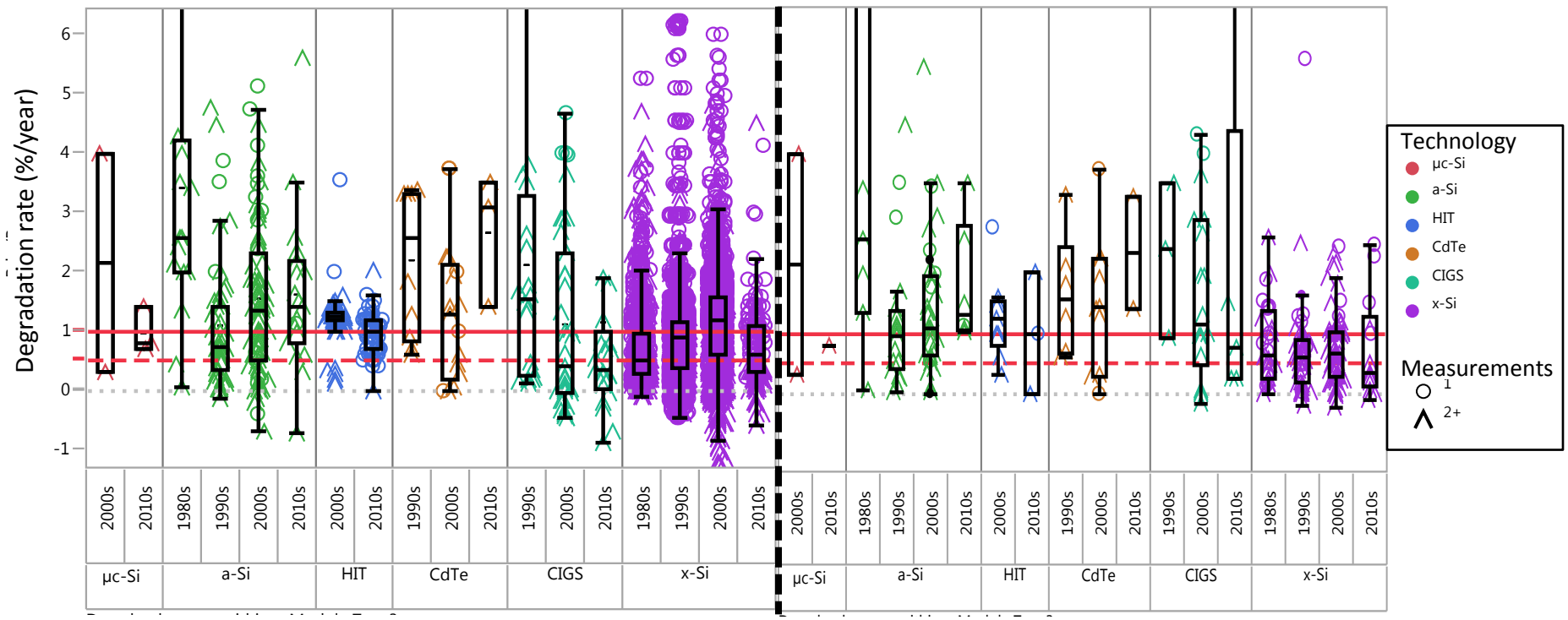



- Indoor IV seem closer to nameplate rating (though limited data)
- Outdoor seem farther away trending towards nameplate rating. Outdoor data may include light-induced degradation (LID)

# Reducing sampling bias x-Si → median 0.5 - 0.6, mean 0.8 %/year

All degradation rates

Median per study & system




Significant difference between all $R_d$ & median per study & system

a-Si $R_d$ > 1 %/year

Hetero interface (HIT) $R_d$ similar to a-Si than x-Si

CIGS around 0.5 %/year

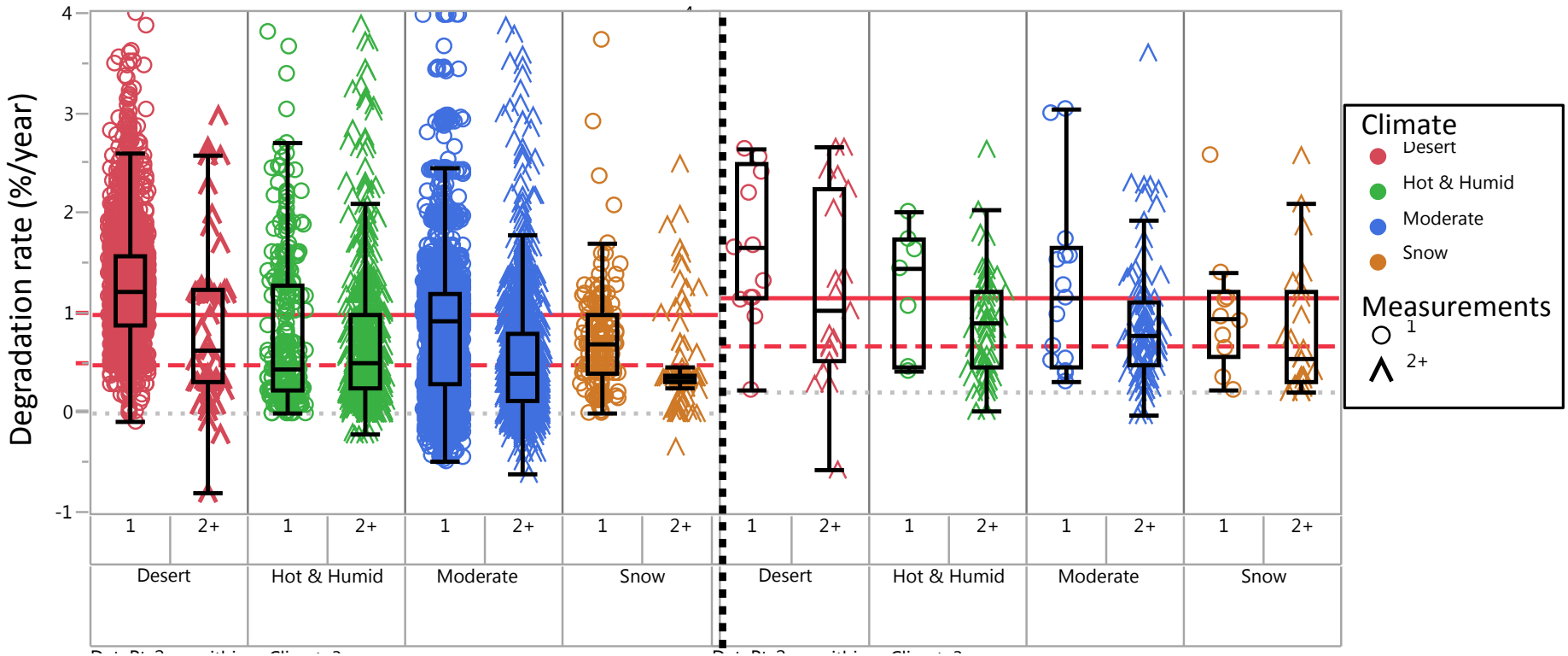
- Economic & technical motivation
- Literature degradation & methodologies
- Climate
- Module ↔ System
- Non-linearities & degradation modes

# Hotter climates may show higher $R_d$

Climate category: simplified Köppen-Geiger

All degradation rates

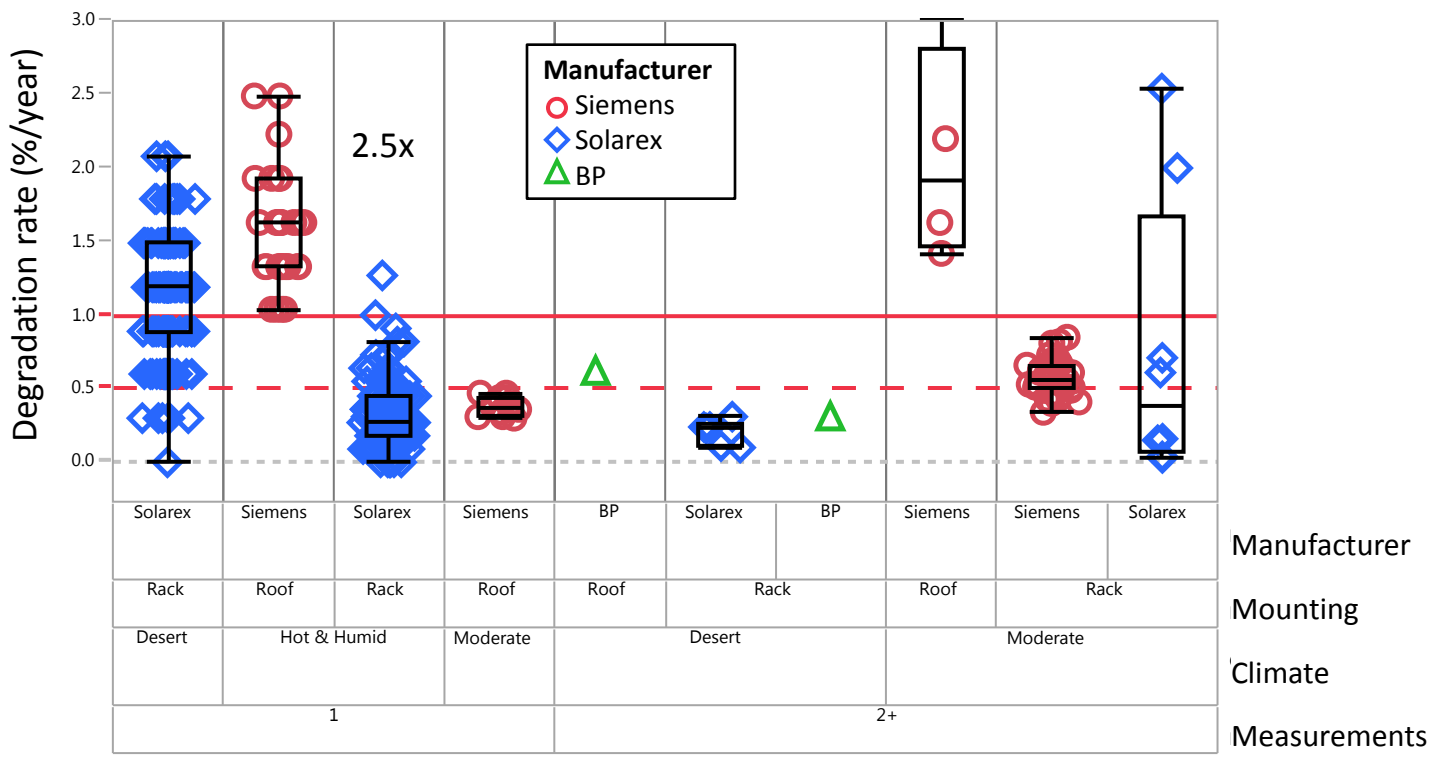
Median per study




1-measurement studies show statistically significant higher rates

Hotter climates appear to show higher $R_d$

# Some modules more susceptible to hotter climates & mounting.




Solarex:

- Show low median $R_d$ across climates
- Desert (1-measurement) shows higher $R_d$ → 1-axis tracker & 2.5x concentration

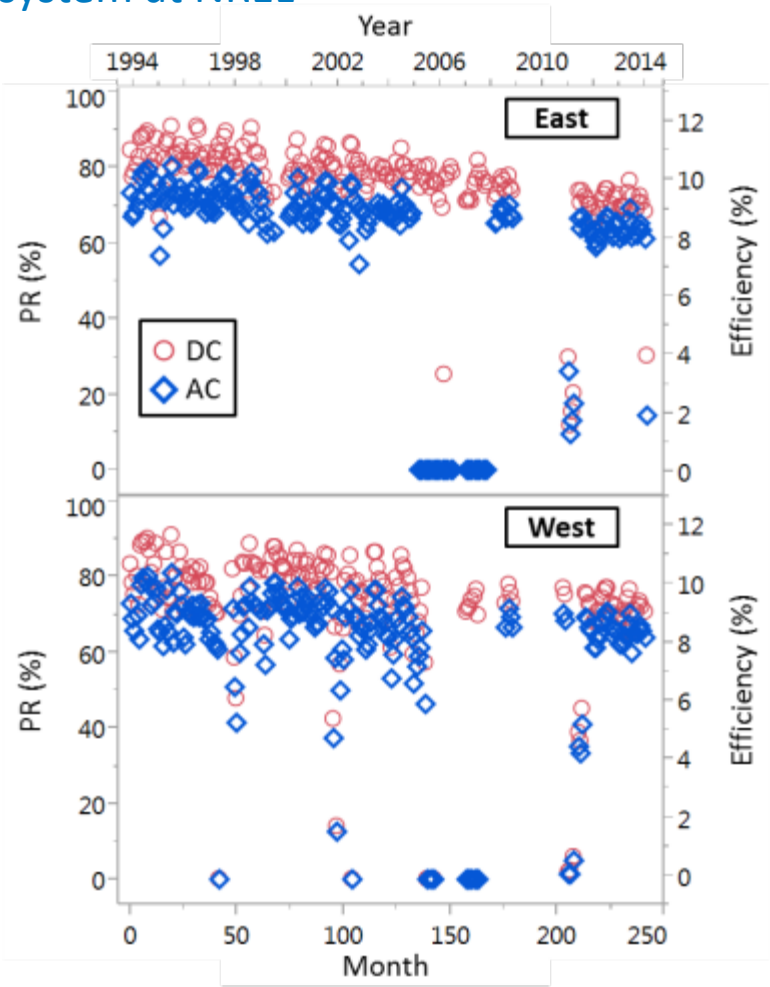
Siemens:

- Roof mounting shows higher $R_d$ even for moderate climate
- Hot & Humid shows higher $R_d$ than Solarex

- Economic & technical motivation
- Literature degradation & methodologies
- Climate
- Module ↔ System
- Non-linearities & degradation modes

# System vs. module degradation?

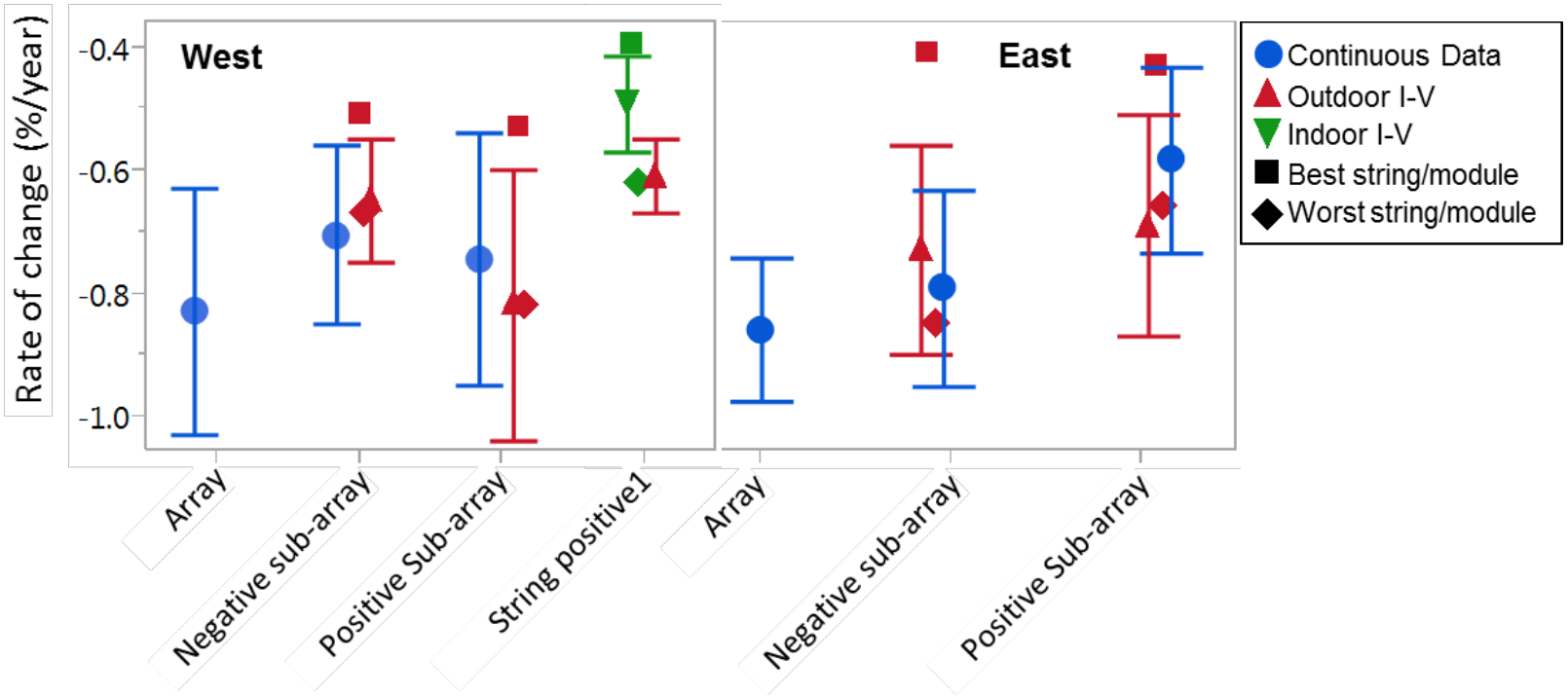
20 year old mono-Si system at NREL




Siemens M55 modules
Size: 7.4kW
No inverter clipping

Performance and Aging of a 20-Year-Old Silicon PV System, Jordan et al., J. PV, 2015.

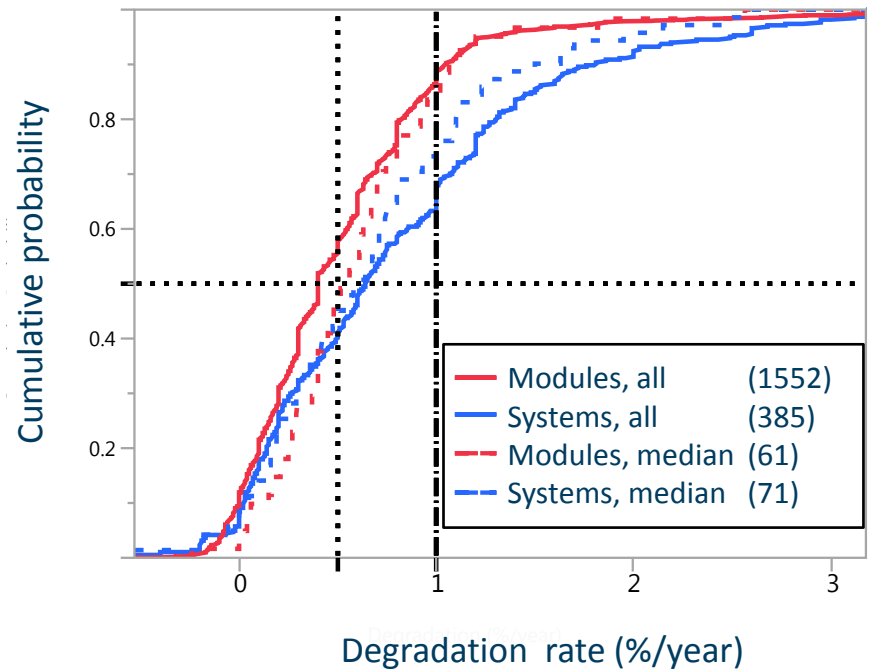
# System & module degrade similarly




- The worst string appears to determine the subarray and array performance
- System degradation matches module degradation if modules degrade similarly, System degradation > average module degradation when large spread

# At median systems & modules degrade similarly

High –quality, x-Si data




At median modules degrade a little less than systems but in general very similar

For less well-performing products more significant gap between modules & systems

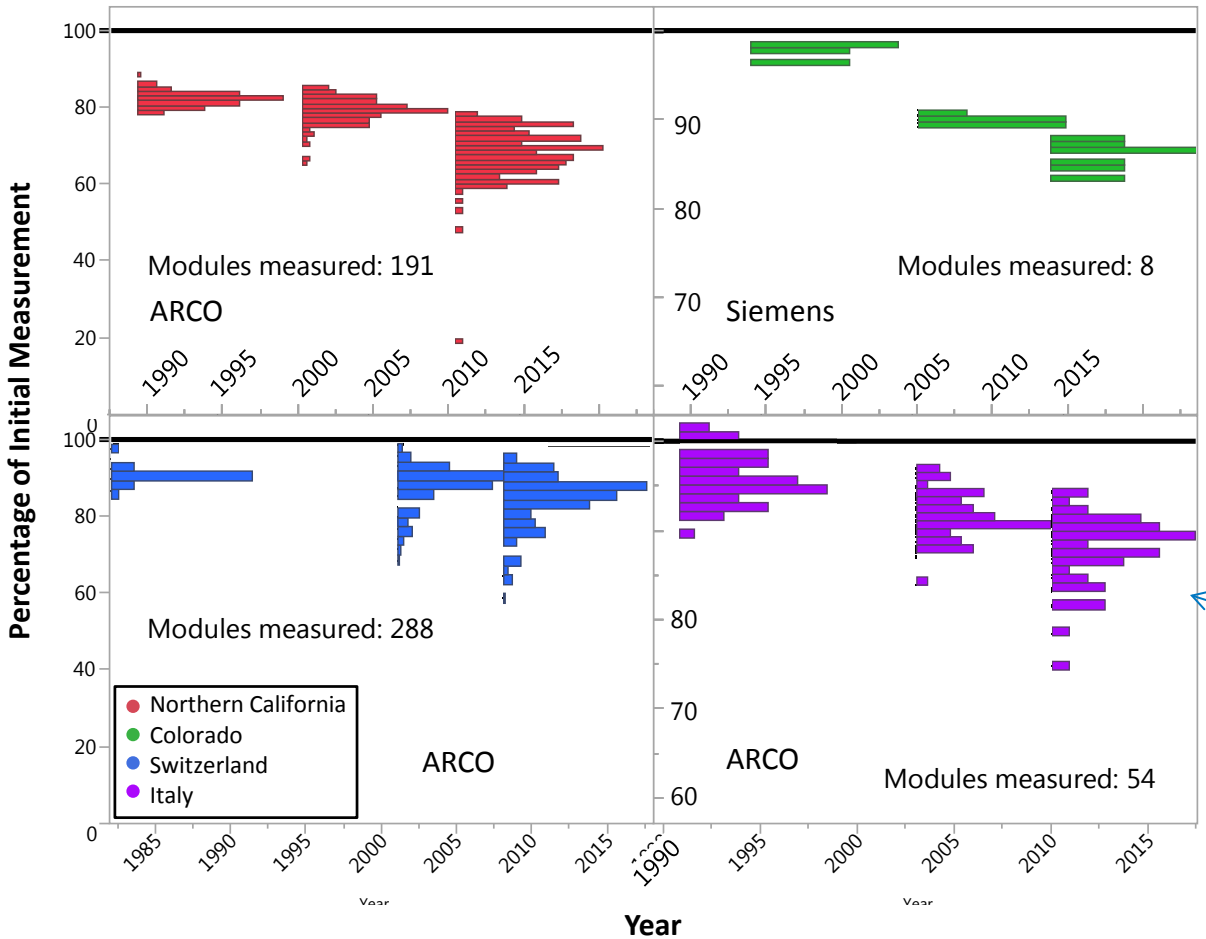
- Economic & technical motivation
- Literature degradation & methodologies
- Climate
- Module ↔ System
- Non-linearities & degradation modes

# Appears linear for most modules, worst modules non-linear

Studies that measured sample modules several times in 20+ years

20 years

30 years

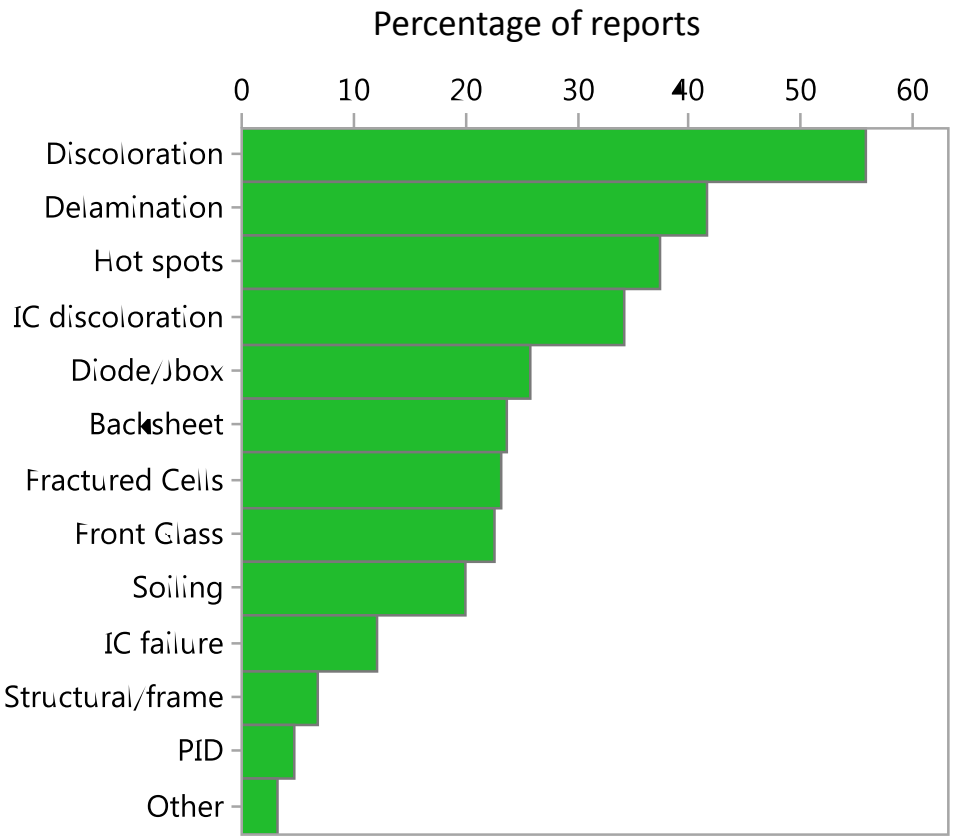



1st measurement taken after 11 years

Distribution skews towards low end → worse performing modules show some non-linearity

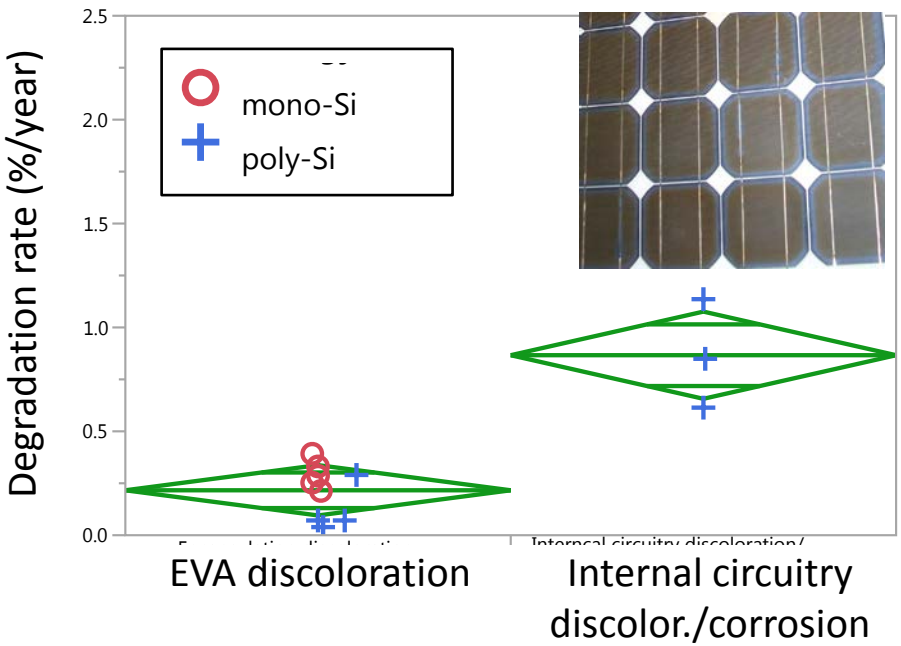
Central tendency & better modules → fairly linear

# Literature degradation modes

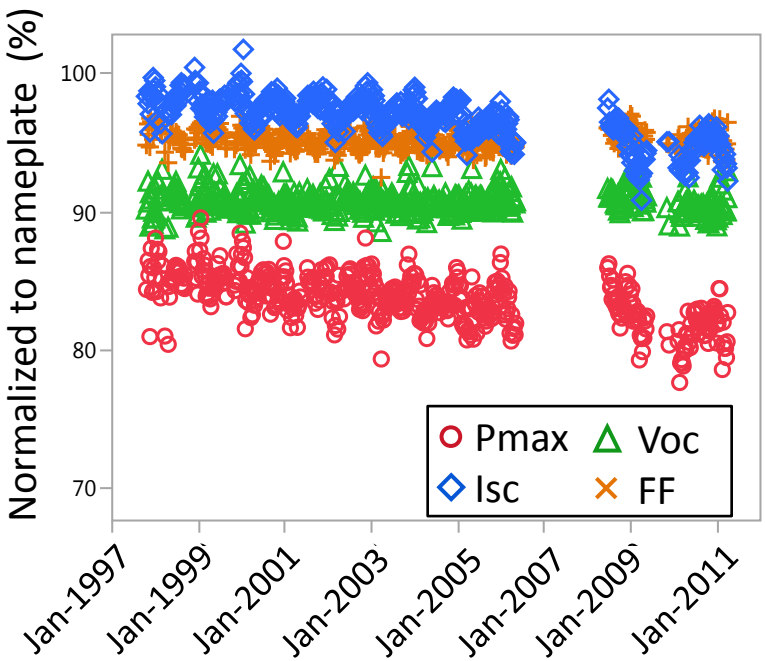



… but is that the most important effect?

# Encapsulation discoloration associated with small power loss



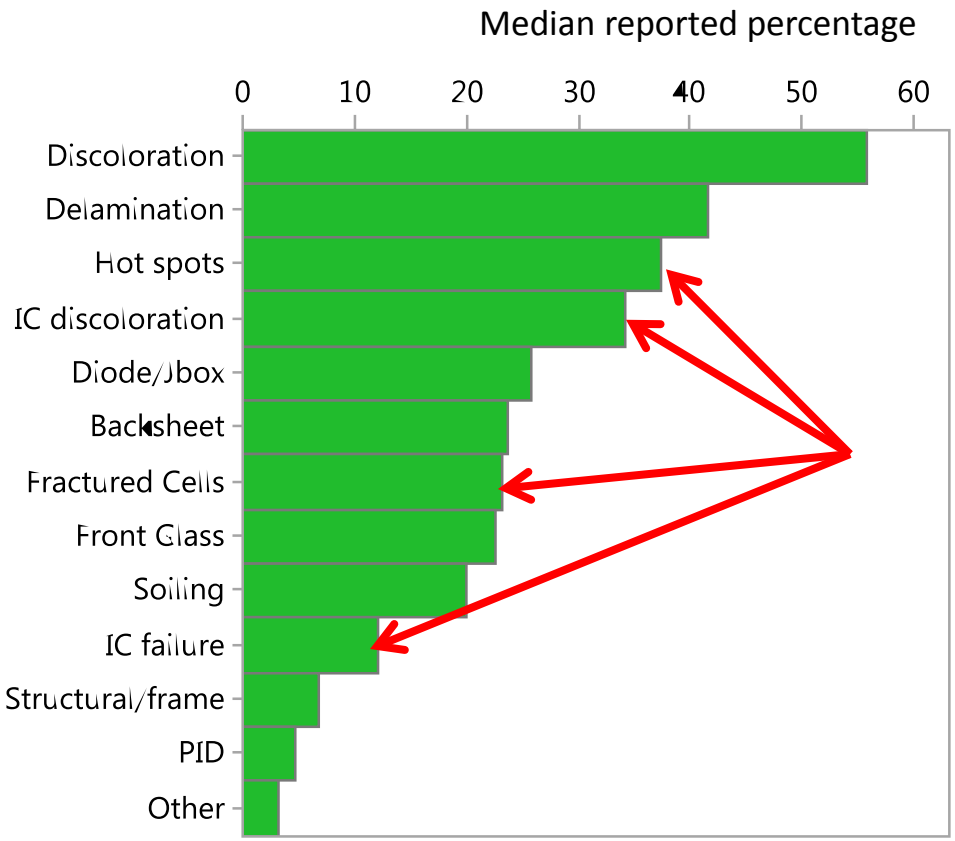

Jordan, et al., 35th PVSC, Honolulu, HI, USA, 2010.

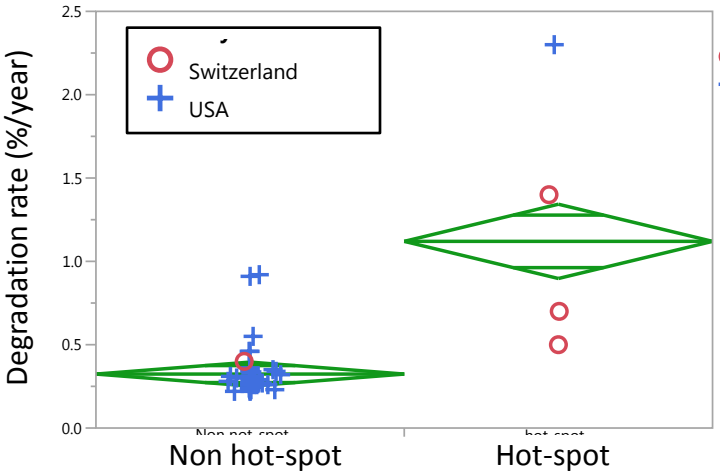



Encapsulant discoloration associated with lower power loss in direct comparison.

Encapsulant discoloration shows linear decline below 0.5 %/year, dominated by Isc losses.

# Modules with hot-spots exhibit higher power loss



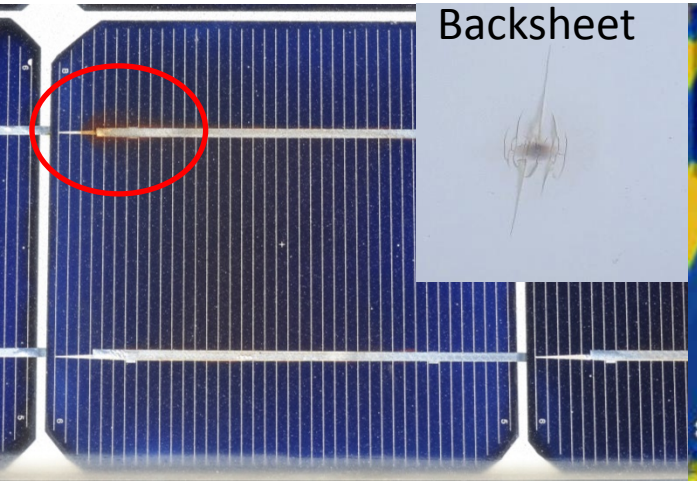




Hot-spots can have several causes such as cracked cells or solder bond failure.

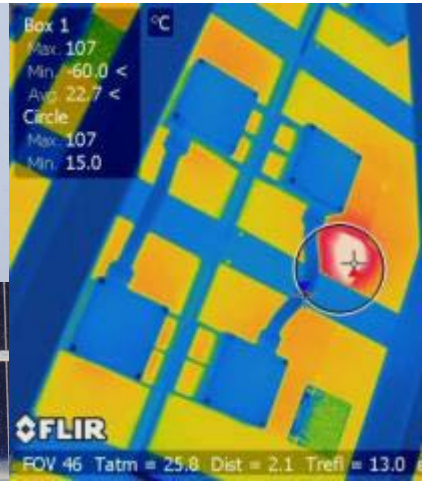
Modules with hot-spots in 1-1 comparison studies showed higher power loss than modules without.

# Single solder bond failure causing hot-spot

Solder bond on cell busbar causing hot-spot in 22 year old mono-Si system

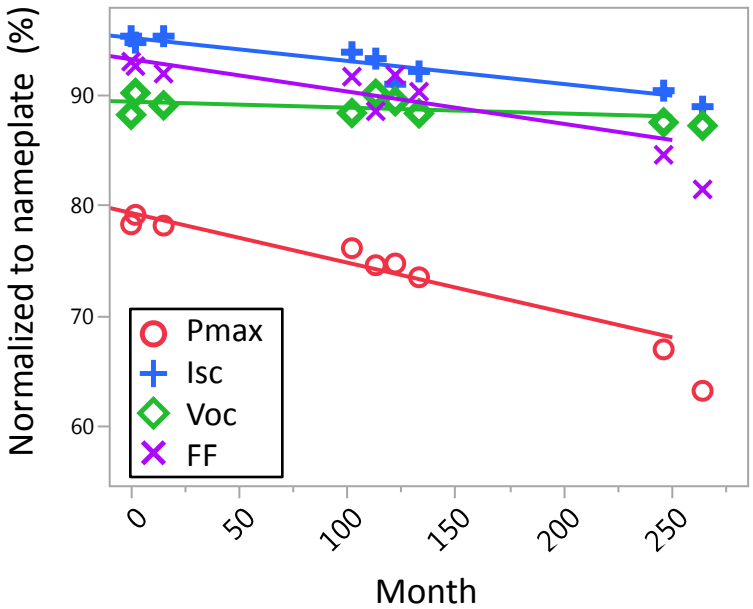



Visual image of affected cell




IR image of the back

String IV measurements



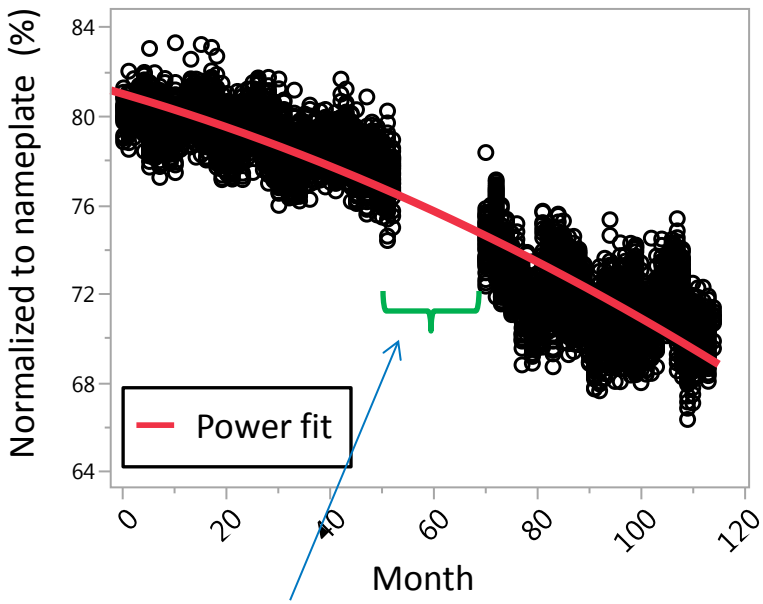

Siemens M55 model
Module was replaced
Only replacement out of 280 modules

The first 20 years decline appears to be around 0.5 %/year.

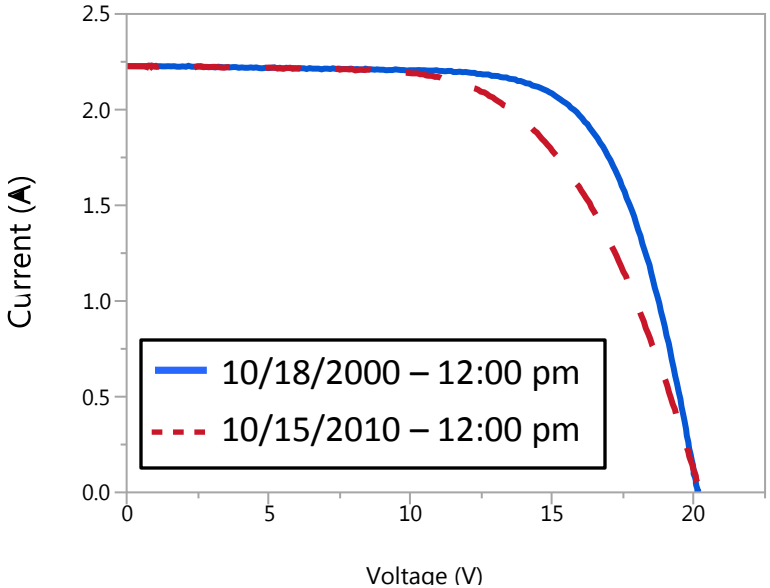
More rapid decline associated with FF loss.

# Multiple solder bond fatigues causing non-linearities

Continuous Pmax data




I-V curves



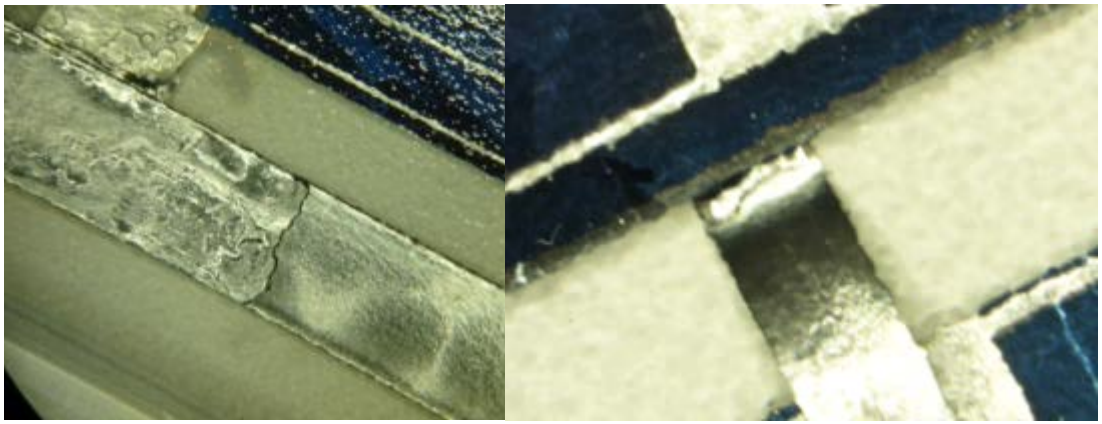

Module exposed outside but problems with data acquisition

Temperature correction to 48C

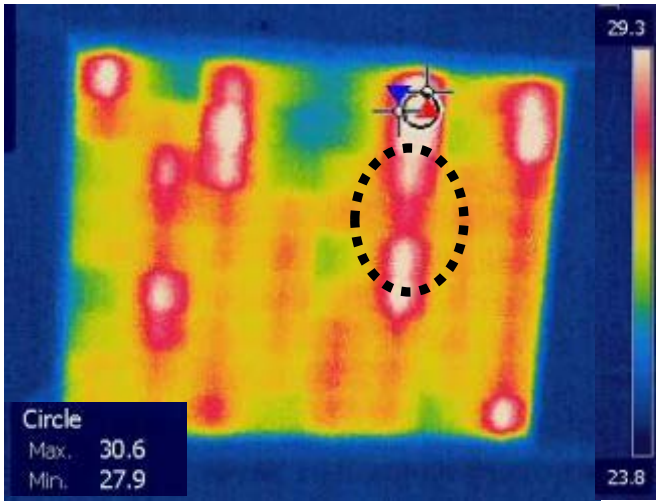
Non-linearity due to solder bonds can be seen in thermal cycling testing.*

*Herrmann, et al., 37th PVSC, Seattle, USA, 2011.

# Solder bond fatigue – non-linear

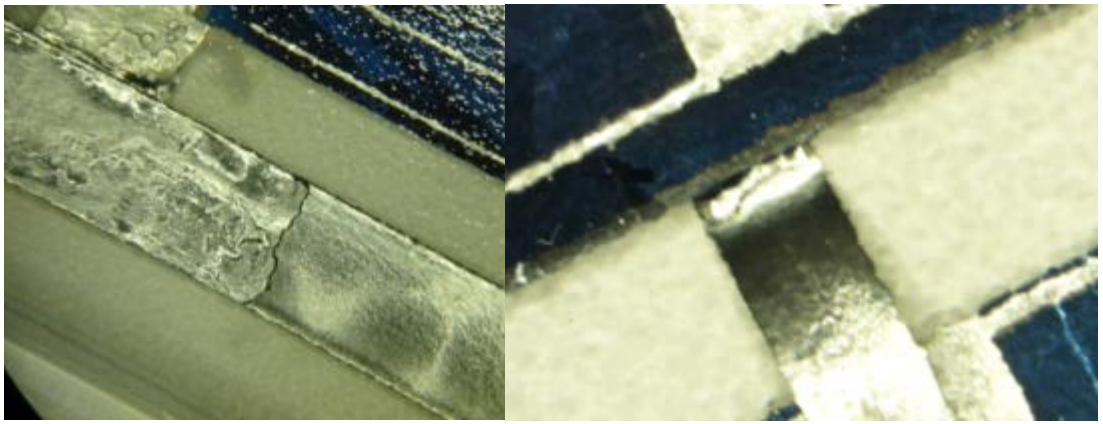


Cracks in interconnect ribbons but haven't failed yet.

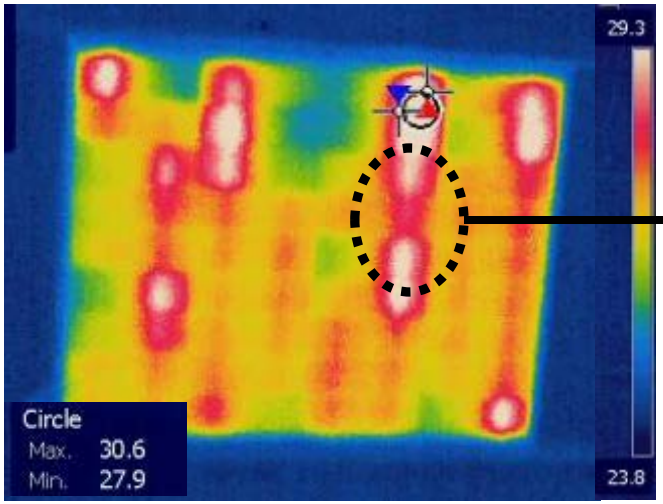



IR image shows hot-spots along cell interconnect ribbons

# Solder bond fatigue – non-linear



Cracks in interconnect ribbons but haven't failed yet.

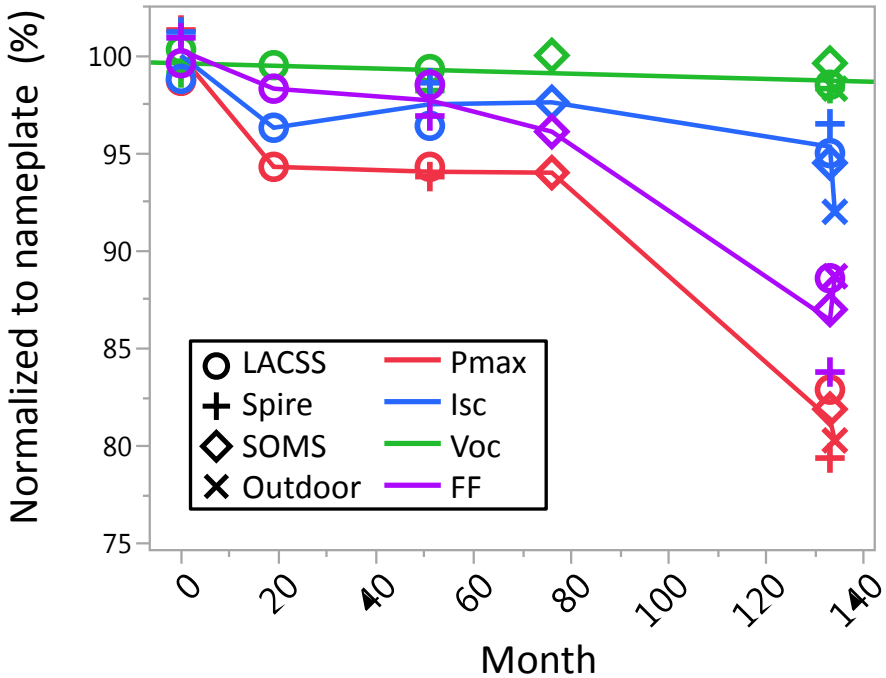


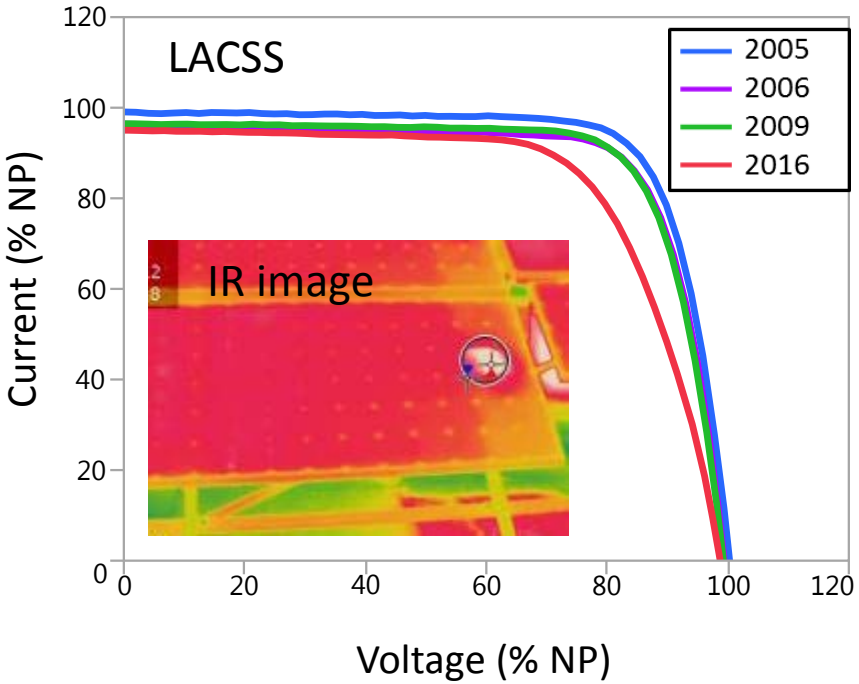

IR image shows hot-spots along cell interconnect ribbons

EL shows change of connectivity when pressure is applied

# Cracked cell causing non-linearity

I-V measurements




LACSS: large area solar simulator
Spire: indoor flash tester
SOMS: standard outdoor measurement system
Outdoor: Daystar field measurements

- Module was stable for several years
- Now we see more precipitous decline associated with FF losses, Rs increase

# Risk priority number can quantify risk

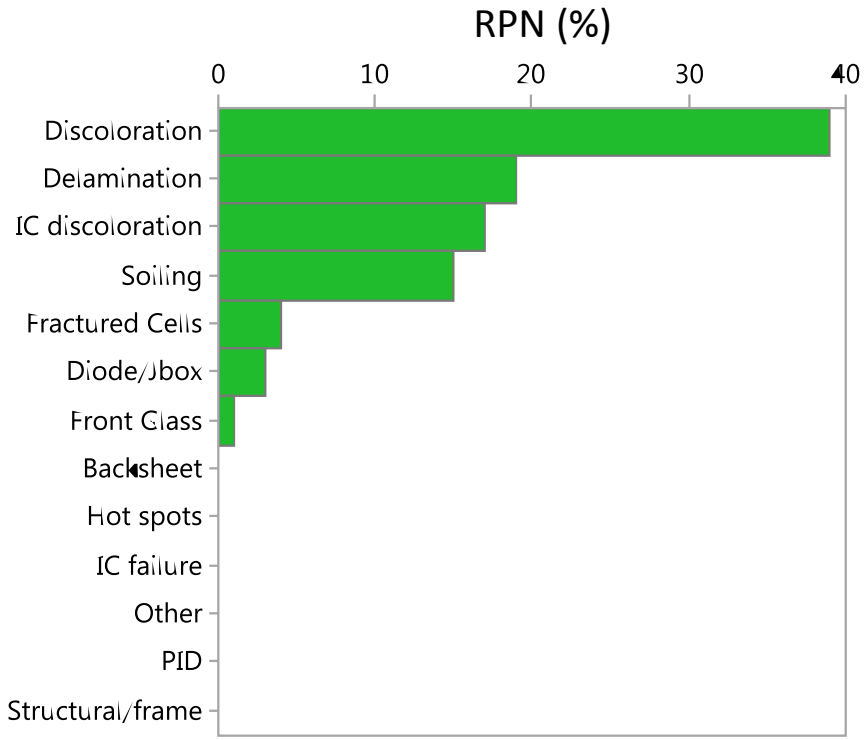
**Risk priority number (RPN)** = Occurrence * Severity * Detectability

= Number of reports*Number of affected modules * Severity * ~~Detectability~~

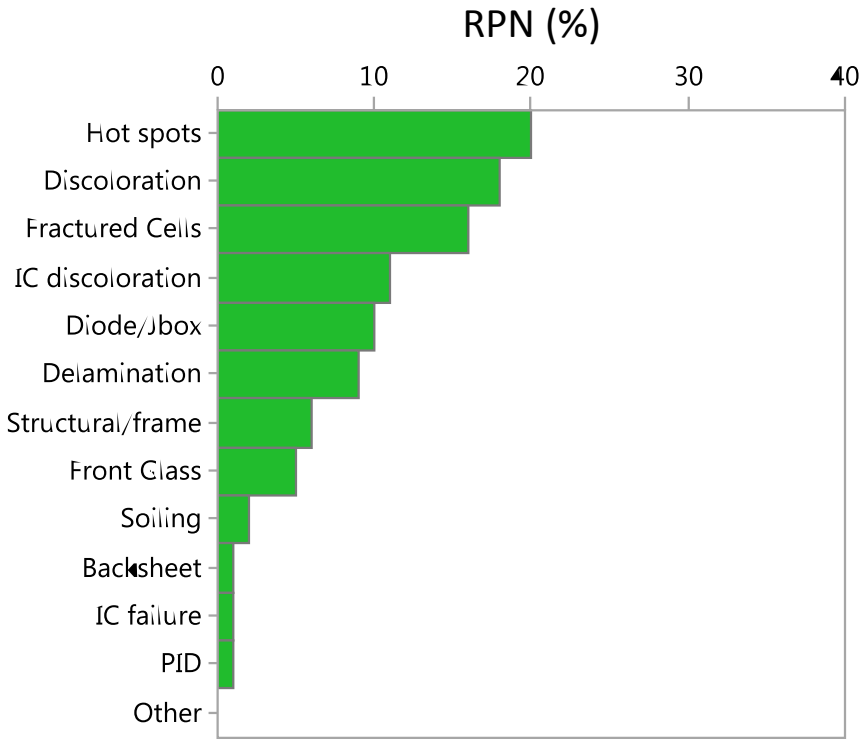
| Severity | Rating |
|---|---|
| Major impact on power & unsafe | 5 |
| Major impact on power | 4 |
| Significant impact on power | 3 |
| Slight deterioration of performance | 2 |
| No effect on performance | 1 |

# Hot spots & fractured cells have become more important recently

Older installations – before 2000




Newer installations – after 2000

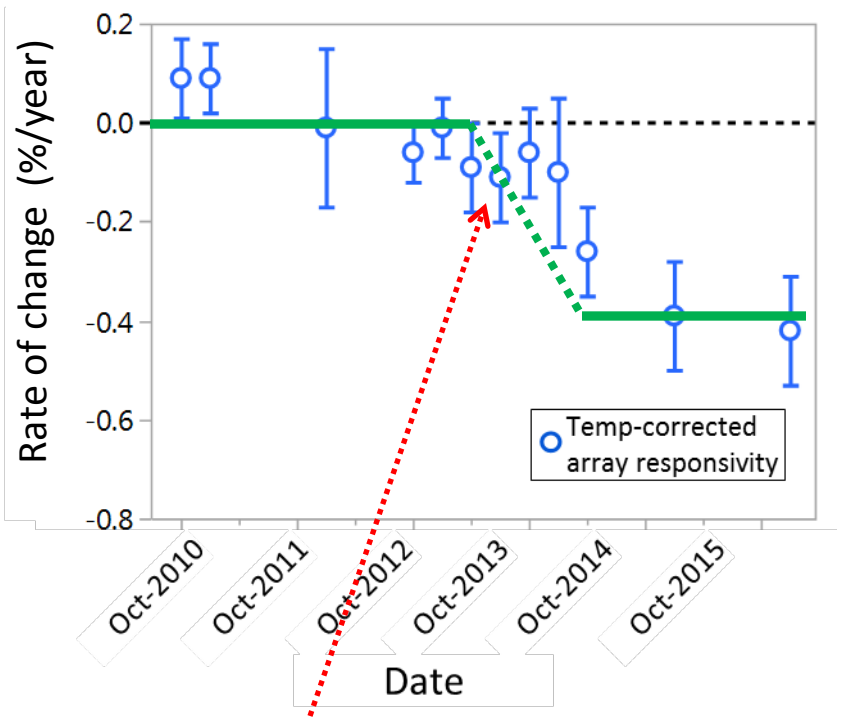



Older installations most important factor was discoloration because large number of modules affected by it

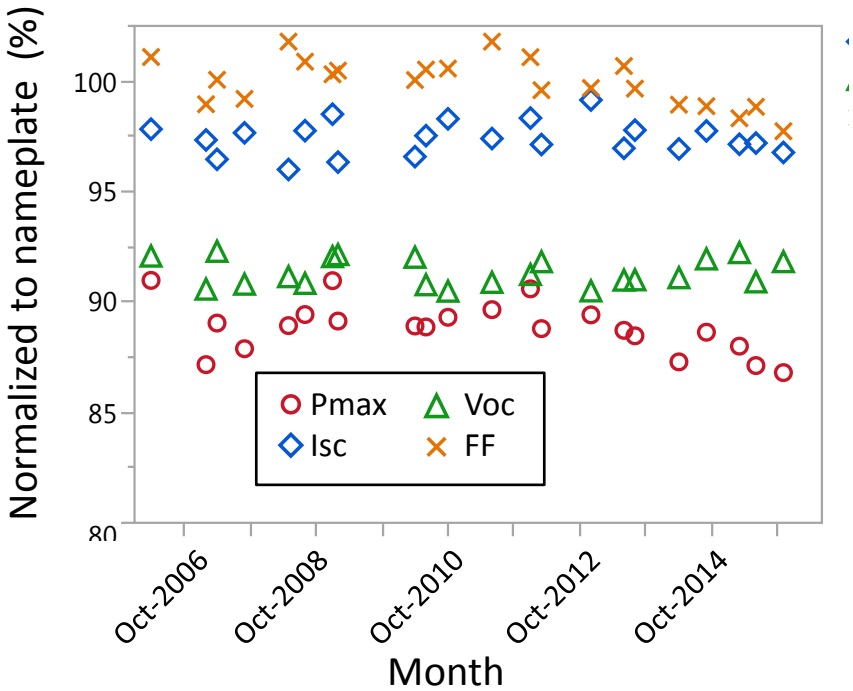
Newer installations most important factors are hot spots & fractured cells. Modules affected are rather small but more publications reporting it.

# Thin-film: Cracked circuit – 2-step profile

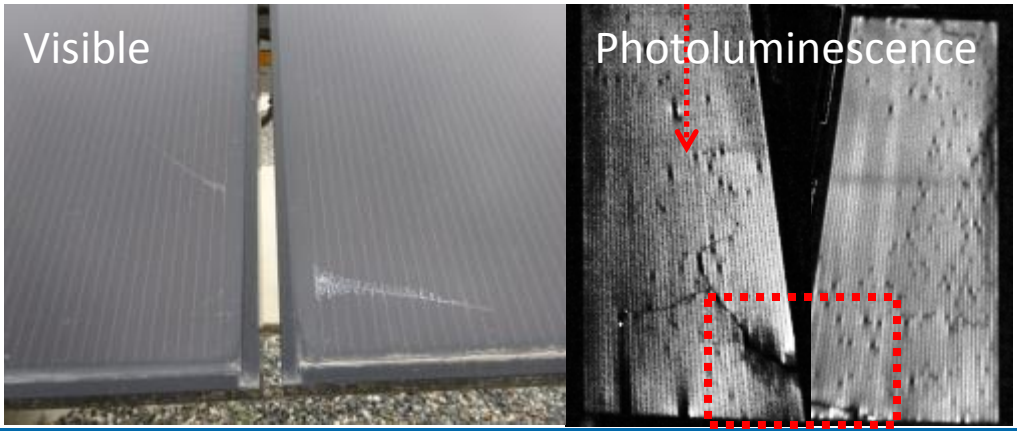
Shell CIS system *




Cracked module first observed




Crack extends into module




May see more 2-step profiles in the future because of inverter clipping .

*Jordan et al. in *37th PVSC*, 2011.

# Summary

- 1-measurement studies show significantly higher $R_d$ probably because of nameplate rating deviation
- Increased $R_d$ in hotter climates & mounting for some products
- x-Si has median in 0.5 – 0.6 %/year range, mean in 0.8 %/year range
- Non-linearities have significant financial impact, need to more accurately measure curves instead of relying solely on rates.
- Discoloration is the most commonly observed failure mode but is associated with less power loss. In contrast, hot-spots are not as frequently observed but show greater power losses.

# Acknowledgments

## Thank you for your attention

NREL reliability group

National Renewable Energy Laboratory
15013 Denver West Parkway, MS 3411
Golden, CO 80401, USA
dirk.jordan@nrel.gov

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

# PVWatts Updates and Validation

## Solar Power International

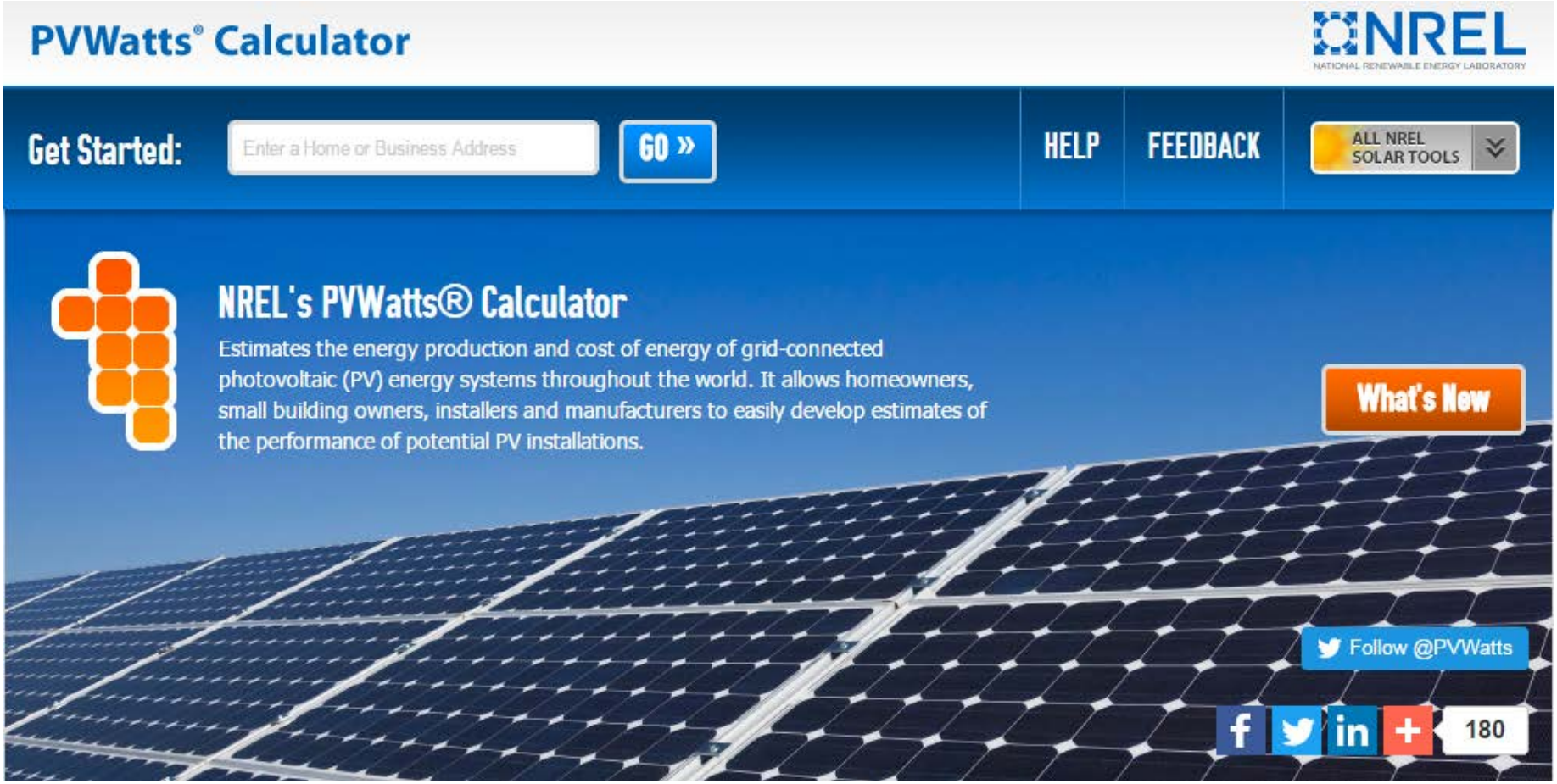
Las Vegas, NV

Dirk Jordan, Chris Deline, Sarah Kurtz

9/12/2016

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

# Motivation: PVWatts v5




http://pvwatts.nrel.gov/

PVWatts v5 released in 2014

# PVWatts v5 DC-AC default loss values

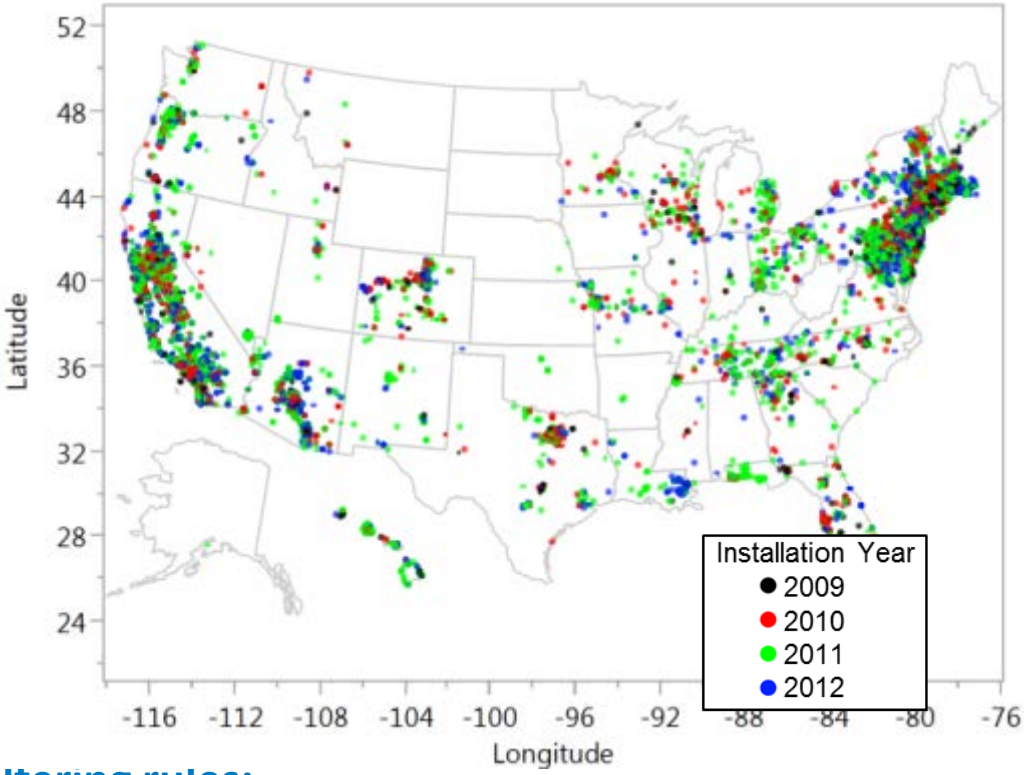
| Loss Mechanism | V5 Loss | V1 Derate |
|---|---|---|
| Soiling | 2 % | 0.95 |
| Shading | 3 % | 1.0 |
| Snow | 0 % | 1.0 |
| Mismatch | 2% | 0.98 |
| Wiring | 2 % | 0.97 |
| Connections | 0.5 % | 0.995 |
| Light-induced degradation | 1.5 % | - |
| Nameplate rating | 1 % | 0.95 |
| Age | 0 % | 1.0 |
| Availability | 3 % | 0.98 |
| **Total losses** | **14 %** | **16.5 %** |
| Inverter Efficiency | 96 % | 0.92 |
| **Effective DC-AC Derate** | **0.825** | **0.77** |

Default DC-AC derate:
PVWatts v1: 0.77
PVWatts v5: 0.825

A. Dobos, PVWatts v5 manual http://www.nrel.gov/docs/fy14osti/62641.pdf

# Analysis of 50,000 systems = 1.7GWatts Capacity

**American Recovery & Reinvestment Act, Section 1603**




**Data available:**

AC production (up to 4 years)
Predicted AC production
Zip code location
Nameplate
Comments

**Data *not* available:**

Irradiance
Orientation

**Data filtering rules:**

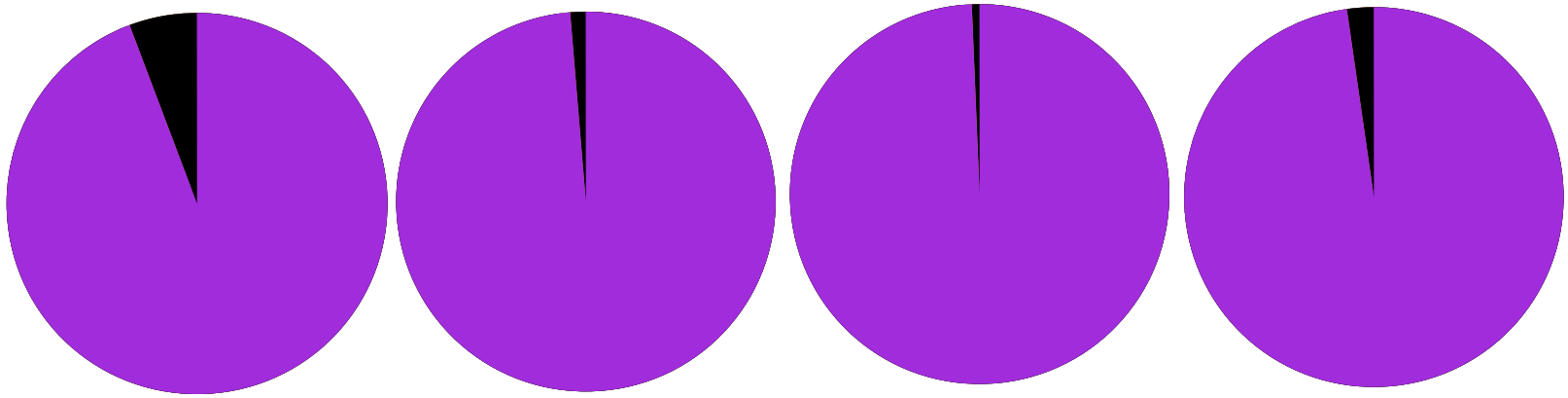
- Nameplate or predicted value =production year1,2,3,4 → reject production years
- Predicted capacity factor: actual production/potential production= 3-40%
- Year1 production = Year2 production → reject year2 entry

Jordan: Field Performance of 1.7 Gigawatts of Photovoltaic Systems, IEEE PVSC 2014

# Categorization of Performance Comments

| Data Category | Sub-category | Comment Example |
|---|---|---|
| **Normal** | N/A | Normal variance in solar irradiance |
| **Project** | Delay | Delay in construction for up to two months. |
| | Utility/Grid | Erratic voltage on grid line shuts down inverter |
| | Construction | PV system turned off  for building's renovation process. |
| | Design | System design (tilt) changed after initial application. |
| | Financials | House went into foreclosure and the system has been shut down. |
| **Hardware** | Inverter | The inverter had a problem and needed to be replaced. |
| | Repair | Maintenance interruptions. Difference due to unscheduled outages. |
| | Fuse, Wiring | Multiple string fuses had to be replaced. |
| | Module defective | Solar panel damage, system underperformed. |
| | Module recall | System was shut down module recall. |
| | Unauth. shutdown | Vandals switched disconnects "off" until locks were secured. |
| **Data Collection** | Missing Data | We are missing production data from April - May. |
| | Data acquisition | Internet monitoring feed problems |
| | Poor initial estimate | Overestimated the systems output in optimal conditions. |
| **Weather** | Snow | Heavy snow fall in the winter reduced generation in the winter. |
| | Shading | Original production was based on the original shading analysis. |
| | Lightning | Local power transformer was struck by lightning, |
| | Hurricane | Power outage due to Hurricane Sandy |

# No Evidence of Massive failure



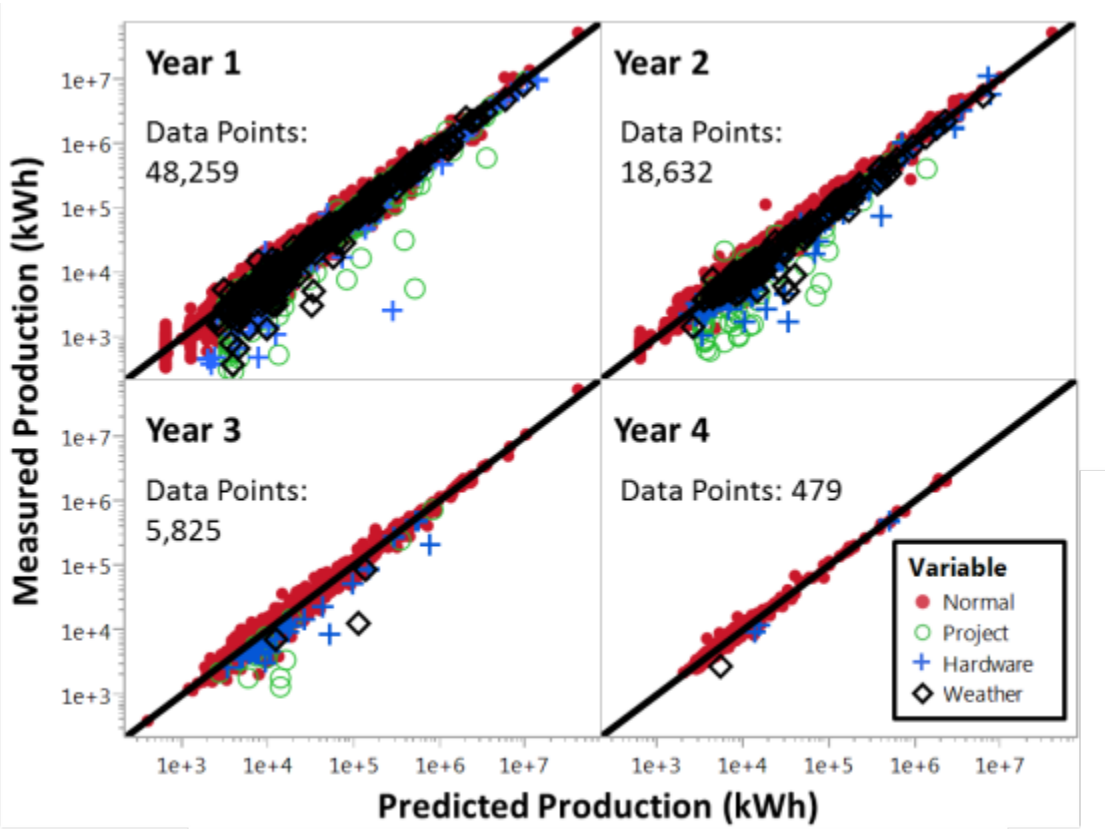
| Year of Operation: | Year 1 | Year 2 | Year 3 | Year 4 |
|---|---|---|---|---|
| **Data Points:** | 48,259 | 18,632 | 5,825 | 479 |
| Normal | 91.5 | 95.3 | 97.6 | 95.8 |
| Hardware | 0.7 | 0.6 | 0.5 | 0 |
| Project | 0.8 | 1.0 | 0.1 | 0.2 |
| Weather | 5.8 | 1.3 | 0.7 | 2.3 |
| Data Collection | 0.9 | 0.9 | 0.6 | 0.8 |
| Hardware | 0.2 | 0.9 | 0.7 | 0.8 |
| No information | | | | |

Project/Site: Delay, grid interconnection, construction etc.
Weather: Snow, soiling, lightning, hurricanes etc.
Data Collection: Data acquisition, less than a year of data, etc. (not performance related)
Hardware: Inverter, module, breaker, fuses etc.

Jordan: Field Performance of 1.7 Gigawatts of Photovoltaic Systems, IEEE PVSC 2014

# Most systems produce as expected

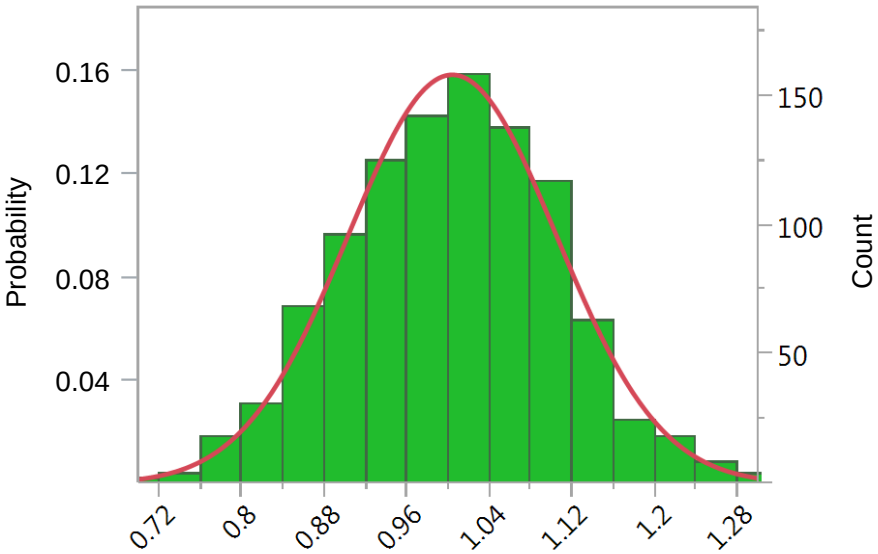
Measured vs. predicted production for all operation years




Project issues data points tend to be farther away from unity line →
They don't occur that often (previous slide) but if they do they tend to have larger impact

Jordan: Field Performance of 1.7 Gigawatts of Photovoltaic Systems, IEEE PVSC 2014

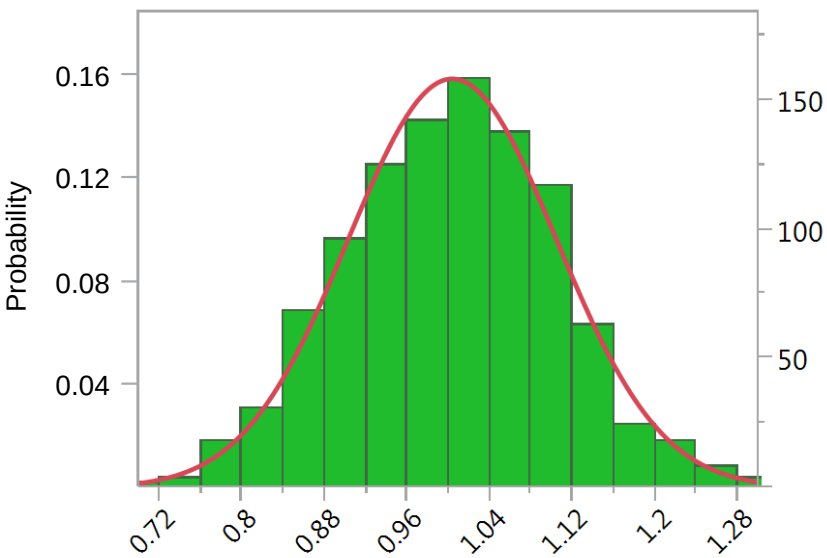
## Histogram
## Probability density function



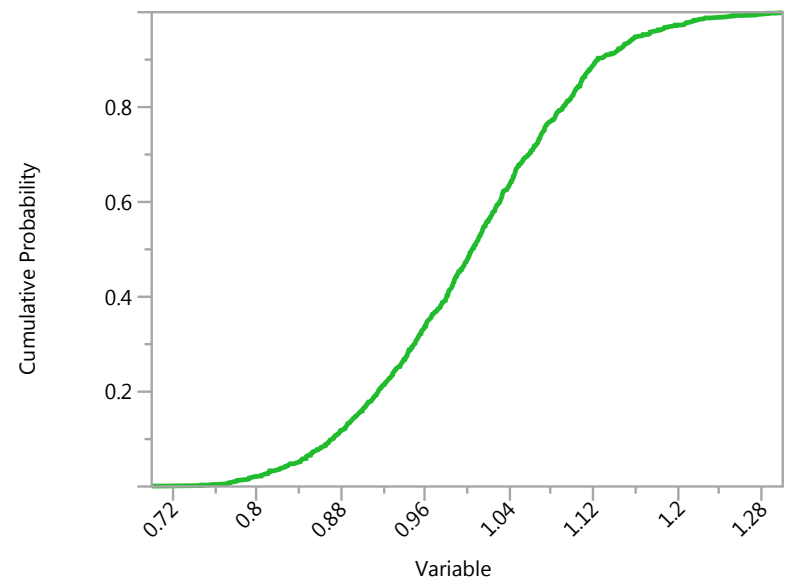

+ Easy to see shape, central location
- Hard to determine probability

Jordan: Field Performance of 1.7 Gigawatts of Photovoltaic Systems, IEEE PVSC 2014

Histogram
Probability density function




Cumulative distribution function




Area under curve
from -∞ to x

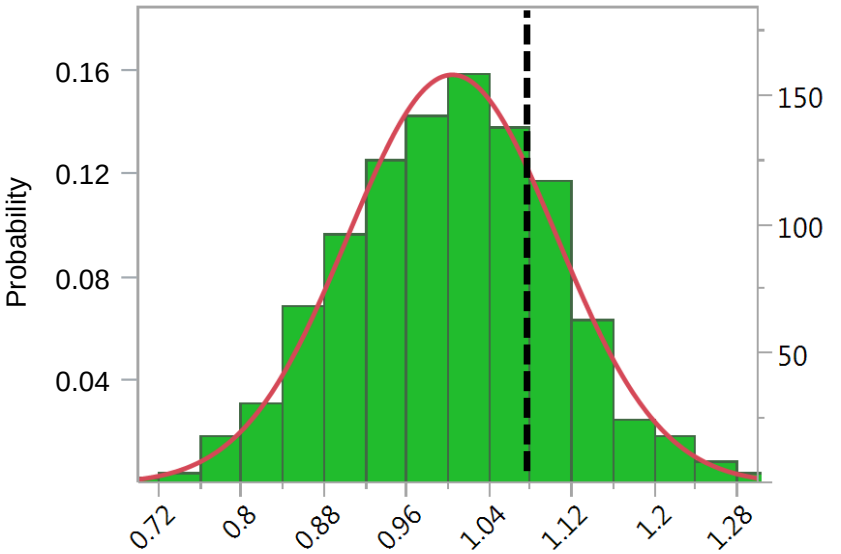
+ Easy to see shape, central location
- Hard to determine probability

- Easy to determine probability
+ Hard to see Shape, central location

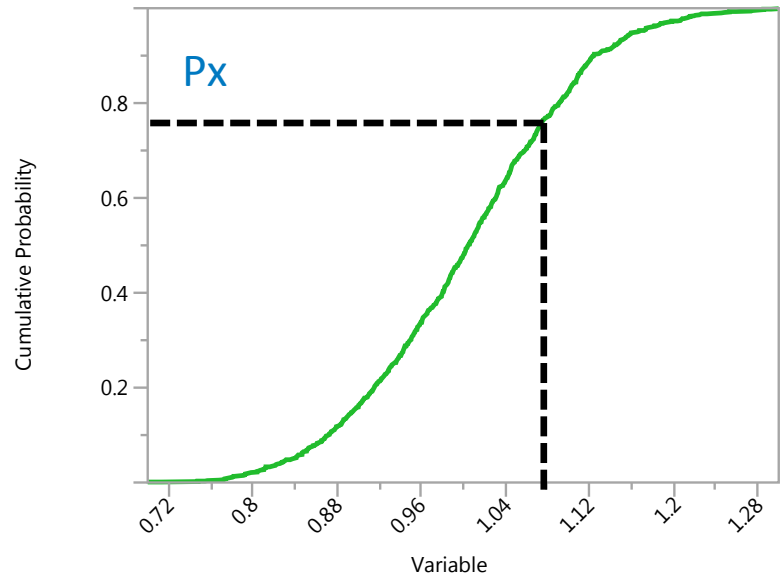
Jordan: Field Performance of 1.7 Gigawatts of Photovoltaic Systems, IEEE PVSC 2014

# Cumulative Distribution Function (CDF) is often used in risk analysis

Histogram
Probability density function




Cumulative distribution function




Area under curve
from -∞ to x

+ Easy to see shape, central location
- Hard to determine probability

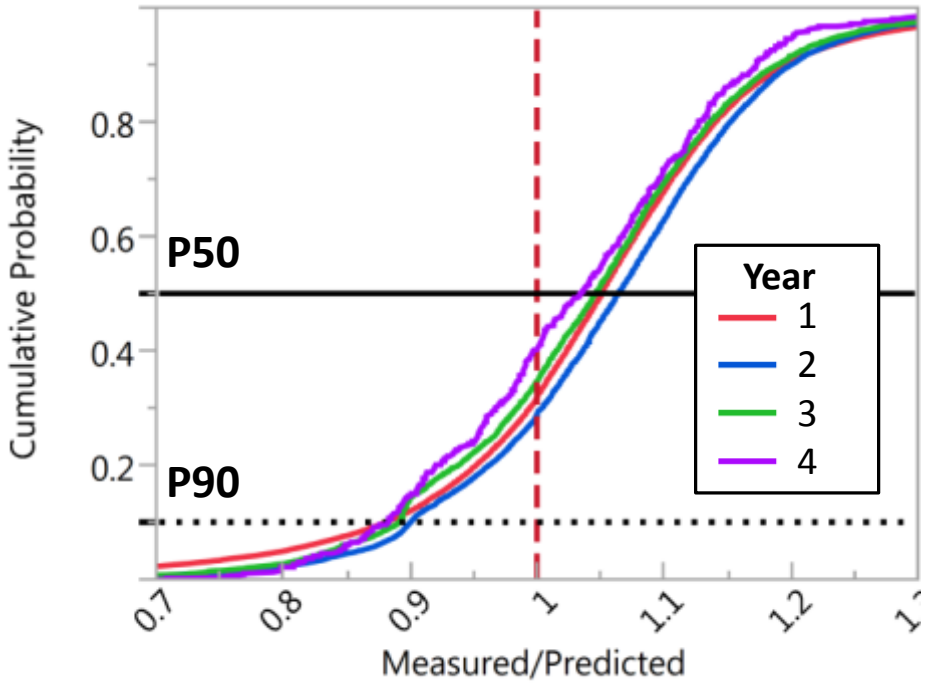
- Easy to determine probability
+ Hard to see Shape, central location

Jordan: Field Performance of 1.7 Gigawatts of Photovoltaic Systems, IEEE PVSC 2014

# 90% chance that production exceeds 90% of predicted

CDF measured/predicted production

**Normal data**




P50: 50% of the data lie above it (median).

P90: 90% of data lie above it.

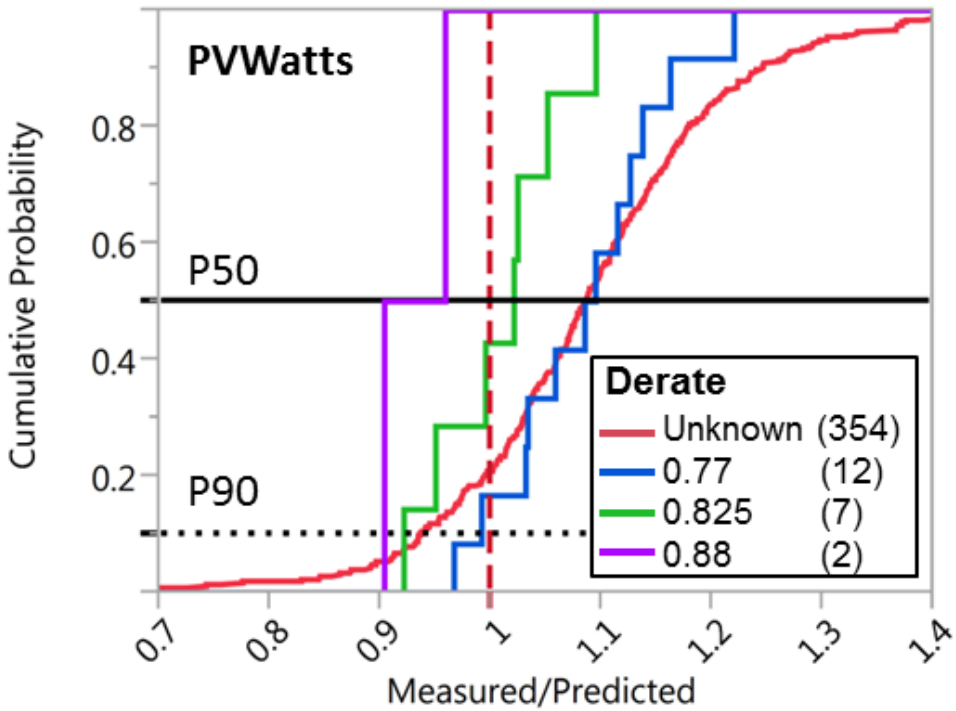
- Absence of discontinuities → smooth tails of distribution
- P90 ca. 90% of predicted
- P50 by several percent higher than predicted

Jordan: Field Performance of 1.7 Gigawatts of Photovoltaic Systems, IEEE PVSC 2014

# New PVWatts default derate appears to fairly accurate

***PVWatts:*** free modeling tool that estimates the energy production of grid-connected PV

Measured/Predicted production




P50: 50% of the data lie above it (median).

P90: 90% of data lie above it.

Brackets: number of data points per category

Derate: DC-to-AC conversion efficiency, default = 0.77

Jordan: Field Performance of 1.7 Gigawatts of Photovoltaic Systems, IEEE PVSC 2014

# Acknowledgments

Thank you for your attention

National Renewable Energy Laboratory
15013 Denver West Parkway, MS 3411
Golden, CO 80401, USA
dirk.jordan@nrel.gov

US Department of the Treasury, Section 1603 of the American Reinvestment and Recovery Act
Edward Settle
Jason Coughlin
Doug Gagne

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory

# Thank you!

Chris Deline (chris.deline@nrel.gov)
Nick DiOrio (nicholas.diorio@nrel.gov)
Fatima Toor (fatima-toor@uiowa.edu)
Dirk Jordan (dirk.jordan@nrel.gov)

www.nrel.gov

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.