

Challenges of PV Degradation Analysis: PVLIB and Performance Data Analysis

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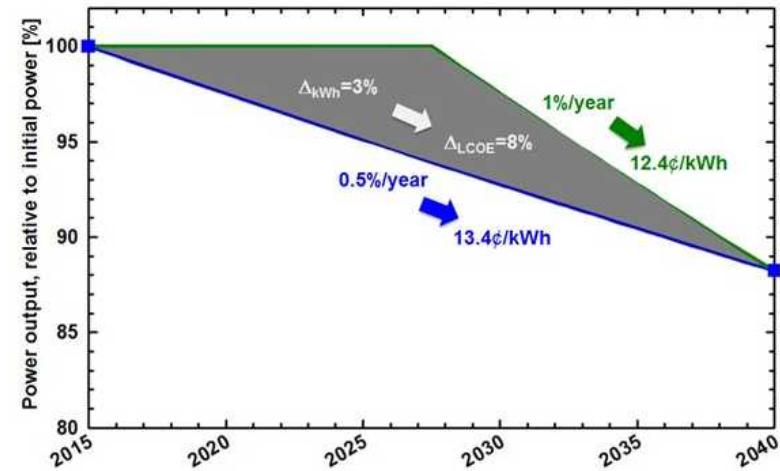
PV Degradation and Performance Modeling



- 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



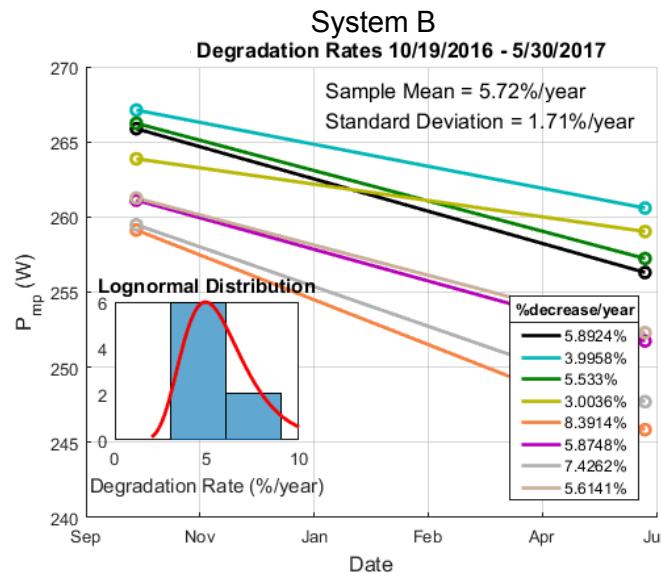
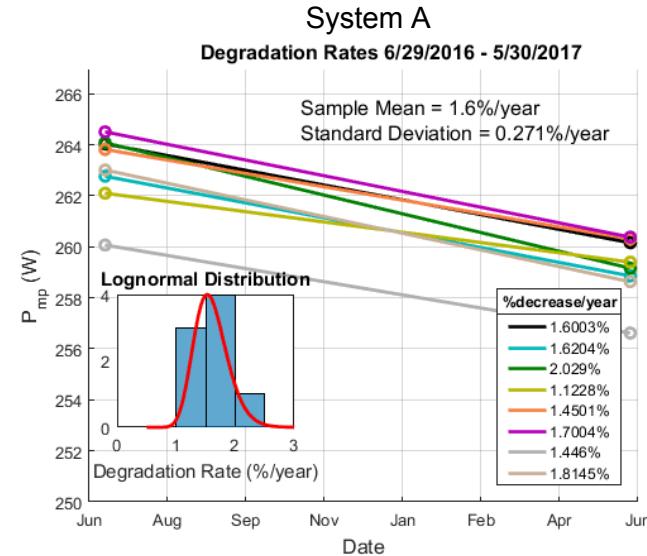
Test Systems in NM

- 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 $\sim 20\text{kWh/m}^2$ of light exposure).
- A sample of 8 modules were reflashed after 7-12 months in the field.
 - System A: P_{mp} went down $\sim 1.6\%$ 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 $\sim 5.7\%/\text{yr}$.
- System degradation should be higher than module degradation due to mismatch
 - Lowest performing modules in each string drag others down.

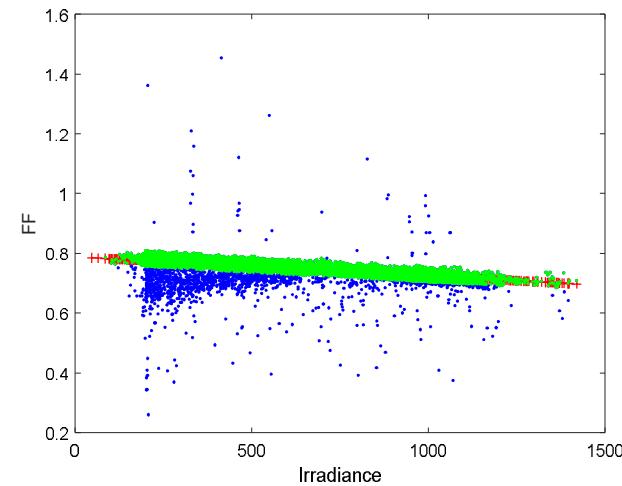


Outdoor IV Curve Analysis (NM)

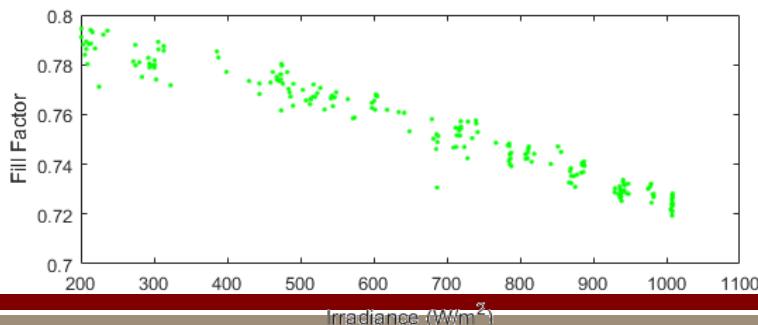
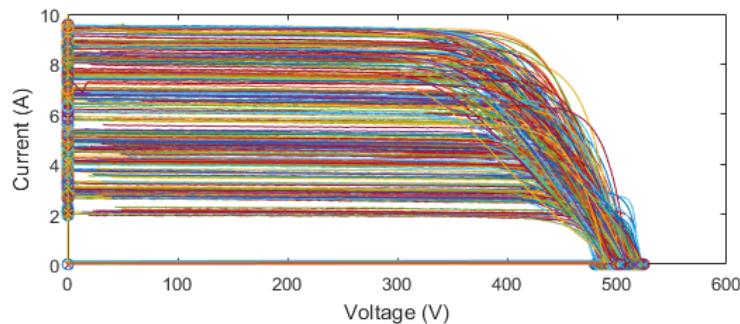
- IV curve measurements began several months after systems were connected.
- IV curves are easy to measure but hard to interpret.
 - They take several seconds to measure and irradiance can vary in that time
 - Capacitive tracers do not go to 0 V or I_{sc} . There can be noise at low voltage values
 - I_{sc} and V_{oc} 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

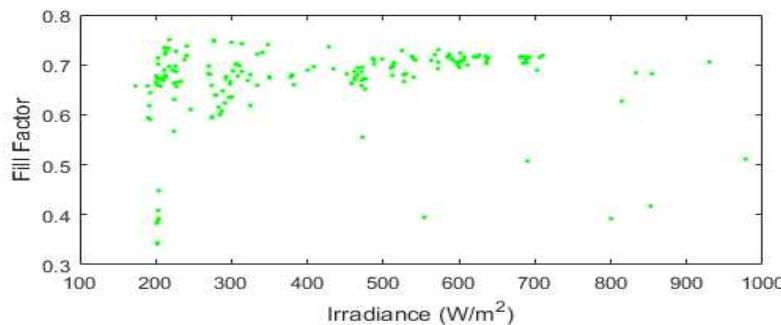
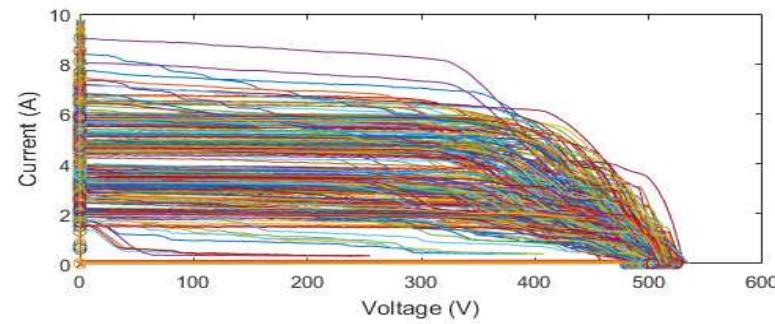
- Fill factor tends to decrease with irradiance.
 - Filtering on this trend helps to remove spurious measurements
 - Shading, irradiance variability



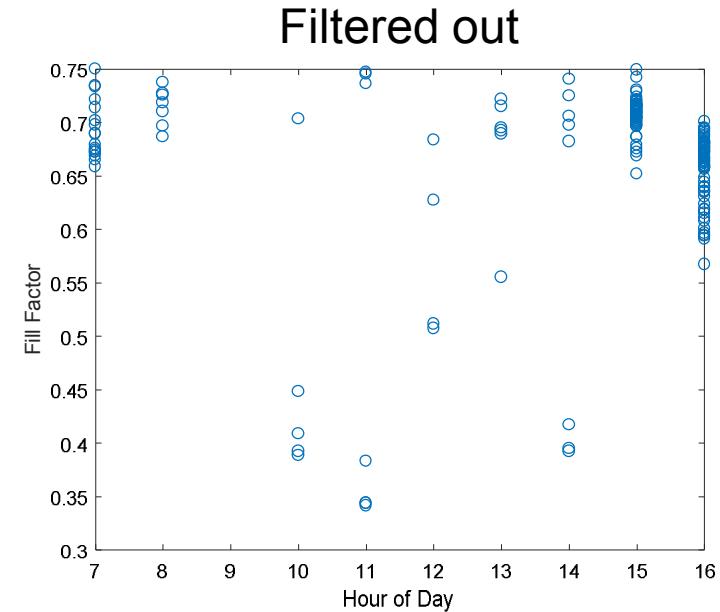
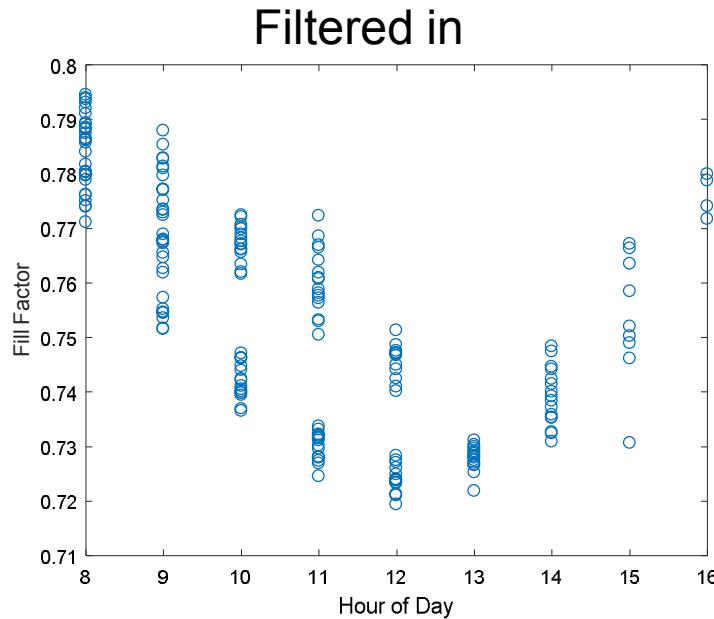
200 IV curves filtered in by FF



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

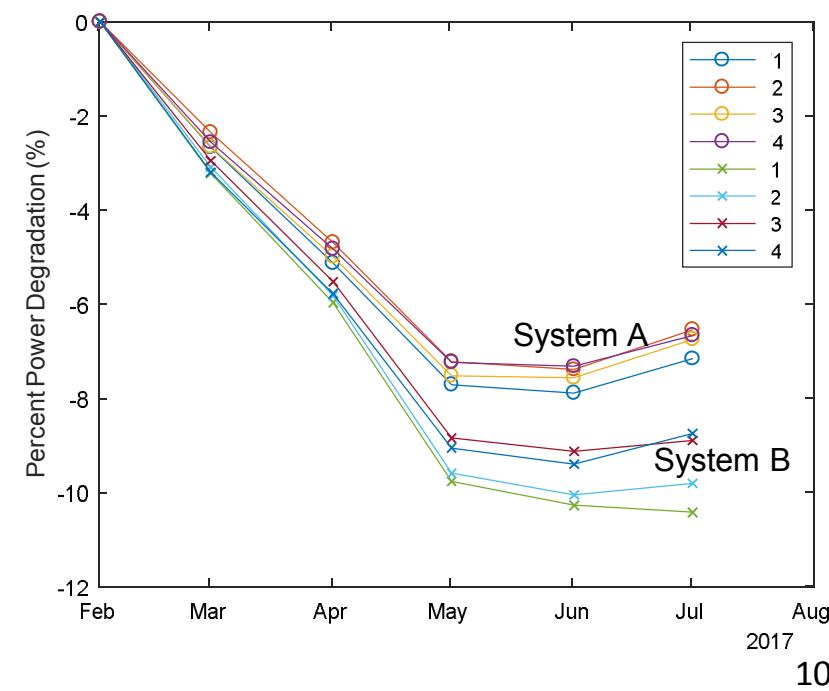
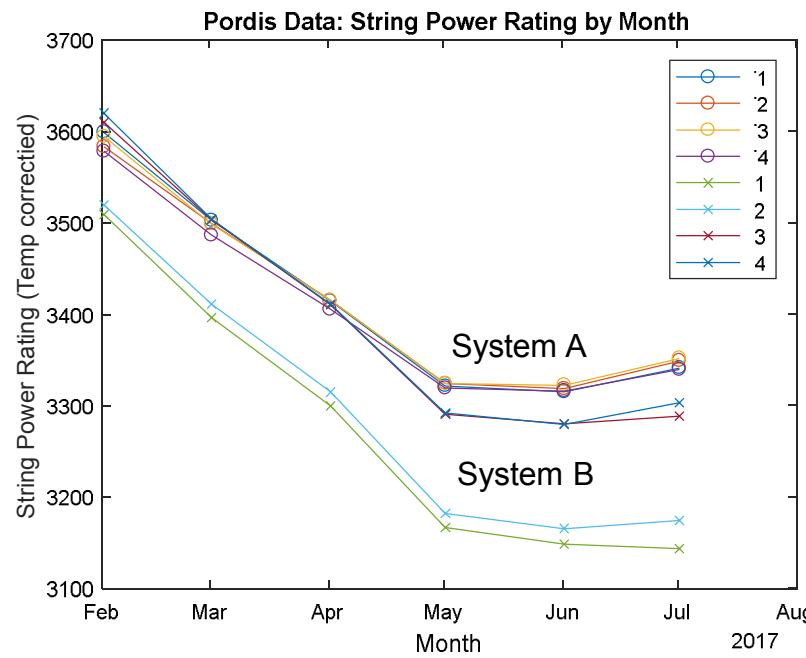
Example Degradation Calculation

- 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/m² is taken as “string rated power”
- This rated power is plotted over time
- Similar analyses of I_{sc} , V_{oc} , R_s , R_{sh} are helpful for identifying the source of the degradation (Not covered in this talk).

Preliminary Monthly String Degradation

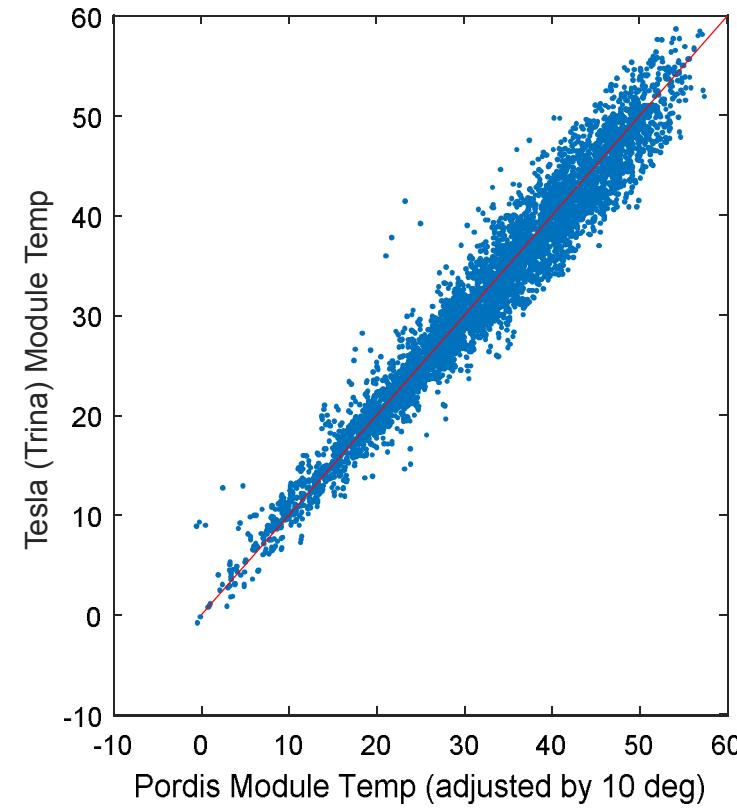
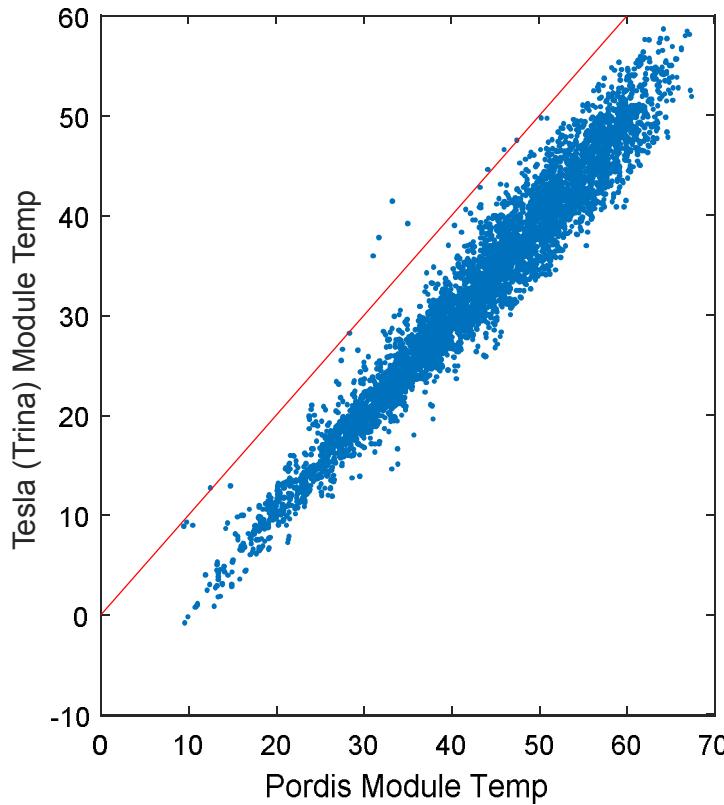
Results

- 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!



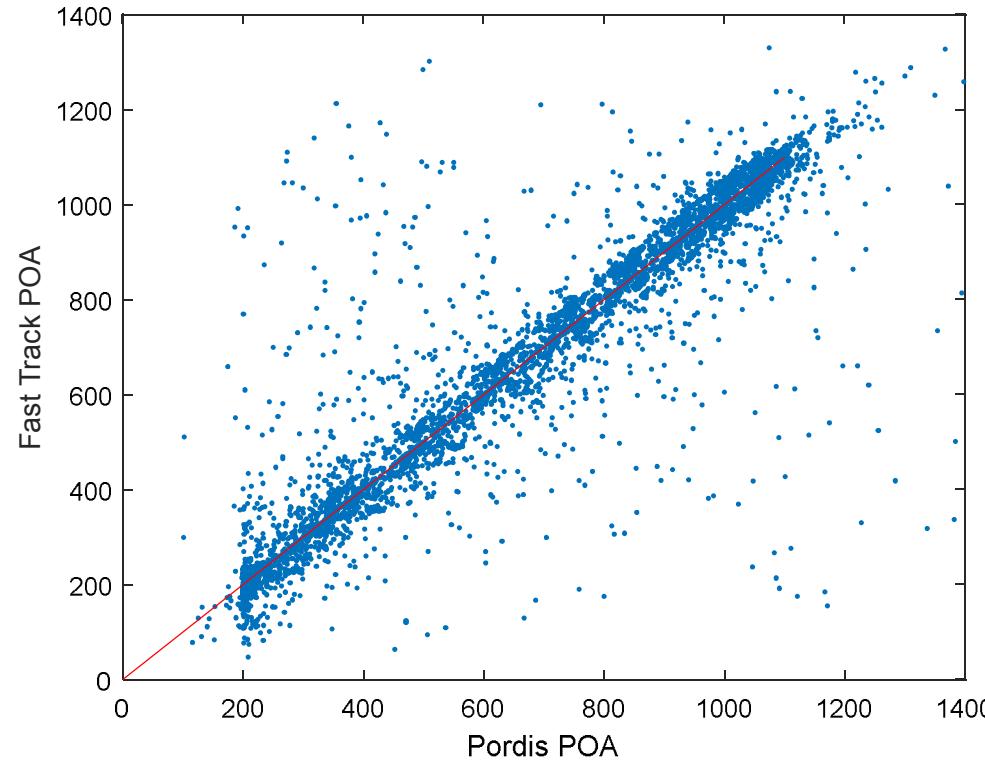
Check Module Temperatures

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



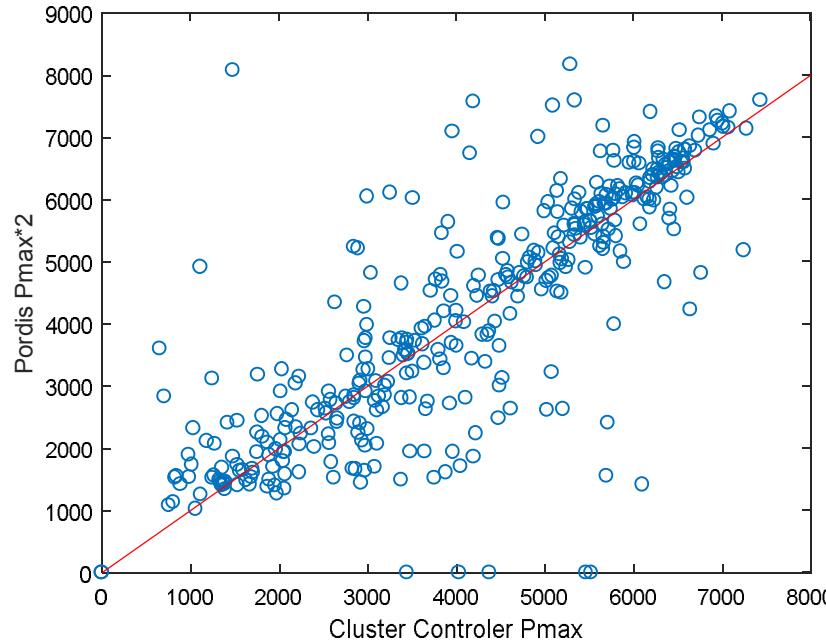
Check POA Irradiance

- 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!



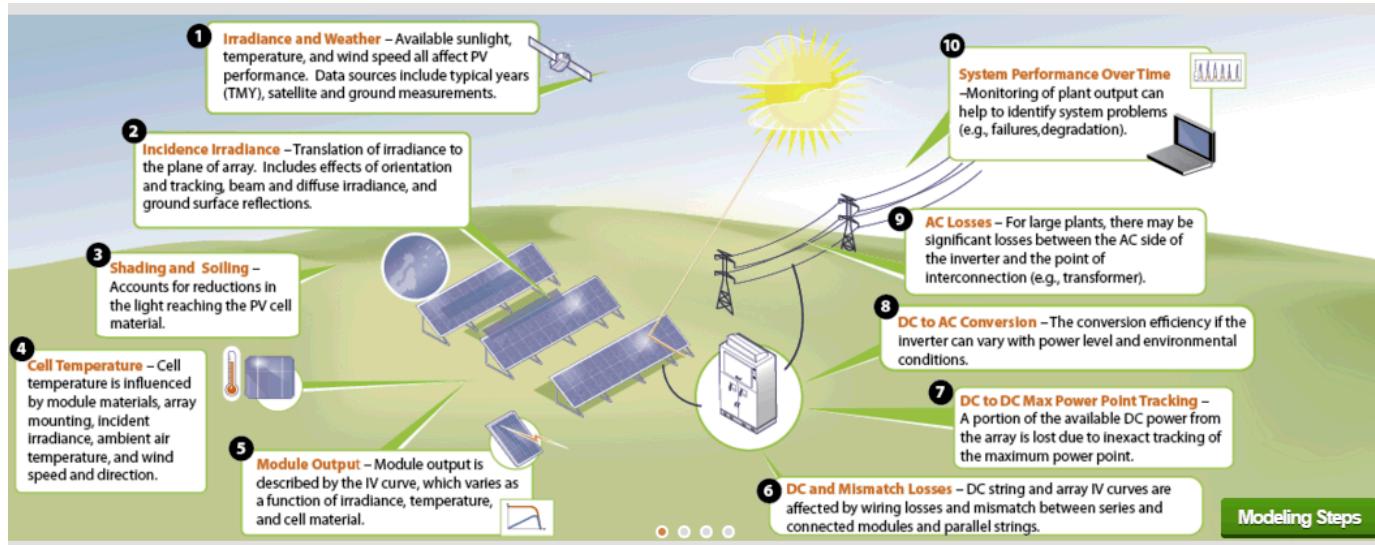
Preliminary Conclusion

- 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.
 - $PR_{DC} = c_1 + c_2(T_{mod} - 25) + c_3 \log(POA) + c_4 POA + c_5 WS + \frac{c_6}{POA}$
 - | <u>Dependency</u> | <u>Comments</u> |
|---|-----------------------------|
| 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. $R_{SHUNT} \propto 1/\exp(G)$ | varies by technology |
 - These can be “calibrated” each month and then run for “reference conditions” to track degradation.

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 losses, mismatch, array utilization, etc.)
- Model inverter performance (P_{ac})
- Compare with measured data.

PV Performance Modeling Collaborative (PVPMC)



- 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_grounndiffuse** – 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_SNLIverters** – 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_calcparms_Desoto & pvl_calcparms_CEC & pvl_calcparms_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.

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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

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