Module Lifetime Prediction through Integrated Modeling of Known Failure Modes

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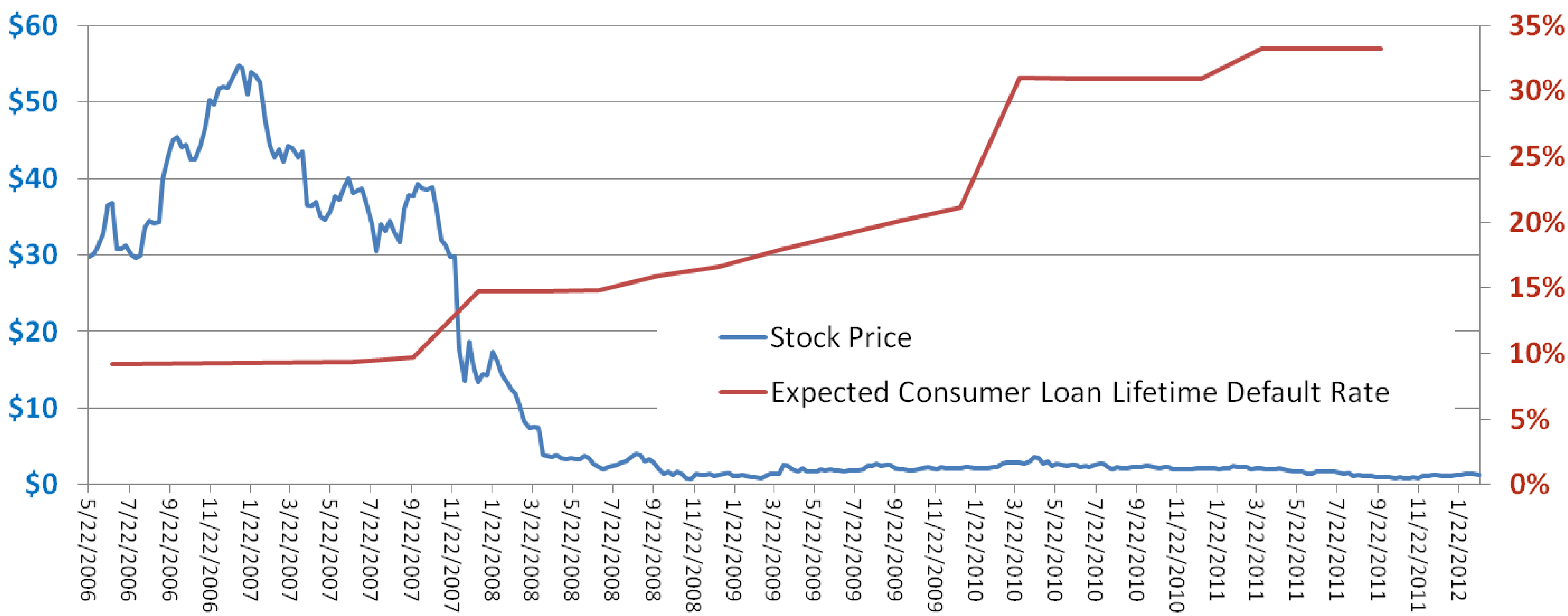
Motivation: analogy from the financial industry

- NYSE-traded **consumer loan** (not PV!) company, >$3B market cap at peak
- Balance sheet impact if defaults exceed expectations or default expectation increases
- Company used empirical data to infer future default behavior … not a behavioral model



What can PV companies do to be vigilant against "black swans"?

- Quality and Reliability Processes[1]
  - Reliability:
    - Failure Mode and Effects Analysis, Quality & Reliability Test Plans during product design / process development
  - Manufacturing Quality
    - Supplier quality control: Change notification, PSC (Prevention, Standardization/Simplification/Scalability, and Customer satisfaction) audits, STARS (Supplier Total Achievement Rating System) score
    - Statistical Process Control, Out-of-box audit, Reliability Monitoring Program
- Research into potential failure and degradation modes
  - Failure analysis on fielded modules to seek new possible modes
  - Physics of failure research into individual modes
  - Evaluate expected failure & degradation budgets/timing via physics-based modeling

[1] DeGraaff, "Case study: SunPower Manufacturing Quality Methods", NREL 2010 PVMRW; DeGraaff et al, "Qualification, manufacturing and reliability testing methodologies for deploying high-reliability solar modules", PVSEC Valencia, Spain, 2010.

PVLife

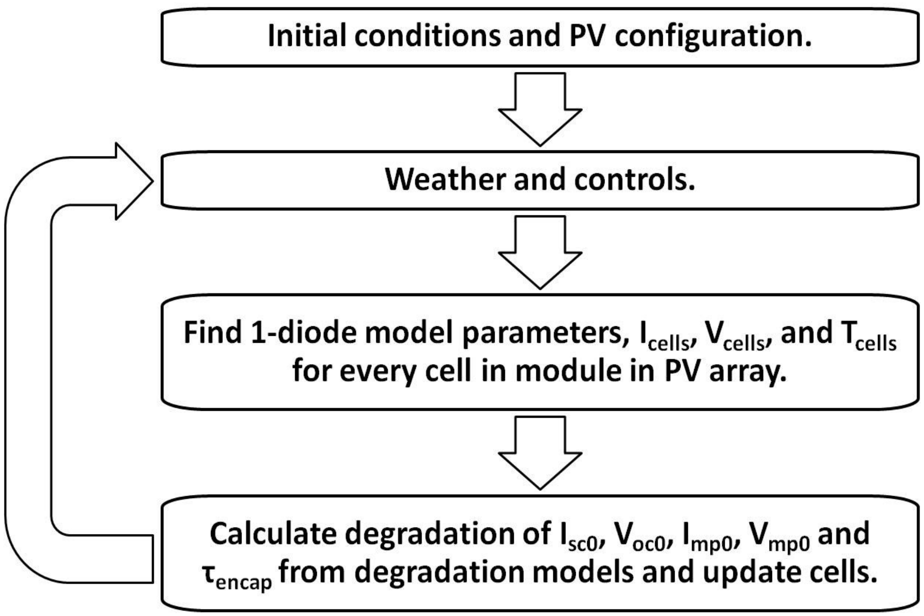
PVLife is:

- A behavioral model for PV modules, strings, eventually systems
- Attempts to capture as many known drivers as possible
- Includes key physics and chemistry models
  - Electrical/thermal behavior affects degradation and failure rates
  - Degradation affects electrical/thermal behavior

Why are we investing in this?

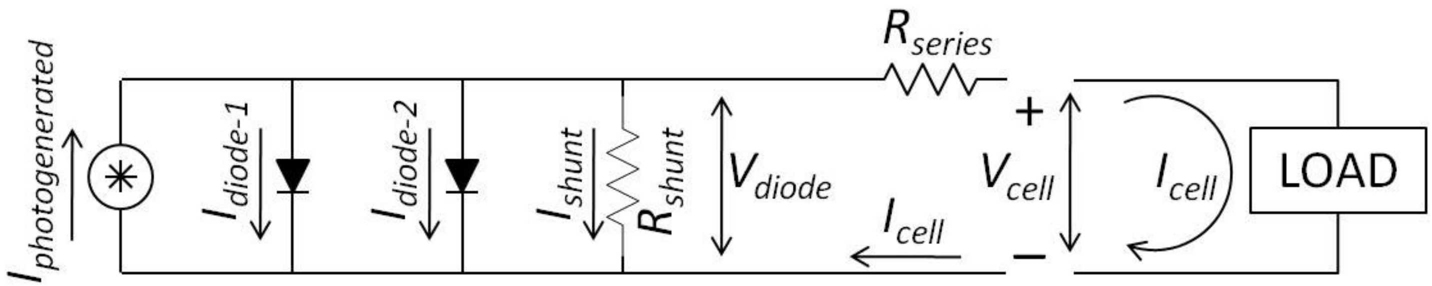
- Reduce uncertainties in our expectations, catch issues early
- Understand possible positive (bad) feedback loops that simple models cannot capture
- Rationalize and improve designs
- Quantify warranty expectations, degradation budget

Using array configuration & weather data, model computes performance for all cells in PV system



Electrical and thermal submodels

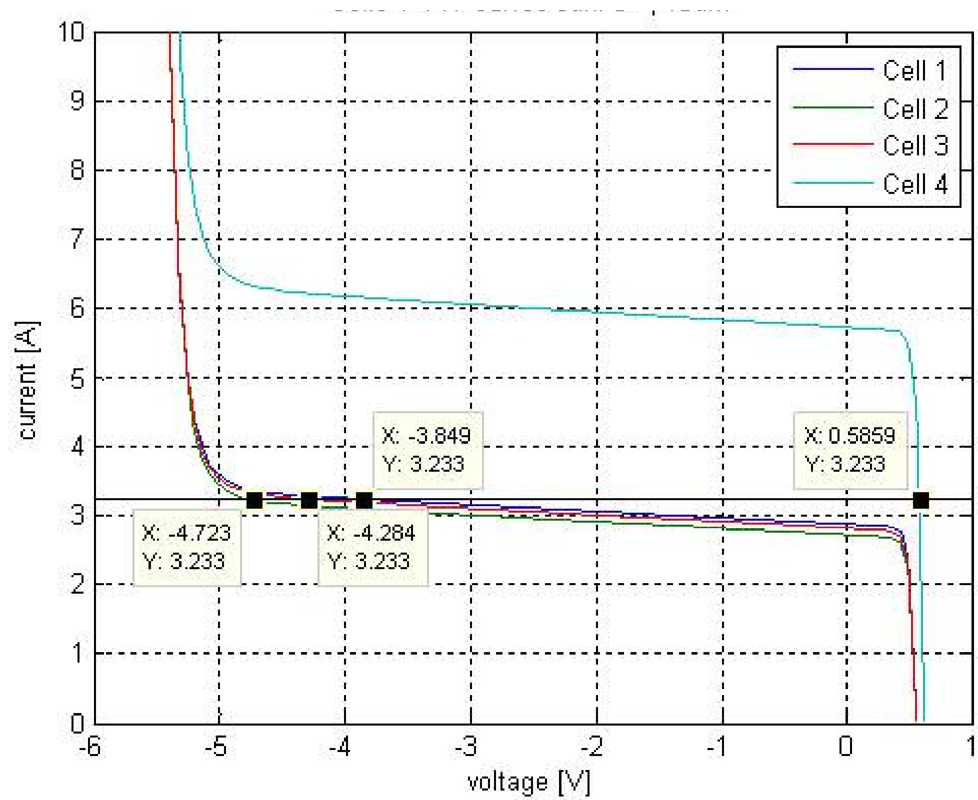
- 1- or 2-diode electrical model for each cell



- Thermal model for each cell
  - Resistance analogy w/quasi-steady state assumption
- Quasi-steady state assumptions
  - Electrical and thermal equilibrium established much faster than any form of degradation

Electrical characteristics obtained from data

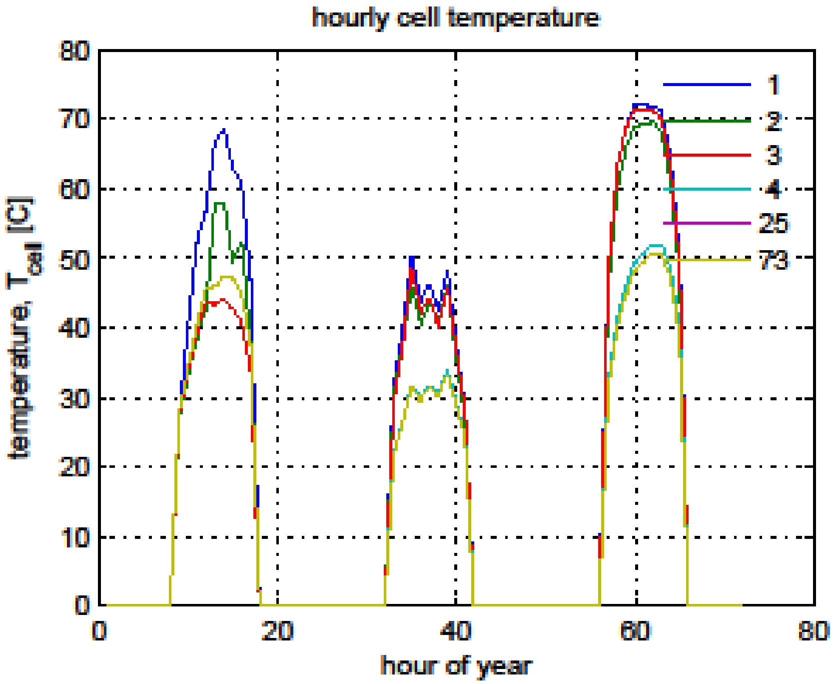
- I-V curves for cells obtained from real production data
  - Statistical or specific cases
- Sandia database for temperature coefficients
- Bypass diodes and other components also based on measured electrical characteristics

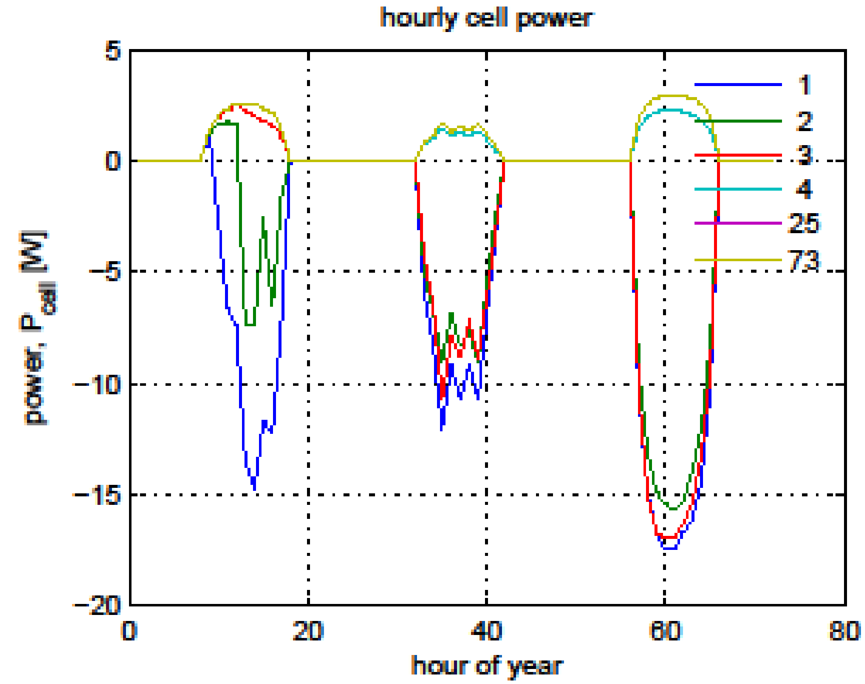


Example: I-V curves for 4 cells in series; Cells 1-3 are shaded

Cell-level model handles mismatch, shading

Example: a 72-cell module with 1st 3 cells progressively shaded, actual weather for Jan. 1-3, 2011



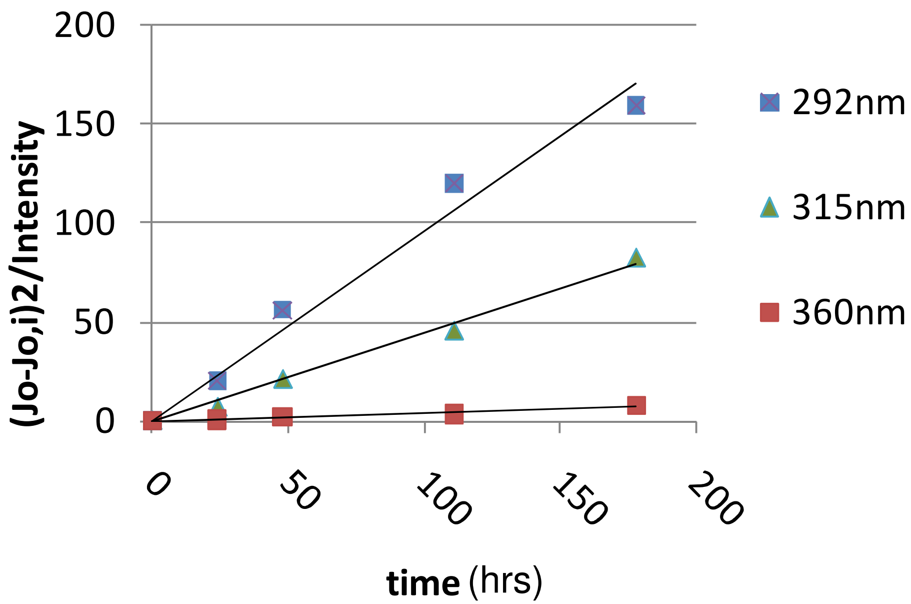


Potential Degradation and Failure Modes for PV Panels

- Continuous degradation modes
  - UV degradation
  - Encapsulant transmission
  - High voltage (potential-induced) degradation / polarization
  - Soiling
  - Reverse-bias cell degradation
  - Humidity-induced cell degradation
  - Cell cracks
  - Metal corrosion
  - Ion migration
- Binary failures
  - Solder joint failure
  - Bypass diode failure
  - Encapsulant adhesion failure
  - Backsheet cracking/delamination

Degradation mode example: UV degradation

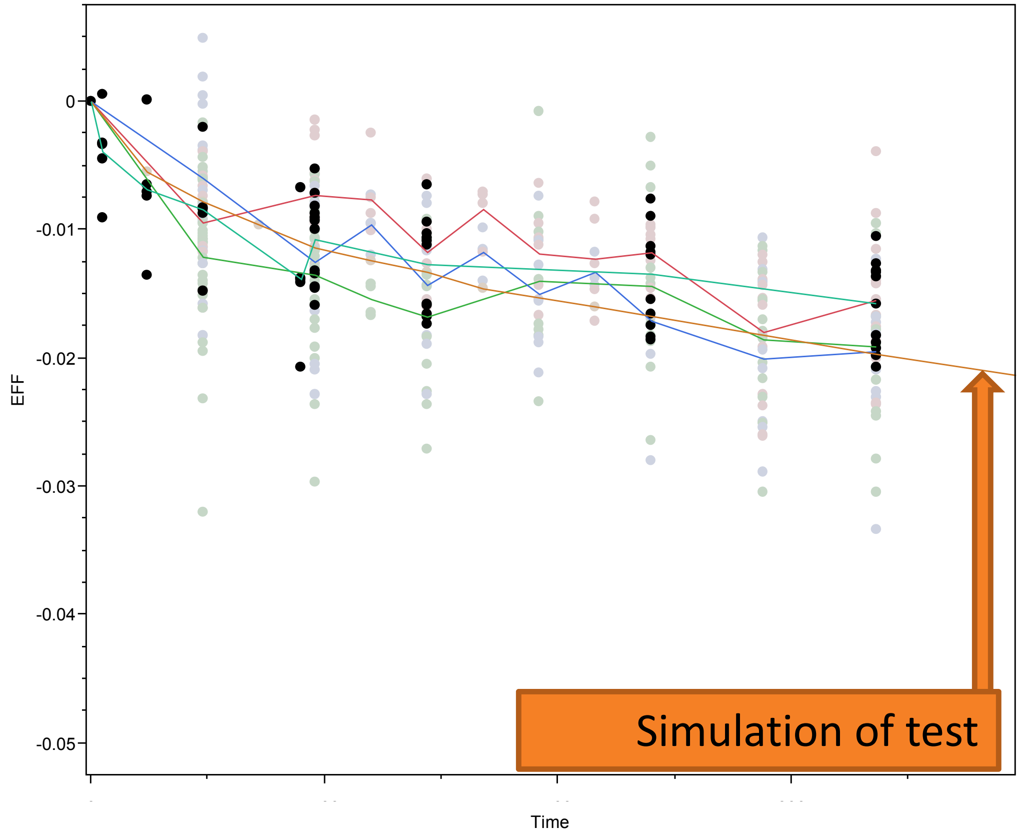
- Silicon subject to slight UV surface damage over time
  - Effect on recombination current, J_o
  - Initial rate consistent with MOSFET degradation literature
- Extensive modeling and laboratory observations of SunPower cells:
  - Scaling of initial rate
  - Strong wavelength dependence



$$J_0 = J_{0,i} + \sqrt{\int_{250nm}^{400nm} \left(\frac{m \cdot t}{I_{bandpass}} \right) \cdot I(\lambda, t)\, d\lambda}$$

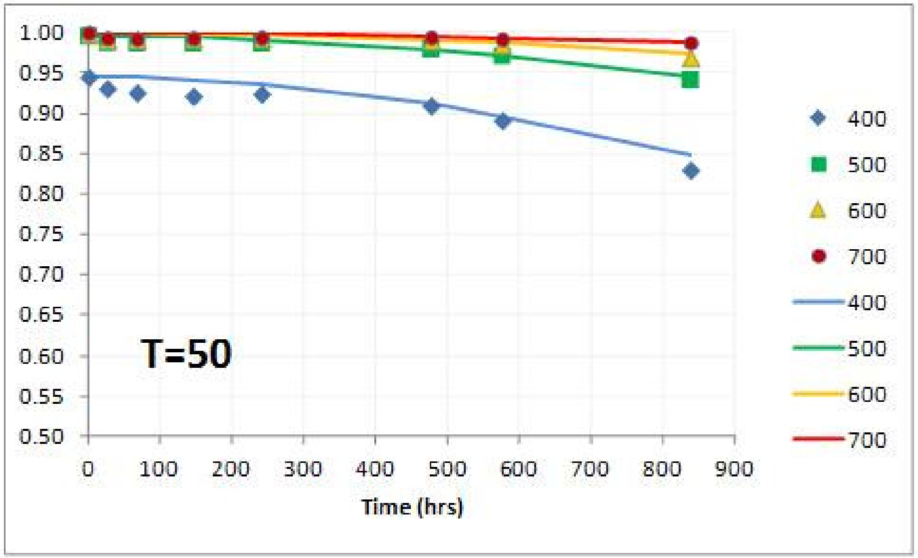
Cell UV degradation integration into PVLife

- Accelerated test data are obtained by exposing cells from multiple production lines to various UV intensities and temperatures
- Differential equations are constructed from fits of a physical or empirical model to lab data.
- Model is backtested by ensuring match to accelerated test data
  - Raw cells and EVA-encapsulated coupons
  - Temperature-dependent data
- Model is then validated against field exposure data

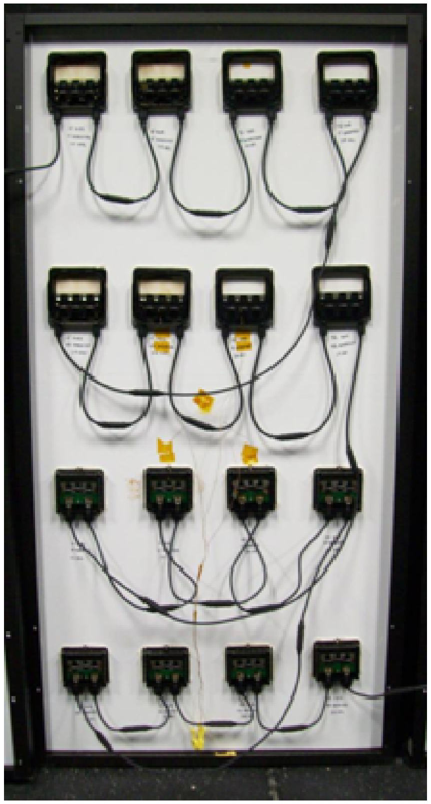


Photothermal Encapsulant Transmission Degradation

- UV & heat causes browning, decreasing transmission
- Approach:
  - Photothermal kinetics model, coupled with Beer's Law for absorption
  - Fit lab data to kinetics model, assess fit and reciprocity
  - Write as differential equations in time for absorber/chromophore concentration
  - Backtest against accelerated data, cored EVA samples from RMA modules

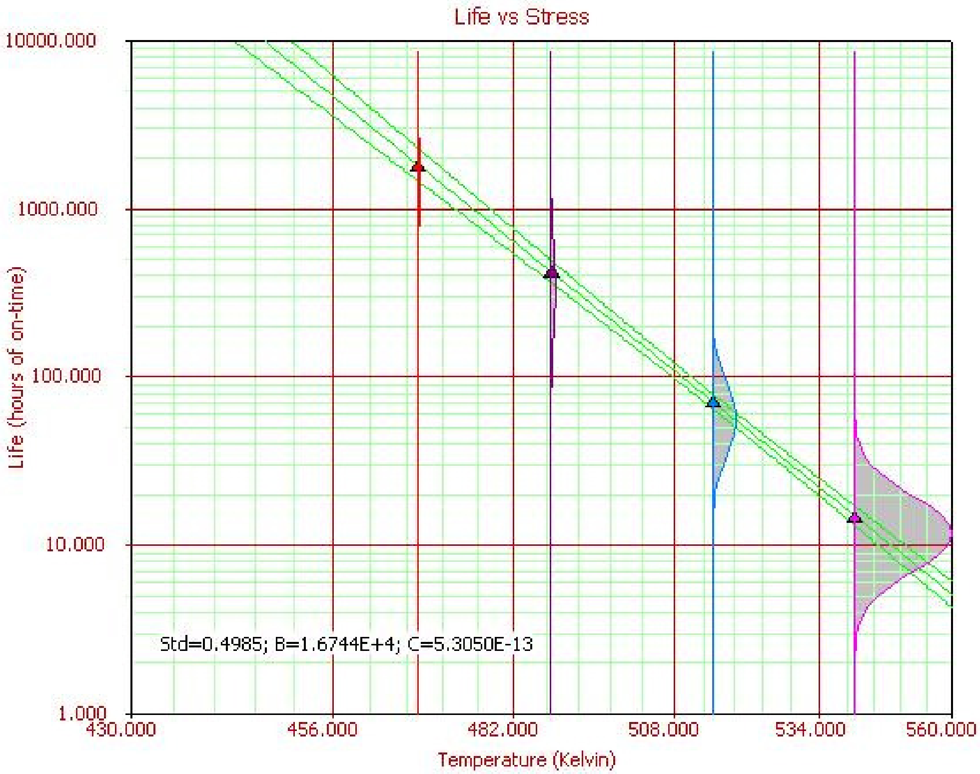


Failure mode example: Bypass diode failure



Dummy module,
DH 85, 6A current

Custom ceramic
diode fixture
Up to 16A current

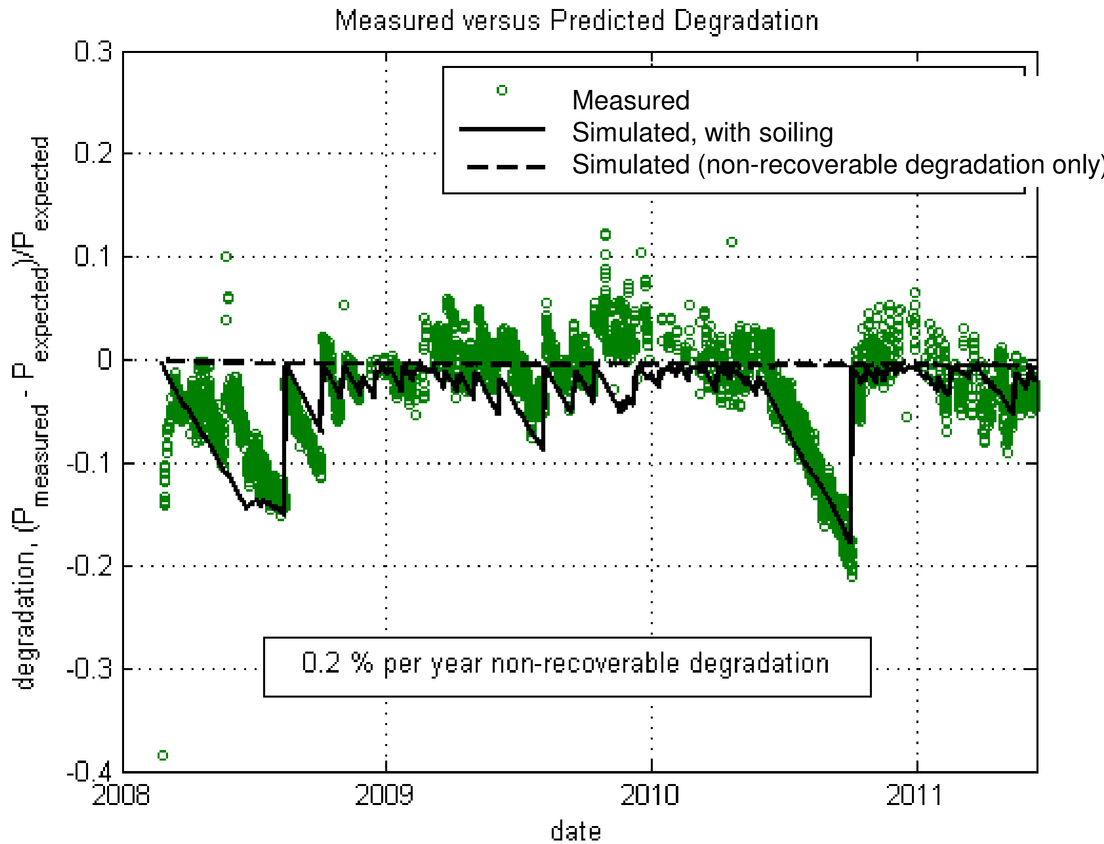


Results: *Lognormal Arrhenius*

Due to low reverse bias voltage, SunPower modules do not require bypass diodes for reliability, but we still care about diode failure to predict performance accurately

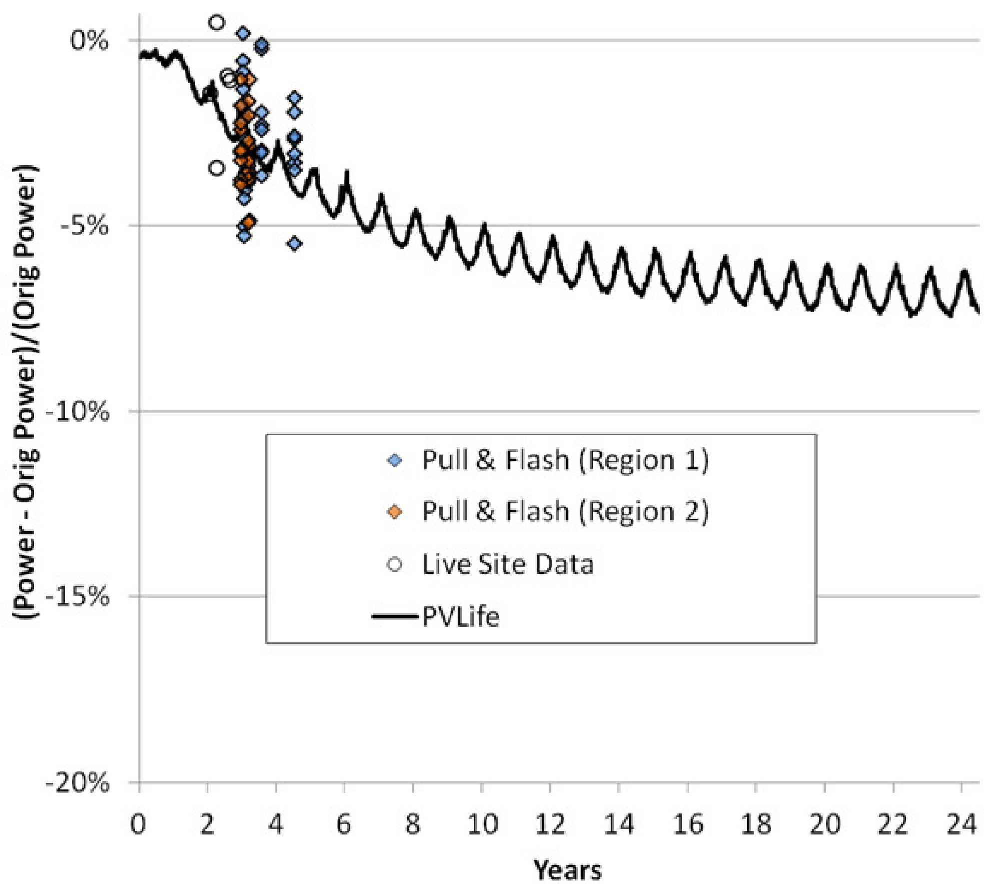
Results: Short-term

- Site in Manteca, CA, USA; rooftop system, SunPower modules. Weather data including rainfall from nearby meteorological stations
- Good agreement overall
- “Sawtooth” waveform due to soiling (and recovery with rainfall/washes) dominates, but is recoverable
- Simulation predicts initial NON-recoverable degradation = -0.2%/yr



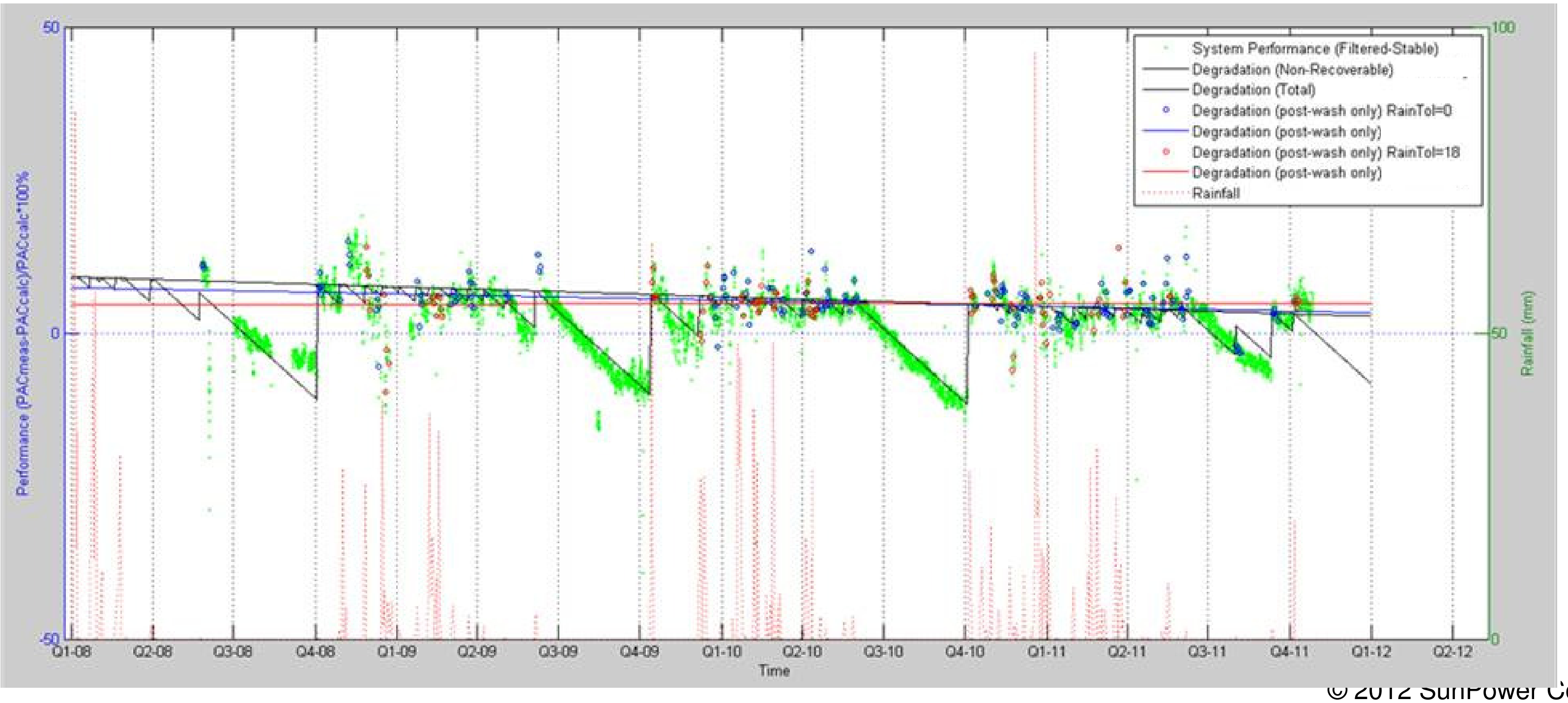
Results: Long-term simulations compared with field data

- Model within scatter; live-site data has significant uncertainty
- Data based on
  - Live site AC production data
  - Modules pulled from residential rooftops and re-flashed after time in the field.
- Prediction is well above SunPower warranty line
  - Rationalizes low RMA rates to date



Uncertainty in assessing degradation from site monitoring data can be substantial

- Normalize actual output by model's expected (Similar approach to Jordan, Kurtz et al)
- Filter data to only look at clear, stable-irradiance days
- Two approaches to deal with soiling:
  - Filter data by post-rainfall (or wash) only … within *x* days of *y* mm of rainfall
  - Fit data using model with additional free parameters to account for soiling effects
- Results ±0.8% … prompting us to confirm with Pull/Flash program



Conclusions

- Physical model based on extensive lab and field research suggests low (and slowing) degradation of SunPower modules
- Creating this type of model requires a major investment …
  - Substantial investment in experimentation
  - Tens to hundreds of experiments per mode
  - Long timescales for experimentation
- … but it also yields major dividends
  - Major degradation modes are captured
  - We can observe coupling and non-linear effects
  - Able to prevent problems in the design phase, before they reach customers
  - High confidence warranty