Testing at Scale: Methods and Challenges Associated with Curated, Grid-Tied PV System Research

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DuraMAT Webinar Series

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Outline

- Background
- System Design Considerations
- Field Instrumentation
- Module Characterization
- System Analysis
- Summary

Background

Why Curate?

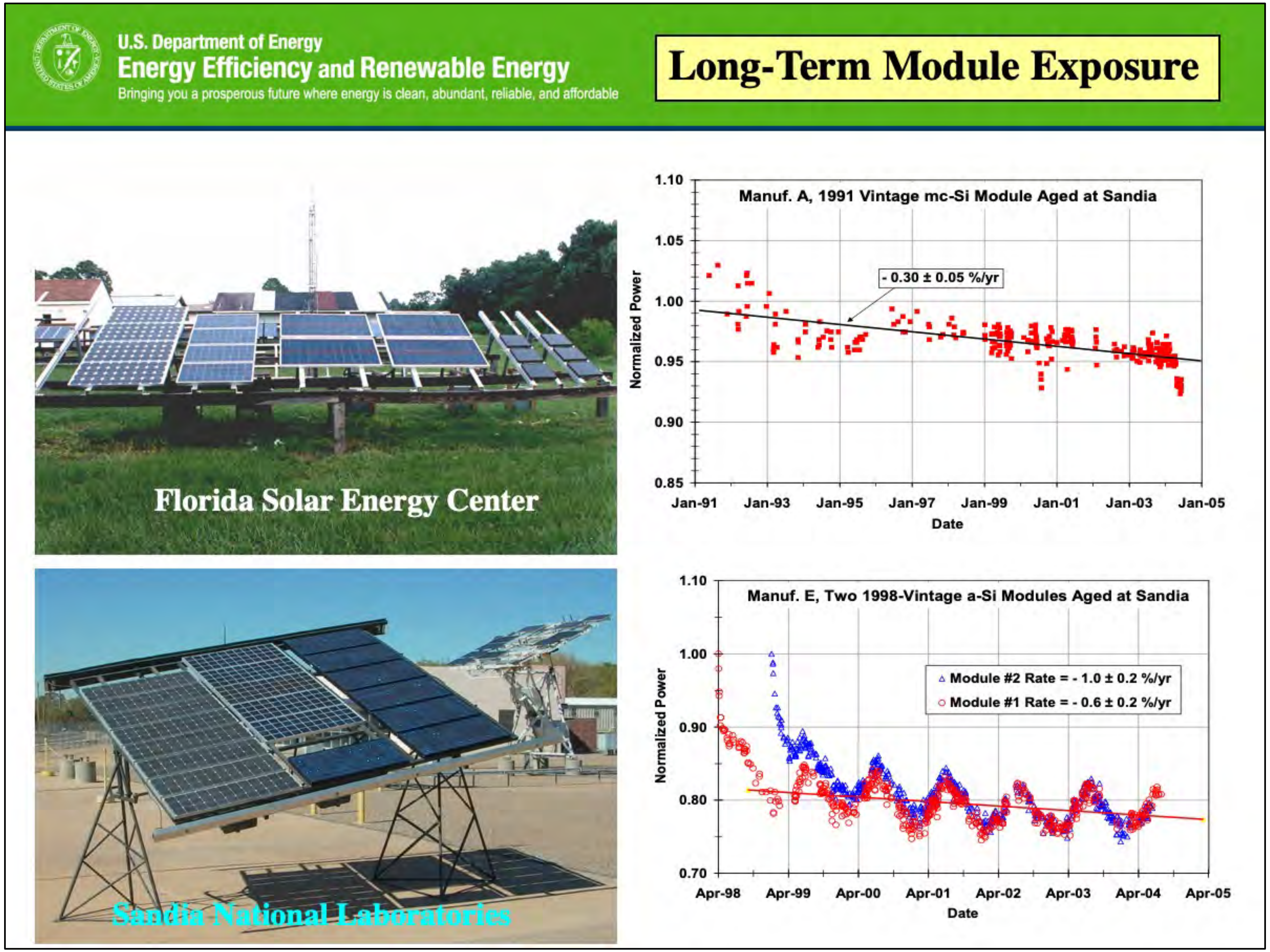
- Ambitious module lifetime goals (e.g. 50 years) requires that PV systems maintain their predicted performance over time…how to validate claims?
- Side-by-side technology comparisons require normalization methods to avoid unintentional bias or misinterpretation of results
- Careful performance monitoring coupled with appropriate analysis can help with both

System/technology considerations
- Documented history, known starting point
- Targeted technology
- Control over environment/common environment

Instrumentation considerations
- Detailed point measurements (e.g. periodic flash, EL)
- Control over monitoring system/*in situ* measurements
- Data continuity, year-over-year

Ownership
- Work to the test plan, not a performance guarantee

Early Experience – Module Long-Term Exposure



- Conducted from 1991 to 2005
- Long-term goal of supporting development of modules with a 30 year lifetime
- Utilized manufacturer-supplied production modules
- Modules were installed on fixed resistors
- Monthly in-field IV sweeps
- Established early industry expectations for degradation rate of c-Si (~ 1%)

D. L. King*, M. A. Quintana, J. A. Kratochvil, and B. R. Hansen, “Module Reliability Characterization,” DOE Solar Energy Technologies Program Review Meeting, Nov. 2005

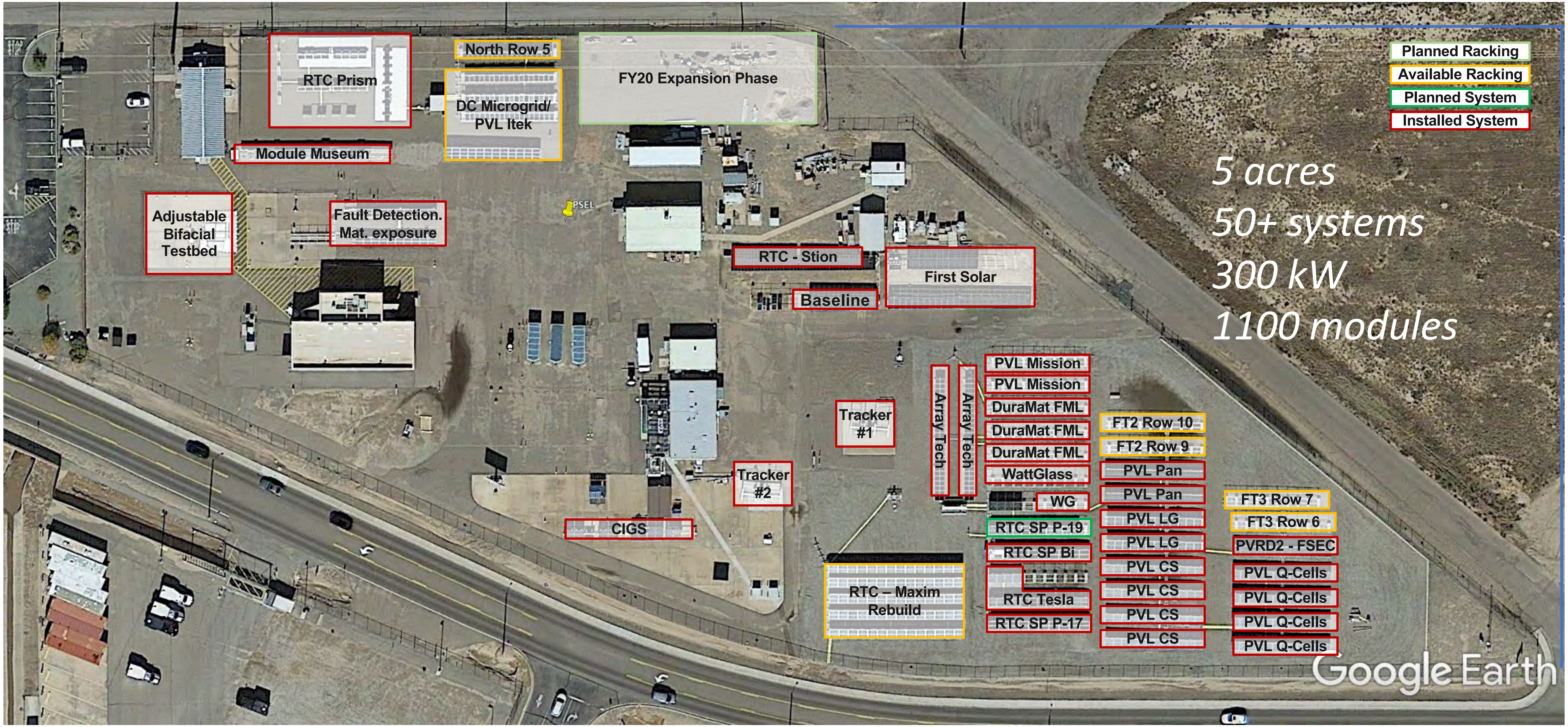
** Not to be confused with B. H. King*

Early Experience – System Long-Term Exposure

- Conducted 2010 – current
- Three module types in three climates
- Grid-tied small systems
- High data rate DC monitoring (1-minute averages)
- Modules characterized thoroughly before deployment
- Detailed recharacterization underway at Sandia in FY19-20
- Initial experience with remote time-series data provided important learnings around how NOT to do it
  - Inverter clipping
  - Data outages
  - Unreliable data transfer
  - Inconsistent O&M practices

Technology	Size, W	Voltage, V	Inverter
mono-Si	690	146	SMA SunnyBoy 700U
Thin Film	580	177	
mc-Si	880	146	

Sandia's System Research Today



System Design Considerations

System Planning

Size

- What are the research goals? Number of modules?
- How much land is required/available?
- Racking?
- Adequate electrical infrastructure?
- Power dissipation/inverter sizing

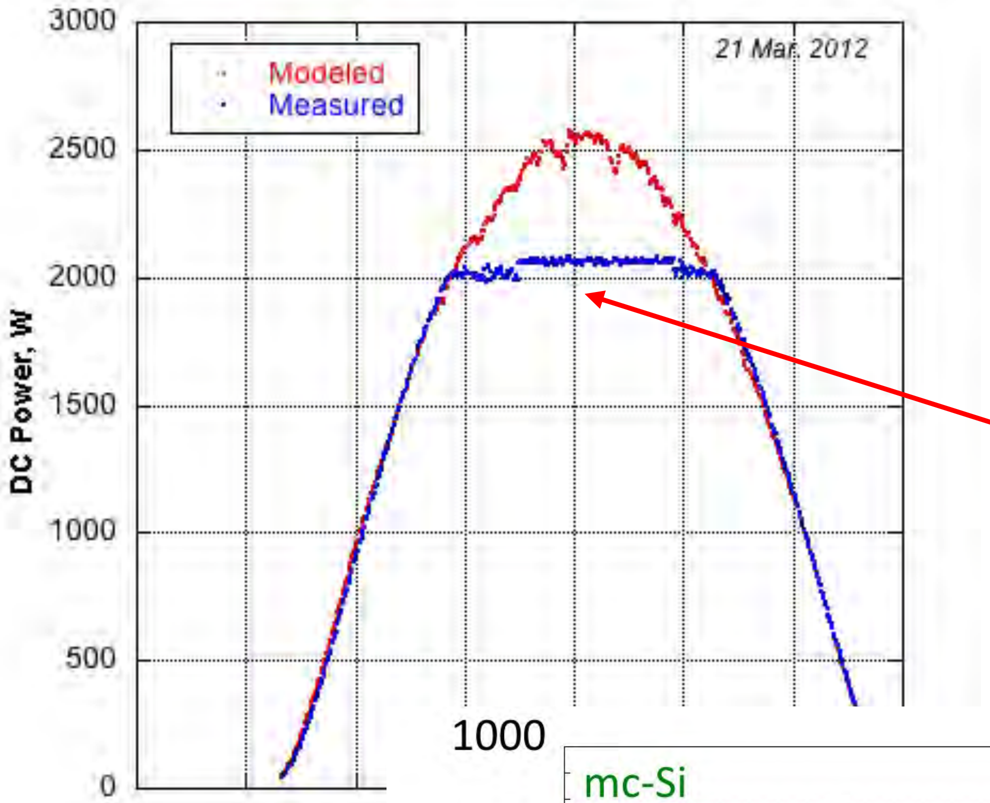
Design

- Electrical: NEC/NFPA 70E Article 690
- Structural: International Building Code
- Local permitting and inspections

Safety

- Adequate protections for researchers AND the general public?
- Appropriate Lock-out Tag-out program
- PPE

Importance of Proper Inverter Sizing/configuration



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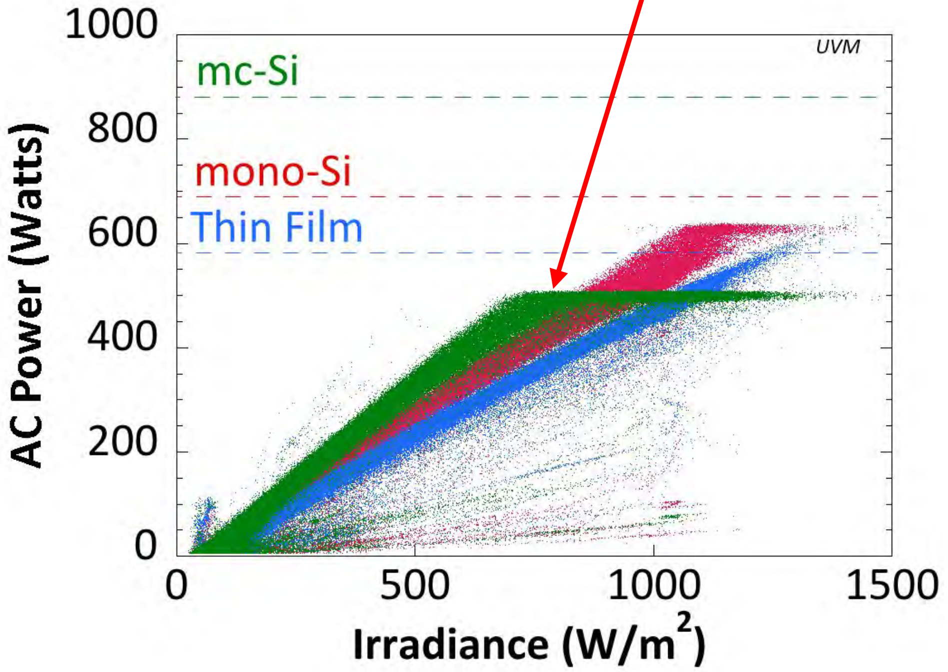
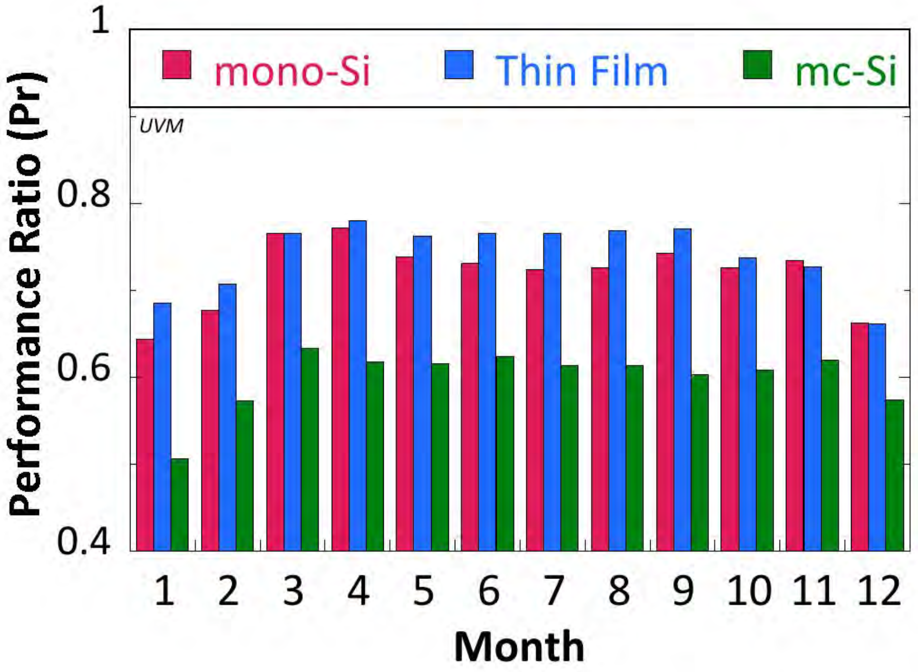


- Undersizing inverters is a common practice among system designers
  - Reduced costs, flatter power profile
- Complicates analysis
  - Masks degradation
  - Masks performance differences between different technologies
  - Limits ability to perform analysis at specific times of day, e.g. at Solar noon

Impact to system analysis



Fast Track – Sandia's Prebuilt Racking System

- Standard Design: design once, deploy anywhere
- Fast deployment of new systems
- Installation costs on par with private industry

- Above ground, ballasted systems
    - Recycled concrete blocks
    - No ground penetrations, no dig permits
    - Fast site restoration
- Structural design based on SunPower E20/435
    - Easily resized to hold smaller modules
- Electrical Infrastructure
    - 480VAC/3-phase can accommodate any inverter
    - Wireways allow fast routing of DC, signal wires
- MODBUS network for flexible digital data acquisition interconnection
- Common irradiance sensor network serves multiple systems

Field Instrumentation

Monitoring Systems

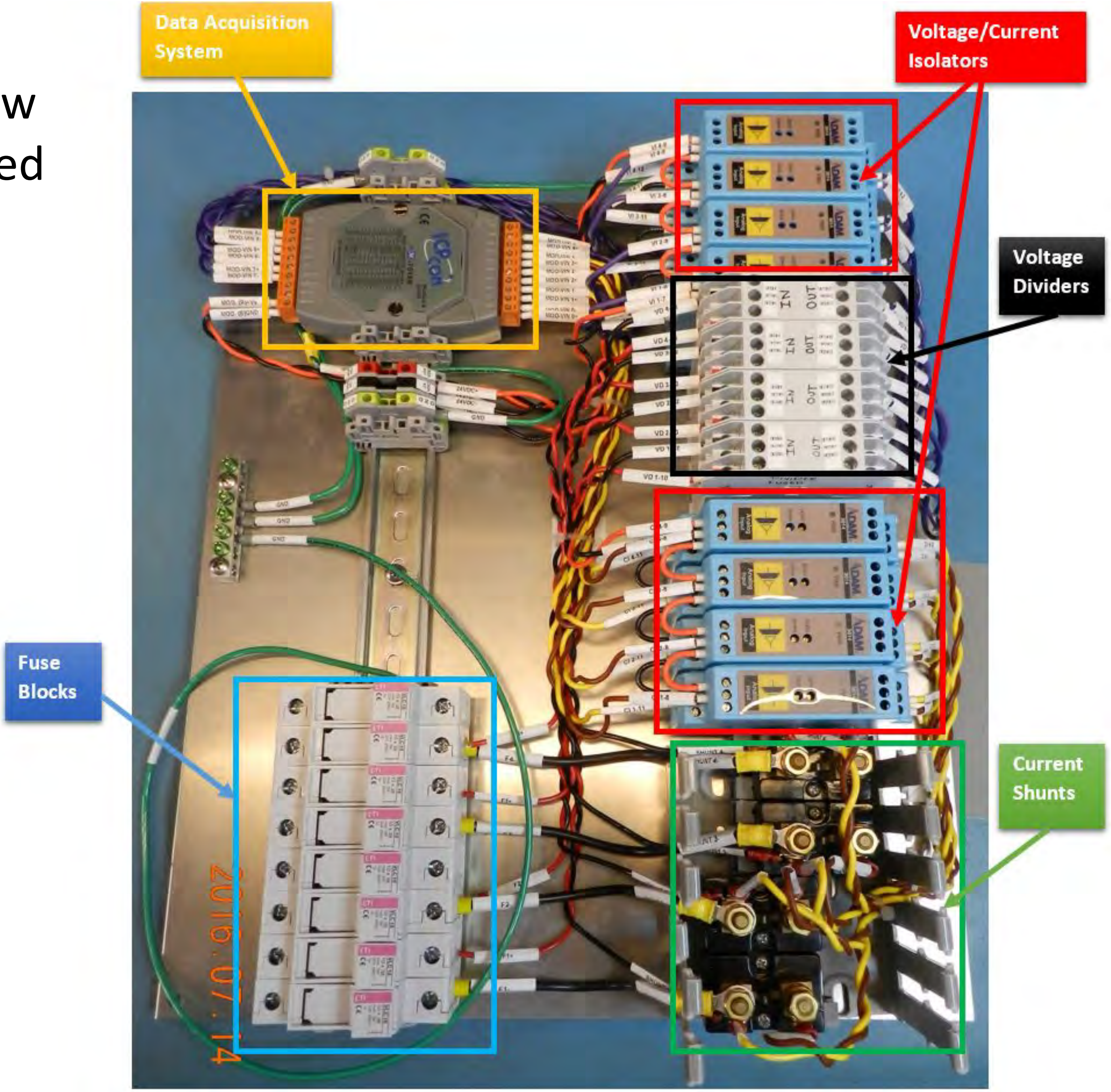
- Monitoring needs should be defined during System Planning and coupled to research goals
- Balance between cost, accuracy, channel density and system configuration
- Typical quantities - DC voltage and current, AC power, module temperature
- Inverter data historically considered to be the most basic, but newer generations are adding more functionality

Option	Accuracy	Channel Density	Measurement range	Data Access	Aux input	Module Temp	Timestamp	Cost
Inverter	Low	Low	Very good	Limited	Limited	N/A	Internal clock	Lowest
Off-the-shelf	Low to High	Low to High	Limited	Typically Unlimited	Limited	Limited	Internal clock, GPS	Moderate
Custom	High	High	Very good	Unlimited	Unlimited	Unlimited	GPS	Low to High

Boilerplate – ”Custom” Sandia Reference Design

- Standard Design: design once, deploy anywhere
- Outsourced assembly and bulk purchasing keeps costs low
- Easy expansion, multiple measurement systems connected

- High-accuracy Empro current shunts
  - Easily sized to match system current
- Custom voltage dividers, SNL design
  - Designed for 1200V strings (adaptable to 2000V)
- On-board analog-to-digital conversion
  - 16 bit resolution
  - Chamber tested to 50C for linearity, accuracy
  - MODBUS communication to data logger
- NEMA 4 enclosure for continuous deployment at the array



Additional Monitoring Considerations

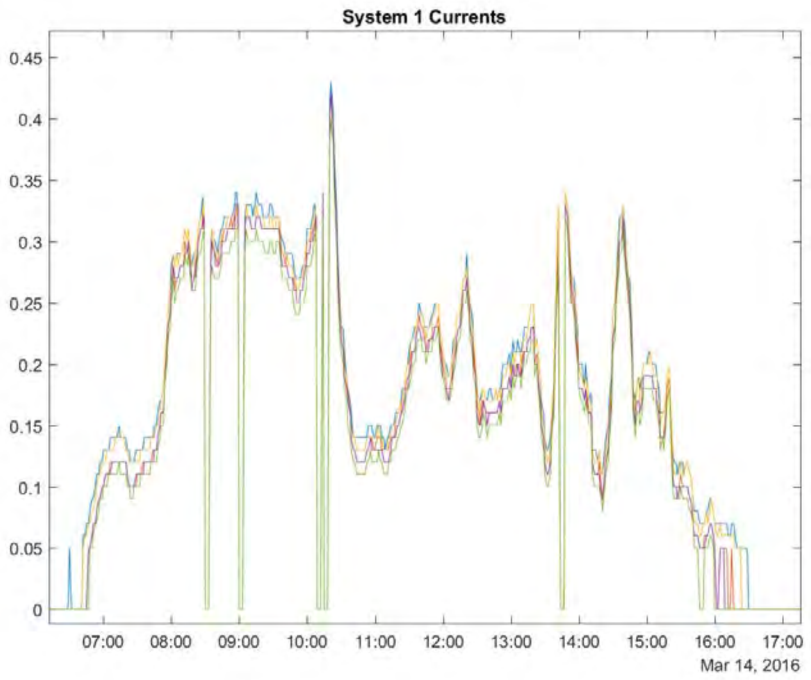
Choice of data logger

- In principal, use anything that can communicate over MODBUS/RS-485
- Historically have used Campbell* data loggers
  - Robust operations in field environments….
  - ….but redundant functionality
- Field trials with Raspberry Pi
  - Python!
  - On-board use of PV-Lib functions

* This is NOT an endorsement!

Proper current shunt sizing

- 10A and 20A measurement systems are common and appropriate for high current c-Si modules
- For low current systems (typically thin-film), this results in visible quantization error under low irradiance conditions
- Whether this matters should be considered when establishing research goals



Solar Irradiance Measurements

The simplistic view: The Sun is a PV power plant's fuel…. accurate estimates of how much fuel is available are key to accurate estimates of system efficiency.

Comprehensive Weather Platform
- Primary and secondary trackers
  - DNI, GNI, diffuse, spectrum
- Fixed orientation
  - GHI, Global Latitude, UV, spectrum
- Non-irradiance
  - Ambient temp, windspeed/direction (10m), barometric pressure, humidity, rainfall

In-field Measurements
- Plane-of-array pyranometer, reference cells

Data Collection
- 1-second data rate
- Written to database, GPS synchronized with other field measurements

Other as needed
- Rear-side irradiance for bifacial,

All on-site calibrations traceable to the World Radiometric Reference via NREL Pyrheliometer Comparison

In-situ IV Curves

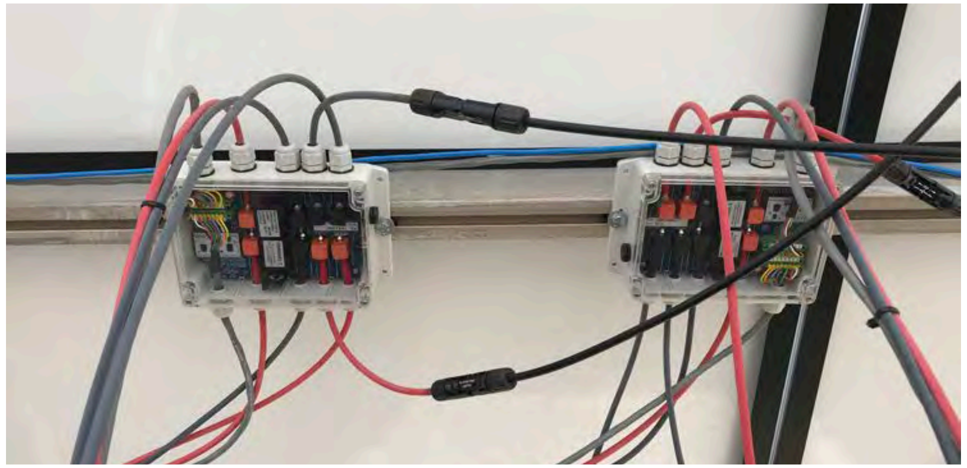
Daystar Multi-tracer
- Single modules, up to full strings
- Not grid connected, no inverter
- Not weatherized, must be enclosed
- Data must be pulled remotely

Stratasense
- Module-level IV
- Grid connected, isolates module during IV sweep
- NEMA 4 enclosure, fully weatherized
- Automatic data import to database

Pordis 140A2
- String-level IV
- Grid-connected, isolates string during IV sweep
- 2 or more strings - may cause nuisance arc-fault trip on inverter
- Automatic data import to database

Multitracer Cabinet

Pordis string tracer



Stratasense module tracers

Module Characterization

Module Characterization

Purpose:

- More detailed measurements than can be made *in-situ*
- Baseline characterization prior to system installation
- Intermediate and final characterization to track changes throughout the project
- Defined to meet the research goals of the project
- For system research, typically must be non-destructive

Electrical Performance – Solar Simulator

1-Sun Flash Tester. Spire 4600SLP, Class AAA

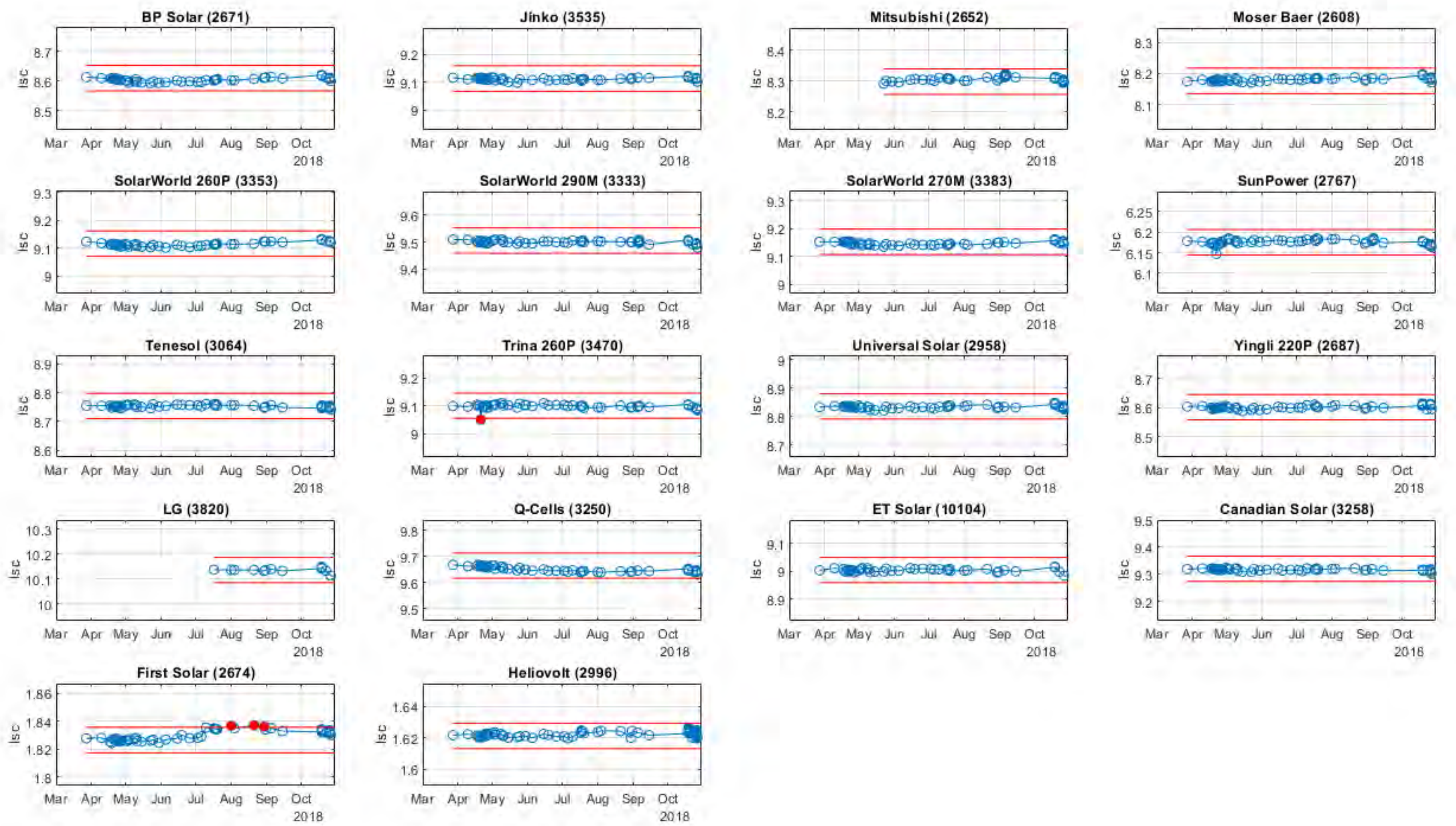
Advantages:

- Indoor, controlled environment
- High throughput, 30-50 modules/day
- Possible to test 100% of the modules in a system

Limitations:

- Limited range of environmental conditions
  e.g. temperature, spectrum
- Array must be taken off-line for fielded module characterization
- Stability of flash tester must be closely tracked
  Can you measure 0.5% annual degradation with a 5% accurate flash tester?
- Accuracy is best if room temperature is tightly controlled to 25 ± 0.5°C

Tracking Accuracy – Module Control Library

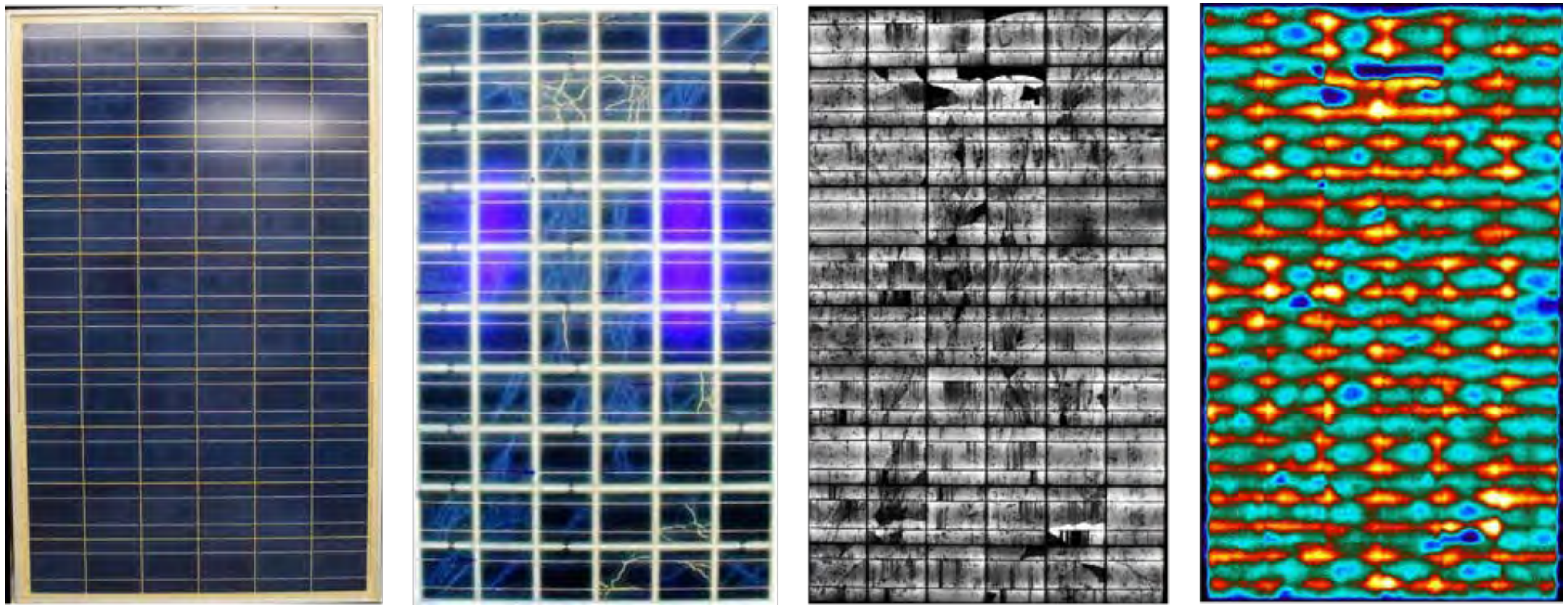


- Collection of 18 modules; different vintages, power ratings and technologies
- Entire collection flashed prior to and at the conclusion of significant flash test measurements
- Control limits of ± 0.5% on Isc, Voc, Pmp
- Stored near flash tester, no thermal equilibration required
- Modules with significant deviation from control limits are flagged for inspection or removal

Non-Destructive Module Characterization

Custom dark chamber designed to accommodate modules up to 2.1m tall

- Co-located visual, electroluminescence (EL), infrared (IR) and UV fluorescence (UVF) imaging
- Non-destructive defect mapping

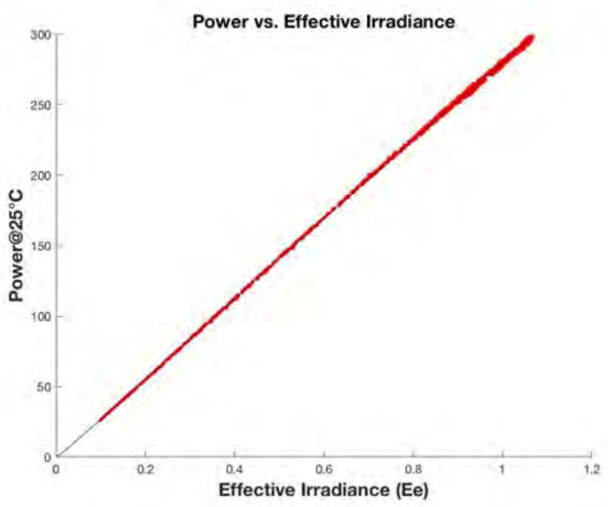


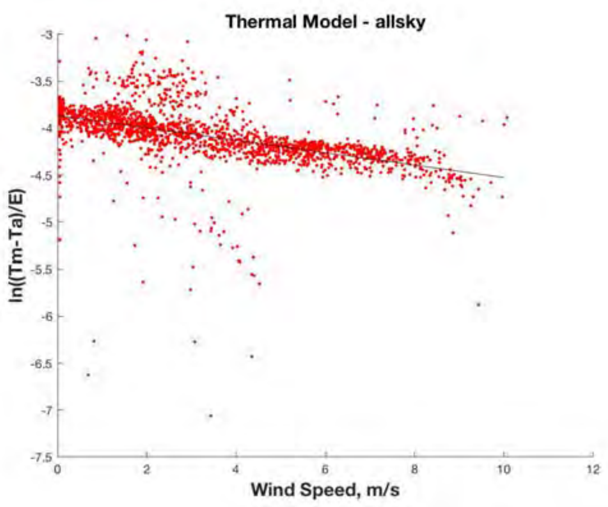
Electrical Performance – Outdoor Testing

- Testing under a much wider range of conditions than are possible with indoor solar simulator
- Determine temperature coefficients, angle of incidence response, spectral response, thermal model
- Data used to calibrate performance models
  e.g. Sandia Array Performance Model, single-diode

Procedure

- Two-axis solar tracker, modules held normal to sun, 2-4 weeks.
- Tracker held on sun from sunrise to sunset, multiple days, clear and cloudy conditions
- IV curves measured at 2 minute intervals
- Typically 1000 IV curves minimum for model calibration

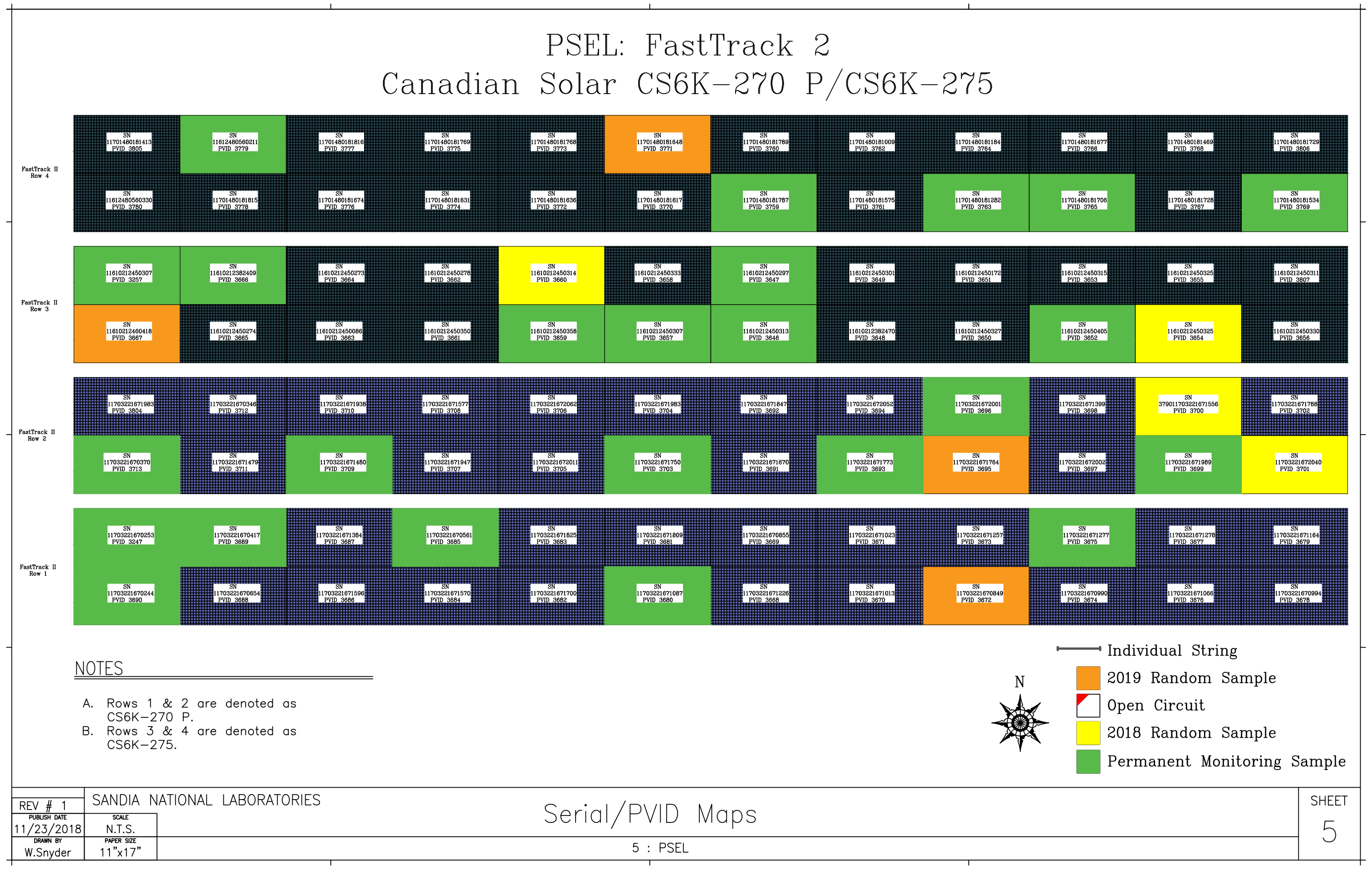




Limitations

- Very low throughput relative to solar simulator
- Weather rarely cooperates
- Seasonal limits (too cold, air mass too high, too much atmospheric pollution)

Annual Flash Test Campaign



- Annual full-field shutdown for module recharacterization
- Conducted in January when conditions are unfavorable for outdoor testing
- Typically, 300 - 500 modules, permanent control group + random sample
- Significant streamlining of recharacterization, given the number of modules that must be tested
- Non-destructive Imaging of permanent control group + outliers

Considerations

- Sampling plan
- Module labeling
- Training for proper handling
- Material movement
- Module breakage

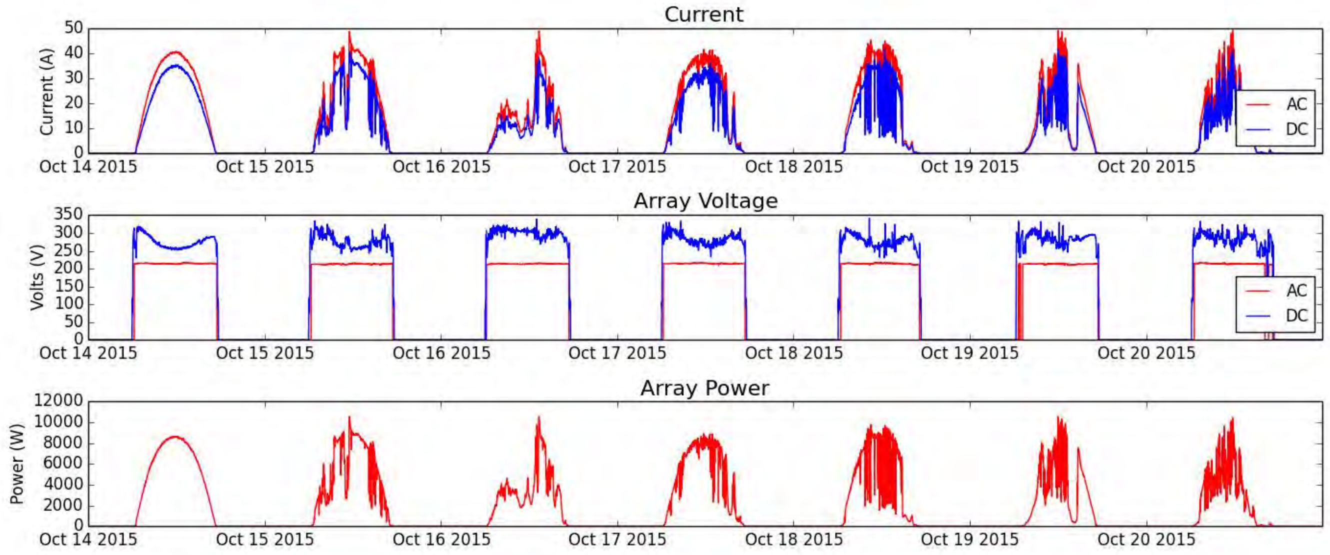
System Analysis

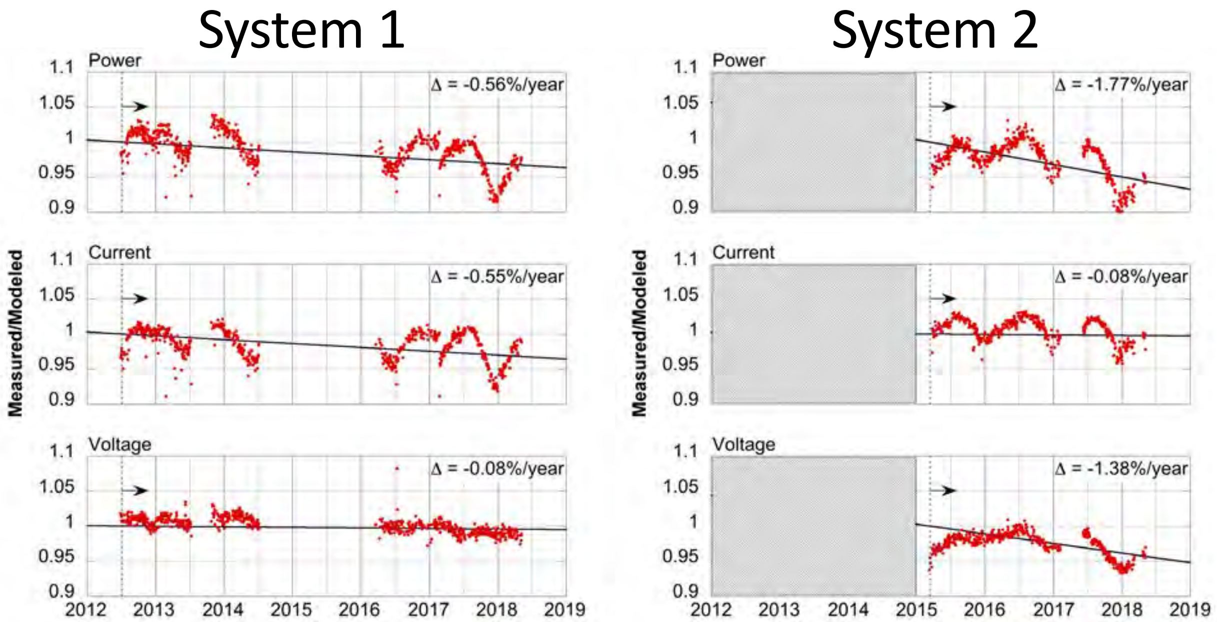
System Analysis

Processing of time-series data to learn something from system performance

- Short term changes in performance
  - LeTID – PERC
  - Metastability – CIGS, CdTe
- Medium term changes in performance
  - Seasonality – Amorphous Si
  - Early degradation
- Long-term changes in performance
  - %/year degradation

- Side-by-side technology comparisons
- Geographic variability
  - Effect of cumulative environmental stressors
  - Hot/humid, hot/dry, cold, etc.
- Visualization tools for 100,000's or 1,000,000's of data points





Normalization - Performance Ratio (IEC 61724)

PR: ratio of actual energy produced to reference energy. Includes overall effect of losses including temperature and other inefficiencies. *k* = time interval of interest (e.g. 1 month)

$$PR = \frac{\sum_k (Measured\ Power)_k (time)_k}{\sum_k \frac{(Array\ Power\ Rating)(Measured\ Irradiance)_k (time)_k}{(Reference\ Irradiance)}}$$

PR-STC: As above, but Array Power Rating is adjusted for module temperature.

$$PR = \frac{\sum_k (Measured\ Power)_k (time)_k}{\sum_k \frac{(temperature\ correction)(Array\ Power\ Rating)(Measured\ Irradiance)_k (time)_k}{(Reference\ Irradiance)}}$$

$$temperature\ correction = 1 + \gamma_{pmp}((module\ temp)_k - 25°C)$$

PR-PPI: Power Performance Index, ratio of actual power produced to predicted power from a performance model run using actual weather conditions

$$PR = \frac{\sum_k (Measured\ Power)_k (time)_k}{\sum_k (Predicted\ Power)_k (time)_k}$$

Example: PR-PPI using SAPM

- Inputs – local weather, irradiance
- Calculate Net plane of array irradiance, corrected for angle of incidence

$$E_{net} = E_{POA} - E_{DNI}\cos(AOI)[1 - f_2(AOI)]$$

- Calculate effective cell temperature from net POA irradiance, ambient temperature and wind speed

$$T_c = E_{net}\left[e^{a+b*WS}\right] + \frac{E_{net}}{1000}\Delta T + T_a$$

- Calculate current and voltage at max power

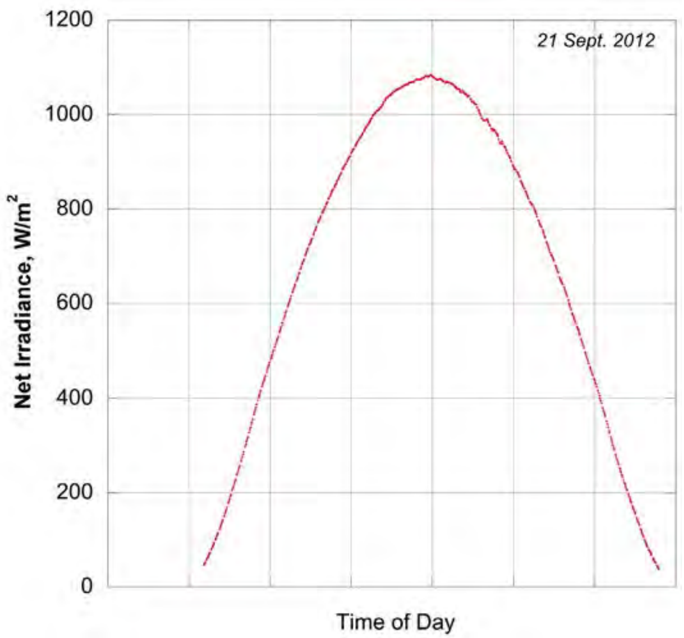
$$I_{mp} = I_{mpo}\left[C_0 E_e + C_1 E_e^2\right]\left[1 + \hat{\alpha}_{Imp}[T_c - T_0]\right]$$

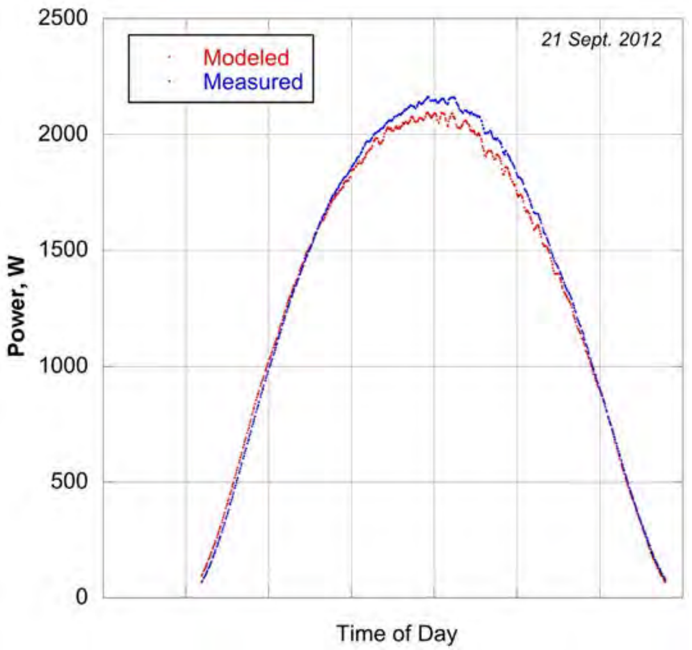
$$V_{mp} = V_{mpo} + C_2 N_s \delta(T_c)\ln(E_e) + C_2 N_s[\delta(T_c)\ln(E_e)]^2 + \beta_{Vmp}[T_c - T_0]$$

$$P_{mp} = V_{mp} I_{mp}$$

- Calculate Performance Ratio for period of interest

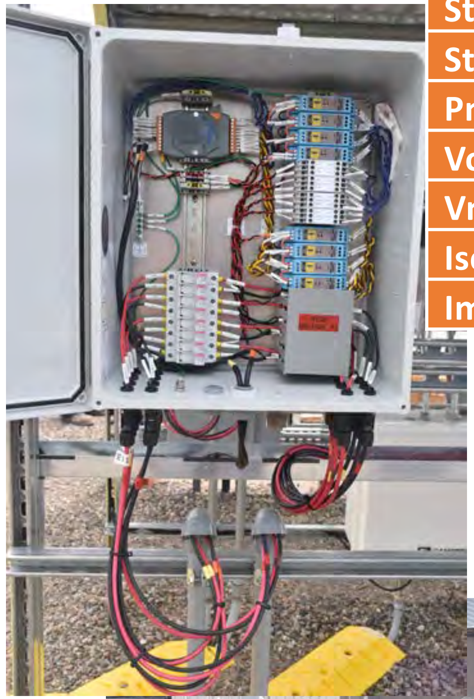
$$PR = \frac{\sum_k (Measured\ Power)_k (time)_k}{\sum_k (Predicted\ Power)_k (time)_k}$$

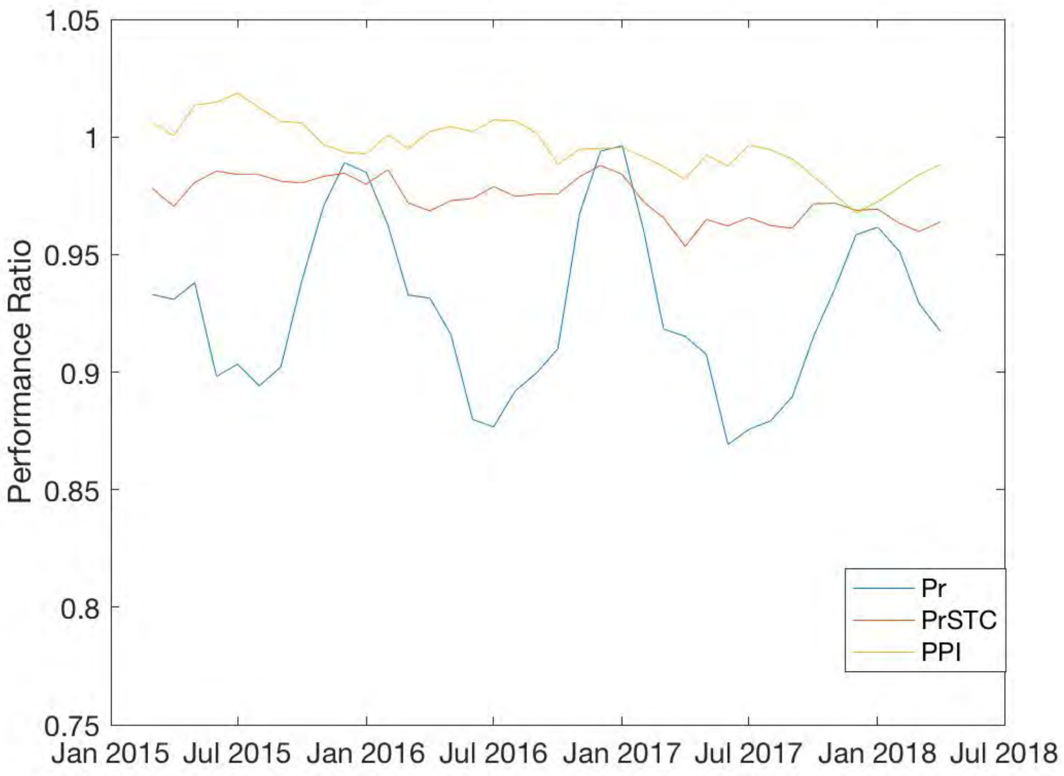




Example Year-Over-Year system losses

	Module	System
Module	Suniva Optimus Mono	
Inverter	SMA SB 3800TL	
String length	12 modules	
Strings	1	
Pmp	270	3240
Voc	38.4	460
Vmp	31	372
Isc	9.18	9.18
Imp	8.7	8.7





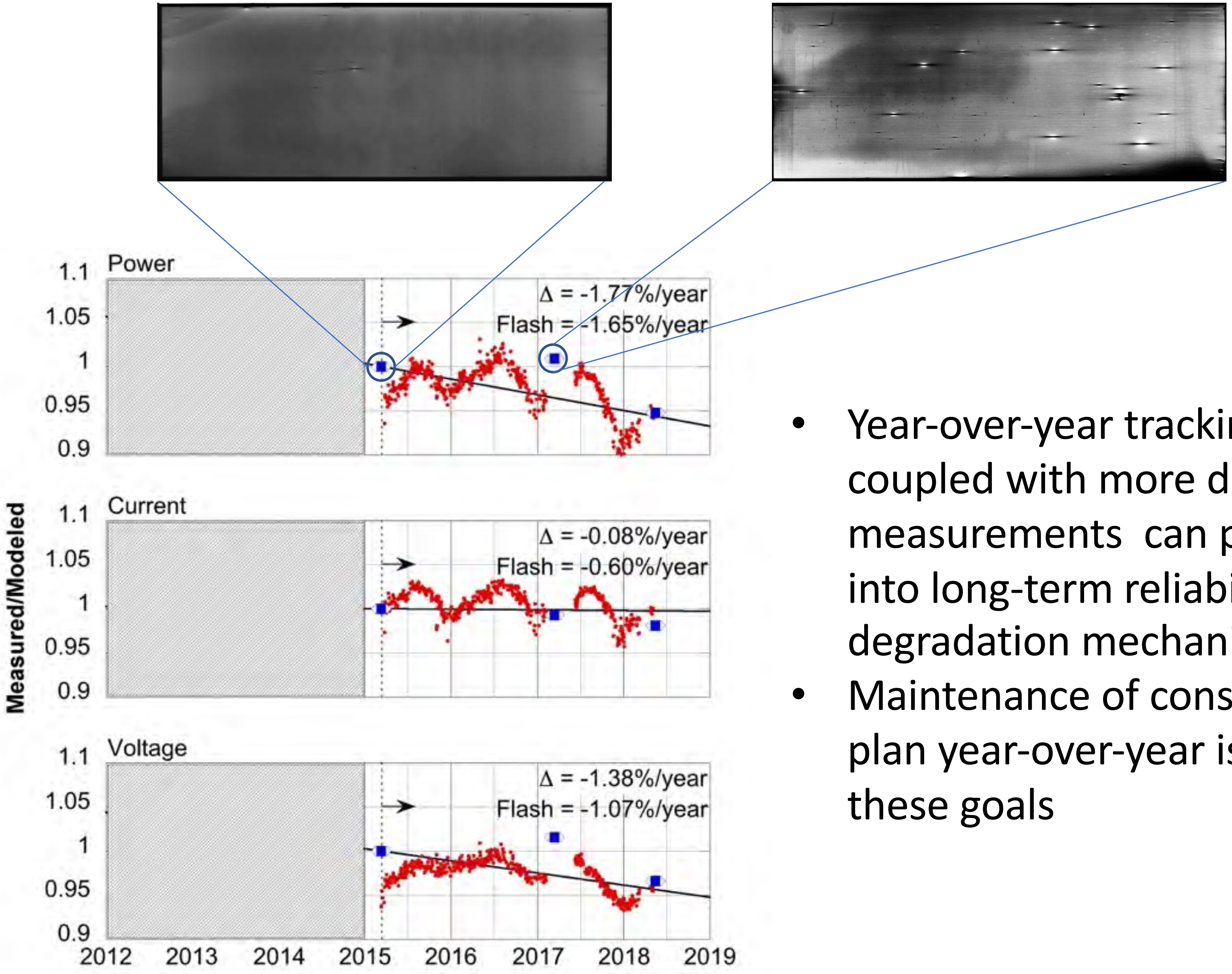
PR: 0.2%/year. R = 0.05

PR-STC: 0.7%/year, R = 0.68

PPI: 1%/year, R = 0.82

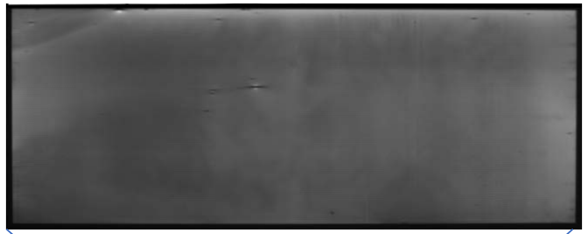
- Suniva mono-Si modules (3kW)
- DC monitoring of string current and voltage (1-min avg)
- POA irradiance using broadband pyranometer (CMP-11)
- Includes ALL DC losses, including soiling (if any)
- PR-PPI provides highest confidence estimate of system losses compared to other PR methods

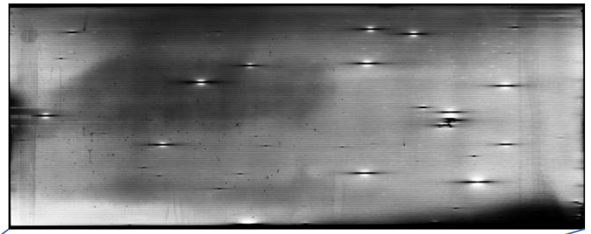
Summary - Putting the pieces together

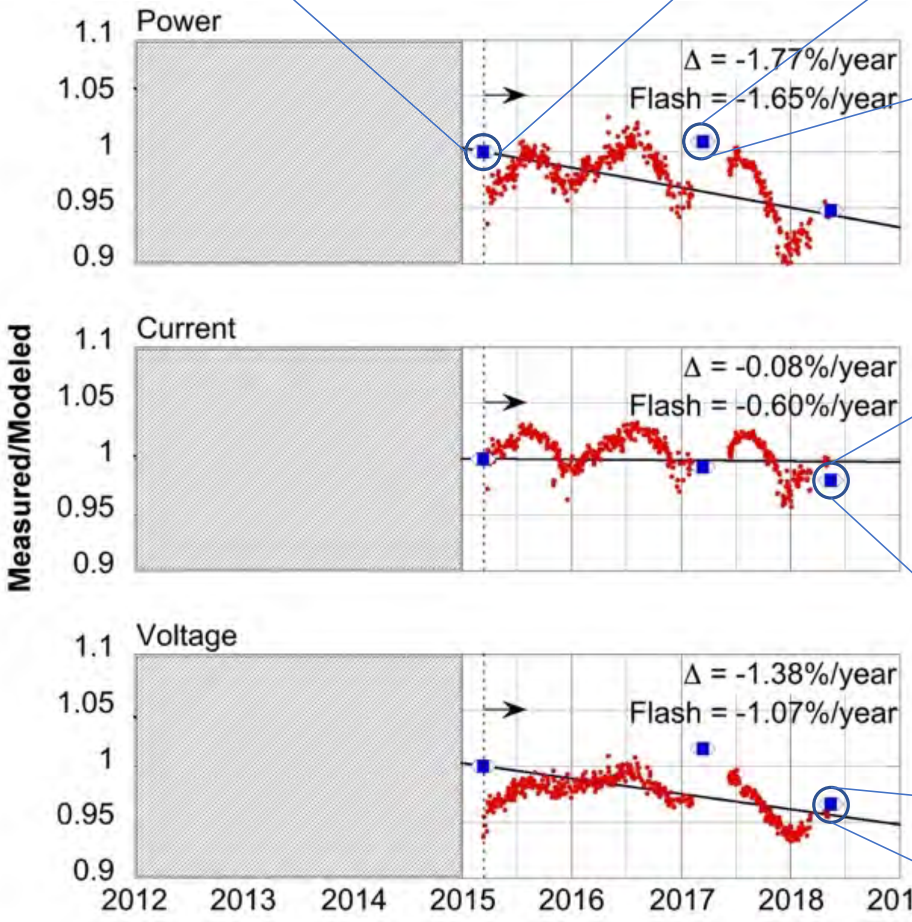


- Year-over-year tracking of performance coupled with more detailed measurements can provide insight into long-term reliability and degradation mechanisms
- Maintenance of consistent sampling plan year-over-year is key to achieving these goals

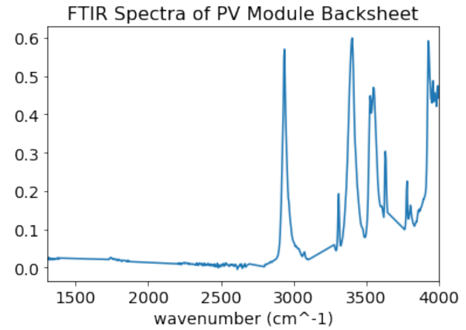
Summary - Putting the pieces together

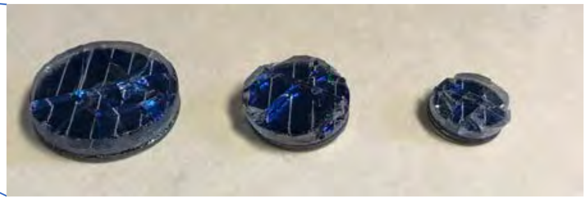






- New forensics capabilities can leverage investment in installed systems to extract more value





Thank you!

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