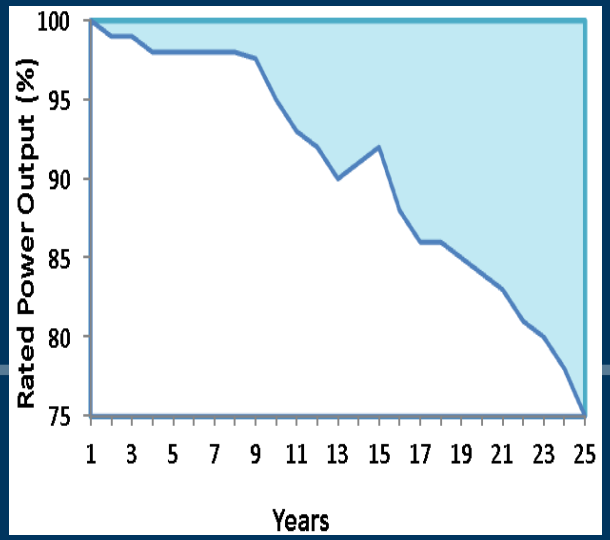
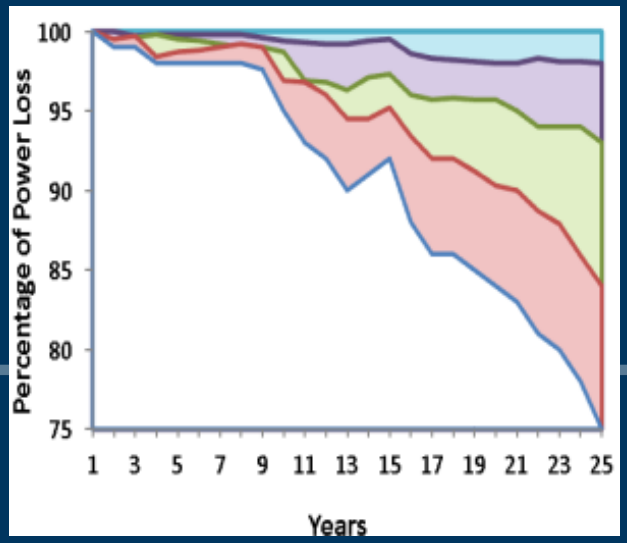
# Lifetime & Degradation Science:
## *A Data Science Approach for Reliability*

**Roger H. French**

**Solar Durability & Lifetime Extension Center**
**Case Western Reserve University**
**Cleveland OH 44106**



# SDLE Acknowledgements

## Research Associates

- Laura Bruckman, Tim Peshek, Yifan Xu

## Graduate Students

- Nick Wheeler, Yang Hu, Abdulkerim Gok,
- Yingfang Ma, Daniel Dryden
- Heather Lemire ,Mohammad Hossain
- Daniel Dryden,, Ian Kidd,
- Yash Gunapati, Yi Hou

## Undergraduates

- Olga Eliseeva, Kelly Peterson, Shay Matthews
- Diana Acosta, Jacob Schimelman,
- Elan Weiss, Robert Kidwell, Joe Degenova

## CWRU Faculty

- GQ Zhang, Jiayang Sun
- Alexis Abramson, Ken Singer
- Hongping Zhao, Nicole Steimetz

## SDLE Staff

- Chris Littman
- Kim Bambakidis

## Solar Durability & Lifetime Extension Center

- Ohio Third Frontier, Tech 11-060, Tech 12-004

## Funding

# Outline

## Lifetime and Degradation Science

- A Data Science approach to reliability

## Photodegradation of Acrylic

- Domain Guided Statistical Analytics

## PV Module Degradation

- Under 85C/85RH Damp Heat Exposure

## Real World PV Module Performance

- Analytics of 20 Brands of PV Modules

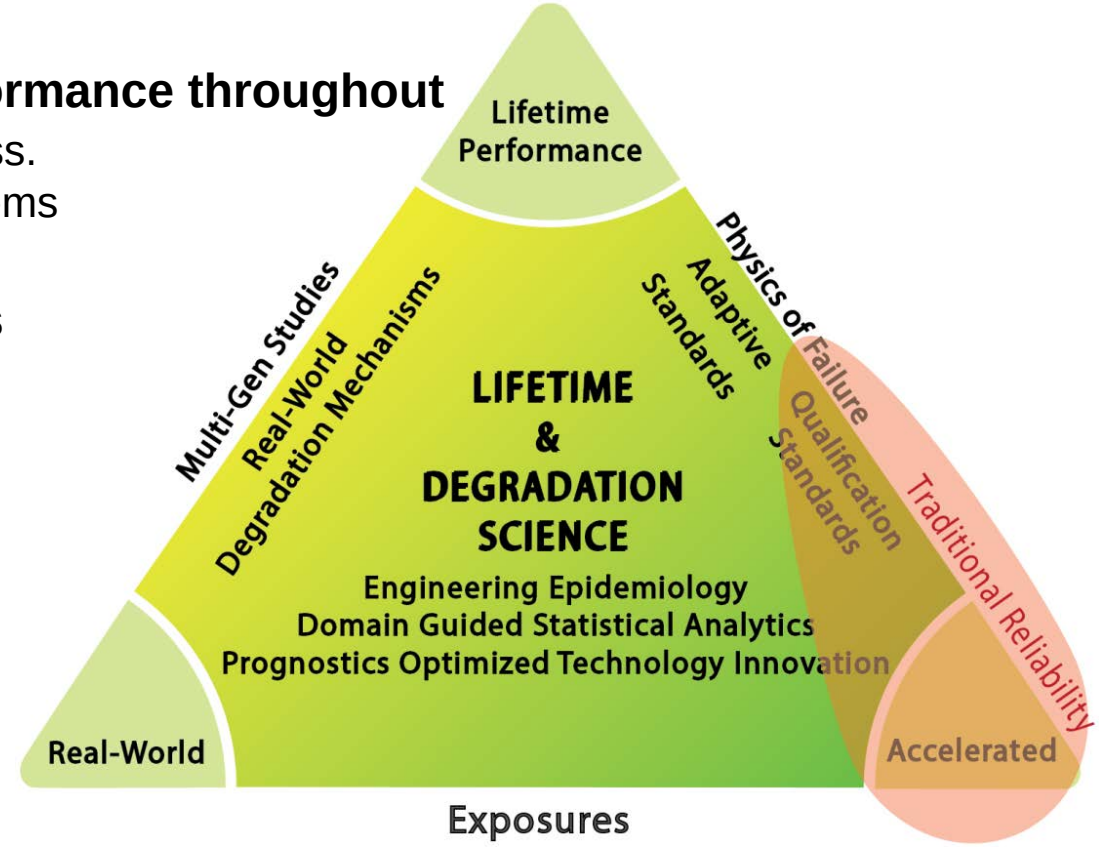
## Conclusions

# The Lifetime & Degradation Science Approach: L&DS Triangle

**Integrate reliability & lifetime performance throughout**
- Entire Technology Development process.
- Applicable to High Cost of Failure systems

**Develop Population-based Studies**
- Real world operational studies
- With accelerated exposure studies
- Across multiple technology generations

**Data Science Approach Using**
- Accelerated Lab Exposures
- Real World Exposures
- Automated Data Acquisition
- Unbiased Analysis




**Develop domain-science guided, statistically informed data analytics**
- Founded in real-world degradation mechanisms

**Based on mechanistic pathway models**
- Predict system's lifetime performance

**Prognostics to guide next generation technology development**

# CWRU

# Solar Durability & Lifetime Extension Center

US Energy Secretary Steven Chu
visits CWRU SDLE & MORE Centers

Focused on the
Societal Impact of
Technology Reliability Fiascos

Long Lived,
Multi-generational
Engineered Systems

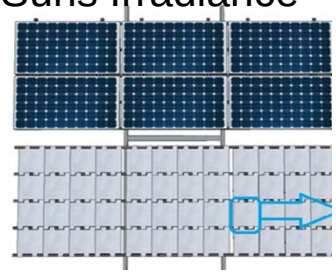
# Solar Durability & Lifetime Extension Center

## Lifetime and Degradation Science

- A stress-response framework
- Determine degradation mechanisms & Rates
- Efficacy and lifetime prediction & standards

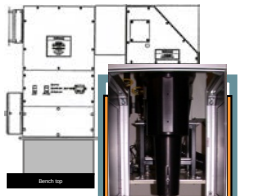

## Exposures: Outdoors, Real Time

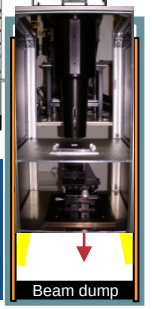
- 14 2-axis trackers & fixed mount
- 142 Modules & 8000 Samples
- 1, 2, 4, 5X Suns Irradiance



## Exposures: Indoors, Accelerated

- Solar Simulators: 1-50 & 50-1200X Suns
- QUV/Spray, Q-Sun, Q-Fog
- CSZ Environmental Test Chambers





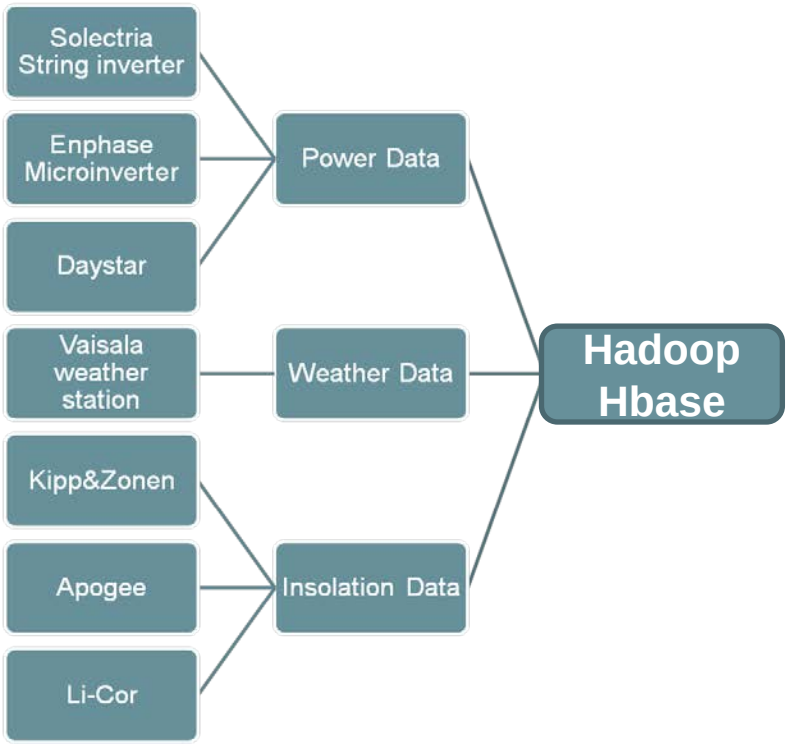

## Evaluations:

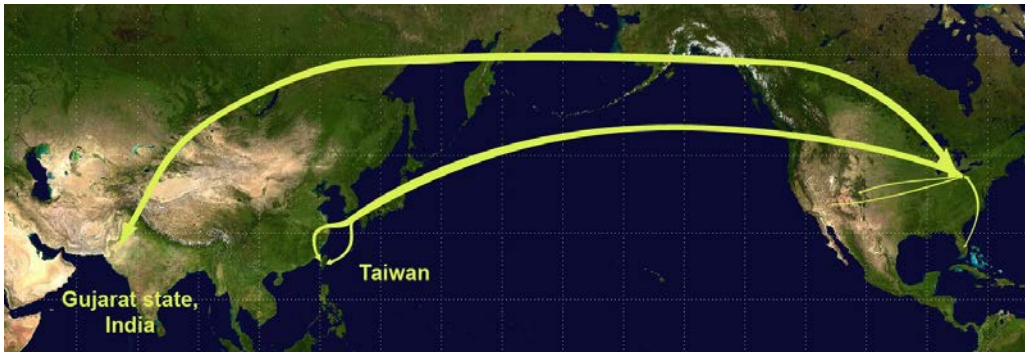
- Optical, Interfacial, Physical
- IR, Raman, UV/Vis VUV,
- Ellipsometry, Light scattering

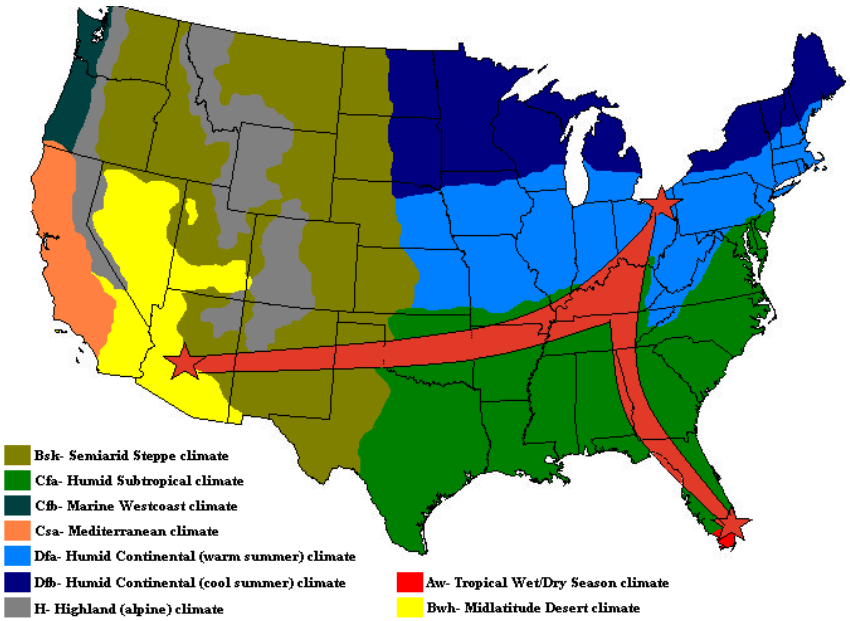
## Integration/Fabrication

- Mini- & full size modules

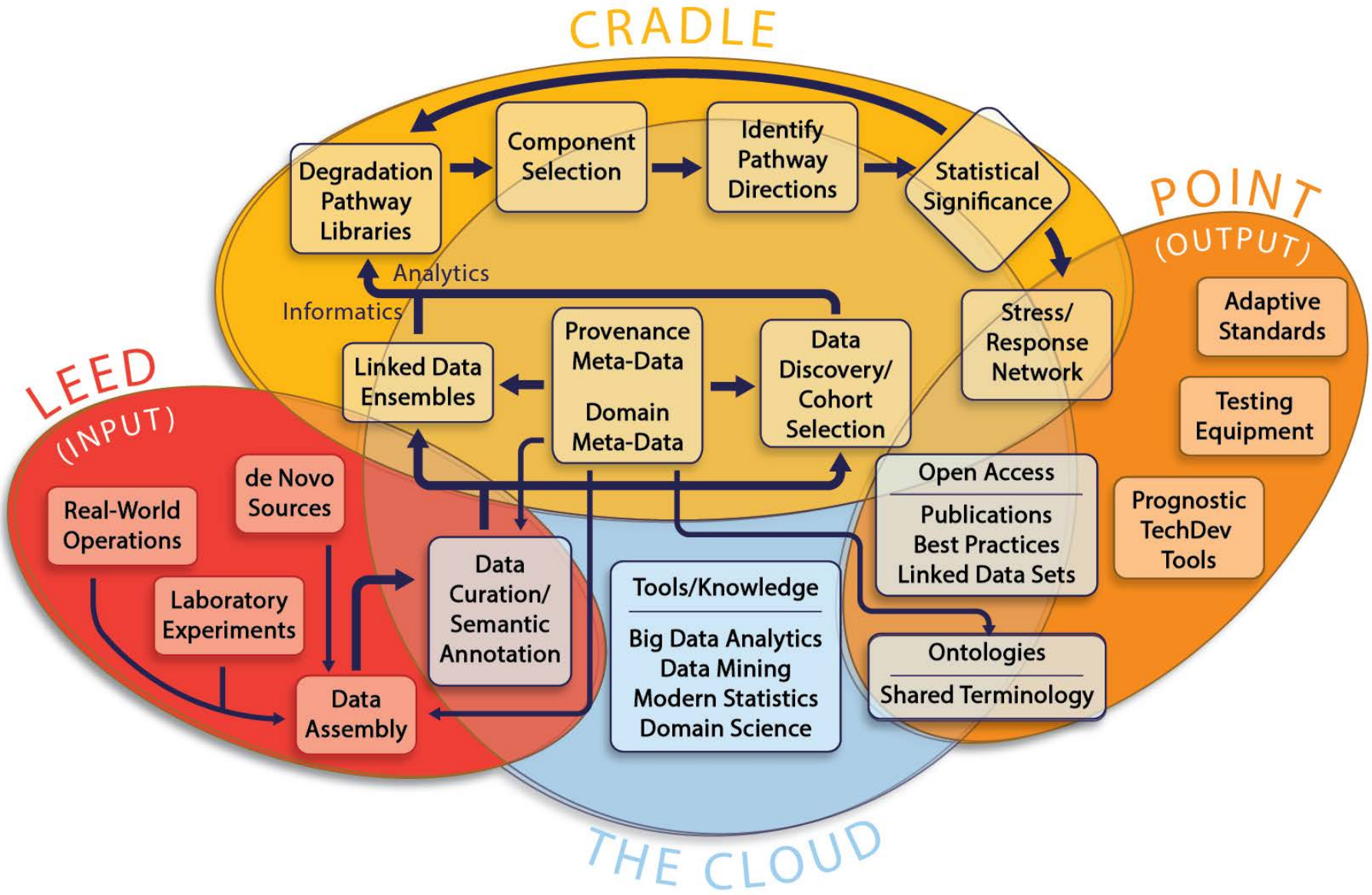

# Energy-CRADLE: data source



# L&DS: System for Lifetime and Durability



# Hadoop/Hbase Energy CRADLE Operational

## Energy CRADLE

- Up and Running
- Processing Data
- Of 4 SunFarms

## Store 7 Years Data

- Minute by Minute

## Only at 10% Capacity

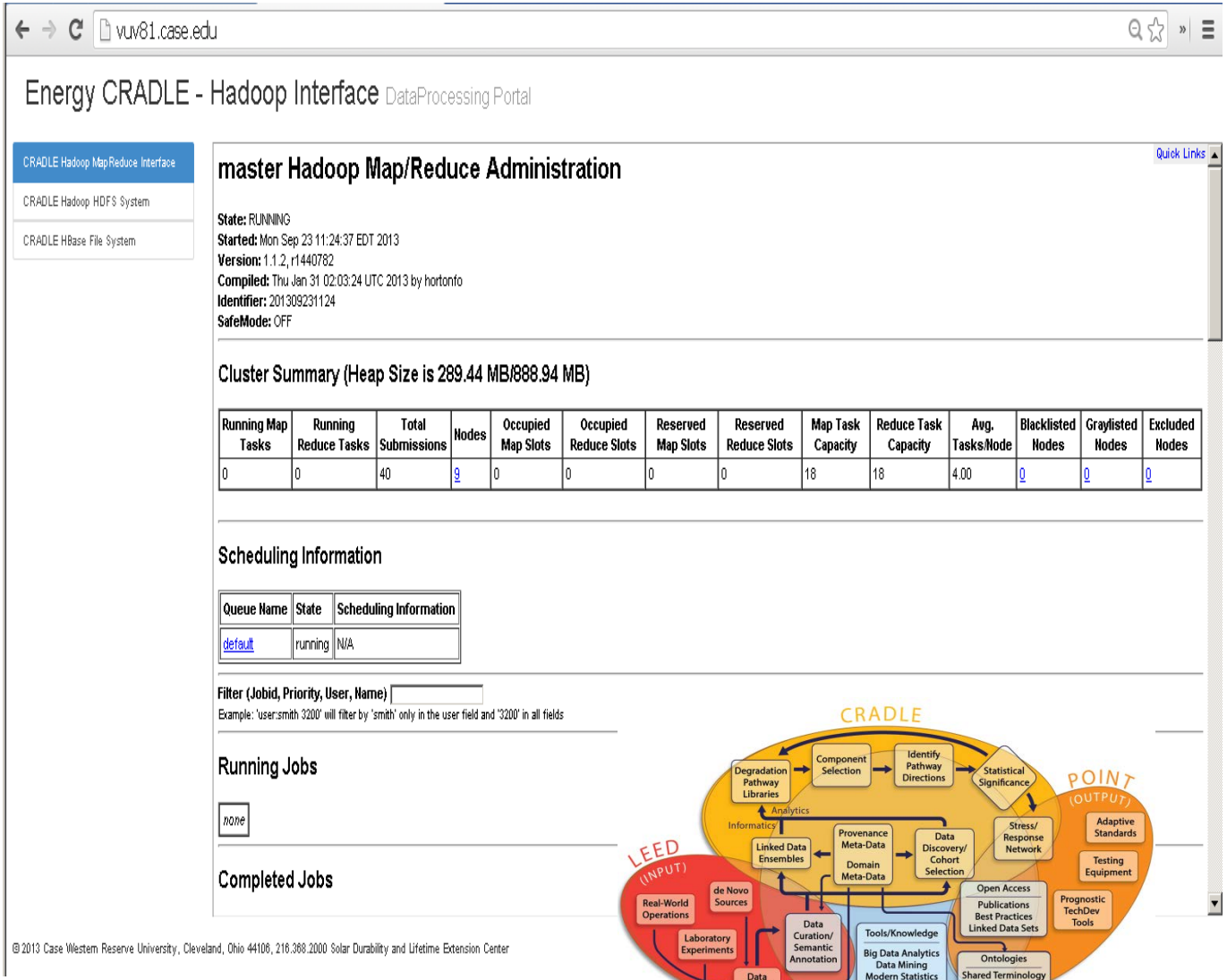
## 10 Node Cluster

- 20 Cores
- 100 Gb RAM
- 1 Tb Storage

## Now Building

- Analytics Servers
- Point in Time Servers

## And Scaling CRADLE



# L&DS: Domain-Science Guided, Statistical Analytics

## Founded in Physical/Chemical Mechanisms

## Exploratory Data Analysis

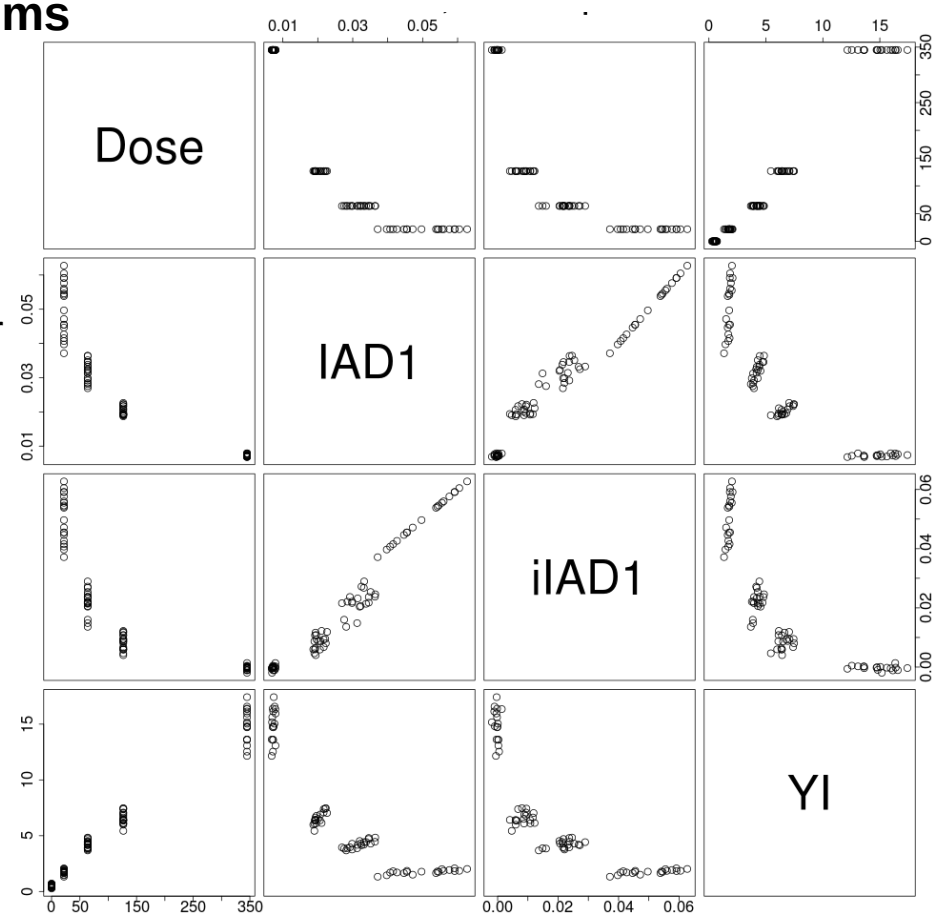
- Pairs Plots: Survey of Large Data Sets
- Explore relationships compared to time/dose
- Explore relationships compared to one another
- Information Content, Correlation, Significance

## Functional Forms among Variables

- Based on Fundamental Mechanisms
- Using realistic functional forms
- No over fitting, check goodness of fit

## Number of Coincident Observations

- n-2
- Degrees of Freedom




## Combination of Metrics for Statistically Significant Relationships

- $R^2$, Adjusted-$R^2$, Predictive-$R^2$
- p-values
- Akaike Information Content (AIC) (Information Entropy)

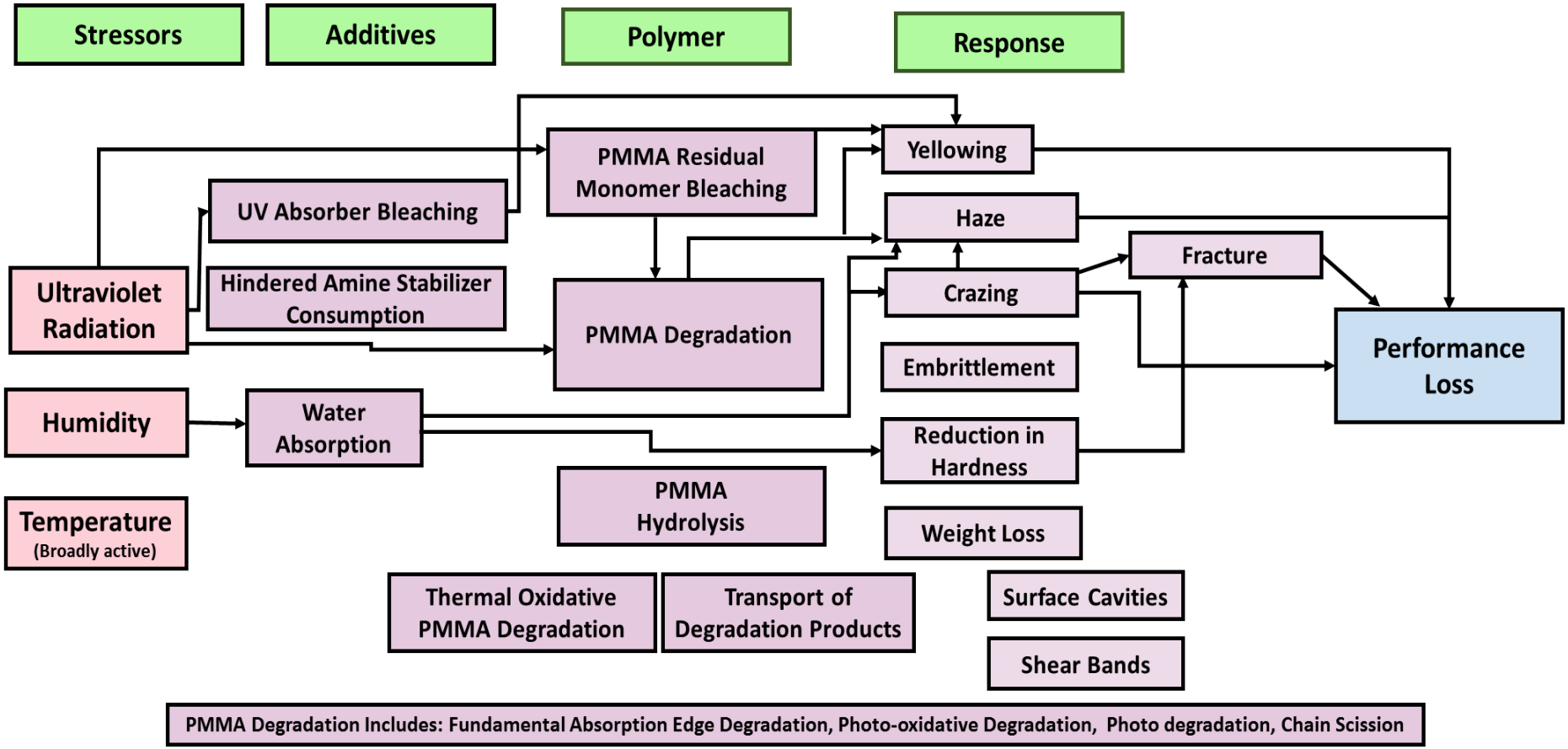
# Analytics of Degradation Pathways of Solar Grade Acrylic

UVT

MPA

Myles Murray, Laura Bruckman

# Acrylic Degradation Mechanism Pathway Library: Survey

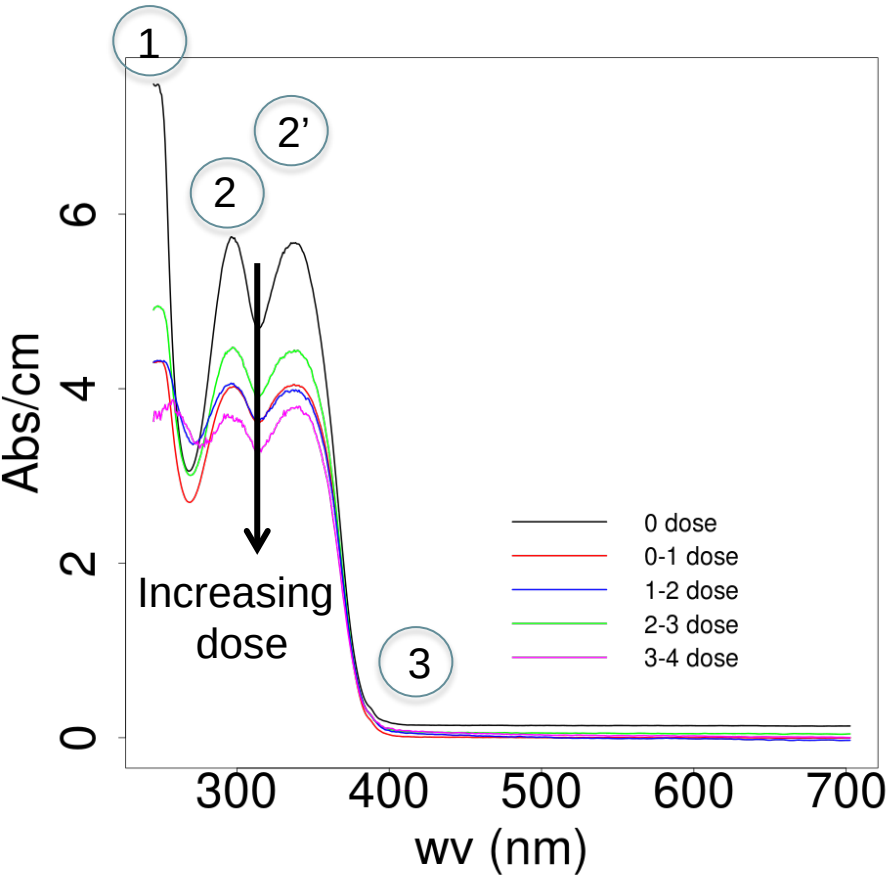


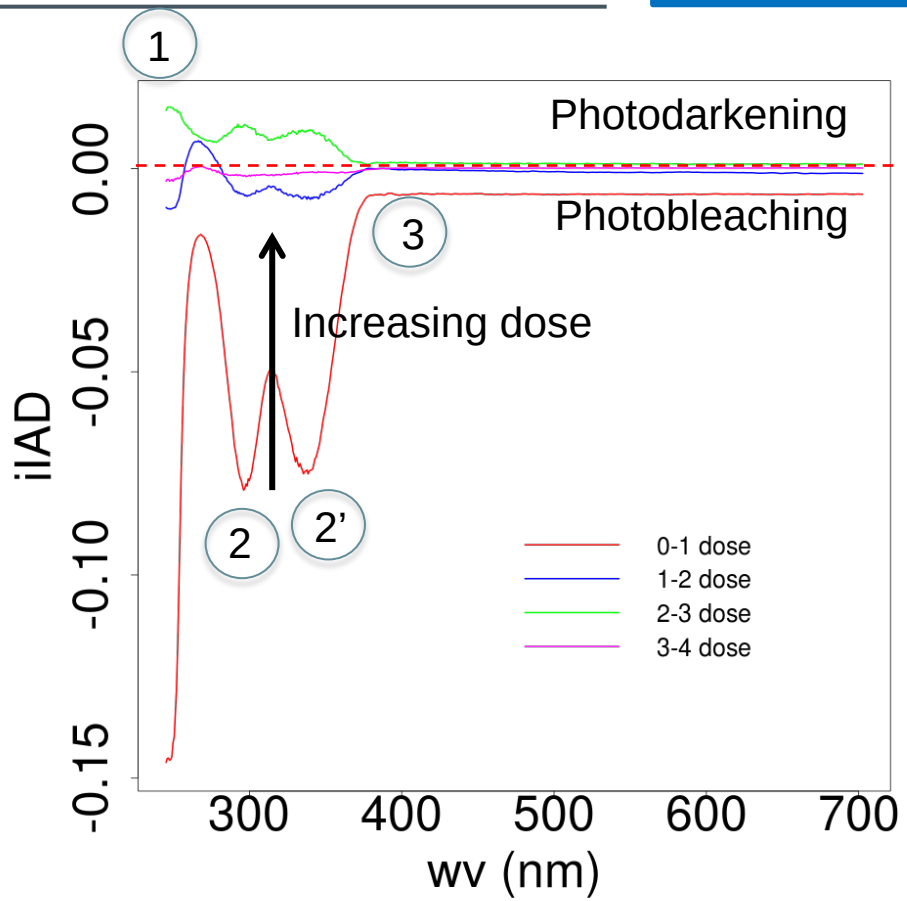

**Each Node Represents a Degradation Mechanism**

Sample of Possible Degradation Mechanism Pathways

# Multipurpose Absorbing Incremental IAD- "Hot QUV"

MPA




**1-Fundamental Absorption Edge**

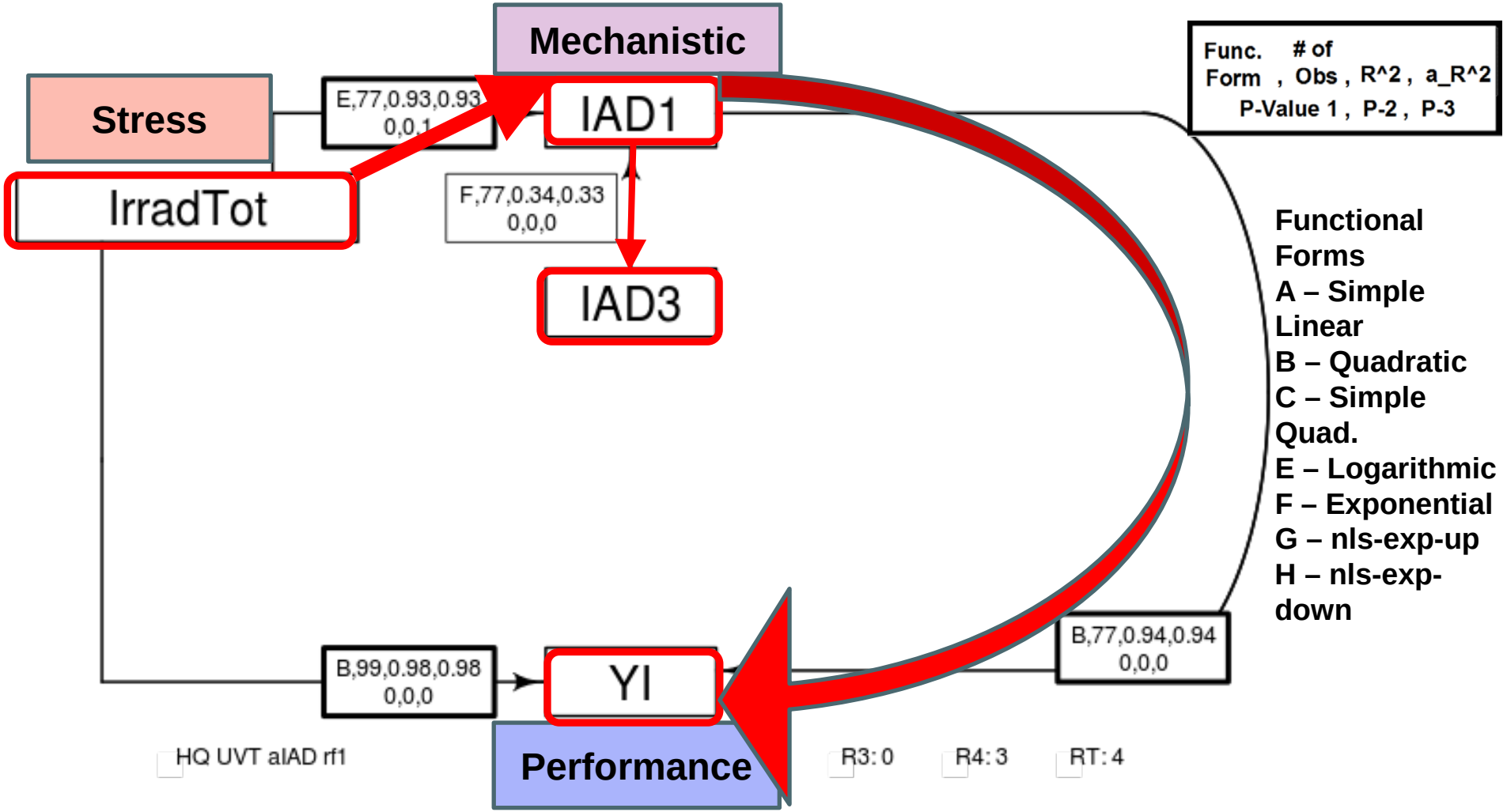
**2 and 2' (297 & 339 nm)-Tinuvin Type Stabilizer Package**

- Initial High Rate of Photobleaching

**3-Yellowing Region**

# Statistical Pathway Diagram: UVT-Base Resin

**UVT**

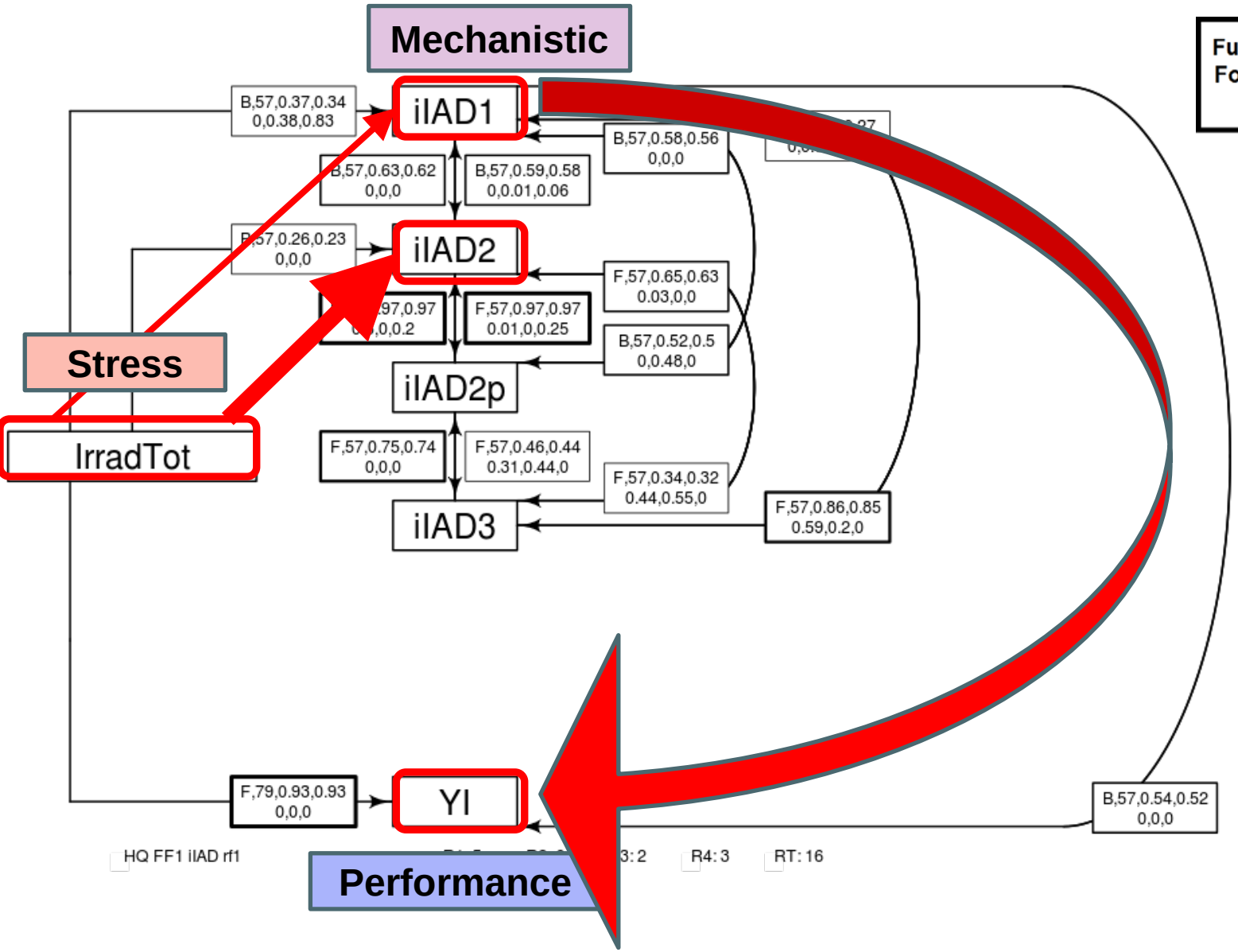



**IAD1 (fundamental absorption edge) degrades-proceeds to yellowing.**

**Weak Relationship between IAD1 degradation and IAD3 (one wavelength)**

# Statistical Pathway Diagram: MPA Stabilizer

**MPA**




| Func. Form | # of Obs | R^2 | a_R^2 | P-Value 1 | P-2 | P-3 |
|---|---|---|---|---|---|---|

**Functional Forms**
**A – Simple Linear**
**B – Quadratic**
**C – Simple Quad.**
**E – Logarithmic**
**F – Exponential**
**G – nls-exp-up**
**H – nls-exp-down**

# Domain-Science Guided, Statistical Analytics: PV Module Study

## Statistical and Domain Analytics Applied to PV Module Lifetime and Degradation Science

LAURA S. BRUCKMAN[1], NICHOLAS R. WHEELER[2], JUNHENG MA[3], ETHAN WANG[4], CARL K. WANG[4], IVAN CHOU[5], JIAYANG SUN[3], AND ROGER H. FRENCH[6] (Member, IEEE)

## Semi-gSEM Methodology

## Semi-Supervised by Domain Knowledge, Generalized Structural Equation Modeling

# L&DS Analytics: Applied To Power Plants, Devices, Materials

## Statistical and Domain Analytics Applied to PV Module Lifetime and Degradation Science

Laura S. Bruckman, Nicholas R. Wheeler, Junheng Ma, Ethan Wang, Carl K. Wang, Ivan Chou, Jiayang Sun and Roger H. French, *Member, IEEE,*

***Abstract*—A better understanding of the degradation modes and rates for photovoltaic (PV) modules is necessary to optimize and extend the lifetime of these modules. Lifetime and degradation science (L&DS) is used to understand degradation modes, mechanisms and rates of materials, components and systems in order to predict lifetime of PV modules. A PV module lifetime and degradation science (PVM L&DS) model is an essential component to predict lifetime and mitigate degradation of PV modules. Previously published accelerated testing data from Underwriter Laboratories on PV modules with fluorinated polyester (FPE) backsheets which included eight modules that were exposed to 4000 hours of damp heat (85% relative humidity at 85°C) and eight exposed to 4000 hours of ultraviolet light (80 W/$m^2$ of 280-400 nm wavelengths at 60°C) (UV preconditioning) were used to determine statistically significant relationships between the applied stresses and measured responses. There were fifteen different variables tracking aspects of system performance, degradation mechanisms, component metrics and time. Modules were analyzed for three system performance metrics (fill factor, peak power, and wet insulation). The results were statistically analyzed to identify variable transformations, statistically significant relationships, and to develop the PVM L&DS model informed by structural equation modeling techniques. The statistically significant relationships and significant model coefficients obtained in the first level above, combined with domain analytics,**

A Recent U.S. Department of Energy workshop on Science for Energy Technologies [1] identified photovoltaics (PV) lifetime and degradation science (L&DS) [2], [3], [4] as a critical scientific challenge for robust adoption of PV. The PVQA Task Force was developed as an international task force to work towards defining what is needed for lifetime qualification standards and tests [5]. Developing and defining useful lifetime qualification standards and tests is complicated since even single degradation modes, mechanisms and rates are not clearly understood and two factor effects are even more complex. Therefore, a methodical domain and statistical approach is necessary to cross-correlate stressors, degrees of stress and degradation modes, mechanisms and rates for materials, components and systems. This cross-correlation can help provide a better understanding of degradation and lifetime performance in order to guarantee the minimal 25-year lifetime performance of PV modules [6].

### A. *Reliability and Prognostic Approaches*

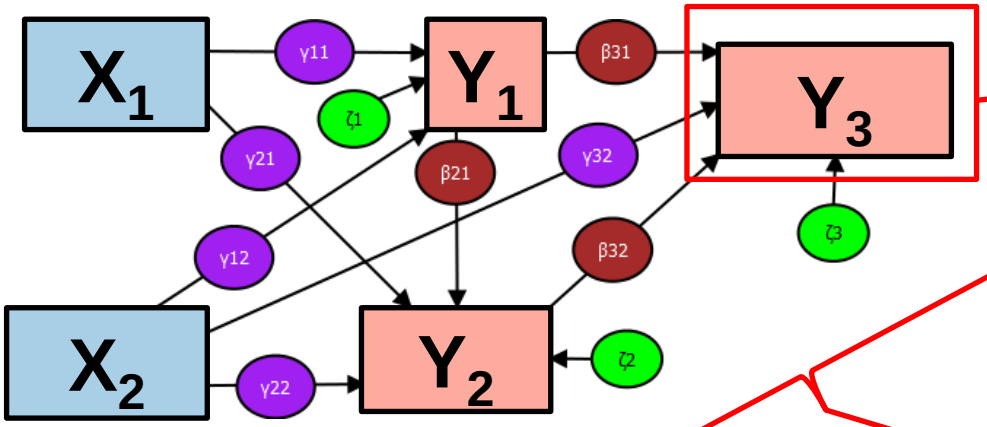
The original method to determine the reliability of a system or component was to collect failure data and use a single,

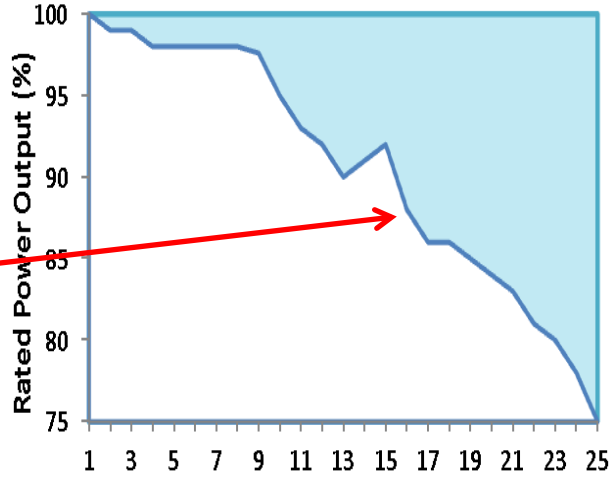
**Laura S. Bruckman, Nicholas R. Wheeler, Junheng Ma, Ethan Wang, Carl K. Wang, Ivan Chou, Jiayang Sun, and Roger H. French, "Statistical and Domain Analytics Applied to PV Module Lifetime and Degradation Science", IEEE Access, invited, 2013. DOI:**10.1109/ACCESS.2013.2267611

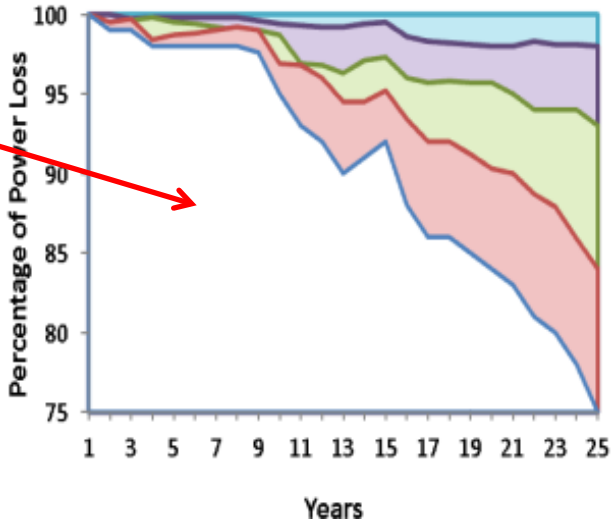
# L&DS: Semi-gSEM Methodology

## A methodology for determining degradation mechanisms and rates

- Connects materials and components
- Bulk material properties and surfaces, interfaces
- To predict and improve system lifetime performance




## Inspiration: Structural Equation Modeling

$$Y_{1i} = \gamma_{10} + \gamma_{11}X_{1i} + \gamma_{12}X_{2i} + \zeta_{1i}$$
$$Y_{2i} = \gamma_{20} + \gamma_{21}X_{1i} + \gamma_{22}X_{2i} + \beta_{21}Y_{1i} + \zeta_{2i}$$
$$Y_{3i} = \gamma_{30} + \gamma_{32}X_{2i} + \beta_{31}Y_{1i} + \beta_{32}Y_{2i} + \zeta_{3i}$$

## Generalized for Non-Linear Relationships

# UL PV Module Experiments – Developed Semi-gSEM Methodology

## 16 Modules Measured While Exposed:

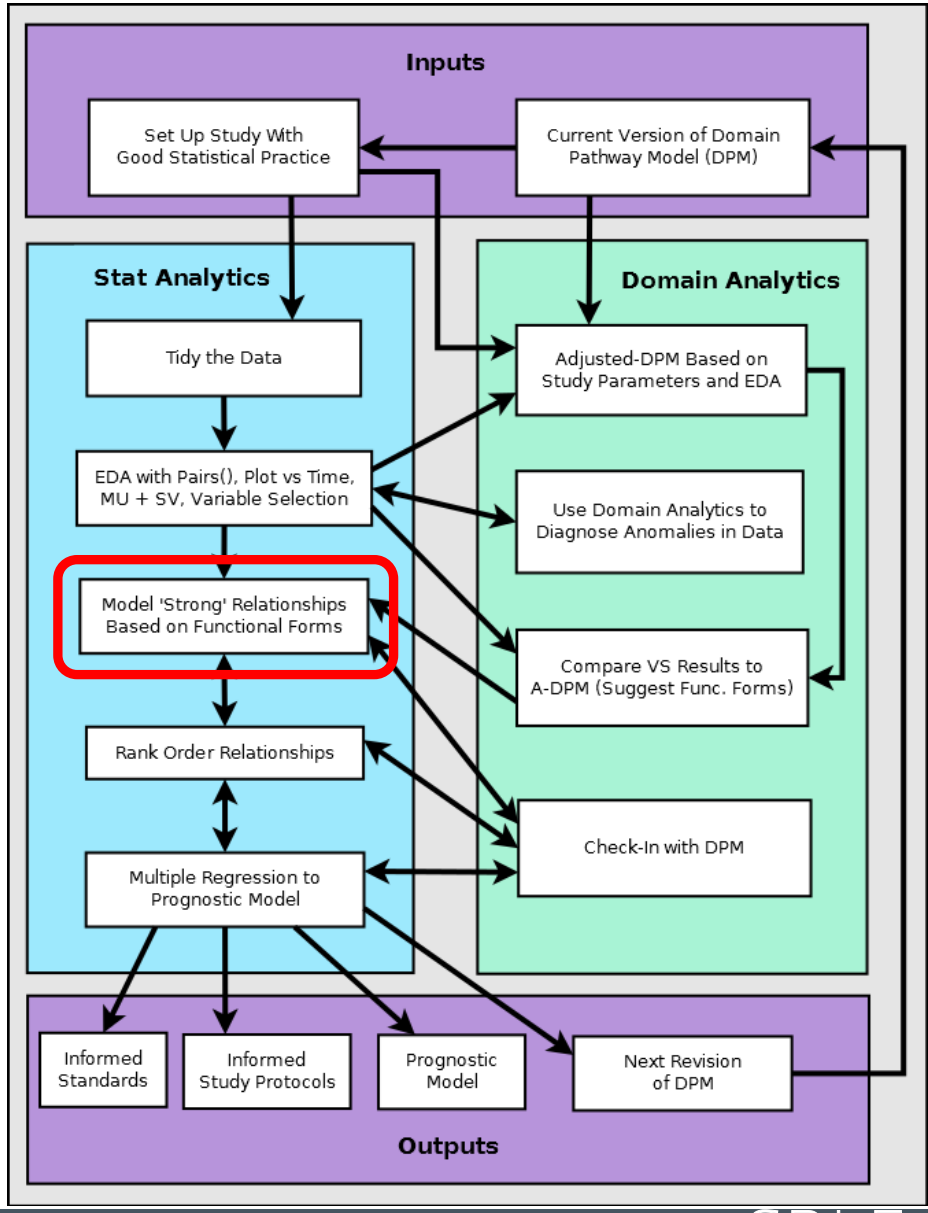
- Damp Heat – 85°C, 85%RH
- UV – 60°C, ~80W/m2

## Every 1000 Hours, 2 Modules:

- Destructively Disassembled and Measured

## Final Dataset:

- 15 Variables Total
- 2 Different Stress Conditions

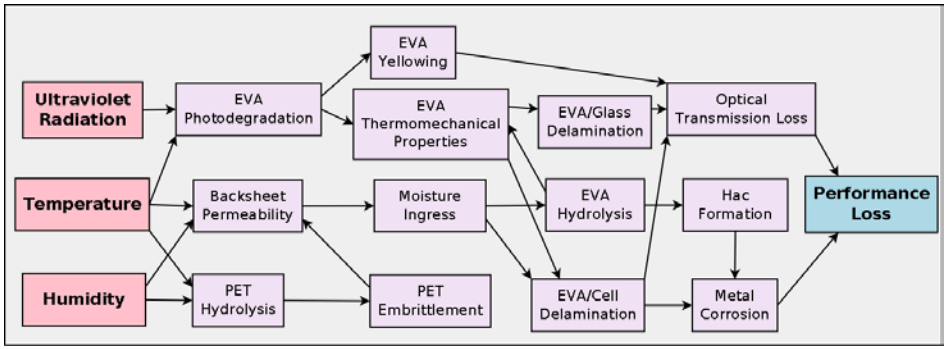


E. Wang, H. E. Yang, J. Yen, S. Chi, and C. Wang, "Failure modes of evaluation of pv module via materials degradation approach," in PV Asia Pacific Expo and Conference, 2012.c

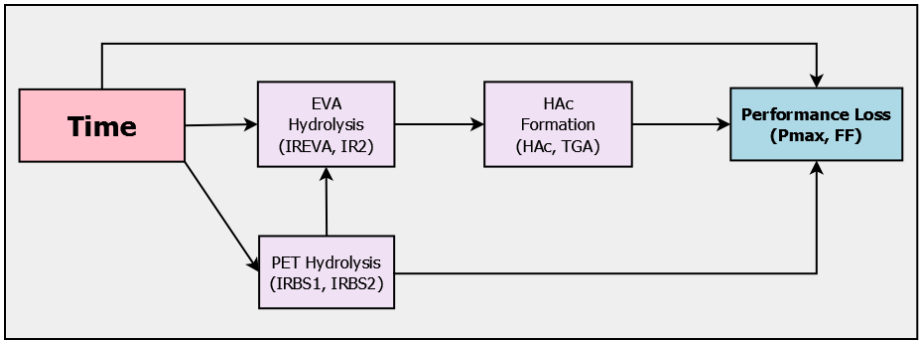
Laura S. Bruckman, Nicholas R. Wheeler, Junheng Ma, Ethan Wang, Carl K. Wang, Ivan Chou, Jiayang Sun, and Roger H. French, "Statistical and Domain Analytics Applied to PV Module Lifetime and Degradation Science", IEEE Access, invited, In Press, 2013.

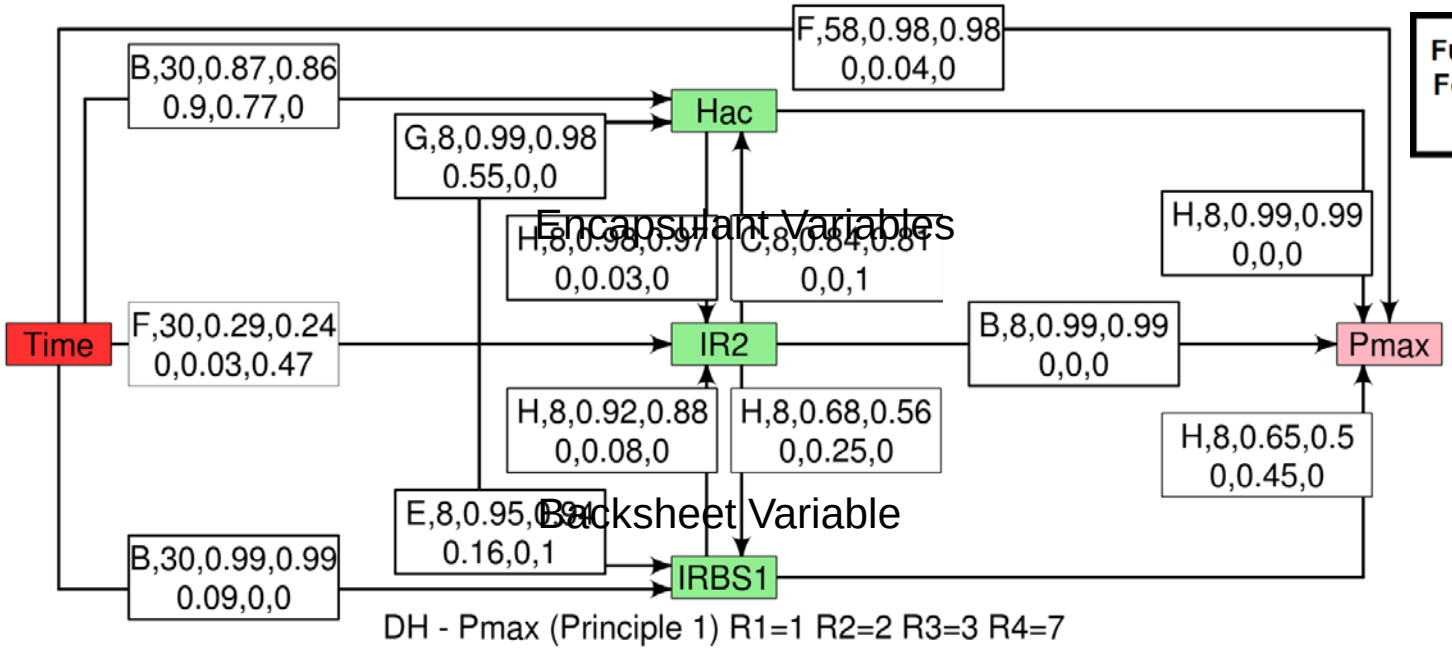
# PV Module L&DS Model Development with Domain Semi-gSEM

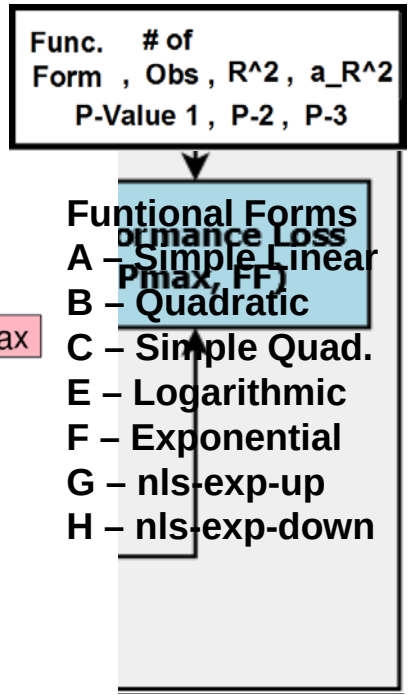
## Domain Pathway Library




## Study Pathway Diagram

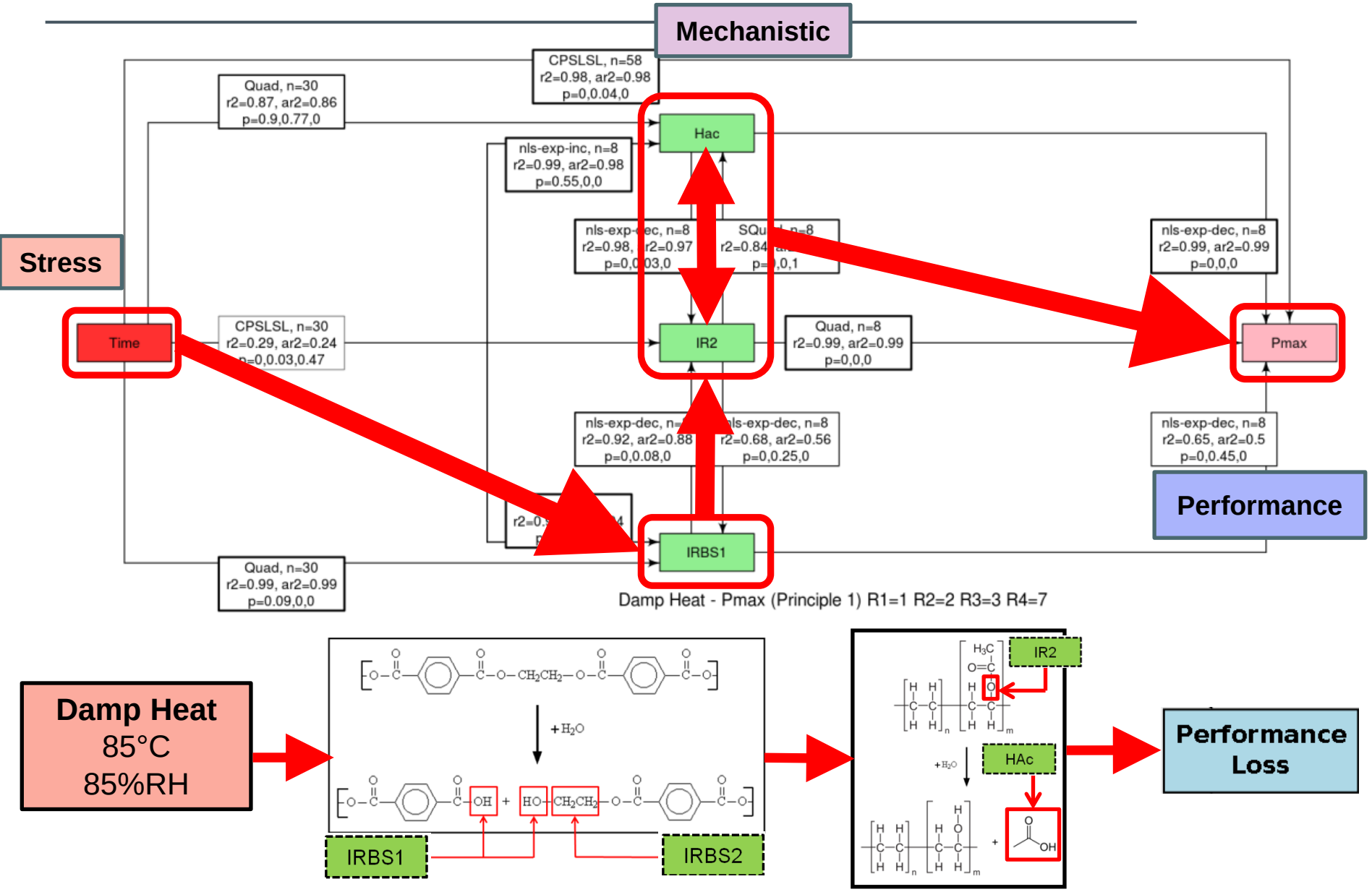


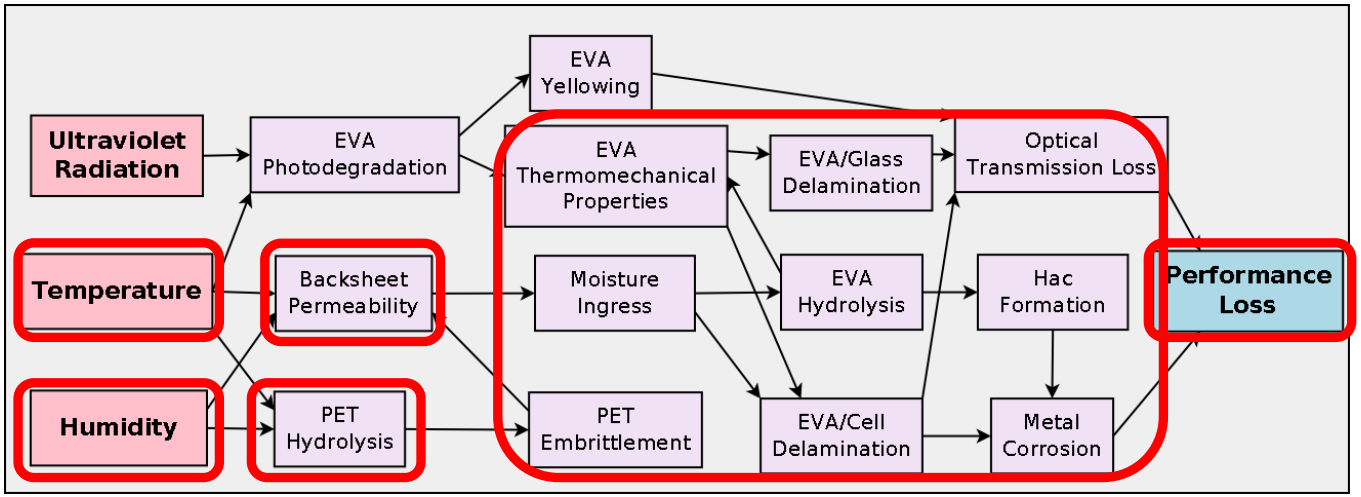

## Statistical Pathway Diagram

# Damp Heat – Indicated Active Degradation Pathways



# Damp Heat Results - Expected vs Observed

**Damp Heat**
85°C
85%RH

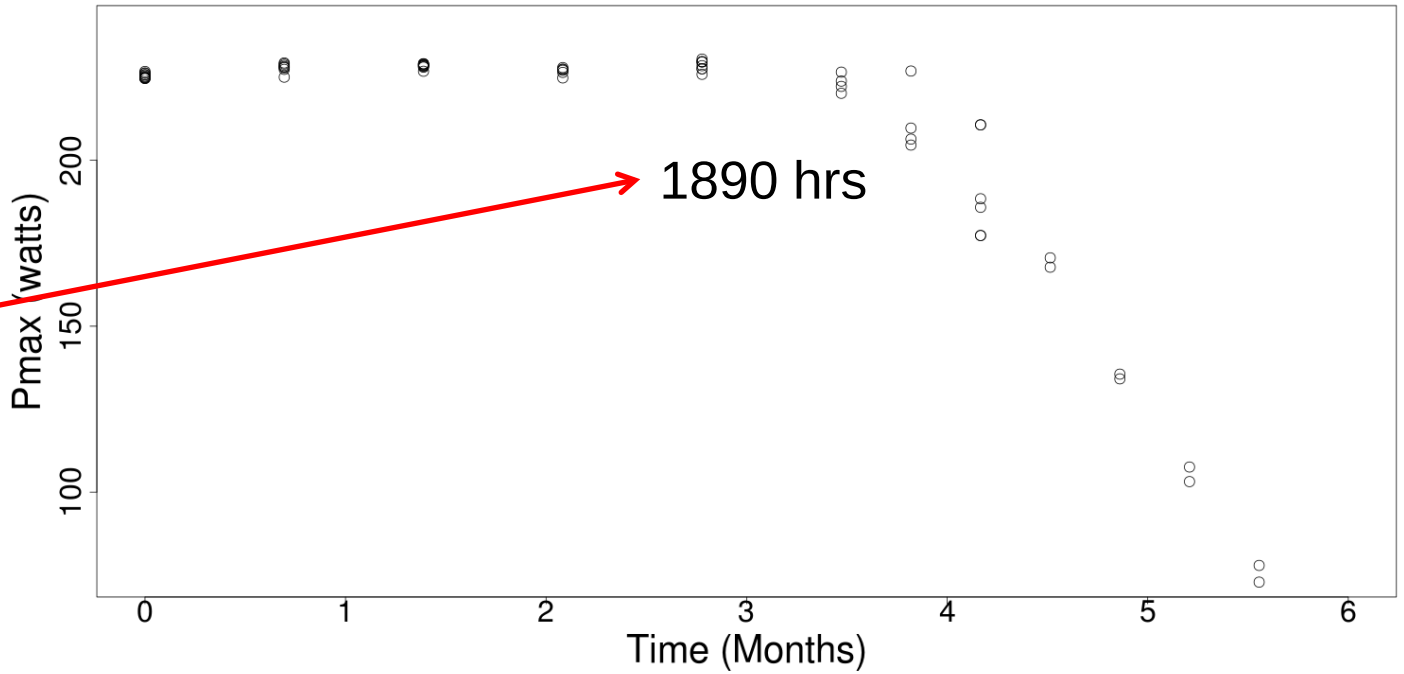



## Expected:

- Moisture Related Responses

## Observed:

- Dramatic Degradation
- Change Point Evident
- Model Shows Many and Strong Relationships



# Case Study of 60 Crystalline Silicon Modules of 20 Brands

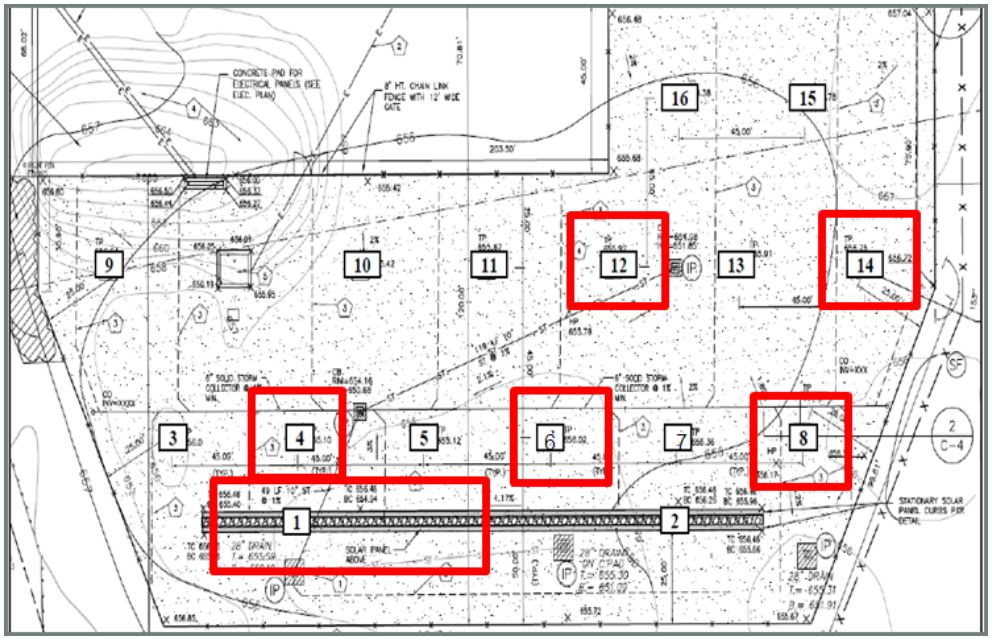
## Cross-sectional comparison of initial performance

Yang Hu, Mohammad Hossain,
Tim Peshek, Yifan Xu,
Jiayang Sun

# Outdoor Test Facilities

## SDLE Center SunFarm

- 14 high precision dual axis trackers
- 2 sites adjustable tilt racking
- 148 PV modules from 24 manufacturers
- Over 8000 samples




## Power Degradation Rates of c-Si PV

- Using time series analysis
- Across many climatic zones

## Lifetime and Degradation Studies of

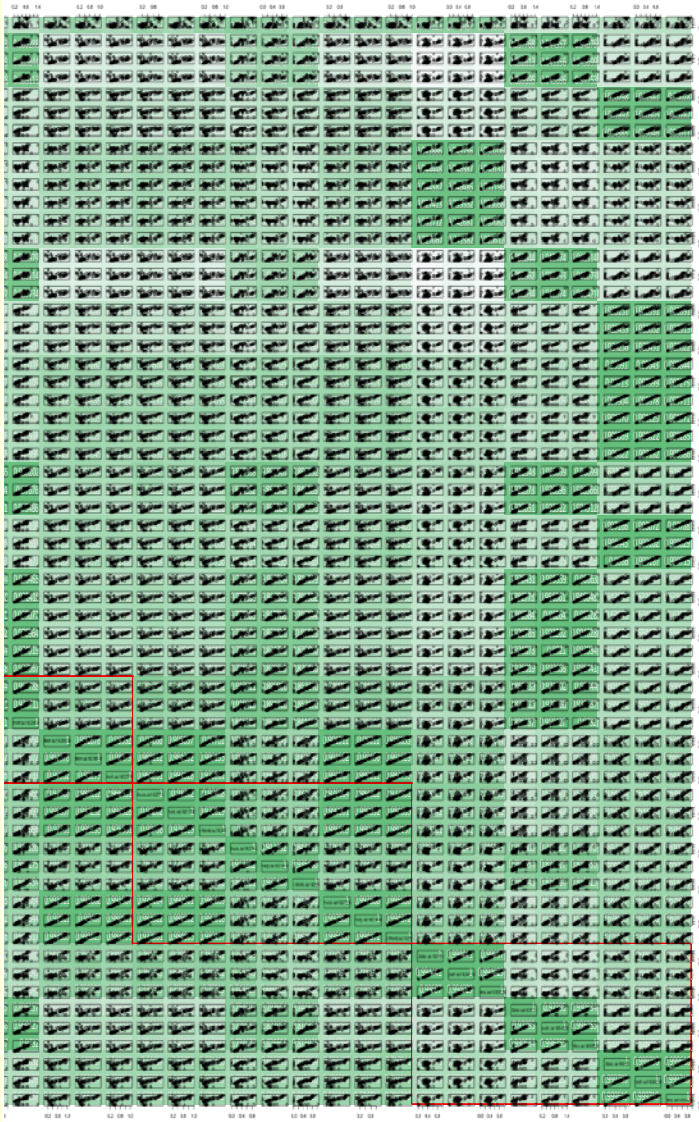
- Systems, Components, Materials

## Data Acquisition

- Minute by minute time series
- Pyranometer: horizontal and Plane of Array
- Weather Stations
- Power Data: Daystar, Enphase, Solectria

# Exploratory Data Analysis: Correlation of 60 Modules Over Time

| Manufacturer | Model | Power |
|---|---|---|
| **Astronergy** | CHSM 6610P 235 watt | 235 watt |
| **AUO** | 240-P Silver Frame | 240 watt |
| **Bosch** | c-si M60-225-16 | 225 watt |
| **Conergy** | PowerPlus 220W | 220 watt |
| **CSI** | CS6P | 220watt |
| **EcoSolargy** | EC O230S156P-60 | 230 watt |
| **ET Solar** | ET-P660235BZ Zero Rack BLK | 235 watt |
| **Helios** | 6T240 | 240 watt |
| **Hyundai** | HiS-M230MG | 230 watt |
| **Kyocera** | KD240GX-LPB | 240 watt |
| **LG** | LG220P1C | 220 watt |
| **Mage** | Powertec Plus 230/PH | 230 watt |
| **MX Solar** | MX60 230 | 230 watt |
| **Perlight** | PLM-250M-60 Mono | 240 watt |
| **REC** | REC230PEBLK | 230 watt |
| **Sanyo** | HIT-N220A01 | 220 watt |
| **Schott** | POLY230 | 230 watt |
| **Schuco** | MPE240-PS-09 | 240 watt |
| **Sharp** | ND-U235Q1 | 235 watt |
| **Siliken** | SLK60P6L SLV/WHT 235W | 235watt |
| **Solar World** | SW230Poly 2.0 Frame | 230 watt |
| **Trina** | TSM-230-PA05 | 230 watt |
| **UpSolar** | UP-M240P | 240 watt |
| **Yingli** | YL230P-29b | 230 watt |



# Case Study2:Cross-sectional comparison of 20 manufacturers

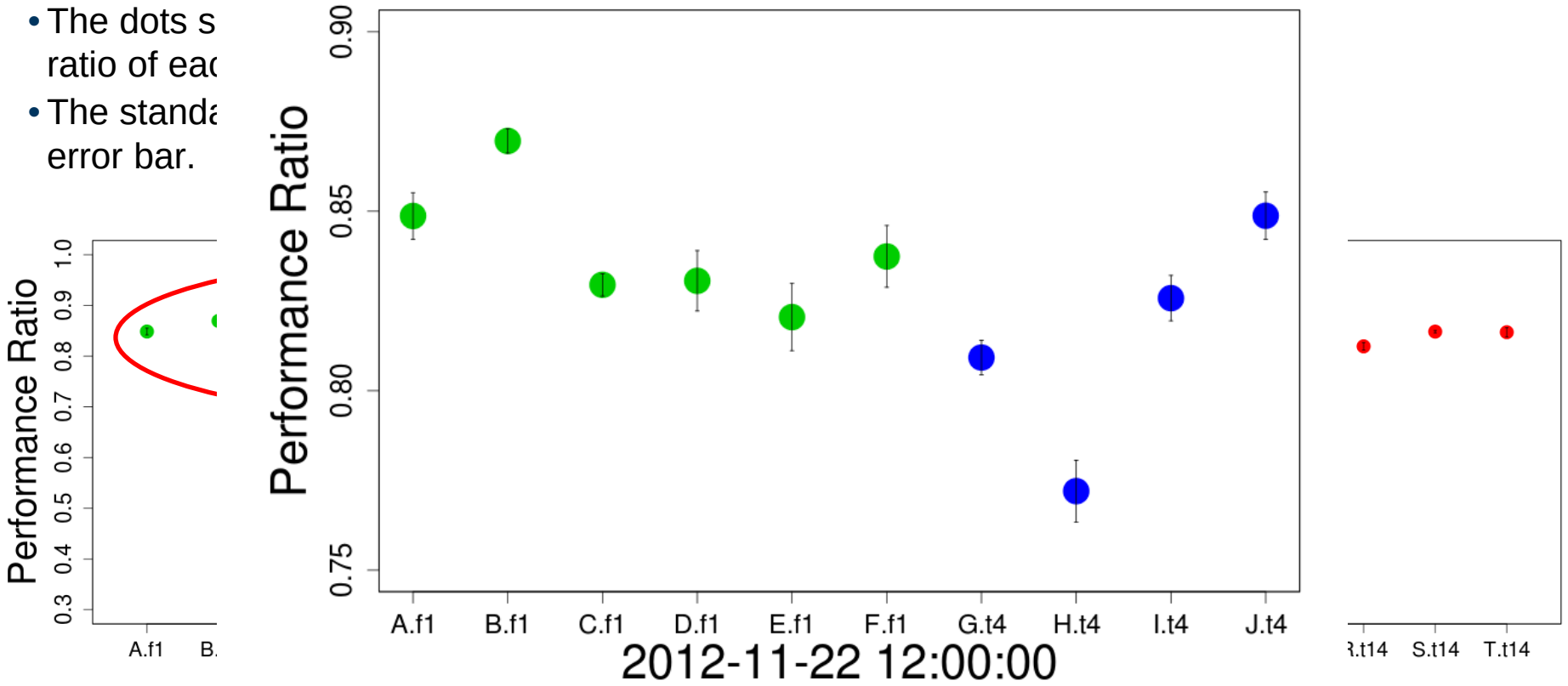
## SDLE SunFarm

- Brand names shown as A through T.
- Letter f or t are for fixed tilt rack and tracker.
- The perfor
  of each bra
- The dots s
  ratio of eac
- The standa
  error bar.

## At noon of a clear sunny day

## Performance Ratio (PR)

- —
- where



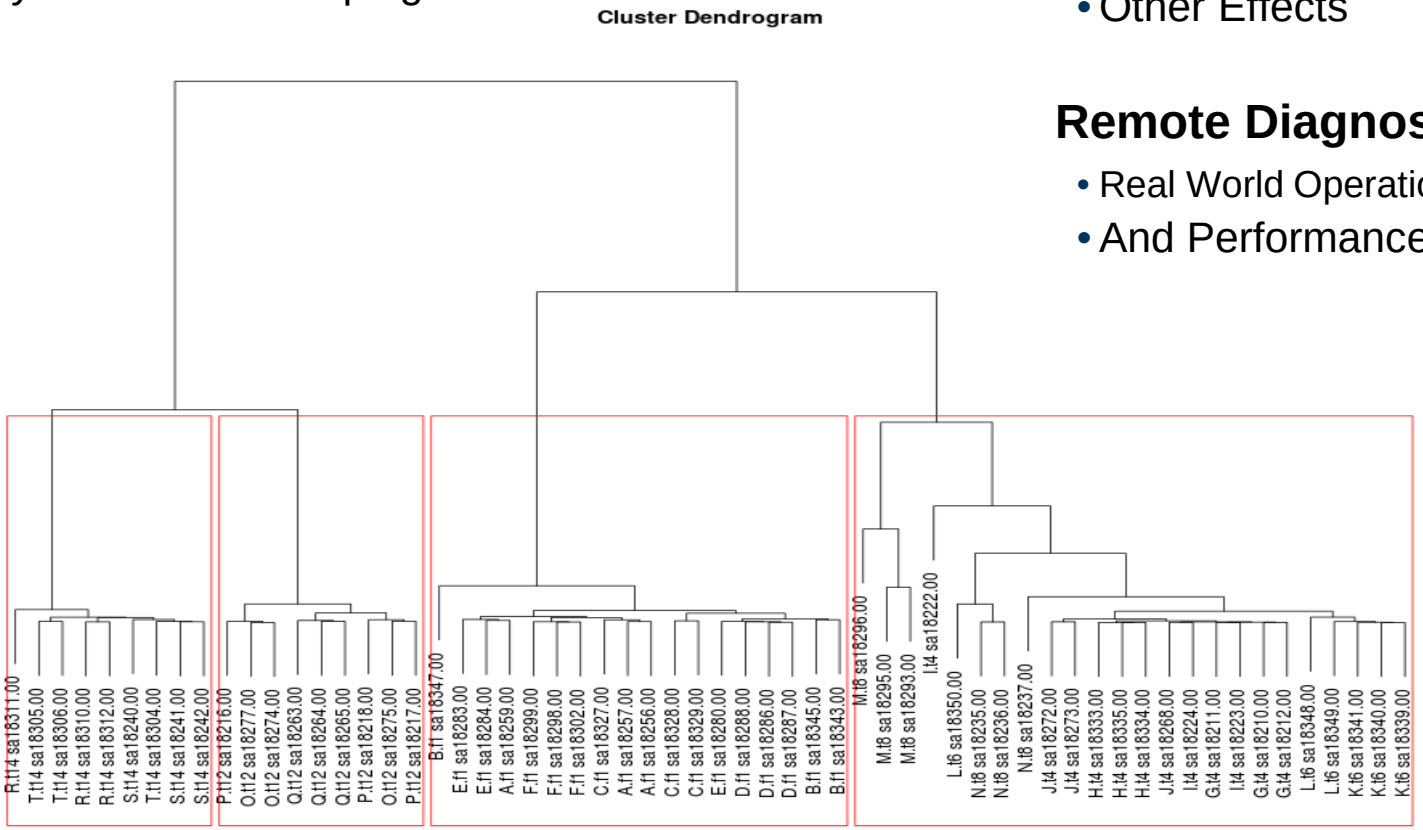
# Similarities/Differences Among “Equivalent” Modules

## Time Series Data

- 15 minute Averaged,
- Over 82 Days

## Hierarchical clustering of 60 modules

- SubSolNoonMean , Pearson, complete
- Dynamic Time Warping




## Clustering Identifies

- Fixed Rack vs. Trackers
- Tracker Reliability
- Module Characteristics
- Other Effects

## Remote Diagnostics Of

- Real World Operations
- And Performance

# L&DS: Mesoscale Science Across Length and Time Scales

## Applied to Photovoltaic Modules and Solar Mirrors

- Real World and Accelerated Lab Studies

## Broadly applicable to

- Multi-generational technologies
- Exposed to harsh environments
- Long lived, High Cost

## Combining

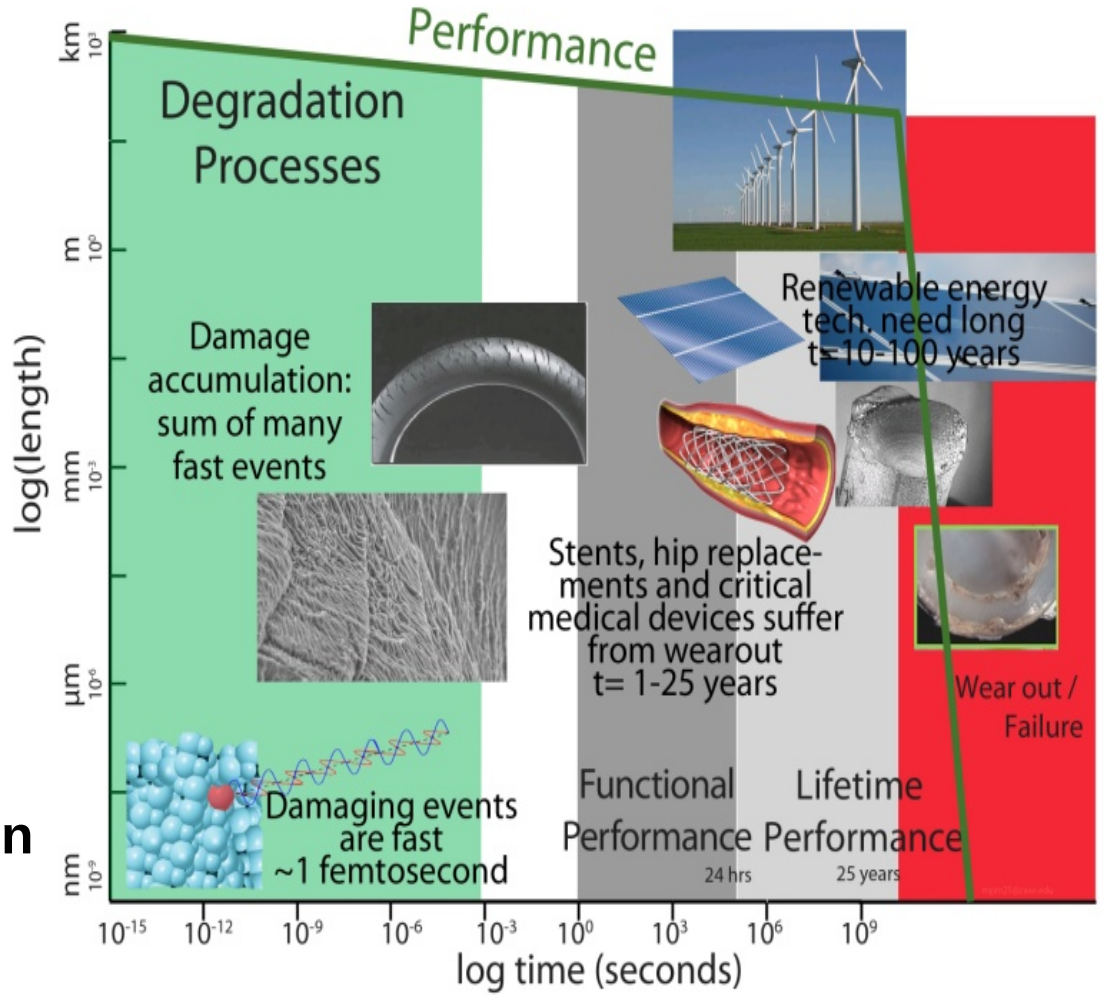
- Population based studies
- Analytics, Prognostics

## Data Science Approach

- Data Sources ⇔Informatics ⇔
- Analytics ⇔ Actionable Intelligence

## For New Technology Insertion

- Optimized Lifetime Performance
- Without Lifetime Penalties



CASE SCHOOL
OF ENGINEERING

CASE WESTERN RESERVE
UNIVERSITY