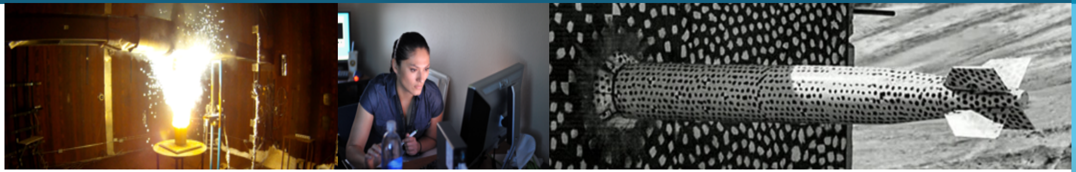
Early Life PV System Degradation Evaluation and Modeling Based on Cumulative Exposure to Environmental Stressors



PRESENTED BY

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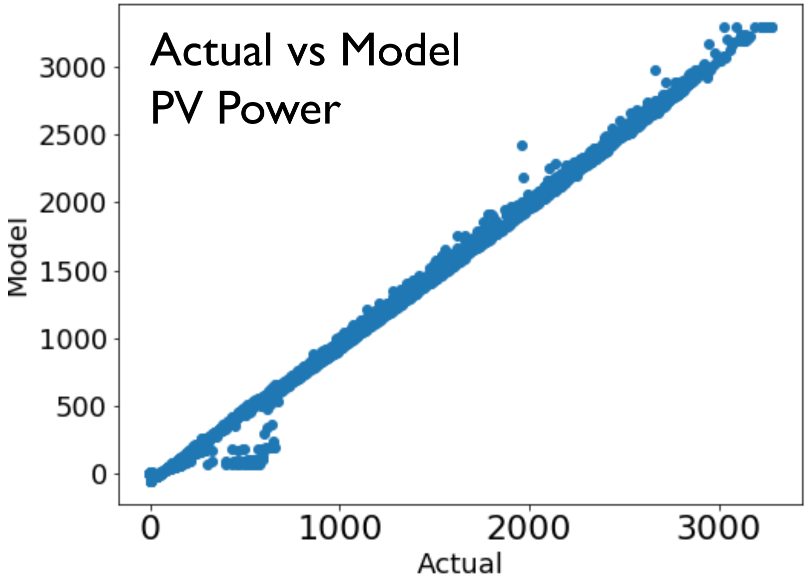
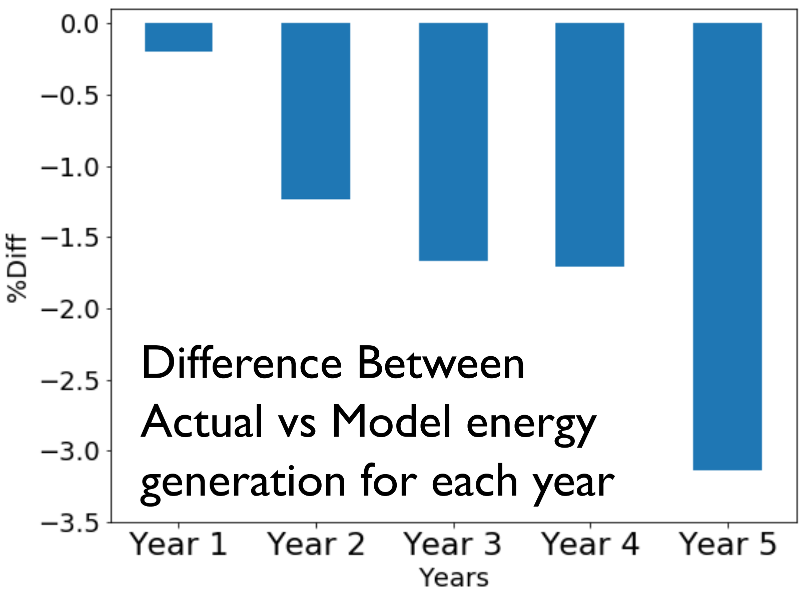
Overview

1. Motivation
2. Proposed Concept
3. Test PV Plants
4. Degradation Stressor Identification
5. Degradation Modeling
6. Conclusion/Future work

Motivation

1. Identify dominate stressor for particular module
   a. Data-driven approach?
2. Decrease model error caused by degradation
   a. Method to account for degradation?
   b. Example Problem:
      - PV System in New Mexico
      - Percent Difference:
        - $\%Diff = (E_{Actual} - E_{Model})/E_{actual}$
      - -3% Diff. After Year 5
      - % Difference Increase = ~0.6%/year

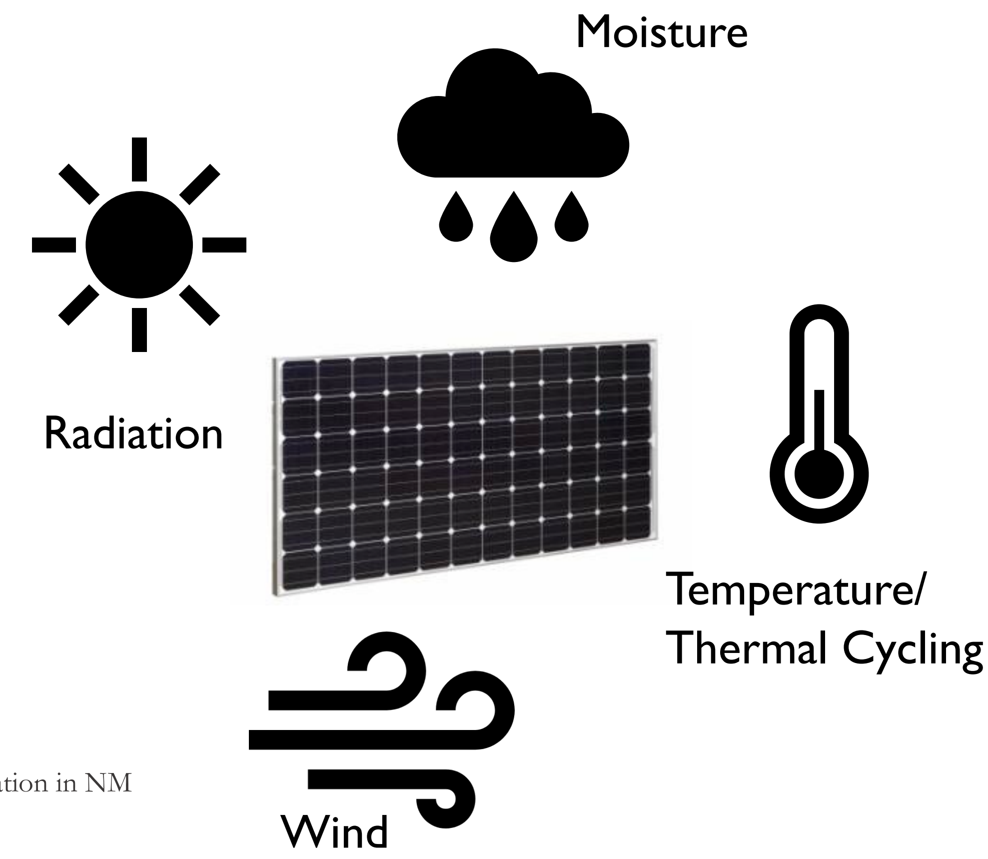




Proposed Concept

Hypothesis: Cumulative Exposure evaluation methodology can identify stressors and improve multi-year models.

1. Measure/Collect
   a) Climate
   b) PV Performance
2. Quantify
   a) Exposure (amount of stress)
   b) Performance Changes (loss in output)
3. Analyze - Identify dominate stressor using data
4. Model - Predict degradation based on ..
   a) Performance in different location
      a) e.g. performance in FL can be used to predict degradation in NM
   b) Indoor accelerated testing results
      a) e.g. use indoor test results to predict degradation



Test PV Plants

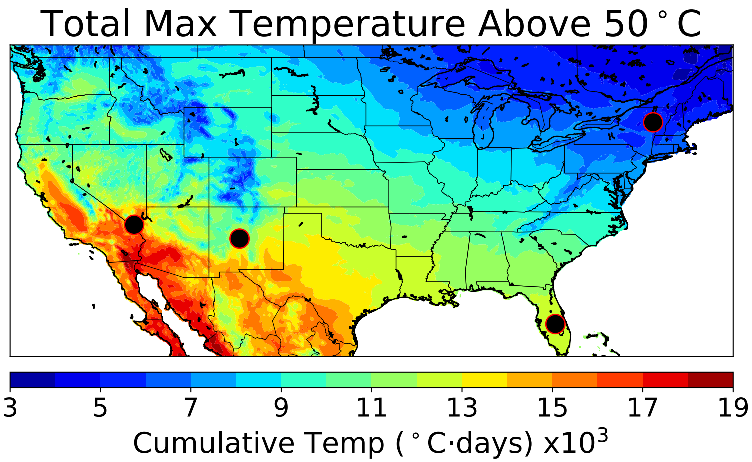
Test PV Plants – Sensors & Locations

Systems

1. Regional Test Center Reference (pv-dashboard.sandia.gov)
1. Size: ~3.4 kW
2. 12 Modules in Series
3. Suniva OPT270 Black

Locations

1. New Mexico
2. Florida
3. Nevada
4. Vermont



Sensors

1. DC Current & Voltage
2. Plane of Array Irradiance
3. Module Temp. Sensors

Degradation Stressor Identification

Data Analysis Methodology: Preprocess

1. Translation

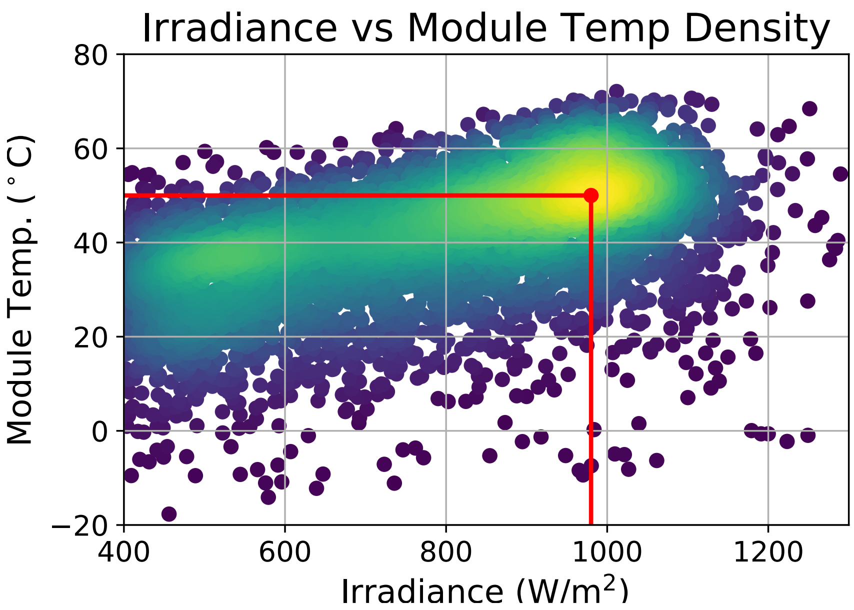
$$I_o = \frac{E_o}{E}\left(\frac{I_{actual}}{1 + \alpha(T_m - T_o)}\right)$$

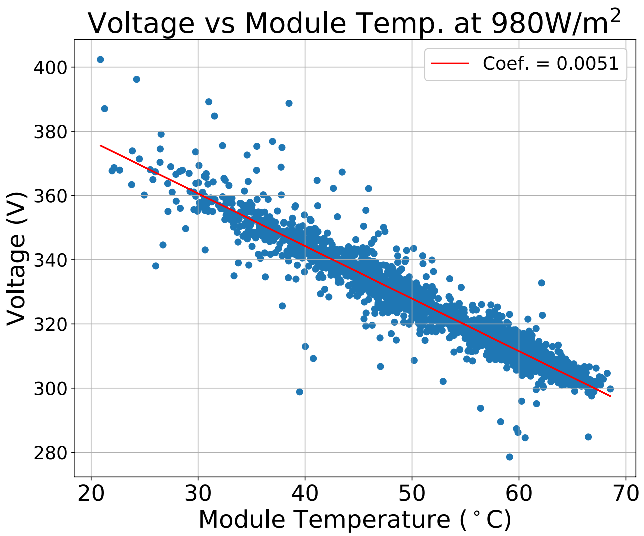
$$V_o = \left(\frac{V_{actual}}{1 + \beta(T_m - T_o)}\right)$$

2. Data Quality Filter: Z-Score

$$Z_{P,i} = \left[\frac{Y_{P,i} - M_P}{|MAD|}\right]$$

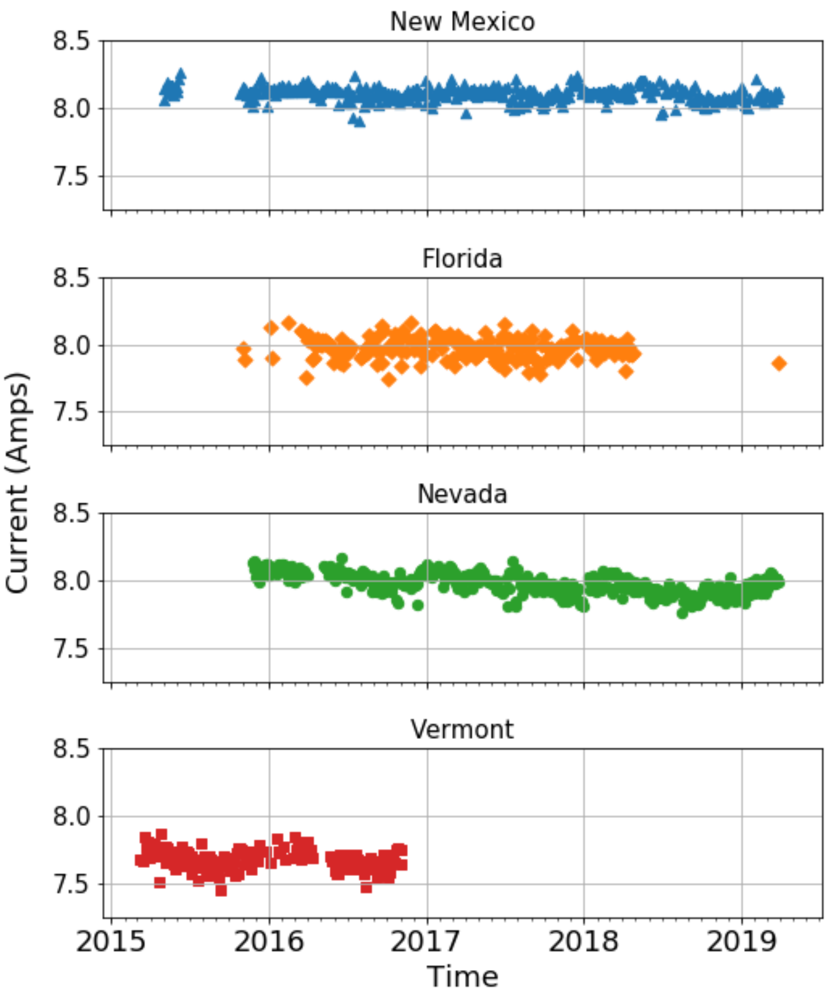
where:
$Y_{P,i}$ parameter at time i,
M_P the median, and
$|MAD|$ the median of the absolute deviation



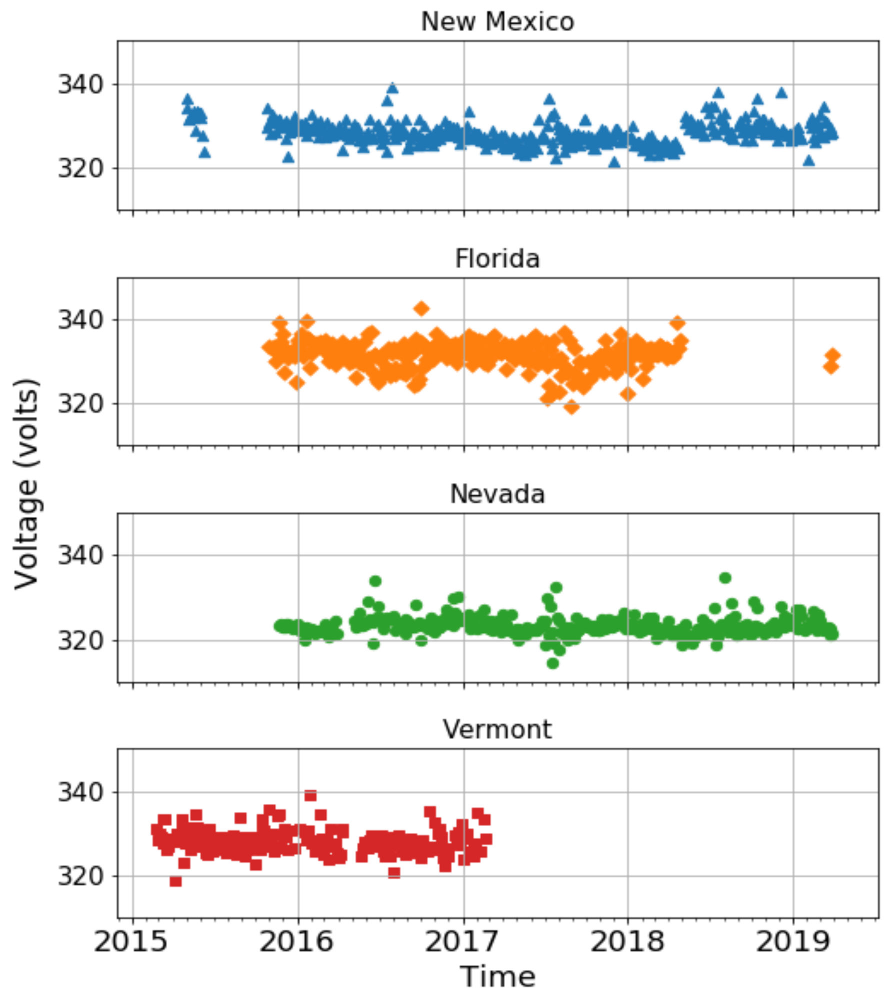


Data Analysis Results: Time-Based Analysis

Translated Max Power Pont Current



Translated Max Power Point Voltage



Data Analysis Methodology – Stressor Exposure

3. Compute Stressor Exposure

- Thermal Cycling [1]

$$CS_{\Delta T} = \sum_{t=0}^{n} (\Delta Tm(t)) exp\left(\frac{-Q_a}{k_b\, T_m(t)}\right)$$

- Wind Load

$$CS_{wind} = \sum_{t=0}^{n} (P_{wind}(t)) exp\left(\frac{-Q_a}{k_b\, T_m(t)}\right)$$

- Humidity [2]

$$CS_{hum} = \sum_{t=0}^{n} (A) exp\left(\frac{-Q_a}{k_b\, T_m(t)}\right) RH(t)^n$$

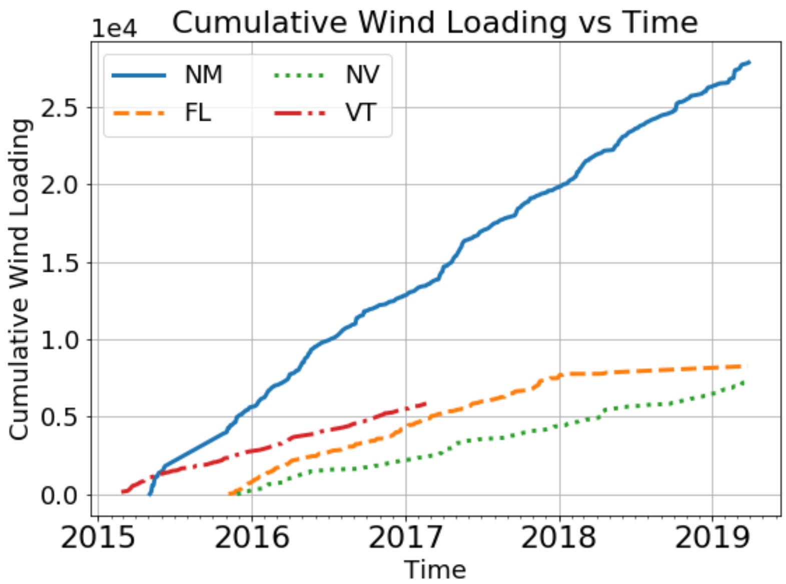
- Radiation [3]

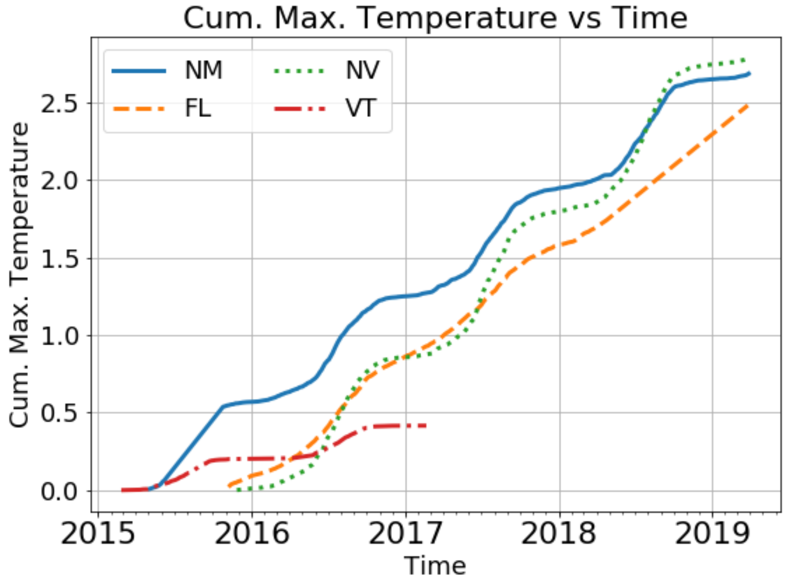
$$CS_{rad} = \sum_{t=0}^{n} (E(t)) exp\left(\frac{-Q_a}{k_b\, T_m(t)}\right) (0.05)$$

- Temperature [4]

$$CS_{temp} = \sum_{t=0}^{n} (Tm(t)) exp\left(\frac{-Q_a}{k_b\, T_m(t)}\right)$$

4. Least-Squares Analysis
   - Compute slopes
   - Compare slopes





Data Analysis Results: Stressor-Based Analysis

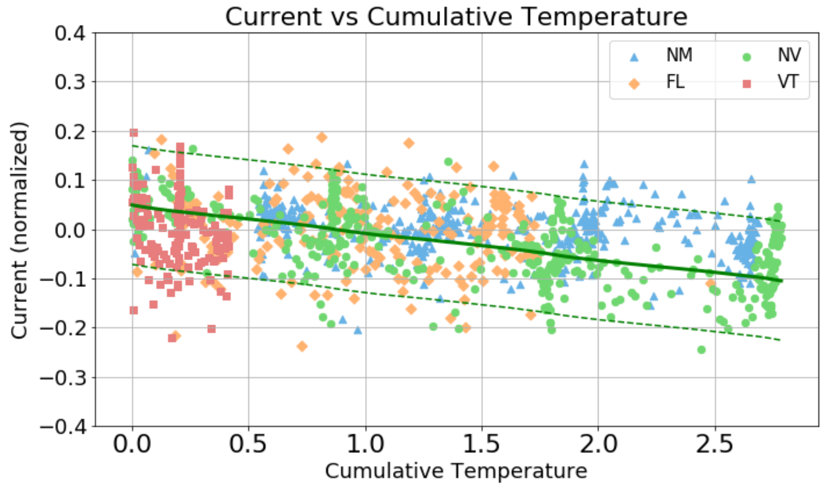
1. System Current Least-Square Reg. Slopes
    1. Time: Similar
    2. Stressor-Based: Similar w/ Cumulative Temperature
2. System Voltage Least-Square Reg. Slopes
    1. Time-Based: Variation among sites
    2. Stressor-Based: Similar w/ Temp. Cycling

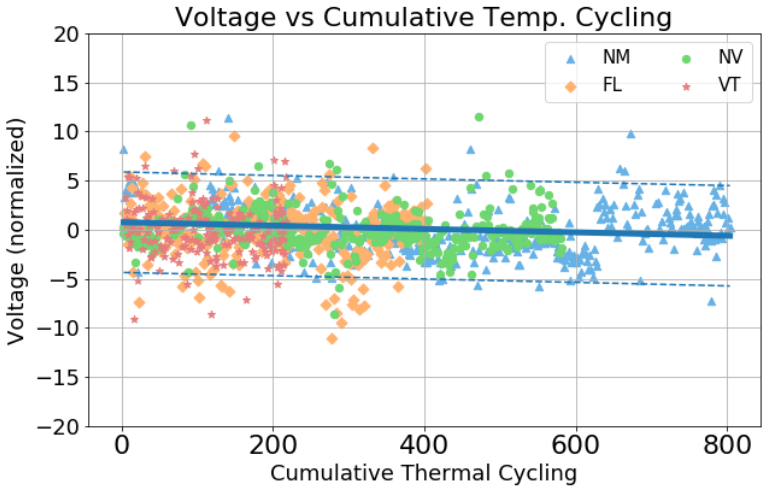
Time-Based Slopes

	NM	FL	NV	VT
Current	-0.01	-0.13	-0.05	-0.026
Voltage	-0.26	-0.58	-0.03	-0.67

Stressor-Based Slopes

	NM	FL	NV	VT
Current vs Temp	-0.018	-0.018	-0.028	-0.13
Voltage vs Temp Cycling	-0.002	-0.0017	-0.001	-0.006





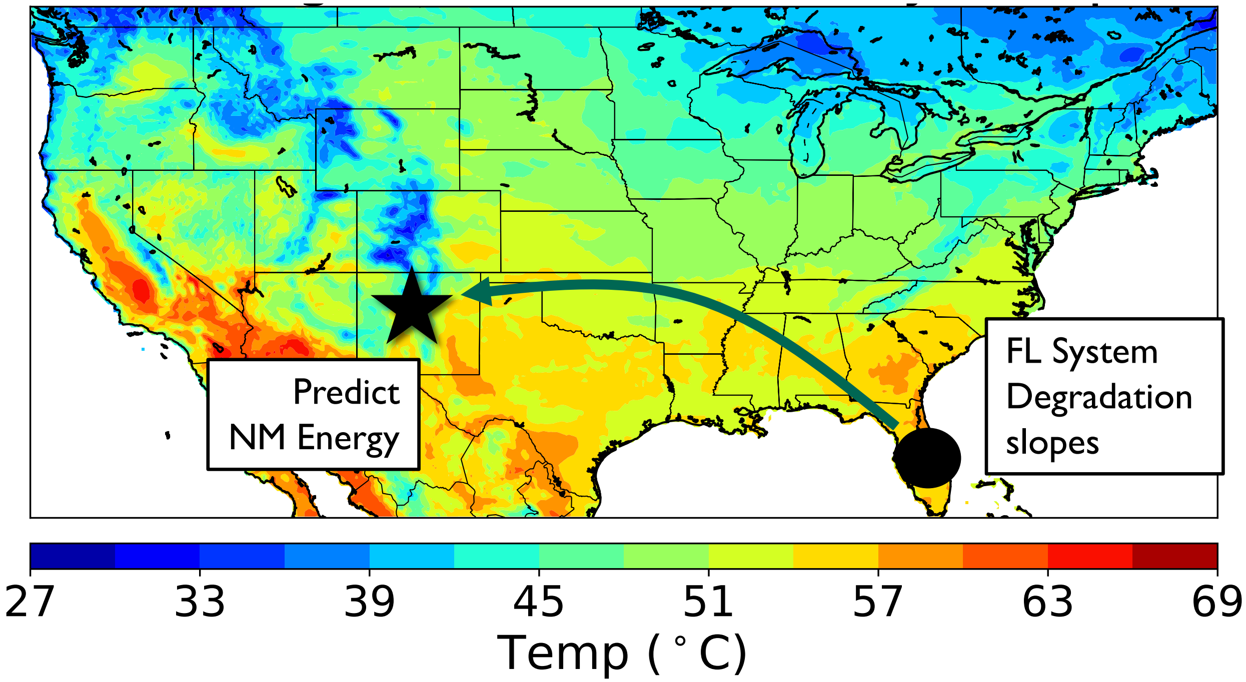
Degradation Modeling

Degradation Models Methodology: Outdoor Data

1. P_{model} = SAPM + Degradation
   - Sandia Array Performance Model (SAPM)
   - Linear Degradation = f(stressor)

2. Time-Based Model
   - Assume 0.5%/year

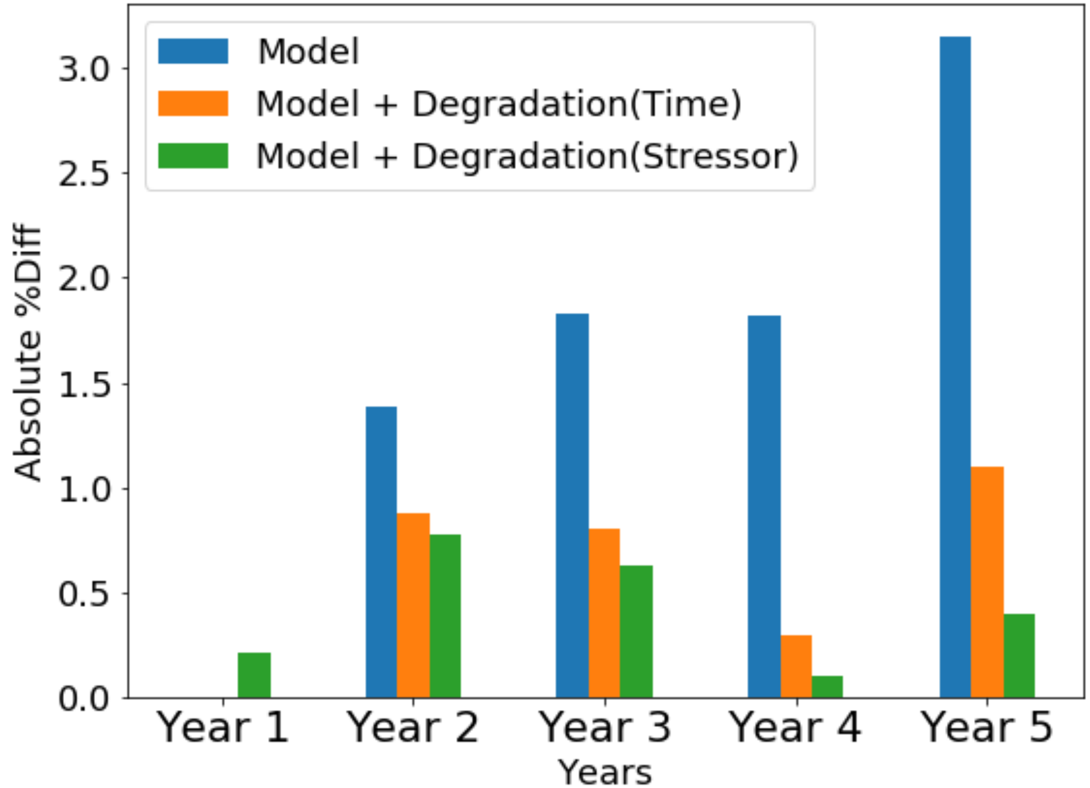
3. Stressor-Based Model
   - Model NM system based on FL results



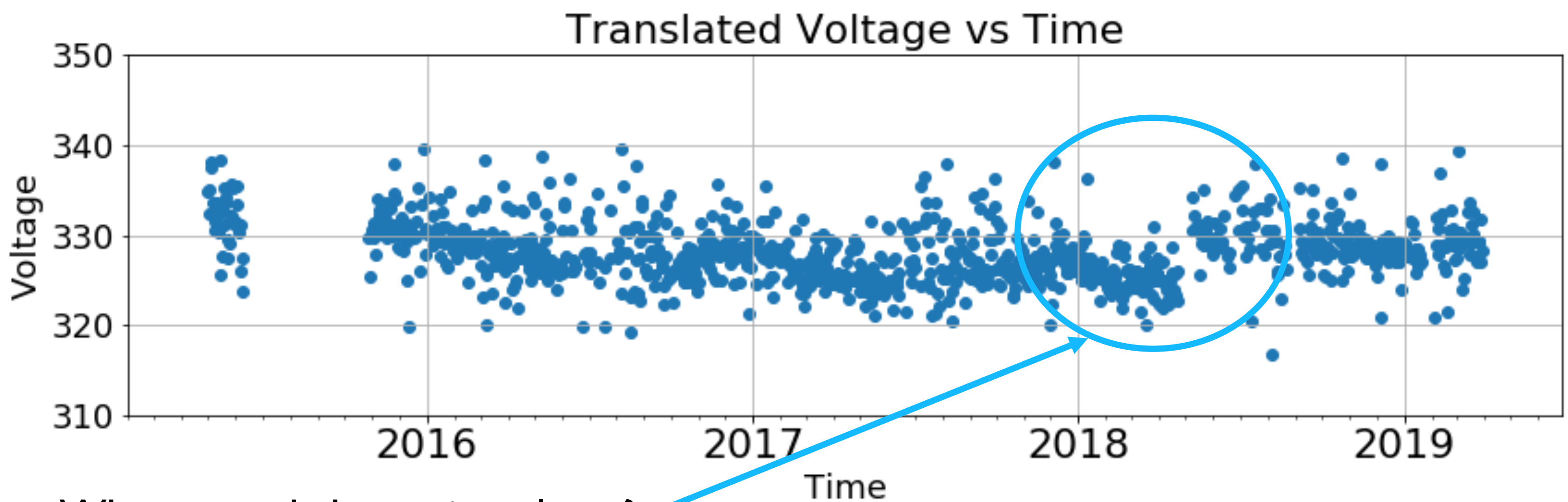
Degradation Models Results: Outdoor Data

1. No Degradation Model
    1. Error = 1.4%
2. Time-Based Degradation Model
    1. Error = 0.57%
3. Stressor-Based Degradation Model
    1. Error = 0.45%

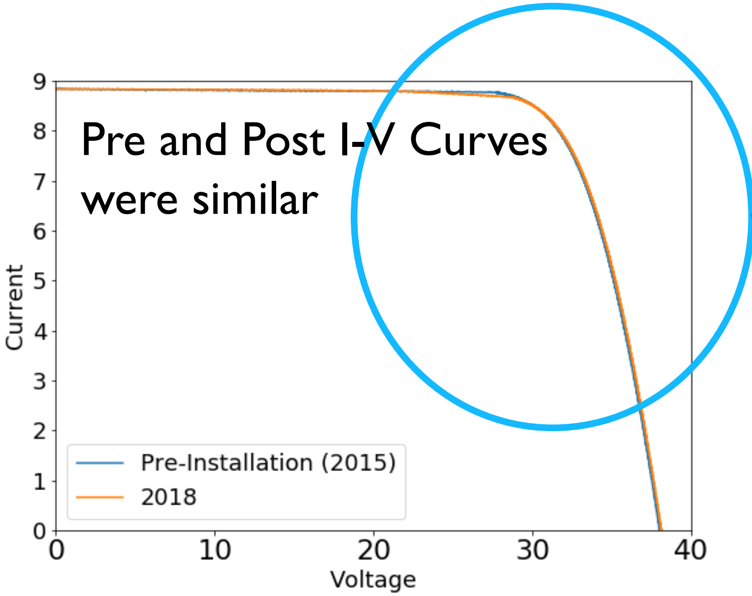
Difference Between Actual and Modeled energy generation for each year

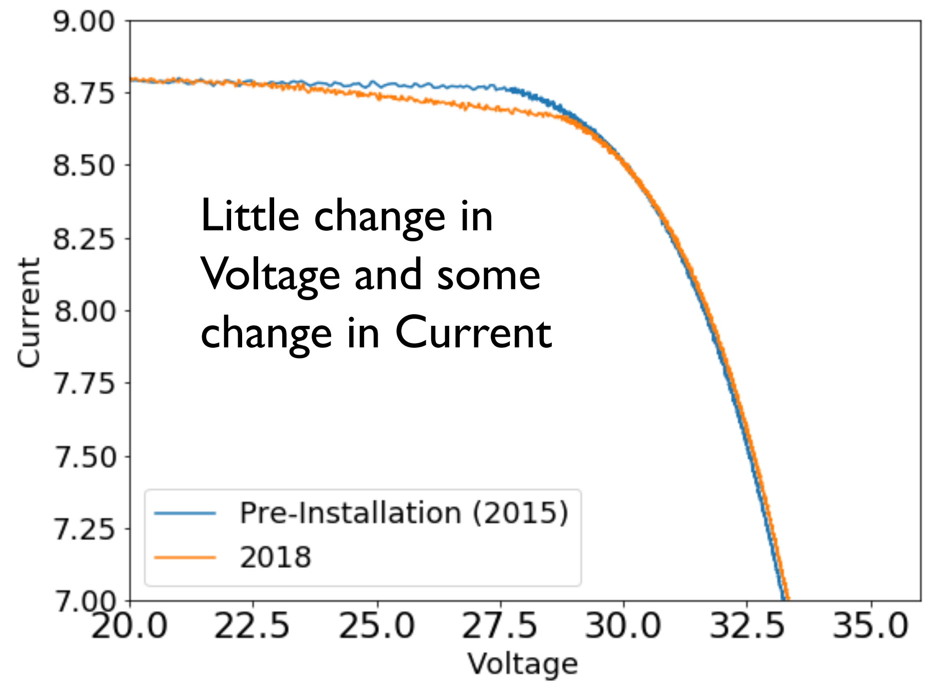


Data Measurement/Analysis Discussion



What caused change in voltage?





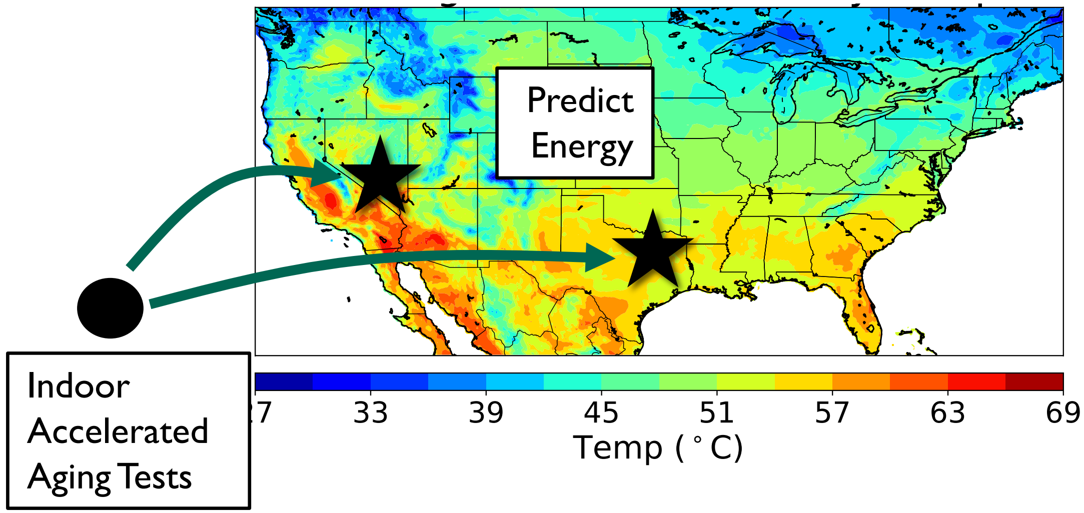
Conclusion/Future Work

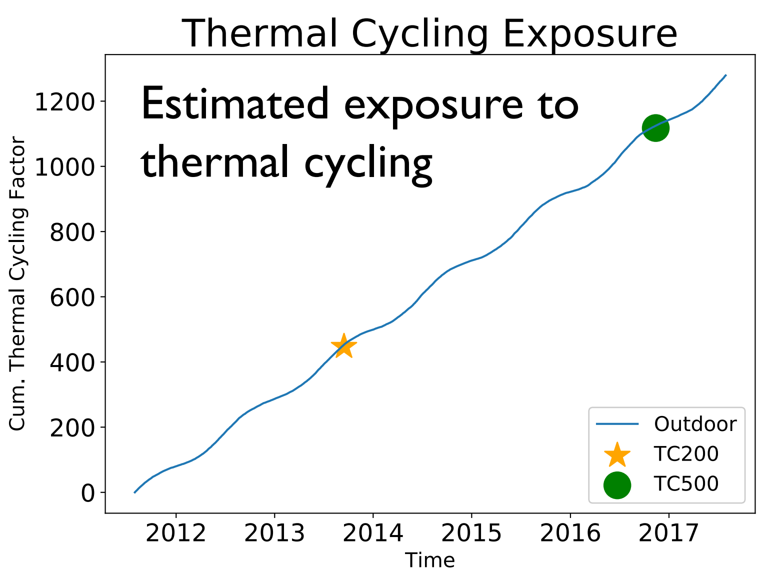
Conclusion

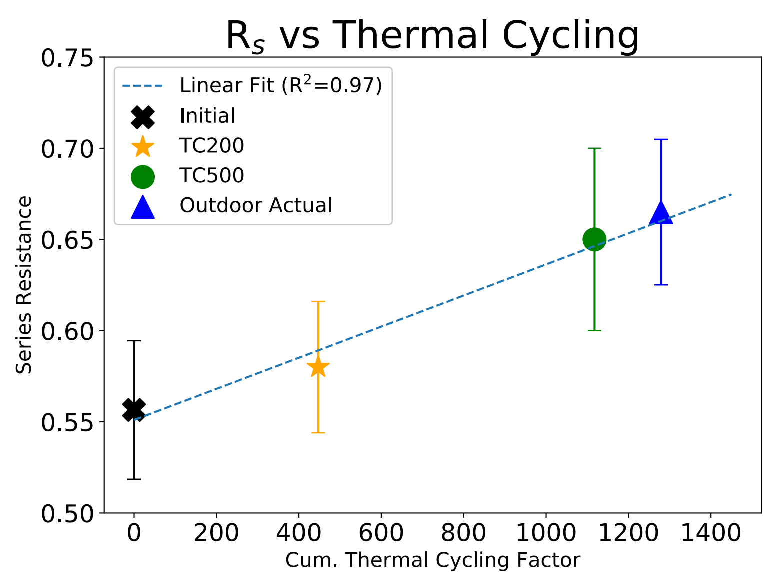
1. Stressor Identification
   1. Voltage:
      1. Cumulative Thermal Cycling
   2. Current:
      1. Cumulative Temperature
2. Improved Modeling
   1. Improved accuracy
   2. Better than standard assumption (0.5%/year)

Future Work: Degradation Models Based on Indoor Tests

1. Estimate Overall Exposure
   a. Indoor - IEC 61215
   b. Outdoor – Weather measurements
2. Performance
   1. Measure Series Resistance from I-V Curves
3. Evaluate
   1. Relationship between change in Rs and Cumulative Temp. Cycling







Questions

References

[1] V. Vasudevan and X. Fan, "An acceleration model for lead-free (SAC) solder joint reliability under thermal cycling," in *2008 58th Electronic Components and Technology Conference*, May 2008, pp. 139–145.

[2] N. C. Park, W. W. Oh, and D. H. Kim, "Effect of Temperature and Humidity on the Degradation Rate of Multicrystalline Silicon Photovoltaic Module," 2013.

[3] M. Koehl, D. Philipp, N. Lenck, and M. Zundel, "Development and application of a UV light source for PV-module testing," in *Reliability of Photovoltaic Cells, Modules, Components, and Systems II*, vol. 7412. International Society for Optics and Photonics, Aug. 2009, p. 741202.

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