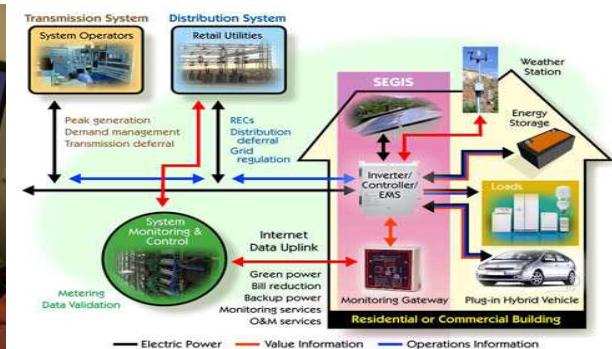


*Exceptional service in the national interest*



[solar.sandia.gov](http://solar.sandia.gov)



# Overview of Photovoltaics and Grid Integration Research at Sandia National Laboratories

Joshua S. Stein PhD

Trina Solar Ltd.

Changzhou, China, November 19, 2014

# Sandia National Laboratories

- On-site workforce: 11,711
- Regular employees: 9,494
- Gross payroll: ~\$1.046 billion

*Data as of April 12, 2013*

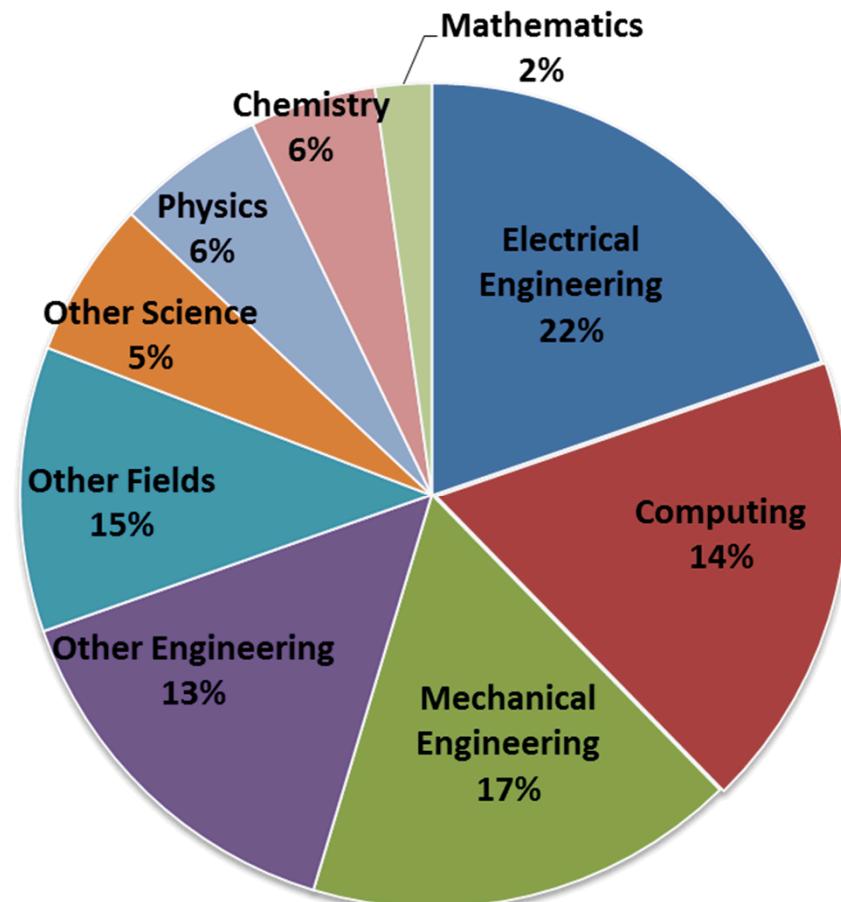
## Four Main Program Areas

- Nuclear Weapons
- Defense Systems and Assessments
- Energy and Climate
- International, Homeland, & Nuclear Security

## Multiple Locations

- Albuquerque, NM
- Livermore, CA
- Carlsbad, NM
- Tonopah, NV
- Kauai, HI
- Amarillo, TX

## R&D staff (4,799) by discipline



# Energy and Climate Program

## Energy



## Infrastructure



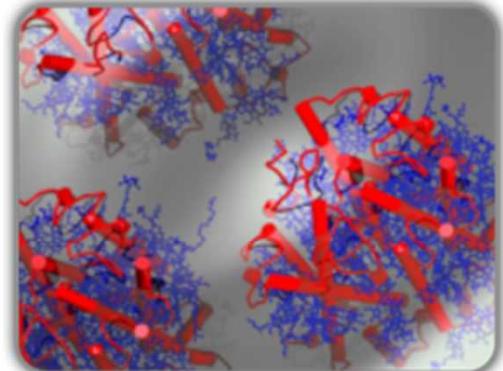
## Enabling Capabilities



## Climate



**jbei**  
Joint BioEnergy Institute



Sandia enhances the nation's security and prosperity through sustainable, transformative approaches to our most challenging energy, climate, and infrastructure problems.

# Sandia's Energy Programs

- Solar Energy
  - Photovoltaics
  - Concentrating Solar Power
- Wind Energy
- Water Power
- Geothermal
- Hydrogen and Fuel Cells
- Fossil Energy
  - Combustion Research Facility
  - Oil and Gas
- Bio Energy
- Nuclear Energy



# Our PV Program Vision



Sandia's PV and Distributed Systems Integration program aims to optimize photovoltaic components and systems to make PV a cost-competitive source of electricity that is easily integrated into the electrical grid.



# PV Technology Validation Facilities



## PV Systems Evaluation & Optimization Lab (PSEL)



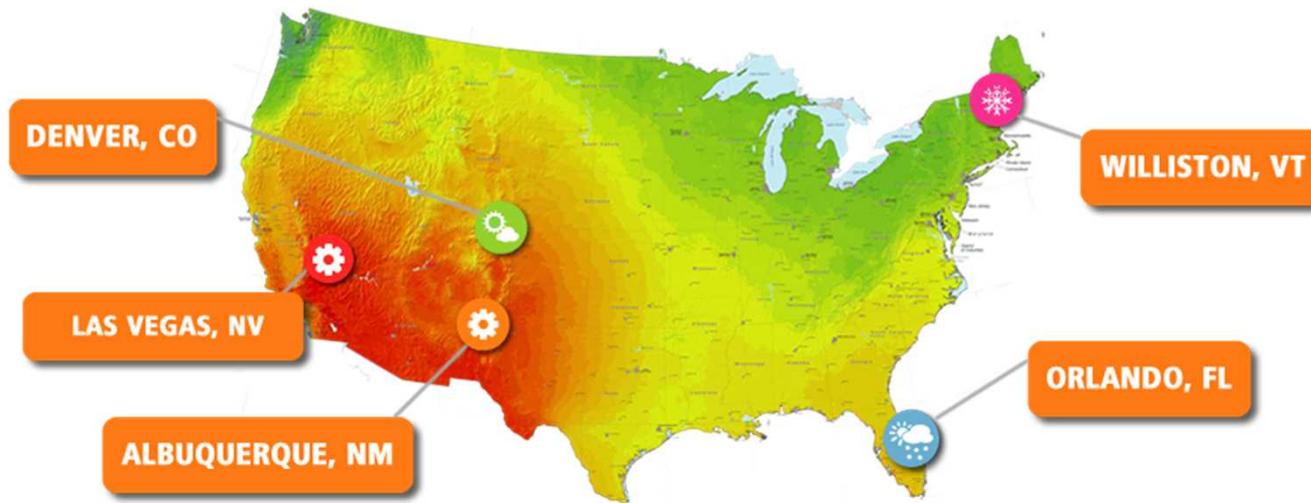
## Distributed Energy Technology Lab (DETL)



- Full-scale cell, module and systems performance characterization laboratory
- Controlled side-by-side system and component characterization
  - PV Arrays
  - All other BOS components
- Fully configurable test platforms for indoor, outdoor and long-term testing
- State-of-the-art measurement and analysis

- Simulate micro-grid, commercial, and community-scale energy systems, including
  - PV, Storage and other Dist. Resources
  - Advanced controllable loads, DC/AC sources and loads
  - Performance/control optimization
  - Technology Development
- R&D testbed for advanced power conversion hardware, controls (including EMS)

# Regional Test Centers



- 5 locations distributed across the U.S. in a range of climates
- Industry partners can install PV systems at a number of sites
- Identical system and weather monitoring systems at each site
- Baseline characterization of PV modules and components
- Predictability of system performance is validated
- Performance degradation is evaluated
- Performance reports delivered to partners

# 340 kW Installed and/or Under Construction

Soitec system in NV



ENKI system in NM



Station being installed in FL



60 kW c-Si system in VT



Heliovolt system in NM



ENKI system in FL



Heliovolt system in FL



Baseline system in VT



Baseline system in NM



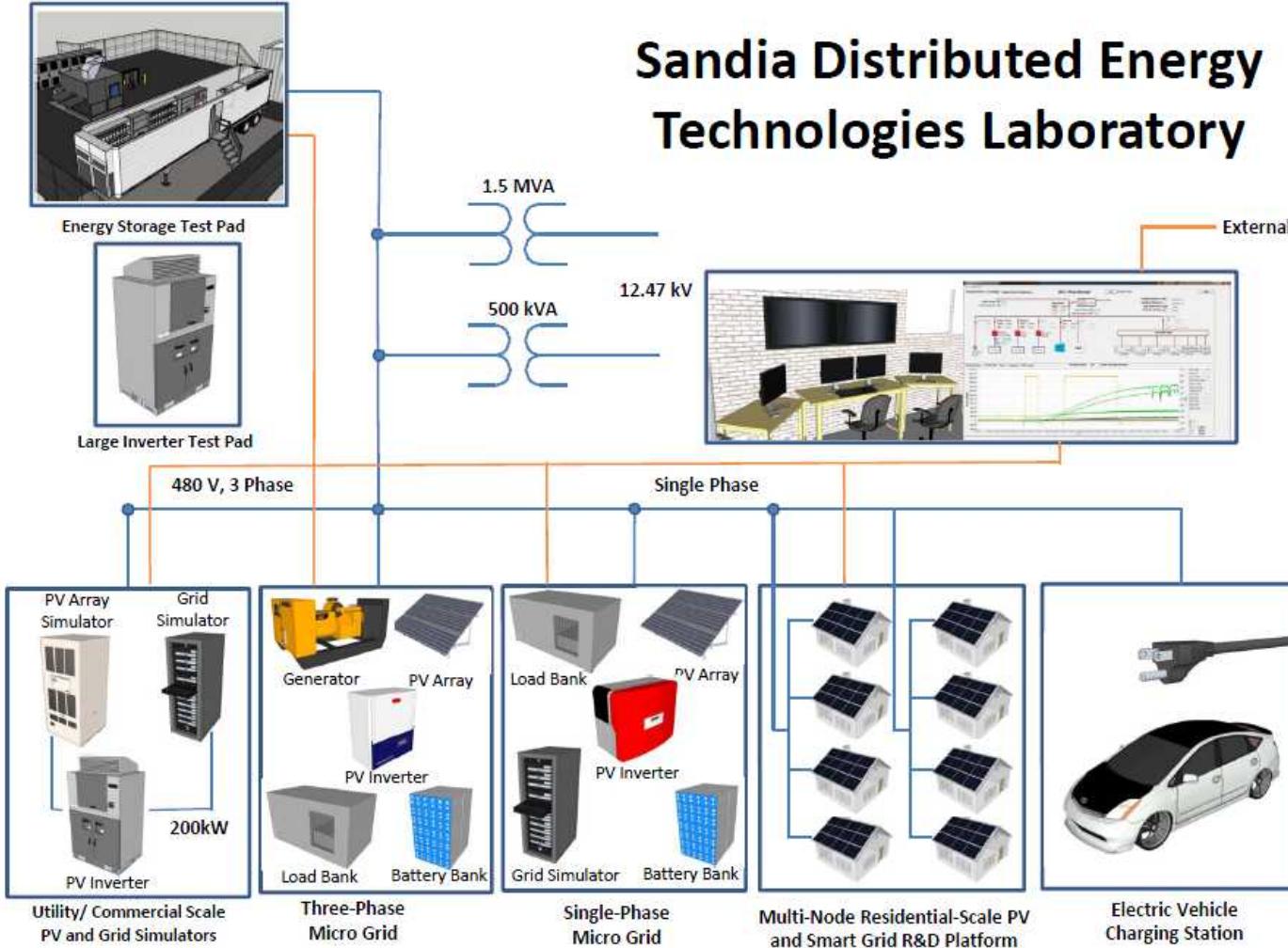
Maxim racks and combiners ready for modules in Florida



Maxim system in CO



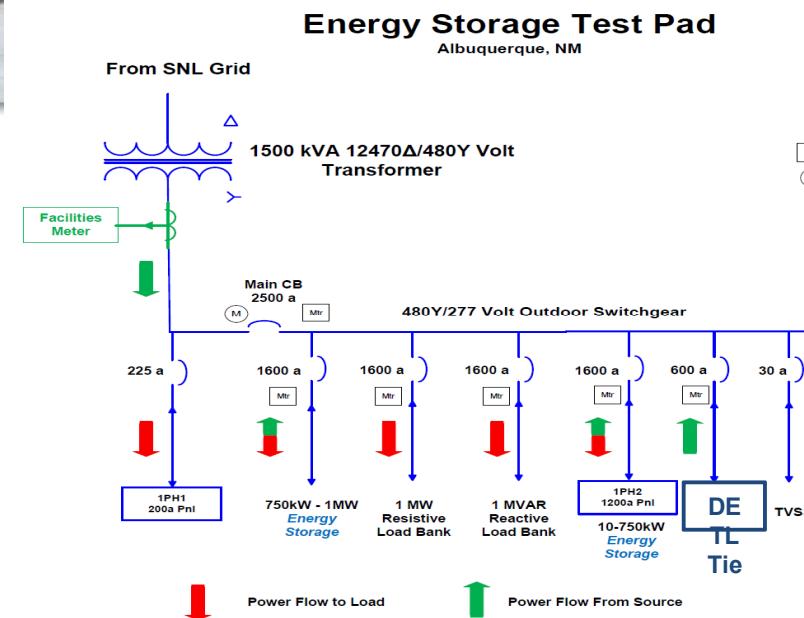
# DETL Components and Capabilities



# ESTP – Large-Scale Energy Storage



- **1 MVA capacity, 480 Vac**
- **Fully programmable RLC load (1 MVA)**
- **Full characterization of large energy storage PCS or PV inverters**



# PV Grid Integration at Sandia



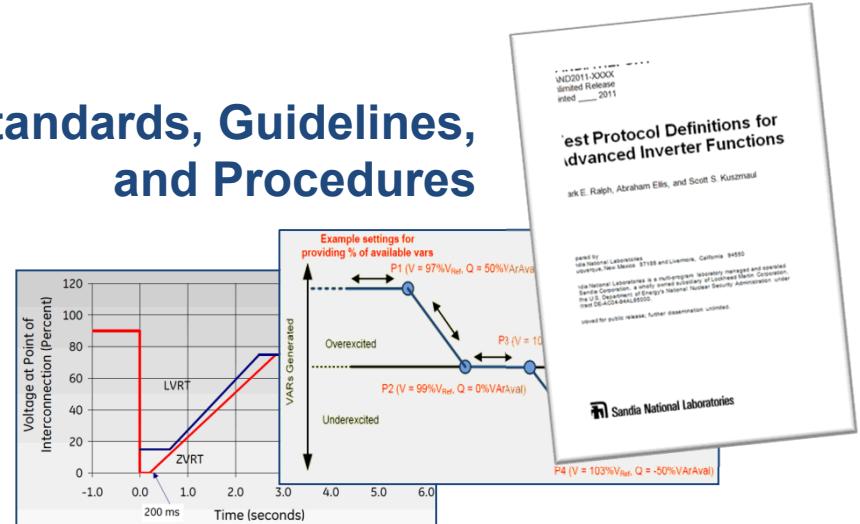
## Grid compatibility characterization



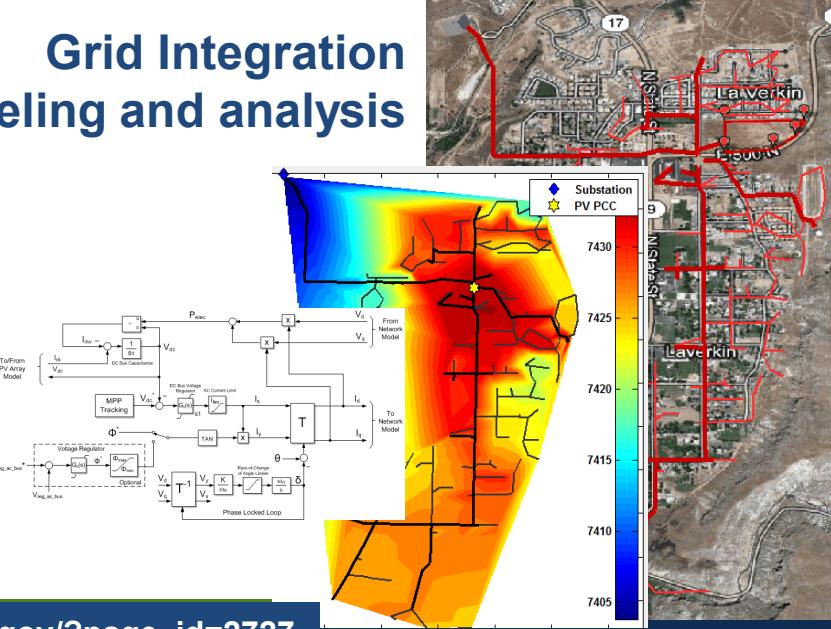
## Technology development and demonstration

More Info: [http://energy.sandia.gov/?page\\_id=2727](http://energy.sandia.gov/?page_id=2727)

## Standards, Guidelines, and Procedures

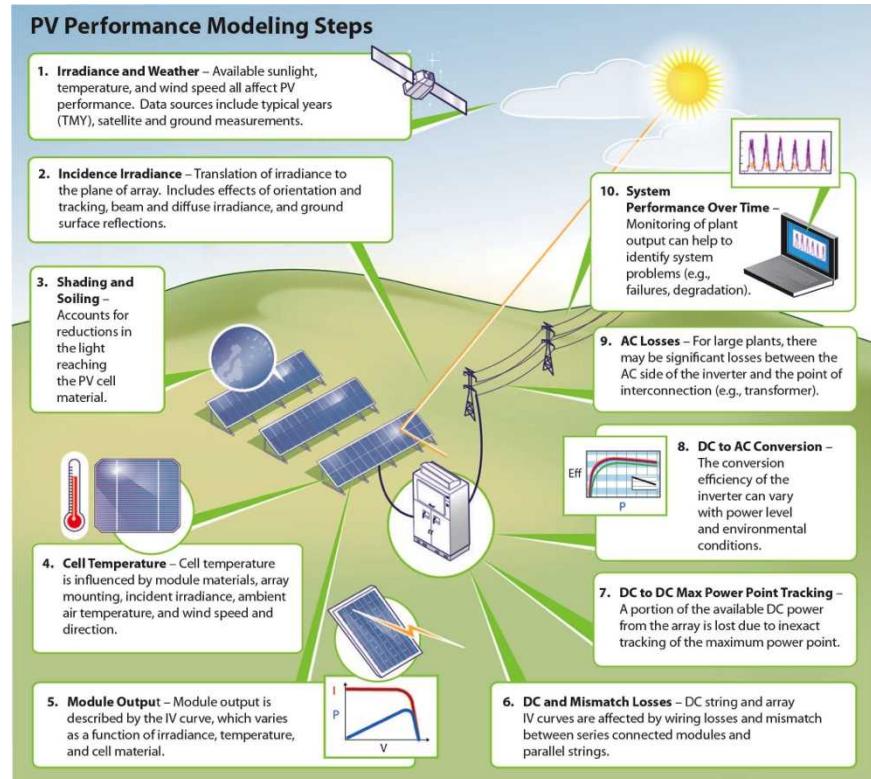


## Grid Integration modeling and analysis



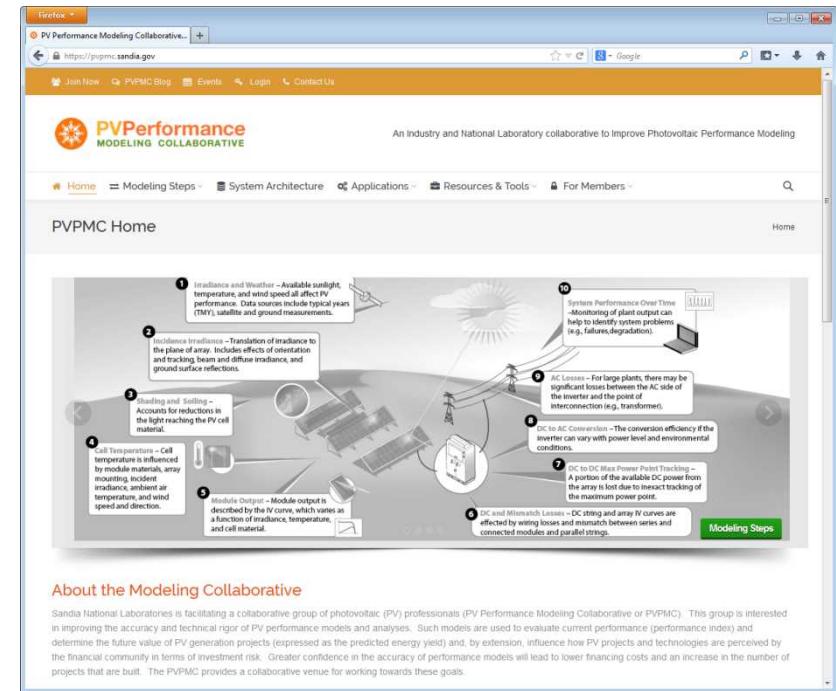
# Selected PV Research Projects

- Outreach: PV Performance Modeling Collaborative (PVPMC)
- New methods to calibrate IV curve models
- Develop new methods to characterize CPV modules and system (e.g., AOI and spectral)
- AC module characterization and modeling methods
- Create and demonstrate novel approaches to PV system health monitoring (more with less data)
- Scientific approach to evaluating soiling effects
- Module-Level Power Electronics (MLPE) reliability



# PV Performance Modeling Collaborative

- **Objectives:** Gather and organize information on PV performance modeling methods and make it available to the PV community.
- **Approaches:** Website, workshops, conference sessions, textbook.
- **Results:**
  - 3<sup>rd</sup> Modeling Workshop held in Santa Clara, over 150 attendees (standing room only), 5 different sessions
  - Tutorial held at IEEE-PVSC in Denver (highly rated)
  - Python version of PV\_LIB toolbox launched in June
  - New functions written for PV\_LIB for Matlab
  - New website and URL (<https://pvpmc.sandia.gov>) is launched
  - Sandia invited to write book section on PV performance modeling.
  - Textbook being written in next year.
- **Significance:** The Sandia-led PVPMC provides a global forum for model developers and users to discuss modeling needs, share methods and document the body of knowledge surrounding PV performance models. No other such forum exists.



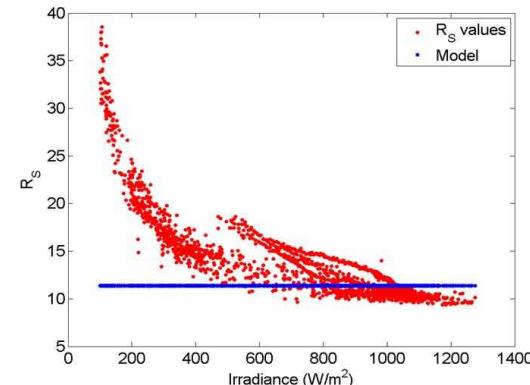
[http://pvpmc.sandia.gov](https://pvpmc.sandia.gov)

# Calibrating PV Models

- **Objectives:**
  - Develop reliable and robust method to extract diode model (i.e., Pvsys, CEC model) parameters from test data.
  - Develop method to extract model parameters without needing a 2-axis tracker.
- **Approach:** Extract diode model parameters using new sequential technique that constrains parameters within physical and assumed limits (e.g., diode factor  $\geq 1$ ). Fit diode model, SAPM to data from modules outdoors on fixed racking.
- **Significance:**
  - Enables improvements to full single diode models by uncovering appropriate relationships between the model parameters and irradiance and temperature.

Manufacturer (cell type)	$I_{sc}$		$I_{mp}$		$V_{oc}$		$V_{mp}$		$P_{mp}$	
	MAE	90th								
Kyocera (poly-Si)	$<10^{-4}$	$<10^{-4}$	0.011	0.003	$<10^{-4}$	$<10^{-4}$	0.0111	0.0032	0.0004	$<10^{-4}$
Sharp (mono-Si)	$<10^{-4}$	$<10^{-4}$	0.015	0.029	$<10^{-4}$	$<10^{-4}$	0.0153	0.0285	0.0002	$<10^{-4}$
Sanyo (mono-Si)	$<10^{-4}$	$<10^{-4}$	0.003	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$	0.0045	$<10^{-4}$	0.001	$<10^{-4}$
Sunpower (mono-Si)	$<10^{-4}$	$<10^{-4}$	0.002	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$	0.0021	$<10^{-4}$	0.0002	$<10^{-4}$
Kaneka (tandem a-Si)	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$
First Solar (CdTe)	$<10^{-4}$	$<10^{-4}$	0.0004	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$	0.0003	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$

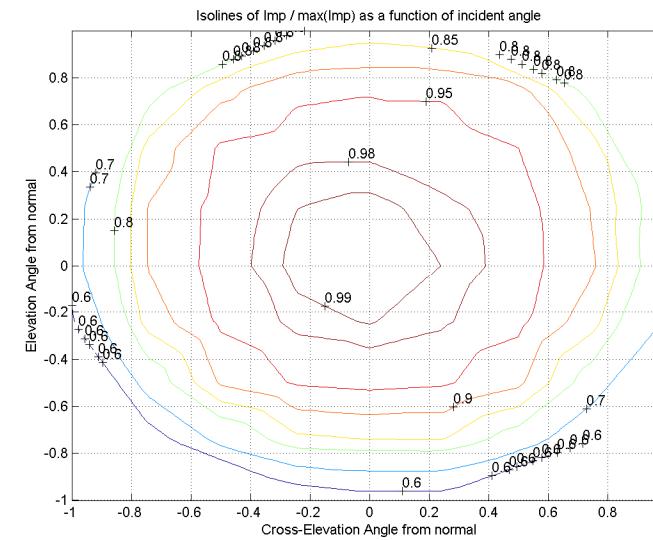
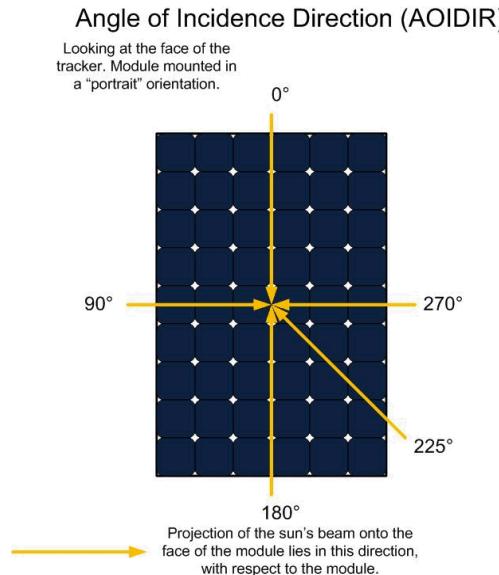
Mean and 90<sup>th</sup> percentile errors for points on predicted IV curves using single diode equation fit to each curve.



Series resistance values estimated for each IV curve compared to the constant value used by Pvsys

# CPV Characterization Methods

- **Objective:** Develop methods for characterizing CPV incident angle modifiers in two dimensions.
- **Approach:** Develop new tracker control algorithms to orient tracker to desired positions off-sun. Use tracker controls to create an IAM map.
- **Significance:** Current methods for CPV characterization do not address anisotropic focusing optics. There is no publicly available CPV performance model (the few that exist are private and specific to a particular manufacturer or technology).

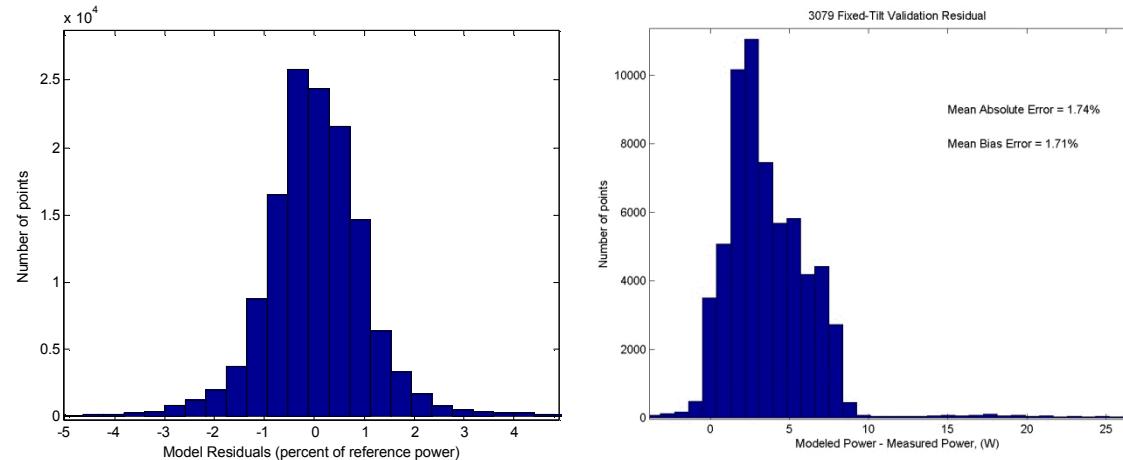


*“Map” of the electro-optical response  
of the HCPV modules as a function of  
incident angle.*

# Characterization and Modeling of AC Modules

- **Objective:** Develop a performance model and calibration procedure for AC modules.
- **Approach:** Develop and test characterization procedures for AC modules.
  - Electrical Performance test
  - Transient thermal test
  - Angle of incidence test
- **Results:** We have successfully adapted the Sandia PV Array Performance Model to describe a purely AC module.

$$P_{ac} = P_{ac_{ref}} \times f_1(AMa - AMa_{ref}) \times \left[ C_0 \times \frac{E_{POA}}{E_{ref}} + C_1 \times \ln \left( \frac{E_{POA}}{E_{ref}} \right) \right] \times [1 + \gamma_{ac}(T_c - T_0)]$$

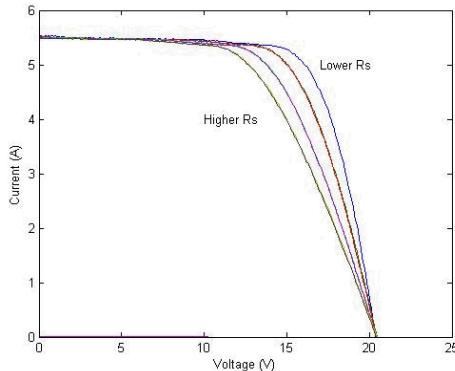


**Model residuals.** The model represented by the above equation can accurately predict the performance of an AC module to within 2.25% of the actual power on a 95% confidence interval.

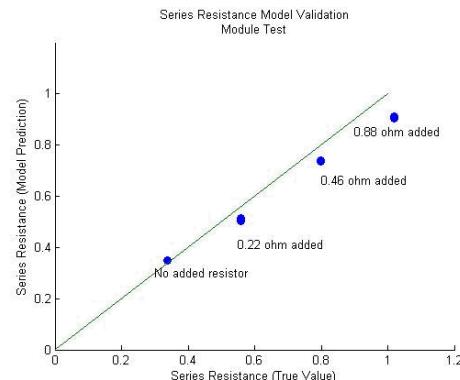
# Novel PV System Monitoring Methods

- **Objectives:** Develop and demonstrate new, low-cost ways to monitor system performance
- **Approaches:**
  - Test and demonstrate ability to monitor changes in series resistance without measuring IV curves.
  - Develop low-cost IV curve monitoring solutions (module and strings)
- **Initial Results:** We have demonstrated the ability to detect changes in  $R_s$  from  $Imp$ ,  $Vmp$ , and  $Voc$ . We have partnered with a company to help develop a module-scale IV tracer. We are working with another company to design and build a combiner-box IV tracer. Both work with a grid connected PV system with no need to disconnect from inverter.

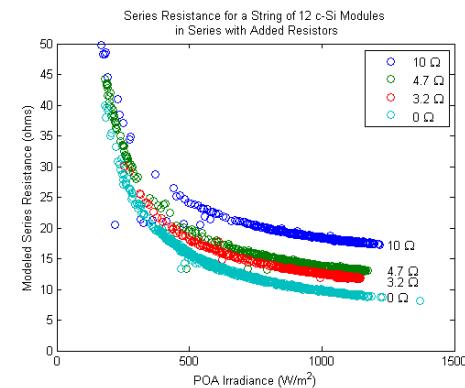
$$Voc = Rs * Imp + b1 * \log(Imp) + b2 + Vmp + b3$$



As  $R_s$  increases, fill factor and power is reduced.



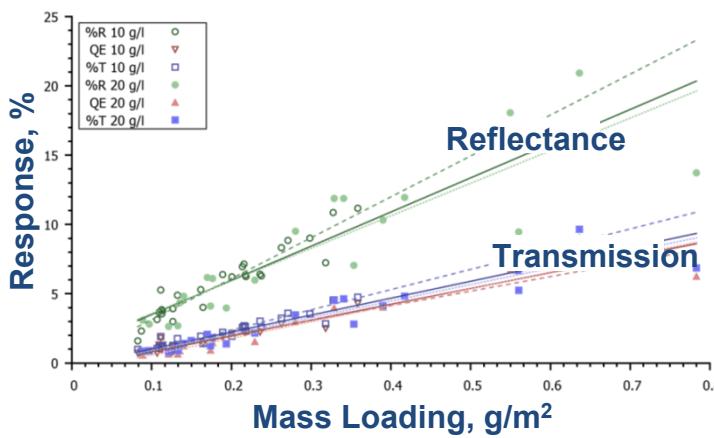
Model was validated by adding known resistors to circuit and comparing measured and predicted  $R_s$



Continuous measurements of series resistance show that the model is robust and able to discern changes in  $R_s$  of 3% or greater. This is a promising result since typical changes are much larger.

# Laboratory Soiling Studies

- **Objective:** Develop repeatable laboratory method to apply artificial soils to module coupons and with consistent effects on reflection and transmission losses.
- **Approaches:** Evaluated different lab methods for measuring effect of soiling (QE, One Sun simulator, UV/vis spectroscopy)
- **Results:**
  - Reliable measurements of grime mass loading could be determined down to a mass loading of 0.1 g/m<sup>2</sup>
  - Minimum detection levels were consistent between laboratory and field studies.
  - Reflectance is promising for field studies, but more validation is needed.
- **Significance:** Soiling is widely recognized as a significant factor that reduces the power output of PV systems, with annual loss estimates ranging from 5 – 25%. The artificial soil application method is being considered as the basis for a proposed test standard.\*



Change in measured  $J_{sc}$  for low mass loadings. Minimum detection level of 1% is dictated by accuracy of the analytical balance

Location	Orientation	Mass Accumulation Rate, mg/m <sup>2</sup> /day
Commerce City, CO	0°	47.3
	40°	34.3
	180°	3.1
Erie, CO	0°	19.3
	40°	12.3
	180°	1.6

Mass accumulation rate as a function of geographic location and coupon orientation. Results obtained for Erie, CO at 40° tilt were used to establish a minimum sampling interval.

# Field Soiling Studies

- **Objectives:** Develop and deploy field soil sampling and soiling rate measurement equipment.
- **Anticipated Outcomes:**
  - Gather soiling data from different regions and compare compositions and rates.
  - Soiling stations will support a “soiling velocity model” under development by Liza Boyle at CU-Boulder as part of her PhD thesis work.
  - This model has the potential to leverage the EPA’s air quality monitoring program to aide in the development of a national soiling map of the US.
- **Significance:** This field work will help guide development of laboratory soiling compositions. Availability of a national soiling map would be of tremendous benefit to PV system planners and operators.



*Atmospheric Particulate Sampling Station. Set-up used for the collection of airborne particulates that settle naturally.*



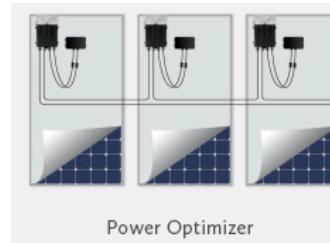
*Electrical Performance Sampling Station. Set-up used to determine performance loss due to natural soiling processes*

Site	Atmospheric	Electrical
NM RTC (Sandia)	x	x
CO RTC (NREL)	x	x
FL RTC (FSEC)	x	x
VT RTC (IBM)	x	x
Arizona State University	x	x

*Sites planned for deployment of both stations. RTC locations will be leveraged*

# PV BOS Evolution

Less copper, combiners,  
reduced installation labor,  
O&M intelligence



The **Trinasolar DC Module**  
MULT - Series PA05 The Optimized Solution



**Sub-Module**

**Module level monitoring**



**String level monitoring**

**Inverter level monitoring**

2006

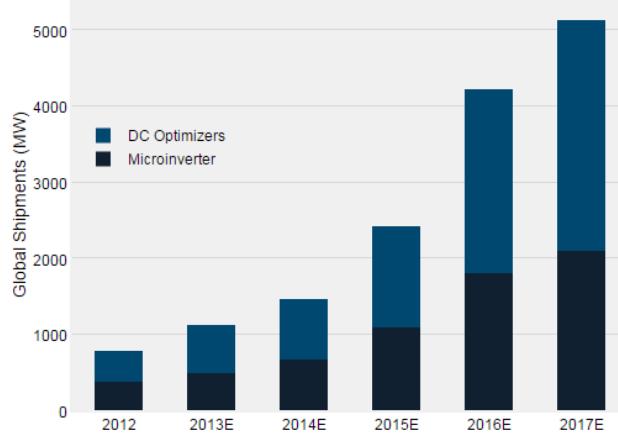
2008

2010

2012

2014

# MLPE – Module Level Power Electronics



**MLPE market is poised to grow significantly.**

**But since this market segment is relatively young, it does not have long-term usage or statistically significant failures and reliability data.**

## Types of MLPE:

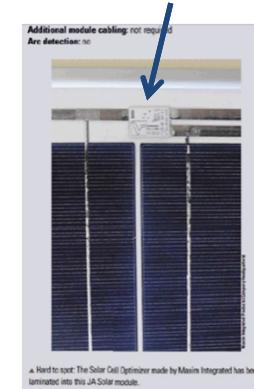
### Optimizer (SolarEdge)



### True AC PV module (SolarBridge)



### Maxim MPPT



PILAWA-PODGURSKI AND PERREAU: SUBMODULE INTEGRATED DISTRIBUTED MAXIMUM POWER POINT TRACKING

### Other state of the art

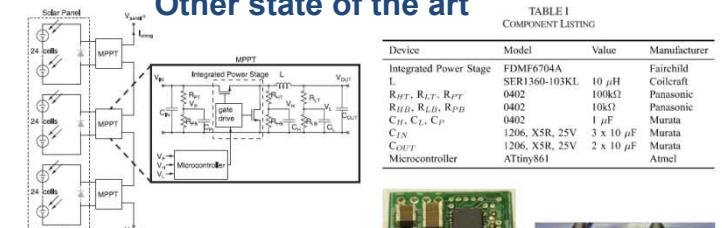
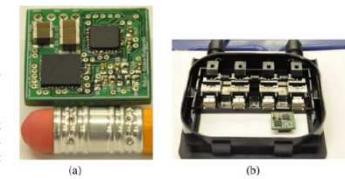


Fig. 2. Schematic drawing of the submodule integrated MPPT system. A component listing is provided in Table I.

Image sources: GreenTech Media

point where they can fit in the existing standard junction box at the back of the PV panel. This leads to further cost reductions, as a large custom outdoor enclosure contributes significant cost to a dc-dc optimizer system.



# MLPE Reliability Goals:

- Research on failure modes, failure rates, and failure mechanisms specific for MLPE and AC modules is needed.
  - New degradation and failure modes may exist since MLPE is exposed to operating conditions of the PV modules.
- Relevant qualification test standards for MLPE are lacking.
  - Need to develop qualification testing, screening, reliability , lifetime and accelerated lifetime testing guidelines to be used by MLPE PV manufacturers and industry.
- Use modeling to define optimal MLPE designs for maximizing unit lifetimes
  - without the need for extensive internal screening or qualification testing
- Assess and quantify any additional lifetime impacts of advanced inverter functionalities in MLPE PV modules for grid support (e.g., VAR capability).