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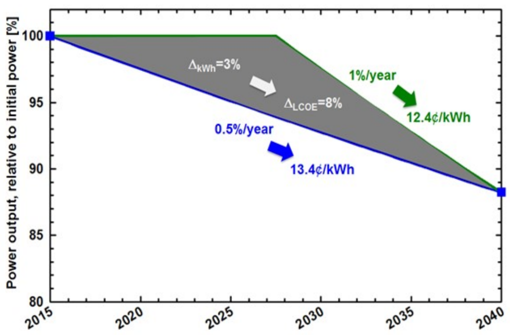

Challenges of PV Degradation Analysis: PVLIB and Performance Data Analysis

Joshua S Stein

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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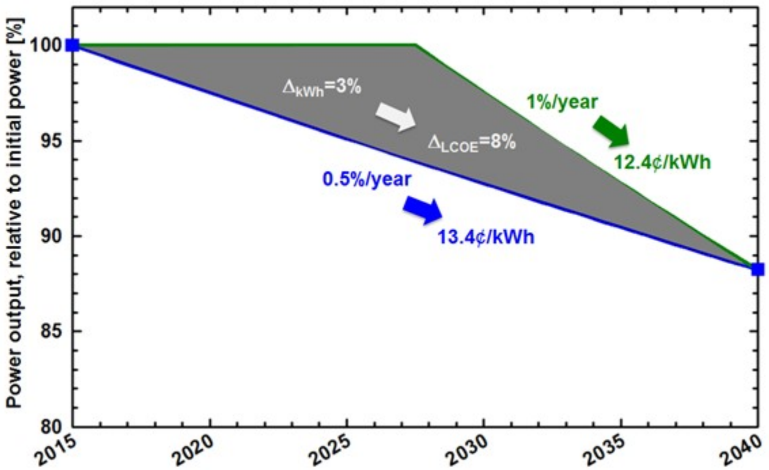
PV Degradation and Performance Modeling

- In order to reach DuraMAT goals of a levelized cost of electricity for PV of less than 3 cents per kilowatt-hour it is necessary to understand and measure PV degradation rates.
- Several of the DuraMAT capabilities are focused on data collection and analysis.
  - DataHub
  - Data Management and Analytics
  - Field Deployment
- Analyzing PV degradation is not really routine or straightforward, especially with outdoor performance data
- This talk will present a current case study underway to measure PV degradation and then introduce an open source toolbox, PVLIB, and show how it can help analyze measured PV performance data.
- Analyses shown here are preliminary and are shown only to better describe general methods used measure degradation.

Case Study – PV Lifetime Project

- PV degradation is likely neither linear nor constant.
- This fact affects the LCOE.
- PV Lifetime project was started in 2016 to carefully track PV module degradation to better understand its progression over time.



- Common and representative PV modules are purchased on the open market and sent to Sandia, NREL, and FSEC.
- Initial indoor characterization is performed (STC flash testing)
- String-level IV curves are automatically and periodically measured
- Annual re-characterization is performed on sample of modules.
- 605 Modules are currently included in the program. More on the way

Test Systems in NM

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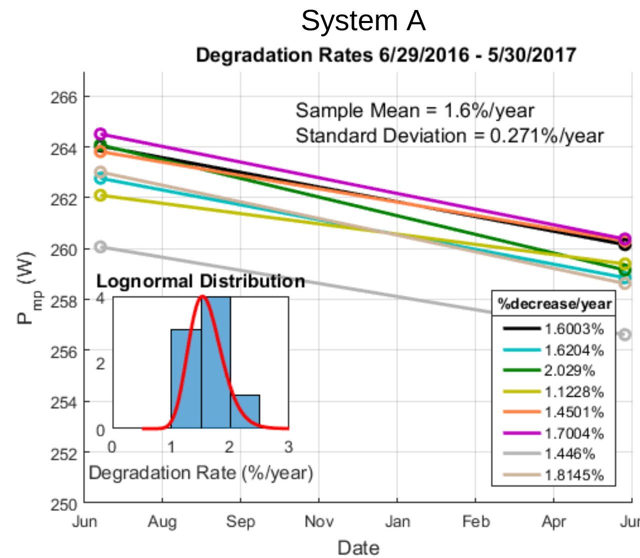
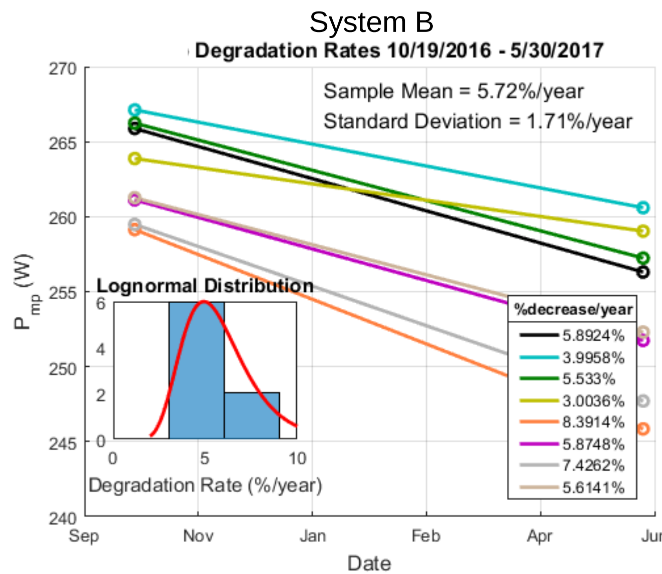
- System A (4 strings)
- System B (4 strings)

- Plane of array irradiance is measured
- IV curves are measured with a Pordis 140A Series II 8-32 Channel In-Line String-level I-V Tracer.
  - Curves taken every 30 min
  - Can be triggered on irradiance, temperature, or other signals (speaks MODBUS)
- DC &AC Current and Voltage measured from inverter every 15 min
- Other nearby systems being monitored for comparison.

Example Flash Test Results (NM)

- All modules were flash tested at the beginning of the project (after ~20kWh/m^2 of light exposure).
- A sample of 8 modules were reflashed after 7-12 months in the field.
  - System A: P_{mp} went down ~1.6% in 1 yr
  - System B: P_{mp} went down an average of 3.3% from initial flash. If this degradation is constant it would equal ~5.7%/yr.
- System degradation should be higher than module degradation due to mismatch
  - Lowest performing modules in each string drag others down.



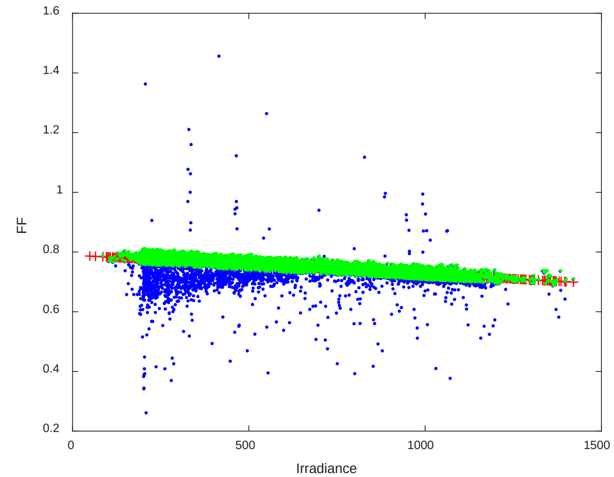


Outdoor IV Curve Analysis (NM)

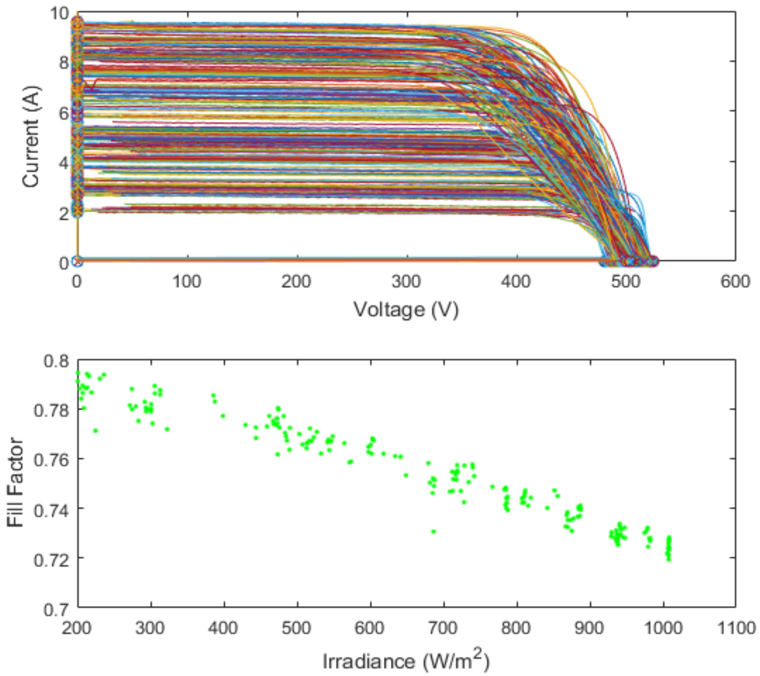
- IV curve measurements began several months after systems were connected.
- IV curves are easy to measure but hard to interpret.
  - They take several seconds to measure and irradiance can vary in that time
  - Capacitive tracers do not go to 0 V or Isc. There can be noise at low voltage values
    - Isc and Voc should be calculated by extrapolating the curve (avoiding any noise).
- Shading or soiling can have large effects.
- “Bad” IV curves must be filtered
  - ***Fill Factor*** is a fairly reliable data quality filter.

Fill Factor Filter

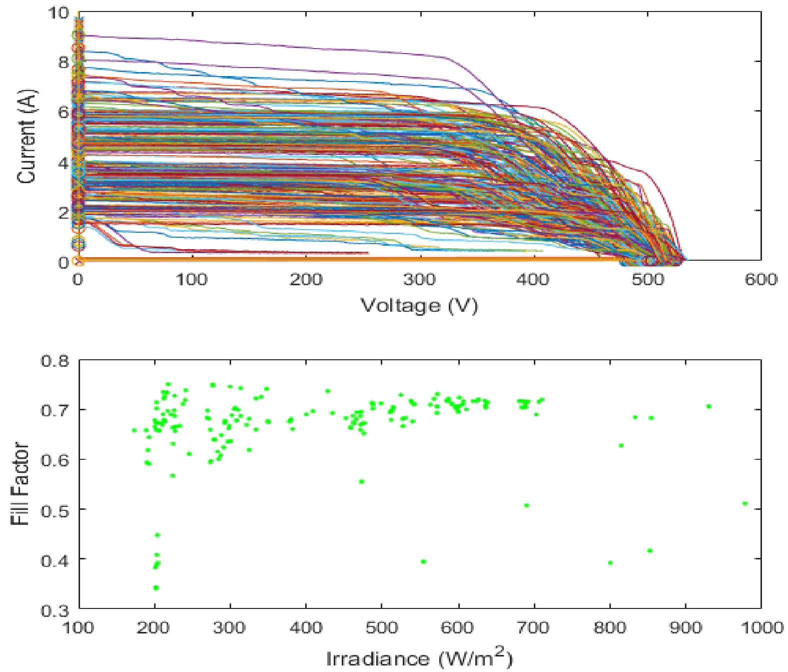
- Fill factor tends to decrease with irradiance.
  - Filtering on this trend helps to remove spurious measurements
    - Shading, irradiance variability



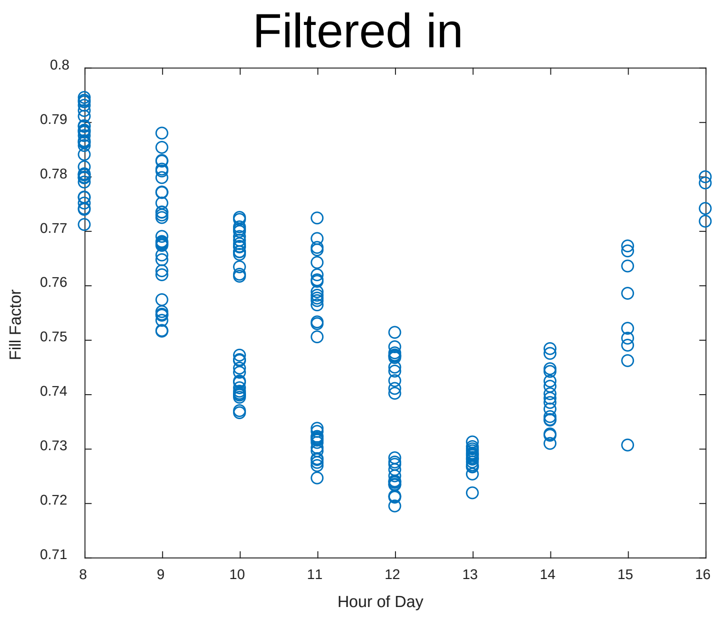
200 IV curves filtered in by FF

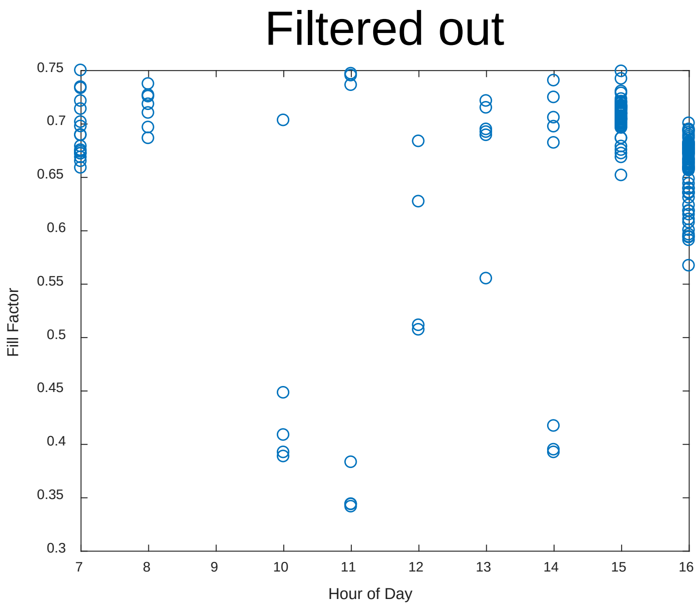


200 IV curves filtered out by FF



Cause of Fill Factor Deviations?





- Most of the curves that are filtered out are from the start and end of the day
  - This is a time when the arrays are partially shaded.
- A few curves are filtered out in the middle of the day
  - Variable irradiance during trace or human caused shade

Example Degradation Calculation

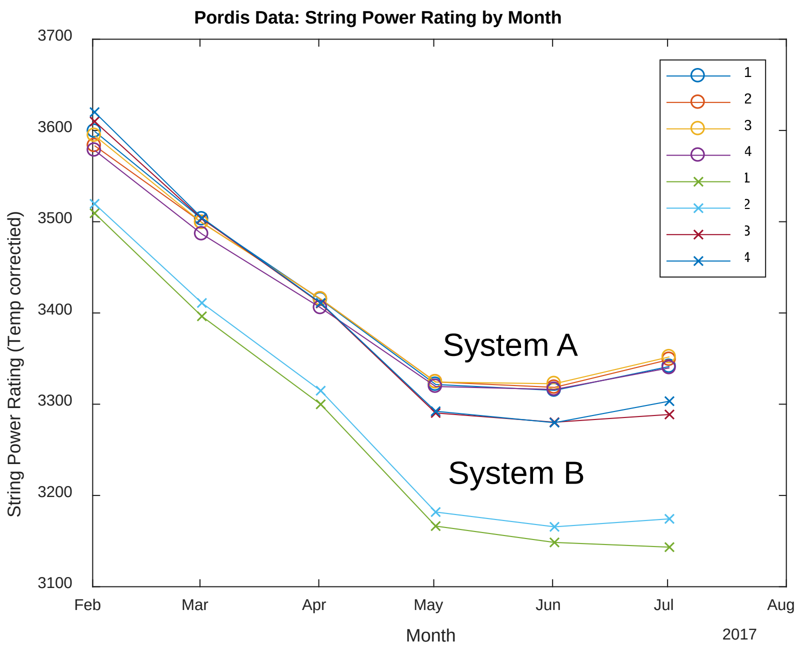
- P_{mp} is calculated for each curve (filtered in)
- Module temperature is used to correct P_{mp} to 25 deg C
  - $P_{mp,25C} = \frac{P_{mp,meas}}{1+\frac{\gamma_{Pmp}}{100}(T_m - 25)}$, where γ_{Pmp} is from spec sheet.

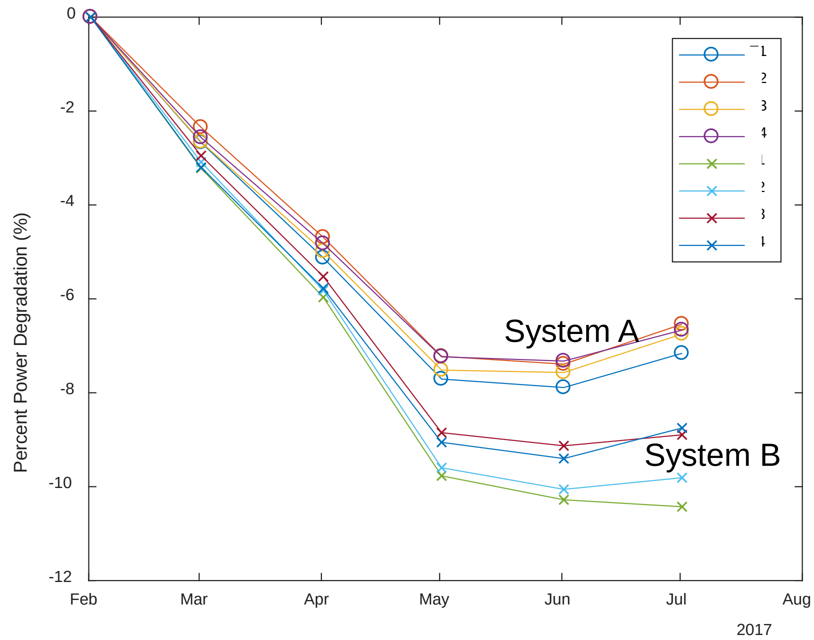
- $P_{mp,25C}$ vs. POA irradiance is fit with a line for a given period (e.g., month)
  - Intercept at 1,000 W/m^2 is taken as “string rated power”
- This rated power is plotted over time

- Similar analyses of Isc, Voc, Rs, Rsh are helpful for identifying the source of the degradation (Not covered in this talk).

Preliminary Monthly String Degradation Results

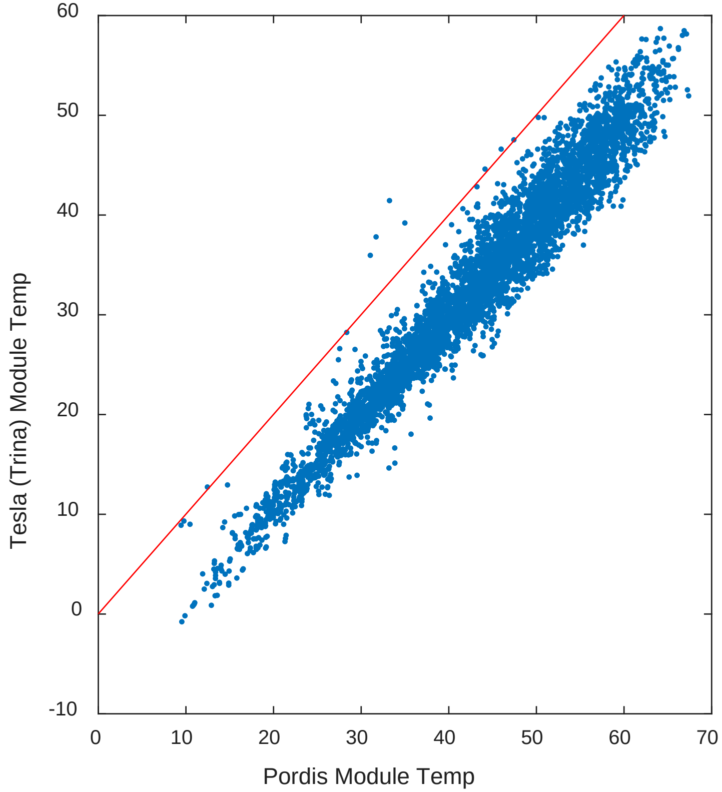
- Monthly string degradation appears to have proceeded until May 2017 when it stops.
  - Systems A and B appear to degrade in a similar pattern.
  - This is suspicious! We must validate this data in case we are observing IV tracer or other input data degradation!

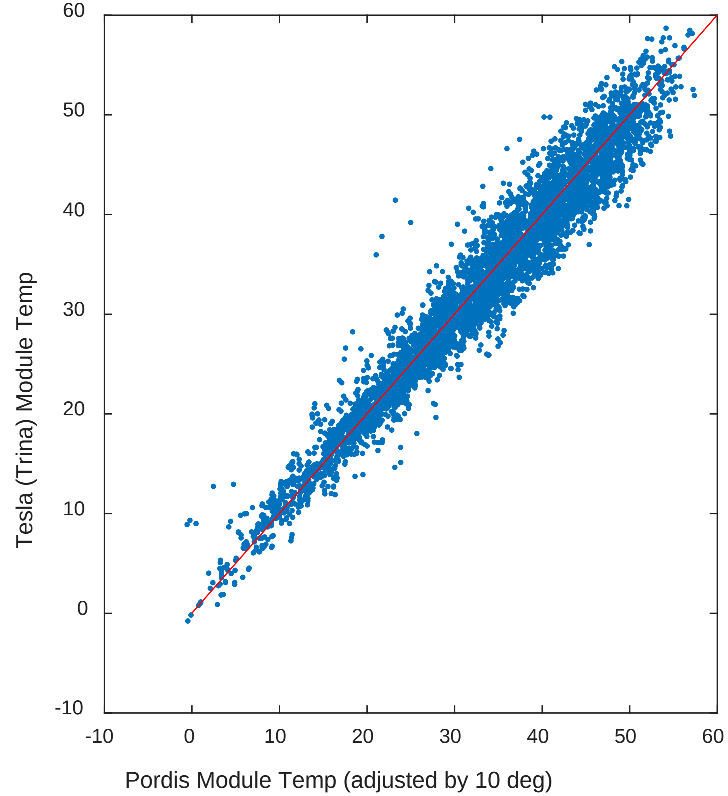




Check Module Temperatures

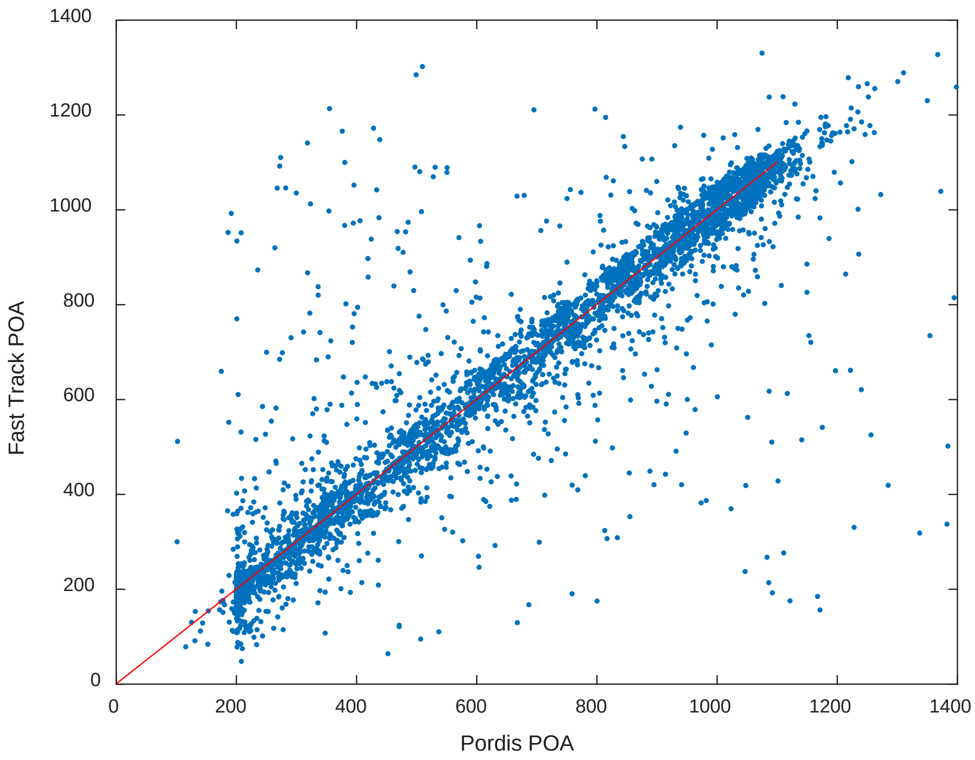
- Module temperature data is actually from an uncalibrated reference cell.
  - 10˚ C offset is apparent. This correction was used in the Pmp temp correction.





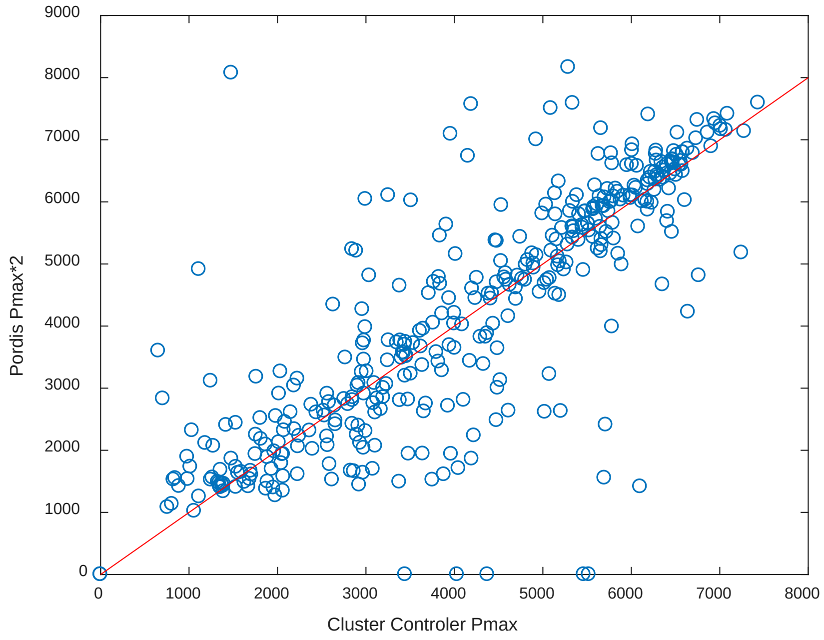
Check POA Irradiance

- POA irradiance was compared with a calibrated reference cell at same orientation located about 200 m away.
  - Nice match! Little to no bias error.
  - Scatter is commonly observed and due to discrete cloud shadows



Check Power Readings

- DC current and voltage are measured by the inverter every 15 min by an SMA cluster controller.
- I matched Pordis times with cluster controller times and compared Pmp values
  - Cluster controller may report time averaged values, which would cause scatter.
  - No bias error is evident!



<u>Preliminary Conclusion</u>

- IV Data appears to be legitimate. Additional checks will be performed before these results will be released publically.

Alternate Methods of Measuring Degradation

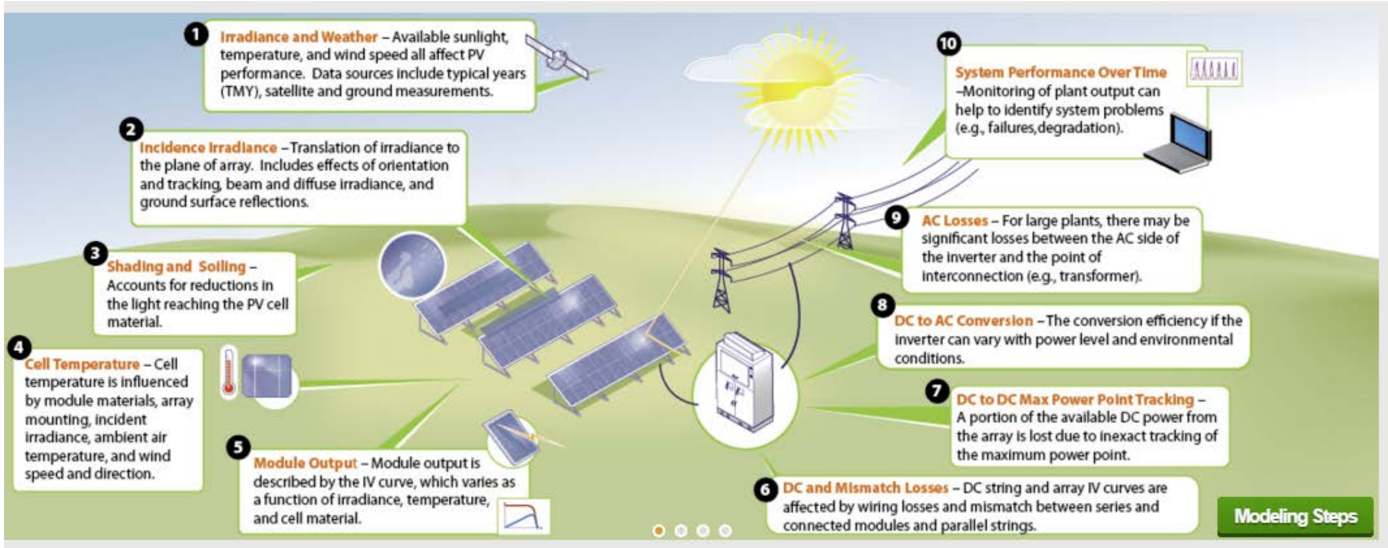
- PVUSA Model fits PV AC output to a function of POA irradiance, ambient temperature (T), and windspeed (WS)
  - $P_{AC} = POA(a + b * POA + c * WS + d * T)$
- "MPM" Model [1] based on knowledge of "sensible behaviours" of PV cells and modules.
  - $PR_{DC} = c_1 + c_2(T_{mod} - 25) + c_3 log(POA) + c_4 POA + c_5 WS + \frac{c_6}{POA}$

Dependency	Comments
1. $I_{MAX} \propto POA$	neglecting Spectral, AOI
2. $V_{MAX} \propto \log(POA)$	from single diode model
3. $T_{MOD} \sim T_{AMB} - fn(WS)$	due to NOCT/NMOT
4. $P_{MAX} \propto (1+\gamma*(T_{MOD}-25))$	P_{MAX} temp. coefficient
5. $\Delta P_{MAX} \propto I_{MAX2} * R_{SERIES}$	Eff falls with GI2
6. $R_{SHUNT} \propto 1/\exp(G_I)$	varies by technology

- These can be "calibrated" each month and then run for "reference conditions" to track degradation.

[1] Ransome and Sutterlueti,(2017) A Systematic Comparison OF 12 Empirical Models used for Energy Yield Predictions vs. PV Technology, EU PVSEC, Amsterdam,

Performance Modeling Methods



- Read inputs:
  - Array design (module, string, inverter, mounting, tracking, ground cover, etc.)
  - Weather (irradiance, temperature, wind speed, etc.)
- Translate irradiance to plane-of-array (POA) (or measure directly)
  - Sun position calculation, irradiance model
- Evaluate ‘effective’ irradiance
  - Angle on incidence effects
  - Spectral effects (air mass correlations or physics models)
- Determine cell temperature (or measure directly)
- Calculate I_{mp}, V_{mp}, and P_{mp}
- Estimate and apply derates (soiling, DC loses, mismatch, array utilization, etc.)
- Model inverter performance (P_{ac})
- Compare with measured data.

PV Performance Modeling Collaborative (PVPMC)

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- Model agnostic, focus on algorithms, methods, data, etc.
- Three Pillars of Communication and Collaboration
  1. **Website** (*PVPMC.sandia.gov*) (>10,000 visits per month)
     - Detailed Modeling Steps (~150 technical webpages)
     - Past workshop presentations (over 300 available for download)
     - Document library, datasets, blog, events, …
  2. **Open Source Software**
     - **PVLIB** - Modeling function libraries for Matlab and Python (50+ functions), BSD 3-clause licenses
     - **Wavelet Variability Model** – calculates geographic smoothing of PV plant power.
     - **GridPV** – Matlab code for analysis of distribution systems with PV
  3. **Workshops**
     - Planning for the 9th and 10th Workshops in China and US is underway

PVLIB for Matlab : Irradiance and Weather

- **pvl_readtmy3, pvl_readtmy2 –** Reads TMY formatted weather files
- **pvl_getISDdata, pvl_readISH –** Reads data from the Integrated Surface Database (source of global weather data)
- **pvl_ephemeris, pvl_spa –** Calculates Sun position
- **pvl_extraradiation –** Calculates extraterrestrial radiation
- **pvl_alt2pres, pvl_pres2alt –** Converts between altitude and air pressure
- **pvl_relativeairmass, pvl_absoluteairmass –** Calculates air mass both relative and absolute
- **pvl_disc, pvl_dirint, pvl_erbs, pvl_louche, pvl_orgill_Hollands, pvl_reindl_1, pvl_reindl_2 –** Estimates DNI from GHI
- **pvl_clearsky_haurwitz, pvl_clearsky_ineichen –** Calculates clear sky irradiance
- **pvl_calcPwat –** Estimates precipitable water in the atmosphere from air temperature and relative humidity

Download PVLIB for Matlab (1.3.2) at

- https://pvpmc.sandia.gov/applications/pv_lib-toolbox/
- https://github.com/sandialabs/MATLAB_PV_LIB

Report issues, submit code, etc. via github

PVLIB for Matlab : Incident Irradiance (POA)

- **pvl_grounddiffuse** – Calculates ground reflected irradiance
- **pvl_isotropicsky** – Isotropic model for sky diffuse irradiance on POA
- **pvl_perez, pvl_reindl1990**, **pvl_kingdiffuse, pvl_klucher1979, pvl_haydavies1980** - models for sky diffuse irradiance on POA
- **pvl_getaoi** – Calculates to the angle of incidence on a tilted plane.

- **pvl_detect_clear_times** – Identify clear periods in irradiance time series
- **pvl_detect_shadows** – Detect the effect of shadows in measured irradiance data (e.g., overhead wires, trees, poles, etc.)

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PVLIB for Matlab : PV Models

- **pvl_sapmmoduledb**, **pvl_SAMLibraryReader_CECModules**, **pvl_SAMLibraryReader_SNLInverters** – Reads in PV module coefficients
- **pvl_physicaliam**, **pvl_martinruiziam**, **pvl_ashraeiam** – Models for estimating incident angle modifiers
- **pvl_Fsspeccorr** – First Solar model for spectral corrections
- **pvl_calcparams_Desoto** & **pvl_calcparams_CEC** & **pvl_calcparams_Pvsyst** – Calculates PV module parameters for the single diode model
- **pvl_singlediode** – Implements the single diode model
- **pvl_sapm** – implements the Sandia PV Array Performance Model
- **pvl_huld** – Implements the Huld performance model
- **pvl_snlinverter**, **pvl_adrinverter** – inverter performance models
- **pvl_singleaxis** – Calculates single axis tracker positions and angles
- **pvl_sapmcelltemp** – Calculates PV cell temperatures from air temp, irradiance, and wind speed.

Download PVLIB for Matlab (1.3.2) at
- https://pvpmc.sandia.gov/applications/pv_lib-toolbox/
- https://github.com/sandialabs/MATLAB_PV_LIB

Report issues, submit code, etc. via github

pvlib-python

- Object-oriented implementation of PV modeling functions
- Location class:
  - Container for latitude, longitude, altitude, timezone data
  - Methods for solar position, clear sky models, air mass models, TMY readers
- PVSystem class:
  - Container for system description data, e.g.: tilt, azimuth, albedo, module and inverter, system topology
  - Methods for POA irradiance, module and inverter performance models
- ModelChain class:
  - Container for a Location and a PVSystem object
  - Specify choice of models using keywords, e.g., clearsky_model='ineichen'
  - Methods for power and energy simulations, e.g., 'prepare_inputs()', 'run_model()'

Pvlib-python v0.5.0 at
➢ https://github.com/pvlib/pvlib-python
Report issues, submit code, etc. via github

PVPMC Workshops

- 1^{st} PVPMC Workshop (Albuquerque, NM, Sept. 2010)
- 2^{nd} PVPMC Workshop (Santa Clara, CA, May 2013)
- 3^{rd} PVPMC Workshop (Santa Clara, CA, May 2014)
- 4^{th} PVPMC Workshop (Cologne, Germany Oct 2015)
- 5^{th} PVPMC Workshop (Santa Clara, CA, May 2016
- 6^{th} PVPMC Workshop (Freiburg, Germany, Oct 2016)
- 7^{th} PVPMC Workshop (Lugano, Switzerland, March 2017
- 8^{th} PVPMC Workshop (Albuquerque, NM, May 2017)
- ***9^{th} PVPMC Workshop (Weihai, China, Dec 5-7, 2017)***
- ***10^{th} PVPMC Workshop (Albuquerque, NM, May 1-3 2018)***

Summary and Conclusions

- Degradation rates of PV modules and components affect LCOE and the value of solar PV.
  - Degradation is unlikely to be uniform or constant
- There are many different methods to measure degradation.
  - Indoor flash testing
  - Outdoor performance monitoring (DC or AC measurements, IV curves)
- All methods rely on a stable irradiance reference
  - Regular calibration and cleaning is important.
  - Comparison with nearby measurements is very useful too.
- Filtering of data is important
  - Transient irradiance conditions or partial shading need to be removed.
  - Fill factor seems to be a reliable filter.
- Many valuable analysis functions are available from PVLIB.

Final Thoughts

- Analysis of PV data is always a challenge
  - What is measured is not always representative
    - E.g., soiling, shading, transient conditions all affect measurements
    - Stability of DUT and uncertainty in the measurement need to be understood
    - Accuracy vs. precision of flash testers
- Data analysis MUST be closely linked with the collection of the data and design of the experiment!
  - DuraMAT DataHub **will only work if** the nuances of the data are understood and transferred from the experiment designers and data collectors to the analysts.