Network Models of Active Degradation Mechanisms and Pathways for Service Life Prediction of Indoor and Outdoor PV Modules

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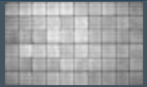

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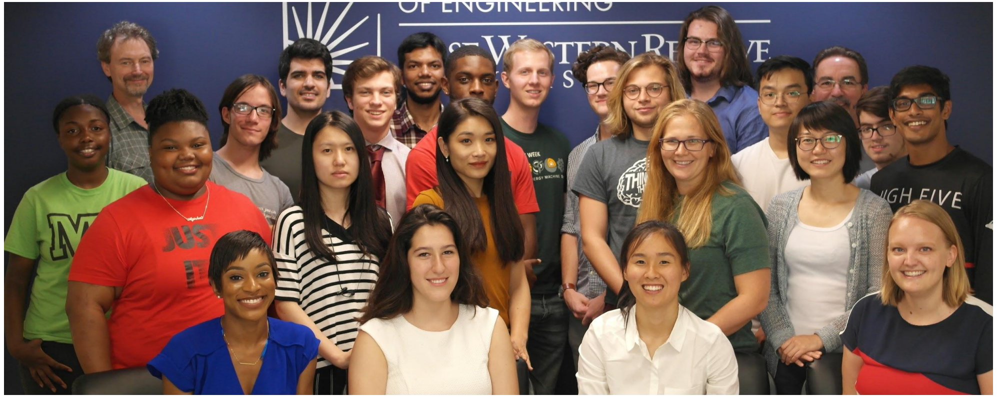
SDLE Research Center: Acknowledgements



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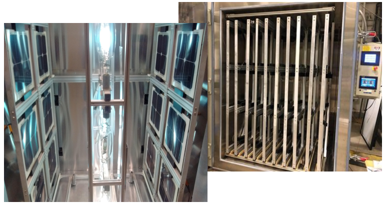
PV Service Lifetime Prediction (SLP)

Accurate PV SLP, is crucial to LCOE, and is the basis of PV lifetime performance

- Challenge: **PV modules are complex systems** with **multiple degradation mechanisms**

Requires: comprehensive study protocol development and data on variants and exposures

Our solution: mapping of degradation mechanisms and pathways with network modeling



Service Life Prediction:
In Lab ⬆️ & Field ⬇️

PV module variants :
BOM
Quality
Design

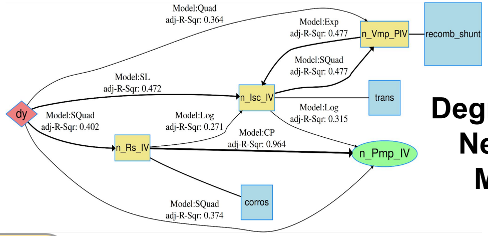
- Cell technology
- Encapsulation
- Glass/Backsheet
- Brand/Suppliers

Weathering exposure stressors:
Climate
Racking

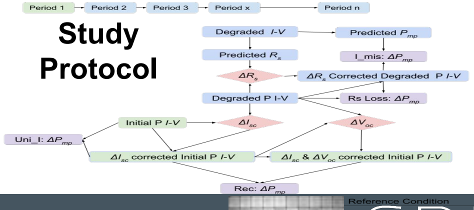
- Irradiance/UV
- Moisture
- Temperature

→ **Degradation Network models** →

- ΔR_s, corrosion
- ΔI_{sc}, optical
- ΔV_{mp}, *recombination*



Degradation Network Model



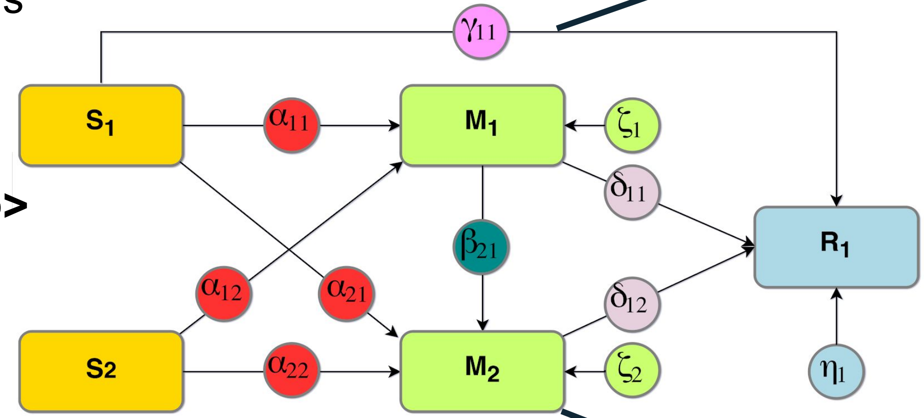
Study Protocol

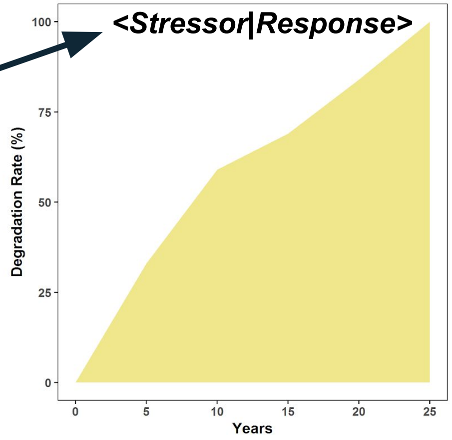
netSEM: Degradation Pathway Network Modeling

Structural Equation Models[1]: System of equations

- Includes non-linear relationships
- S_i are Stressors
- M_i are Mechanisms
- R_i are Responses

NetSEM on CRAN[2]



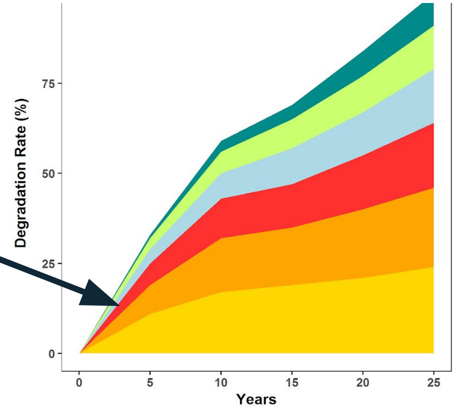


<Stressor|Response>

- total degradation

$$M_1 = x + \alpha_{11} S_1 + \alpha_{12} S_2 + \zeta_1$$
$$M_2 = y + \alpha_{21} S_1 + \alpha_{22} S_2 + \beta_{21} M_1 + \zeta_2$$
$$R_1 = z + \gamma_{11} S_1 + \delta_{11} M_1 + \delta_{12} M_2 + \eta_1$$

<Stressor|Mechanism |Response>



<Stressor|Mechanism|Response>

- rank order degradation mechanisms

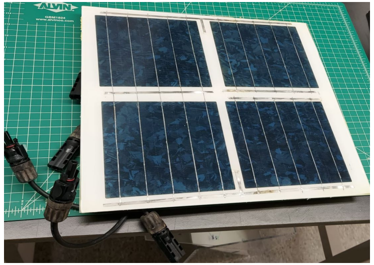
1. Gok, Abdulkerim, et al. "Degradation Science and Pathways in PV Systems." *Durability and Reliability of Polymers and Other Materials in Photovoltaic Modules*. William Andrew Publishing, 2019. 47-93.
2. W.H. Huang, et al., netSEM: Network Structural Equation Modeling, 2018. https://cran.r-project.org/package=netSEM

Degradation Pathways in PERC Minimodules under Accelerated Exposures

Module Architecture: Double Glass vs. Glass/Backsheet

Packaging Materials: EVA vs. POE Encapsulants

Towards 50 Study Protocol: Variants & Exposure Types in the Study



Variants in this study

- **Inner-layer Polymeric material**
  - Encapsulants
    - Ethylene vinyl acetate (EVA)
    - Polyolefin elastomer (POE)
- **Rear-side Layer**
  - Module architectures
    - Glass/backsheet (GB)
    - Double glass (DG)
- **Manufacturer**
  - Brands
    - Canadian Solar (CSI)
    - CWRU

Exposure conditions

- Indoor Exposures
  - Modified damp heat (mDH)
  - mDH with full spectrum light (FSL)

Parametric Studies: MiniModules Variants & Quantities

	SDLE		CSI								Front	PERC Type	Encap Type	Front Encap	Back Encap	Back Type	Back	Module Type
Set #	Qty	Compl Date	Qty	Compl Date	Type Total #	# Retain	# Out-door	# Accel	Accel 1 #	Accel 2 #	Glass	mono-/ bi-facial	EVA/ POE	Trans	Trans/Cut/ Opaq	BS/ Gl	Trans/ Opaq	mono-/ bi-facial
1	6	M4	6	M4	12	2	2	8	4	4	Glass	mono	EVA	Trans	Cut	BS	Opaq	mono
1	6	M4	6	M4	12	2	2	8	4	4	Glass	mono	EVA	Trans	Cut	Gl	Trans	mono
1	6	M4	6	M4	12	2	2	8	4	4	Glass	mono	POE	Trans	Cut	BS	Opaq	mono
1	6	M4	6	M4	12	2	2	8	4	4	Glass	mono	POE	Trans	Cut	Gl	Trans	mono
2	6	M10	6	M4	12	2	2	8	4	4	Glass	bi	EVA	Trans	Opaq	BS	Opaq	mono
2	6	M10	6	M4	12	2	2	8	4	4	Glass	bi	EVA	Trans	Opaq	Gl	Trans	mono
2	6	M10	6	M4	12	2	2	8	4	4	Glass	bi	POE	Trans	Opaq	BS	Opaq	mono
2	6	M10	6	M4	12	2	2	8	4	4	Glass	bi	POE	Trans	Opaq	Gl	Trans	mono
3	6	M16	6	M4	12	2	2	8	4	4	Glass	mono	EVA	Trans	Opaq	BS	Opaq	mono
3	6	M16	6	M4	12	2	2	8	4	4	Glass	mono	EVA	Trans	Opaq	Gl	Trans	mono
3	6	M16	6	M4	12	2	2	8	4	4	Glass	mono	POE	Trans	Opaq	BS	Opaq	mono
3	6	M16	6	M4	12	2	2	8	4	4	Glass	mono	POE	Trans	Opaq	Gl	Trans	mono
4	6	M22	6	M4	12	2	2	8	4	4	Glass	bi	EVA	Trans	Cut	BS	Trans	bi
4	6	M22	6	M4	12	2	2	8	4	4	Glass	bi	EVA	Trans	Trans	Gl	Trans	bi
4	6	M22	6	M4	12	2	2	8	4	4	Glass	bi	POE	Trans	Cut	BS	Trans	bi
4	6	M22	6	M4	12	2	2	8	4	4	Glass	bi	POE	Trans	Trans	Gl	Trans	bi
5	6	M28	6	M27	12	2	0	10	5	5	Glass	TBD	TBD	TBD	TBD	TBD	TBD	TBD
5	6	M28	6	M27	12	2	0	10	5	5	Glass	TBD	TBD	TBD	TBD	TBD	TBD	TBD
5	6	M28	6	M27	12	2	0	10	5	5	Glass	TBD	TBD	TBD	TBD	TBD	TBD	TBD
5	6	M28	6	M27	12	2	0	10	5	5	Glass	TBD	TBD	TBD	TBD	TBD	TBD	TBD

240 Minimodules in Study Protocol: For Accelerated Lab and Real-world Exposures

Number of data points for modeling MM Sets

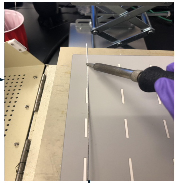
32 minimodules
4 cells each
2 exposures
6 time points
4 features

MM Set #1:
6,144 data points

MM Sets #1 to #5:
32,256 data points

Study Protocol

4 x monofacial multicrystalline PERC

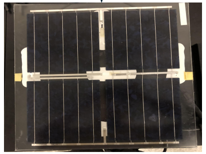


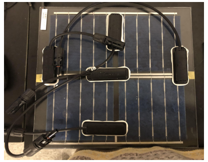
Backsheet or glass
UV-cutoff encapsulant
Solar cells
Transparent encapsulant
Glass
Laminator platten

Brand
- CSI
- CWRU

Architecture
- GB
- DG

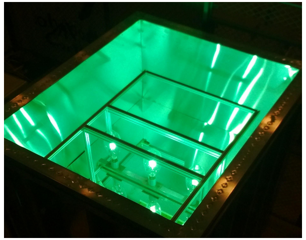
Encapsulant
- EVA
- POE





Fabrication of 8 Variants

mDH: 80°C+85% RH
1 step: 21 days



mDH (14 days) + FSL (7 days, 420 Wm^{-2} light); total: 21 days

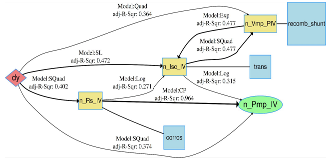
2 Accelerated Exposures (5 Exposure Steps + Baseline)

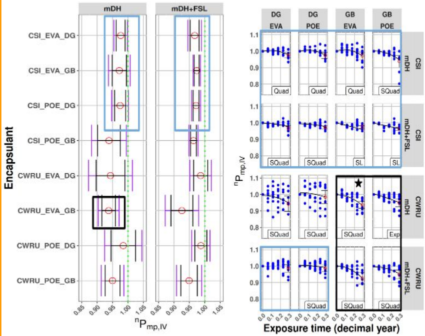
I-V

Suns-V_{oc}

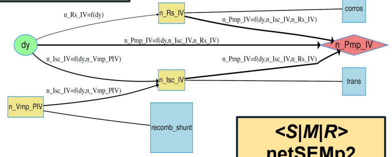
2 Stepwise Electrical Evaluations

<*S*|*M*|*R*> netSEMp1





<*S*|*R*>, <*S*|*M*|, |*M*|*R*> & CIs



<*S*|*M*|*R*> netSEMp2

Data-Driven Modeling

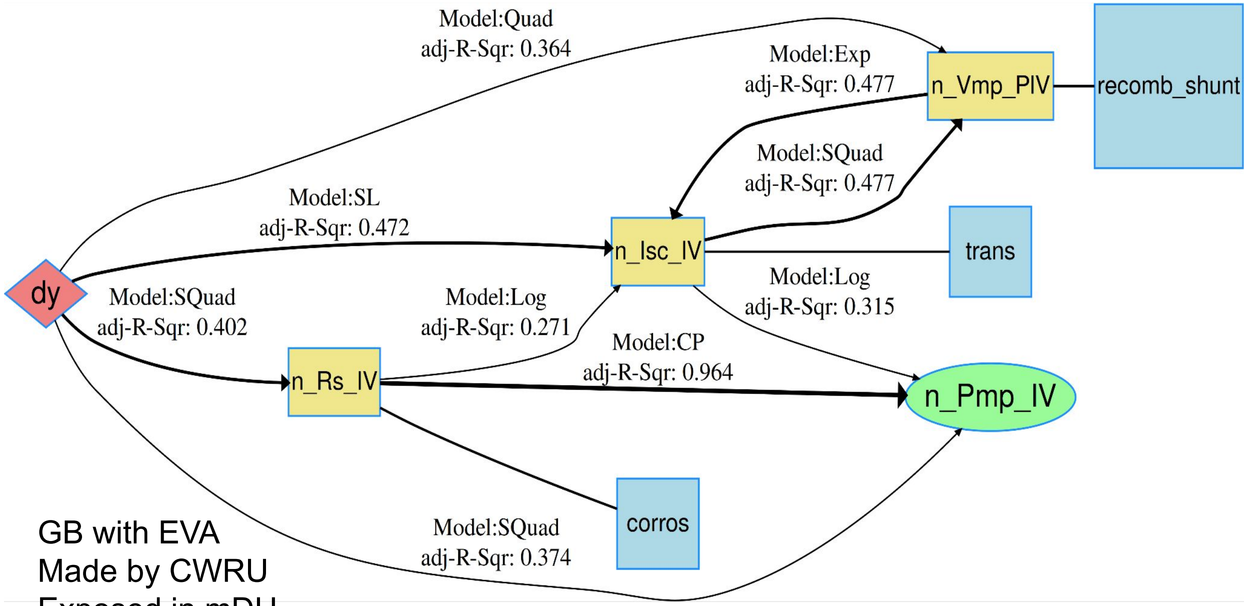
<*S*|*M*|*R*> Modeling Using Principle 1, Assume Markov Property

***<Stressor|Mechanism|Response>* model:**

Pairwise relationships between variables

2 MMs (8 cells) x 6 time points: 48 observations

- Statistical significance



GB with EVA
Made by CWRU
Exposed in mDH

Variables normalized: ↓ noise

Common functional forms

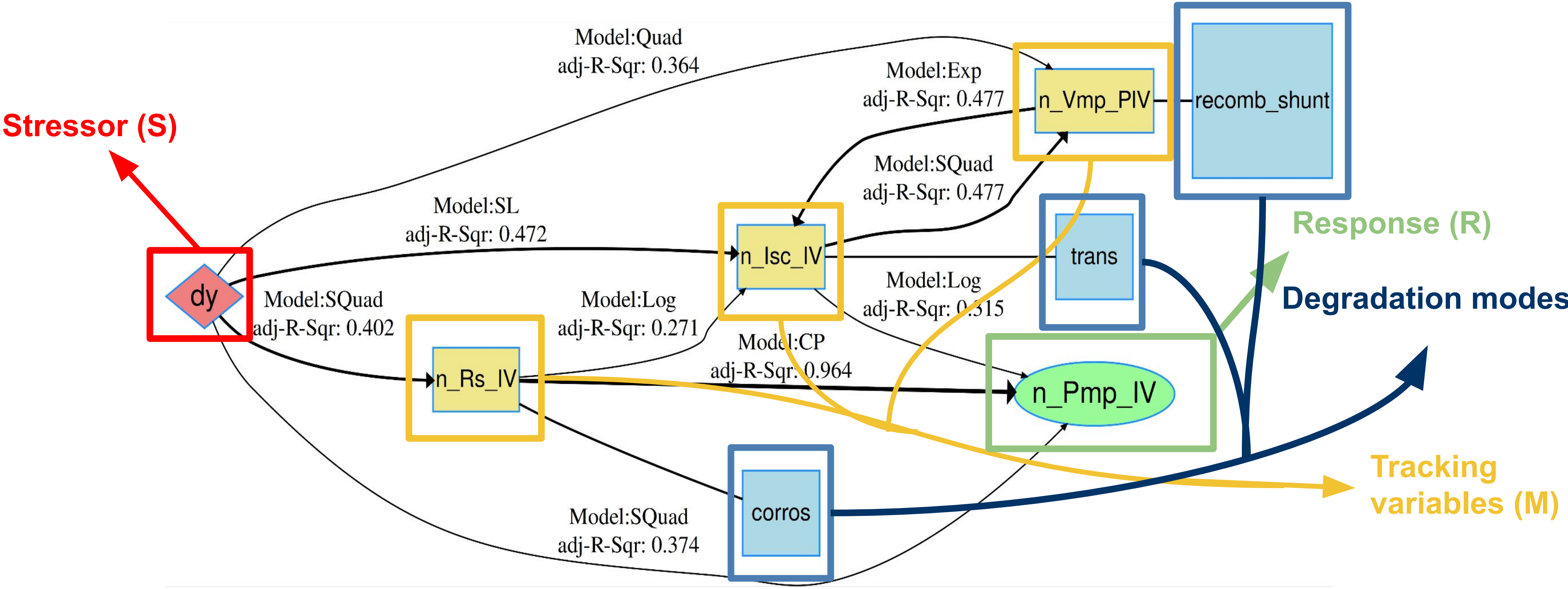
- Based on R_{adj}^2 for all variants
- For a pathway

Path	Model type
dy → ${}^{n}P_{mp,IV}$	SQuad
dy → ${}^{n}I_{sc,IV}$	Quad
dy → ${}^{n}R_{s,IV}$	SQuad
dy → ${}^{n}V_{mp,PIV}$	Quad
mechanism → ${}^{n}P_{mp,IV}$	Quad

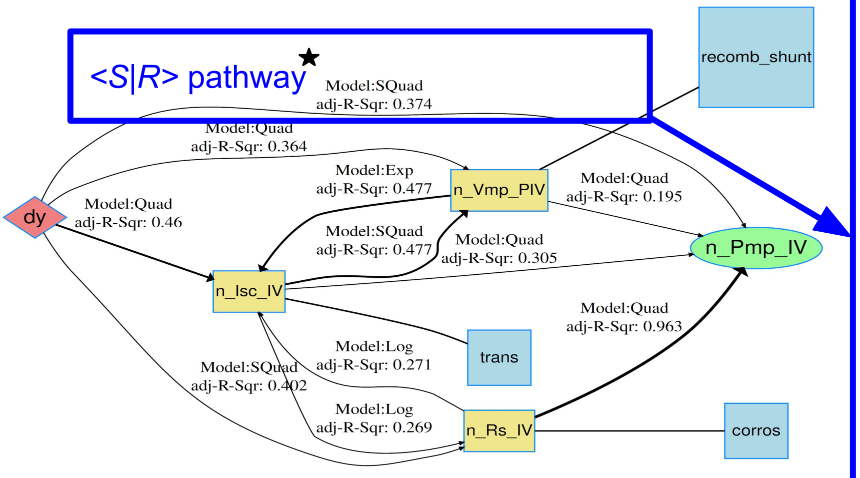
R_{adj}^2: % variance explained by model

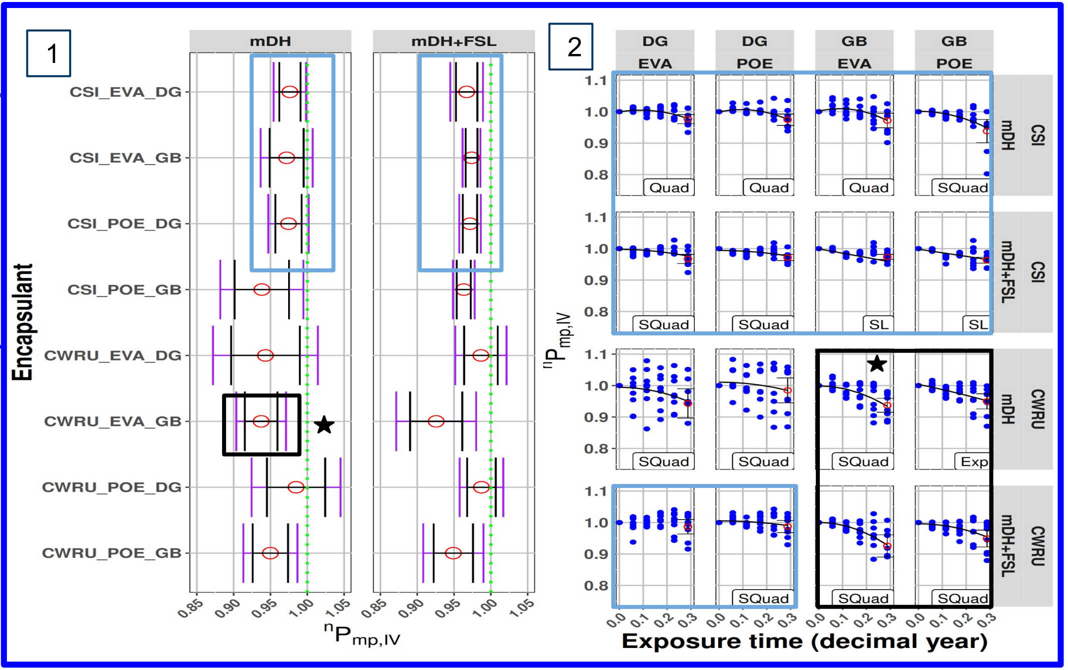
<*S*|*M*|*R*> Model (Principle 1): GB with EVA by CWRU (mDH Exposure)

trans: optical transmission
corros: corrosion
recomb_shunt: recombination & shunting



<*S*|*M*|*R*> Pathway Results





<*S*|*R*>: direct pathway connecting dy and $^nP_{mp,IV}$

95% Confidence Interval (CI)
83.4% CIs
Estimated means
Data points
Best model plot and type

1
2

At end of exposure (step 5)

Durable or degrading: based on 83.4% CIs

DG MMs by CSI: stable

Difference between GB with EVA by CSI and CWRU (fabrication differences)

Most DG MMs: seem to be stable with time

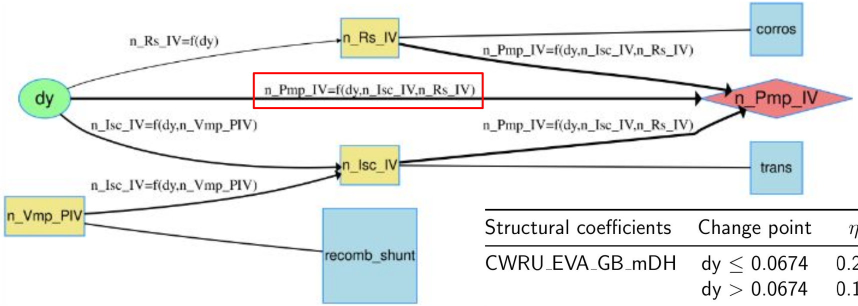
GB MMs (CWRU): power drop

How much ↓ power?

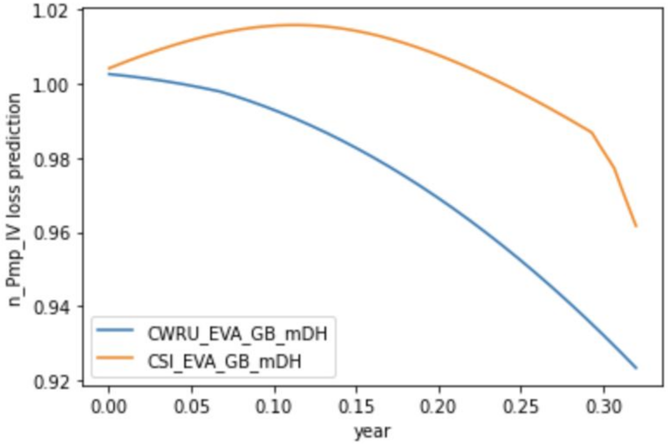
- **~ 5-6%**

Corrosion is a prominent degradation mode (from <*S*|*M*| and |*M*|*R*>)

<*S*|*M*|*R*> Model, Principle 2, Multiple Regression by Step AIC



Structural coefficients	Change point	η	$\gamma_{dy,1}$	$\gamma_{dy,2}$	$\delta_{I_{sc}}$	$\delta_{V_{mp}}$	δ_{R_s}
CWRU_EVA_GB_mDH	dy $\leq$ 0.0674	0.28	0	0	1.05	0	-0.33
	dy $>$ 0.0674	0.19	0	0	1.05	0	-0.26
CSI_EVA_GB_mDH	dy $\leq$ 0.3066	-0.74	0.07	-0.19	2.79	-0.87	-0.18
	dy $>$ 0.3066	-0.45	0.07	-0.19	2.79	-0.87	-0.48



$$^{n}P_{mp,IV} = \eta + \gamma_{dy,1} \cdot dy + \gamma_{dy,2} \cdot dy^2 + \delta_{I_{sc}} \cdot ^{n} I_{sc,IV} + \delta_{V_{mp}} \cdot ^{n} V_{mp,PIV} + \delta_{R_s} \cdot ^{n} R_{s,IV}$$

Principle 1 (P1): Assume Markov Property

- Memoryless property of a stochastic process
- Interpretable model for inferring active mechanisms

Principle 2 (P2): Multiple Regression by Step AIC

- Further train the principle 1 network model
- Using stepwise regression and AIC
- P2 Model used for Prediction of modeled response

P2 <*S*|*M*|*R*> model is for Service Life Prediction

The P2 <*S*|*M*|*R*> model has best R_{adj}^2

- Fits the data most accurately
- Has the highest variance explained
- Is the most accurate predictive model

<*S*|*M*|*R*> models provide both

- **Mechanistic Inference**
- **And Response Prediction**

Degradation & Partial Shading Study of Photovoltaic Modules in the Field: Enabled by Time-series Current-Voltage & Power Analysis

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Degradation mechanisms and partial shading of glass-backsheet and double-glass photovoltaic modules in three climate zones determined by remote monitoring of time-series current–voltage and power datastreams

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J. Liu, et al., "Degradation mechanisms and partial shading of glass-backsheet and double-glass photovoltaic modules in three climate zones determined by remote monitoring of time-series current–voltage and power datastreams," *Solar Energy*, vol. 224, pp. 1291–1301, Aug. 2021, doi: 10.1016/j.solener.2021.06.022.

The Fraunhofer-ISE Dataset: 8 years of *I-V*, P_{mp} *Datastreams*

8 PV modules located in 3 locations
With 3 Köppen-Geiger Climate Zones

- 3 in Gran Canaria (**BWh** by kgc package[1])
- 3 in the Negev (**BSh**)
- 2 on Mount Zugspitze, Bavarian Alps (**ET**)

Mod. ID	Start	End	System Age (Yr.)	Loc.	CZ	Brand Arch.
1	2010-10-19	2018-10-31	8.03	GC	BWh	G:DG
2	2010-02-05	2018-10-31	8.74	GC	BWh	G:DG
3	2010-09-28	2016-11-24	6.16	GC	BWh	F:GB
4	2012-06-11	2018-10-31	6.39	NG	BSh	G:DG
[illegible]	[illegible]	2015-05-17	2.93	NG	BSh	F:GB
[illegible]	[illegible]	2018-10-31	6.39	NG	BSh	F:GB
[illegible]	[illegible]	2013-01-31	2.63	ZG	ET	G:DG
[illegible]	[illegible]	2015-04-02	4.80	ZG	ET	F:GB

Module/System age from 3 to 8 year
8 modules belong to 2 architectures

- 4 glass-backsheet (GB), brand F
- 4 double-glass (DG) of brand G

Dataset:
46 module years,
1 minute interval power, + weather data
+ 3.2 Million I-V curves

=> 270 million points

P_{mp} measured

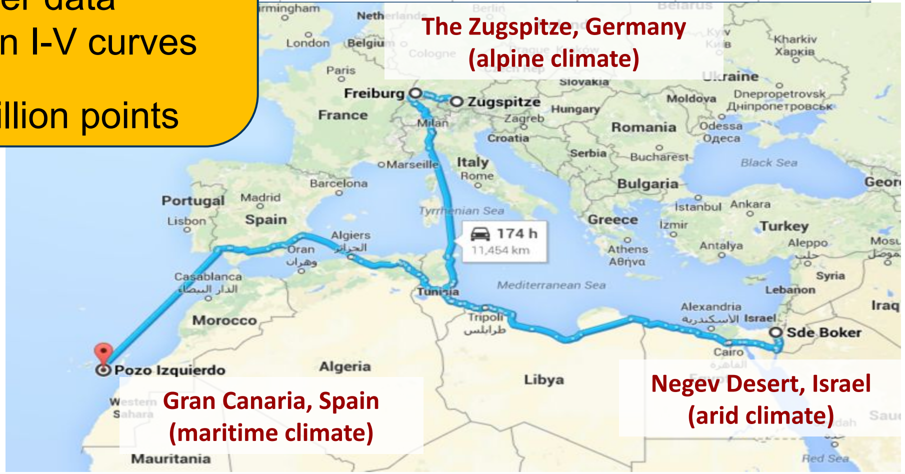
- every 1 min

Time Series *I-V* curves (3.2 Million)

- acquired every 5 mins

Meteorological, Weather Data

- every 1 min
- Temperature. POA Irradiance



Three Related Climates' Description

kgc package (published in CRAN)[1]

Köppen–Geiger climate zone system:

Group B: Dry climates[3]

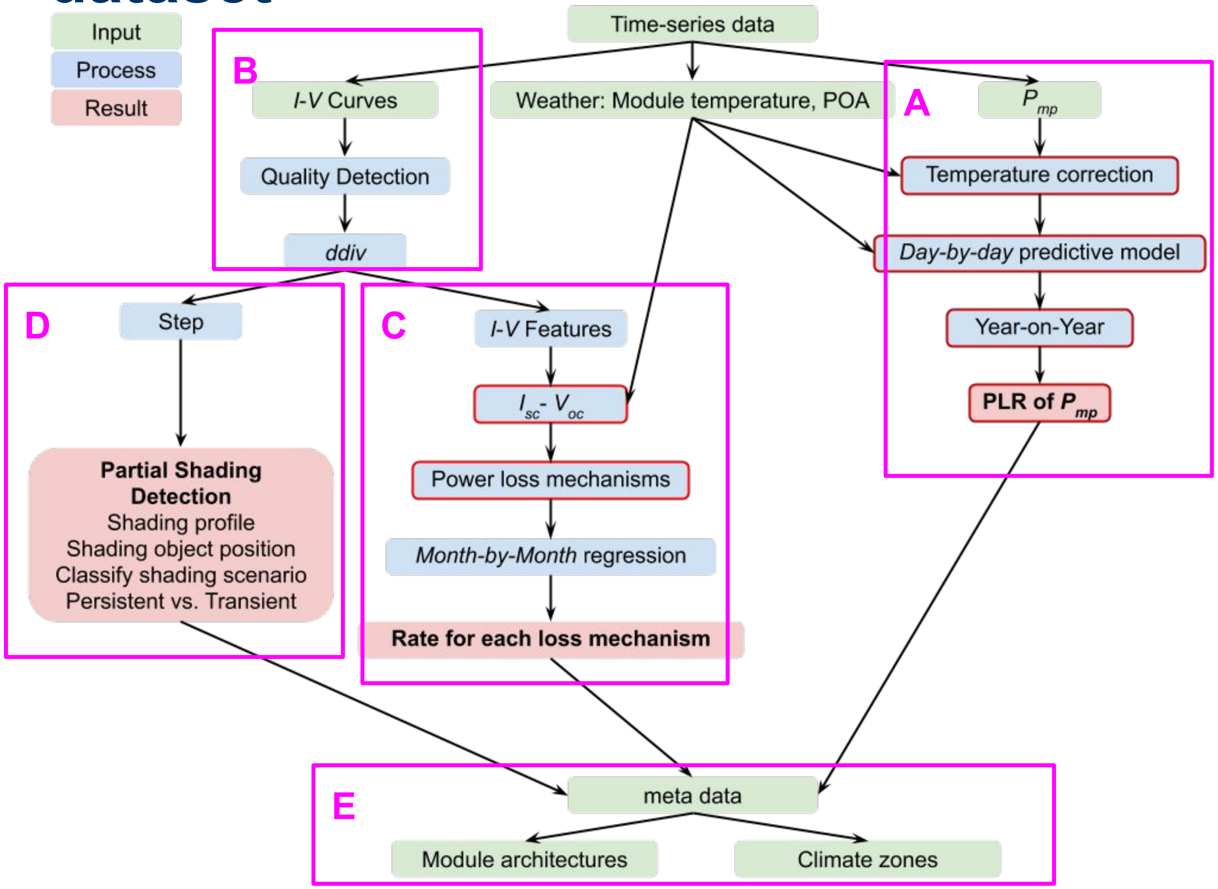
- This climate defined by little precipitation
- **BWh = Hot desert climate**
- **BSh = Hot semi-arid climate**

Group E: Polar and alpine climates[3]

- This climate has each month with avg. temperature **below 10 °C**
- **ET = Tundra climate**
- avg. temperature of warmest month **between 0 °C (32 °F) and 10 °C**

[1]Bryant, Chelsey, Nicholas R. Wheeler, Franz Rubel, and Roger H. French. **kgc: Koeppen-Geiger Climatic Zones** (version 1.0.0.2), 2017. https://CRAN.R-project.org/package=kgc.
[2]Google Maps. "Google Maps." Accessed May 8, 2020. https://www.google.com/maps.
[3]"Köppen Climate Classification." In Wikipedia, May 7, 2020. https://en.wikipedia.org/w/index.php?title=K%C3%B6ppen_climate_classification&oldid=955352420.

Flowchart of the Study Protocol: Timeseries P_{mp}, *I-V* dataset



Input:

- Time-series P_{mp}, *I-V*, POA & MT
- Meta data

Analysis & Result:

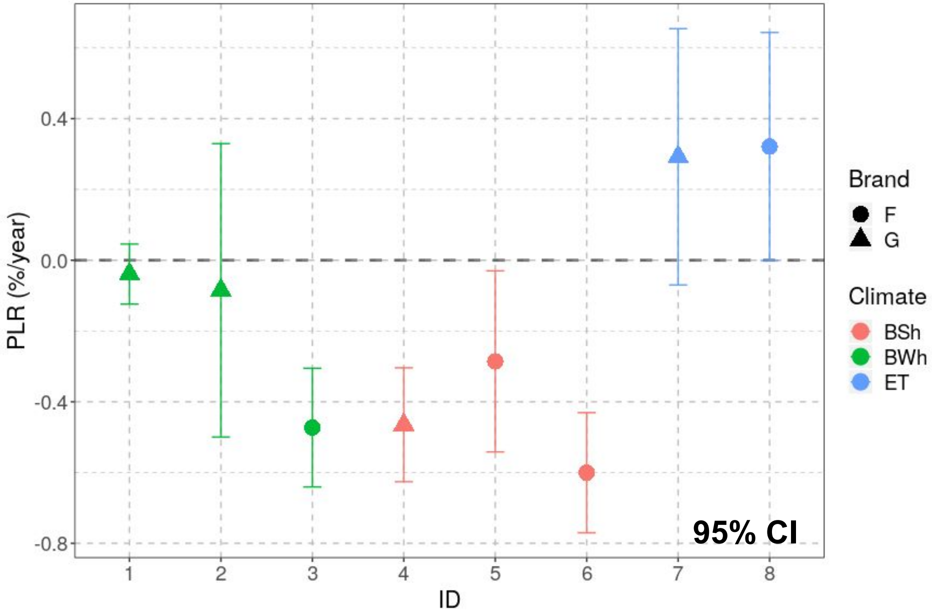
- P_{mp} -> PLR
- *I-V* curves -> *I-V* features & Steps
- -> Outdoor I_{sc}-V_{oc} analysis & Shading
- Comparison across climate zones & module architectures

Advantages:

- By converting *I-V* features' to Power Loss Modes
- Degradation study includes performance & degradation modes
- Partial shading detection based on time-series *I-V* curves

A. Performance Loss Rate (PLR) Varies by KG Climate Zone

PLR result for 8 modules



GB & DG PV Modules Degrade Differently

- Depends on Koppen-Geiger Climate Zone

Brand F (Glass-Backsheet)

- **BWh ~ BSh > ET**

Brand G(Double Glass)

- **BSh > BWh > ET**

Lower degradation rate of Double Glass PV

- For DG module in BWh
- Brand G(DG) has high weather resistance

Modules in ET KG Climate Zone

- Exhibit positive PLR

[1] A. J. Curran, T. Burleyson, S. Lindig, D. Moser, R. H. French, **PVplr: Performance Loss Rate Analysis Pipeline**. CRAN, 2020. https://CRAN.R-project.org/package=PVplr.

B,C. Data-driven *I-V* Features Extraction Algorithm(*ddiv*)[1]

Step 1:

- Fit **smooth.spline** model of *I* ~ *V*
- Evenly **generate 500 points** from it

Step 2:

- Fit **Change Point model `k`**

Step 3:

- **For each change point**,
  decide whether it's a **`step`** by
- Slope for left side should be negative
- The absolute value of left slope minus right slope must exceed **`diff_slop`**

Step 4:

- For each step, moving window to
  determine flat area for I_{sc} and R_{sh}
- **Extract features by definition**

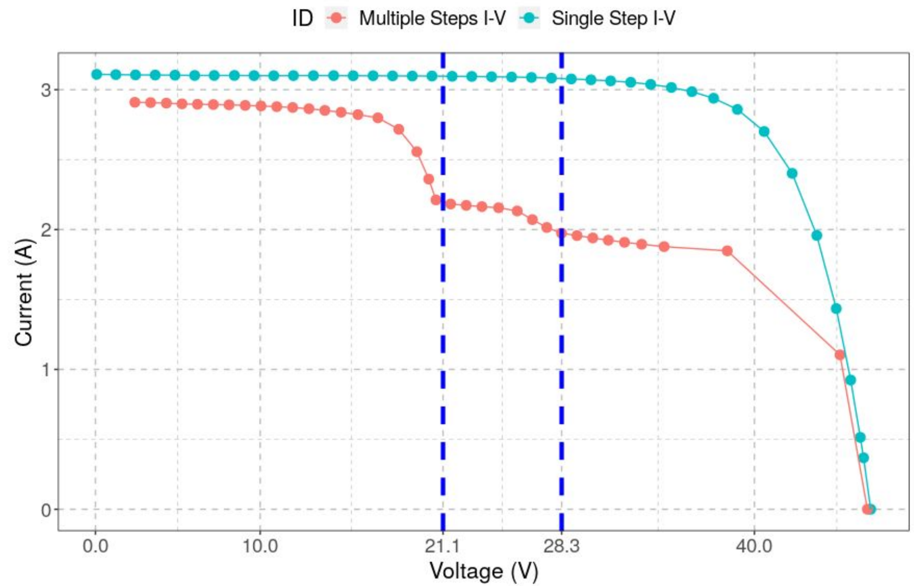


Table 4.1. Extracted *I-V* features result for single step and multiple step *I-V* curves

Step	I_{sc}	R_{sh}	V_{oc}	R_s	P_{mp}	I_{mp}	V_{mp}	FF	$Cutoff$
3	2.915	477.963	43.919	10.389	50.184	2.674	18.767	39.2	21.111
	3.636	14.661	81.756	27.06	55.823	1.979	28.21	18.78	28.27
	2.869	31.698	46.87	1.408	82.129	1.96	41.896	61.08	NA
1	3.109	852.741	47.076	1.24	111.422	2.853	39.059	76.13	NA

[1] Wei-Heng Huang, Xuan Ma, Jiqi Liu, Menghong Wang, Alan J. Curran, Justin S. Fada, Jean-Nicolas Jaubert, Jing Sun, Jennifer L. Braid, Jenny Brynjarsdottir, Megan M. Morbitzer, Roger H. French, and Roger H. French, **ddiv: Data Driven I-V Feature Extraction.** The Comprehensive R Archive Network, 2021. https://CRAN.R-project.org/package=ddiv.

B,C. Outdoor I_{sc}-V_{oc} & Power Loss Modes

Climate Zone	Brand	uni_I(%/year)	Rec(%/year)	R_s(%/year)	I_mis(%/year)
BWh	G:DG	-0.0495	0.0458	-0.0660	**-0.179**
BWh	F:GB	**-0.747**	-0.0532	0.1220	-0.250
BSh	G:DG	**-0.565**	0.0278	-0.0308	0.0560
BSh	F:GB	**-0.750**	-0.0325	0.0042	-0.0825
ET	F:GB	0.1261	0.0792	**-0.1272**	0.4289

Module 5 & 7 has high standard error,

- due to very short system age (< 3 yrs.)

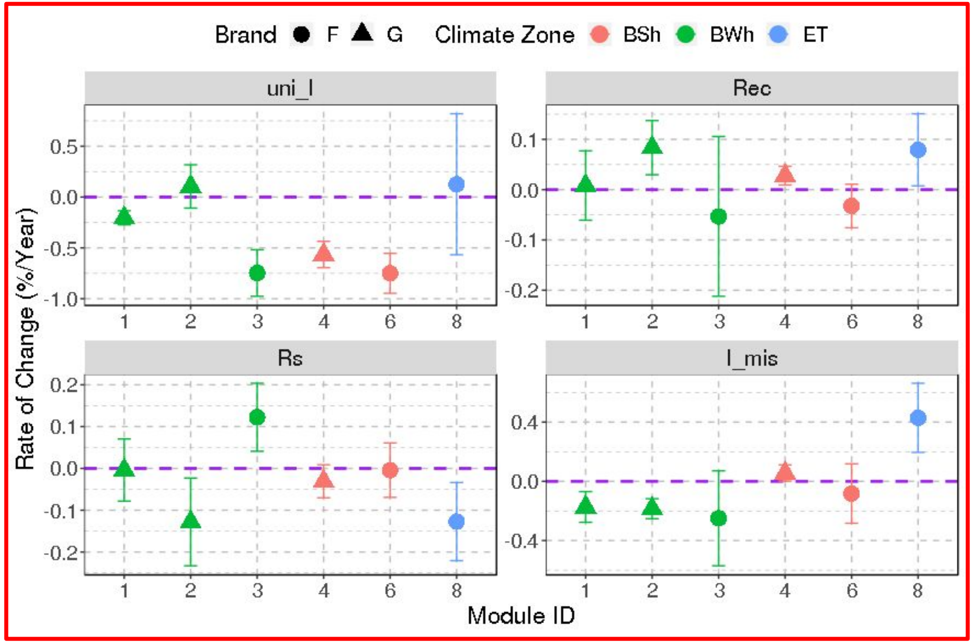
Dominant Degradation Modes chosen by

- Most negative rate of change

Uniform Current Power Loss: BWh + F, BSh + F/G

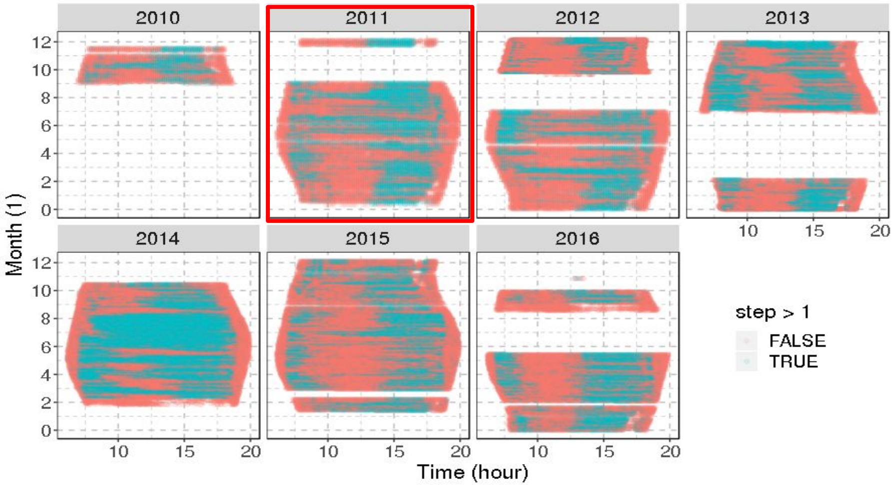
Current Mismatch Power Loss: BWh + G,

Series Resistance Power Loss: ET + F



[1] Menghong Wang, Tyler J. Burleyson, Jiqi Liu, Alan J. Curran, Abdulkerim Gok, Eric J. Schneller, Kristopher O. Davis, Jennifer L. Braid, Roger H. French, and R. H. French, **SunsVoc: Constructing Suns-Voc from Outdoor Time-series I-V Curves**. The Comprehensive R Archive Network, 2021. https://CRAN.R-project.org/package=SunsVoc

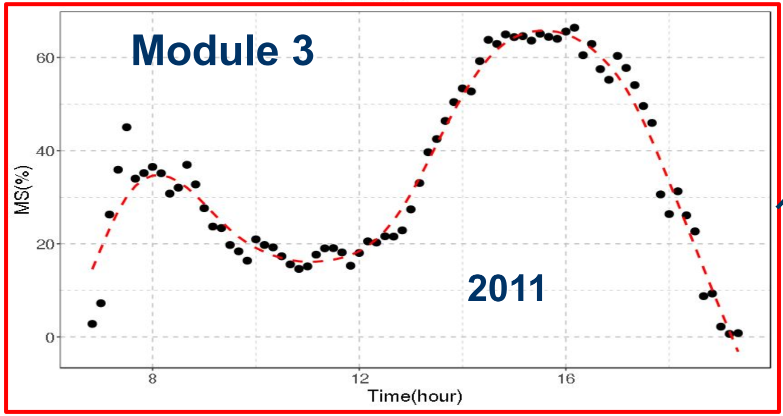
D. Module Shading Profile, From Multi-step (MS) *I-V* Curves



Group data into each year

- **For the years with more than 100 days *I-V***
- **Calculate MS for each time point**
- **Spline model + find local peak**

$$MS_t = \frac{N_{ms,t}}{N_{total,t}}$$



Time in a Day	MS(%)	Year
08:10:00	35.1	2011
15:30:00	65.1	2011
07:10:00	46.9	2012
14:46:00	57.1	2012
08:10:00	55.7	2013
15:20:00	61.9	2013
08:40:00	58.9	2014
15:45:00	78.0	2014
07:55:00	32.1	2015
16:10:00	52.1	2015
07:50:00	40.0	2016
15:15:00	64.0	2016

Conclusions

PV Modules are complex systems, exposed to multiple stressors

- With multiple active degradation mechanisms & pathways
- That interact during degradation

Statistically-informed Study Protocols enable studies of complex systems

- To achieve sufficient measurements, for good confidence intervals
- Focusing on multiple mechanisms

Using step-wise or timeseries P_{mp}, *I-V* datasets

- Provides a common basis for integrating lab and real-world SLP Studies

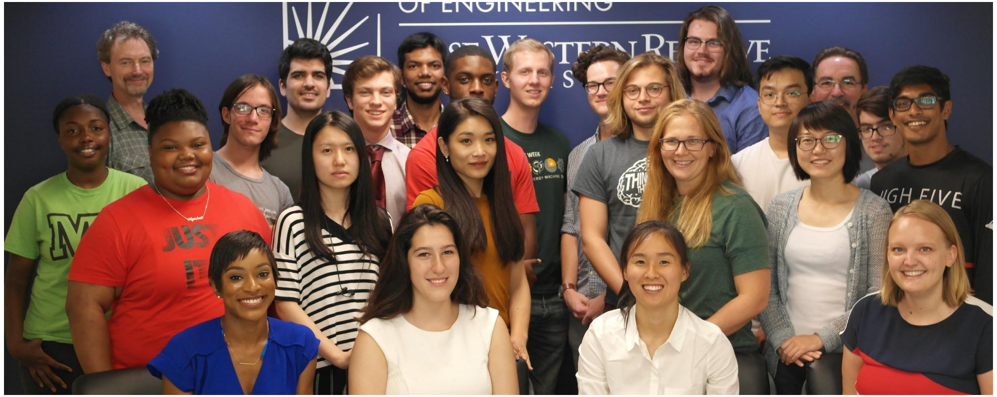
netSEM models can identify and illustrate these complex degradation networks

- Of interacting mechanisms and pathways
- netSEM Principle 1 (Markov property) => inference on mechanisms and pathways
- netSEM Principle 2 (Mult. Regr. by Step AIC) => accurate prediction of Service Life

Data science tools: netSEM, ddiv, SunsVoc, PVplr, kgc, FAIRmaterials, PVimage

- R & Python Packages, Published and available to all the community

SDLE Research Center: Acknowledgements



CWRU Faculty

- Roger French, Laura Bruckman, Jeffrey Yarus, Yinghui Wu, Alp Sehirlioglu, Matt Willard, Vipin Chaudhary

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- Sameera Nalin Venkat, Tian Wang, Steven Timothy. David Meshnick, Mingjian Lu, Yangxin Fan
- Kristen Hernandez, Nat Tomczak, Hein Htet Aung, 1 Open Position

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- Medha Nayak, Cora Lutes, Beck Pierce, Shreeyah Chugh, Sakin Kirti, Kehley Coleman, Shuyue Bian
- Vibha Mandayam, Guo Chen, Nathan Romig, NIkhila Balasubramaniam, Leean Jo, Max Atkinson
- Andre Yost, Asya Orhan, Lena Plover, Glenn Boyette, Nitin Chockalingam, Jakob Wegmueller
- Abhinav Khanna, Carolina Whittaker, Mirra Rassmussen, Ray Le, Rounak Chawla, Peter Schlueter

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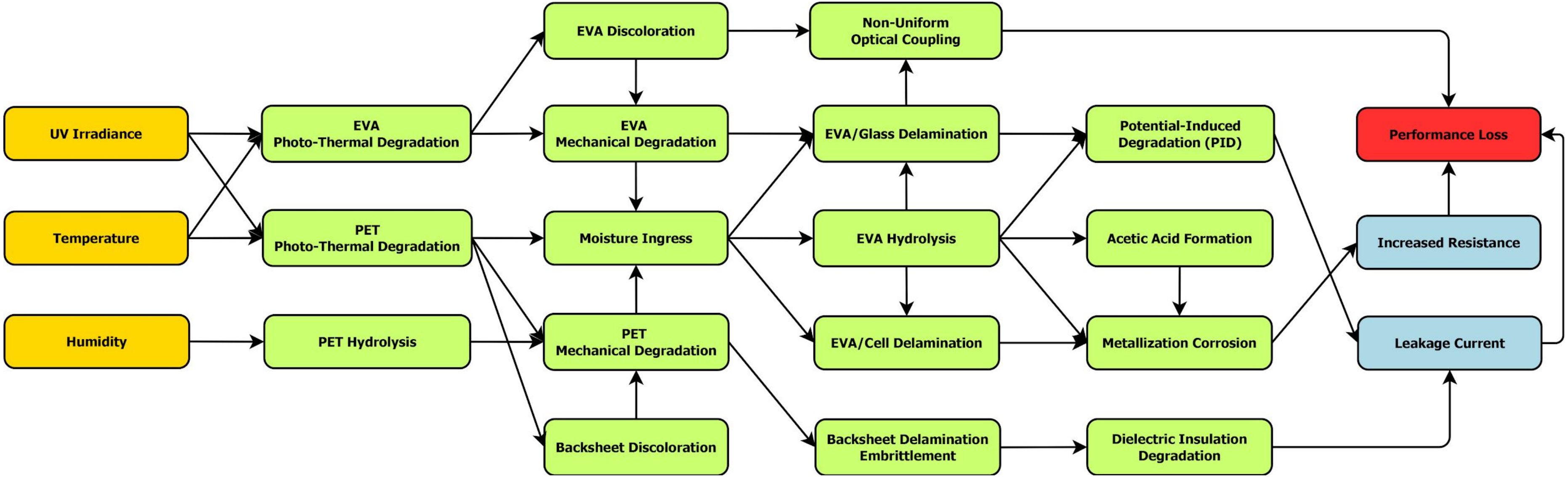
PV Degradation: Affected by Packaging & Module Architecture



Numerous mechanisms of PV module degradation

- Modules are complex systems, in complex exposure conditions

Many are simultaneously activated under real-world exposure conditions

- Assumption of one dominant mechanism is unrealistic
- Reductionism!: Phenomena described in terms of simpler fundamental processes

Gok, Abdulkerim, et al. "Degradation Science and Pathways in PV Systems." *Durability and Reliability of Polymers and Other Materials in Photovoltaic Modules*. William Andrew Publishing, 2019. 47-93.

Normalized $P_{mp,IV}$ at Step 3 of Set #3 & #4 Minimodules

Red points: the mean of $^nP_{mp,IV}$

Black bar: 83.4% confidence interval

- **5%** significance level **2** sample mean t-test

Purple bar: 95% confidence interval

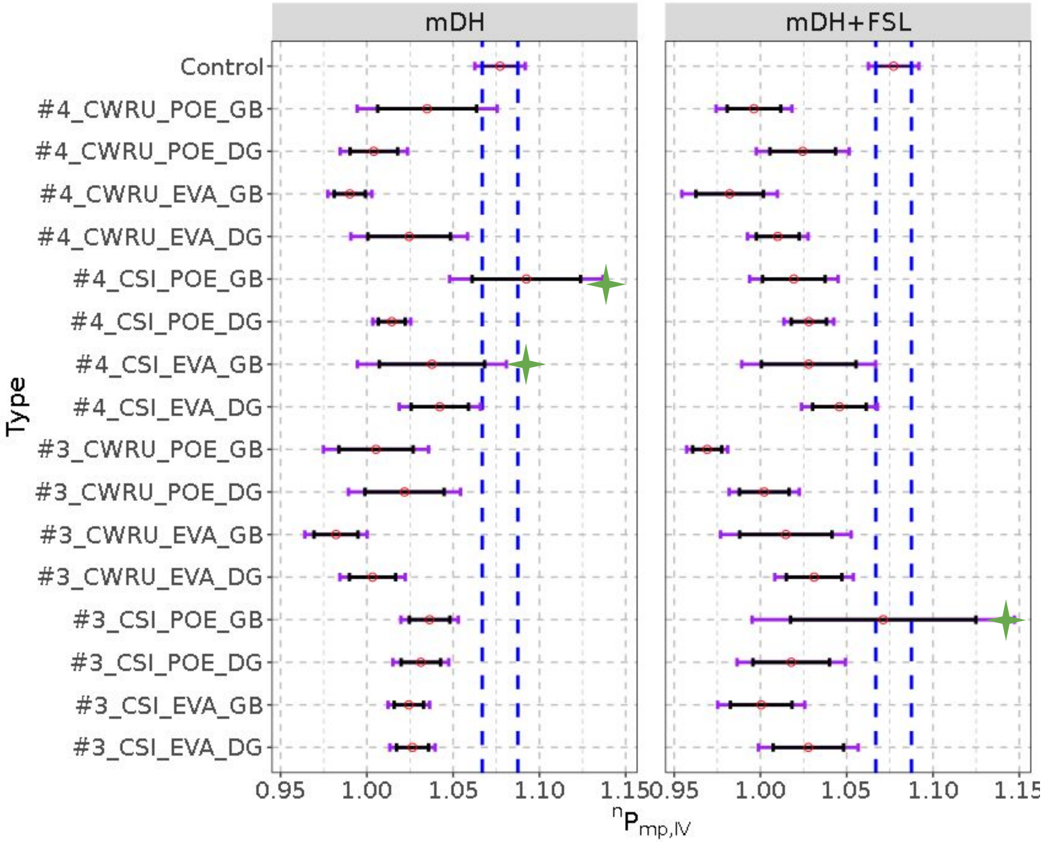
- 0.05 significance level single sample mean t-test

Double dash blue lines

- 83.4% confidence interval of the control

No significant power loss

- **#4_CSI_POE_GB: mDH**
- **#4_CSI_EVA_GB: mDH**
- ***#3_CSI_POE_GB: mDH+FSL***



Conclusion

PV service lifetime prediction

- Complex system & Synergistic effects of multiple factors

Study protocol framework

- Design of experiment: variants, statistically significant
- Aging: different microclimate stressors
- Data: timeseries, obtaining various power loss modes corresponding to degradation mechanisms

Network modeling

- Map out active pathways and degradation mechanisms that best resemble real world

Indoor: more variants

- Series resistance has greater impact on power loss
- GB with monofacial PERC by CWRU has largest power loss

Outdoor: real world

- PLR result shows domain degradation modes
- BWh (Desert) and BSh (Hot semi-arid) are much more aggressive than ET (Tundra)
- Brand G (DG) modules have better performance in BWh (Desert)
- Two brands are similar for other climates

Lab SLP

Study protocol framework

- **Module**:
  - **8 variants** based on manufacturer, architecture, encapsulation
  - **8 samples** per variant
- **Aging**:
  - Modified damp heat to **2,520h**
  - Sequential exposures of modified damp heat and full spectrum light to **2,520h**
- **Data collection**::
  - Stepwise ***I-V***
  - Stepwise ***Suns-V$_{oc}$***

Results	Degradation mode
${}^{n}I_{sc,IV}$	Optical transmission loss
${}^{n}R_{s,IV}$	Corrosion
${}^{n}V_{mp,PIV}$	Recombination and shunting

Network model

- **netSEM**: network structural equation modeling
  - Degradation pathways
  - Active degradation mechanisms
  - Power loss prediction

W.-H. Huang, et al., netSEM: Network Structural Equation Modeling, CRAN, 2018.
Menghong Wang, et al., SunsVoc: Constructing Suns-Voc from Outdoor Time-series I-V Curves, CRAN, 2021.

netSEM: Degradation Pathway Network Modeling

netSEM R Package[1]

- Developed under UL funding[2]
- Improved under DOE SETO Funding
- 1 year NSF IUCRC MDS-RELY
- NetSEM on CRAN

Packages for Reproducible Science

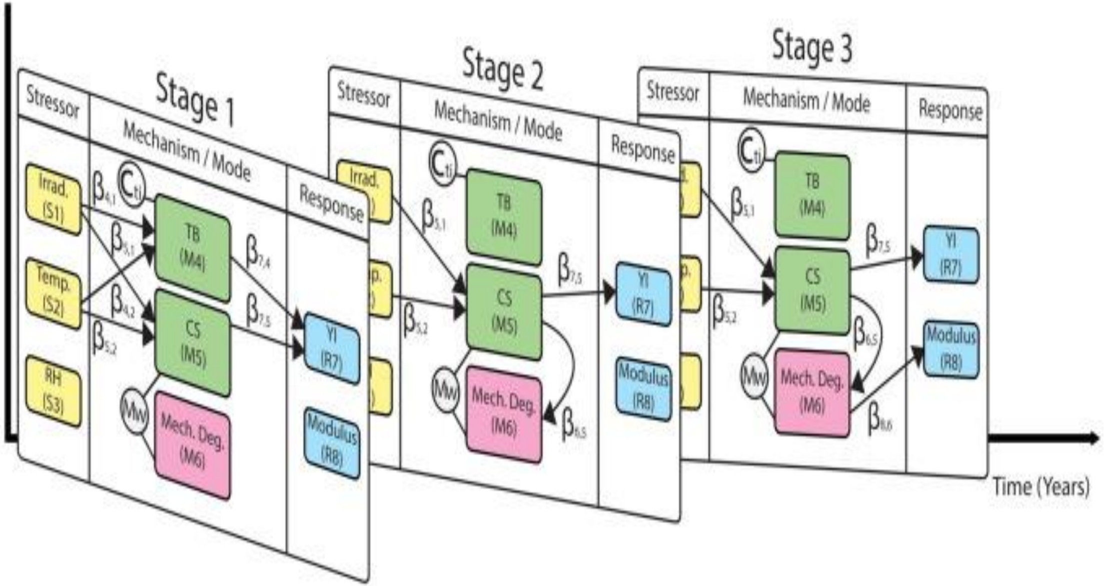
- Well-vetted Open Source Codes
- With Vignettes on Theory, & Use
- With Data Sets and Results for Validation

python R

Build predictive models

- Relate <Stressor|Response>
- Relate <Stressor|Mechanism|Response>
- Enough confidence

<Stressor|Mechanism|Response>



Acrylic degradation occurring in 3 stages as the UV stabilizer is bleached (Stage 1), the acrylic backbone degrades (Stage 2), and the mechanical integrity fails (Stage 3).

1. W.H. Huang, et al., netSEM: Network Structural Equation Modeling, 2018.
2. Bruckman, Laura S., et al. "Statistical and domain analytics applied to PV module lifetime and degradation science." *IEEE Access* 1 (2013): 384-403.

Towards 50 Year Lifetime PV Modules (T50): Double Glass vs. Glass/Backsheet

Study influences of different packaging strategies on the degradation behavior of PV modules

- Identify and mitigate relevant degradation modes (corrosion and mechanical)
  - In GB and DG modules with various cells and encapsulants
  - To reduce the power degradation rate to 0.2%/year

Minimodule (MM) Variants

Cell Types (PERC + multi-Si):
- Monofacial
- Bifacial

Encapsulant Types:
EVA or POE
(Trans/UV Cutoff)
(Trans/Opaq)
(Trans/Trans)

Backside Types:
Backsheet (KPf / transparent BS)
Glass

\+

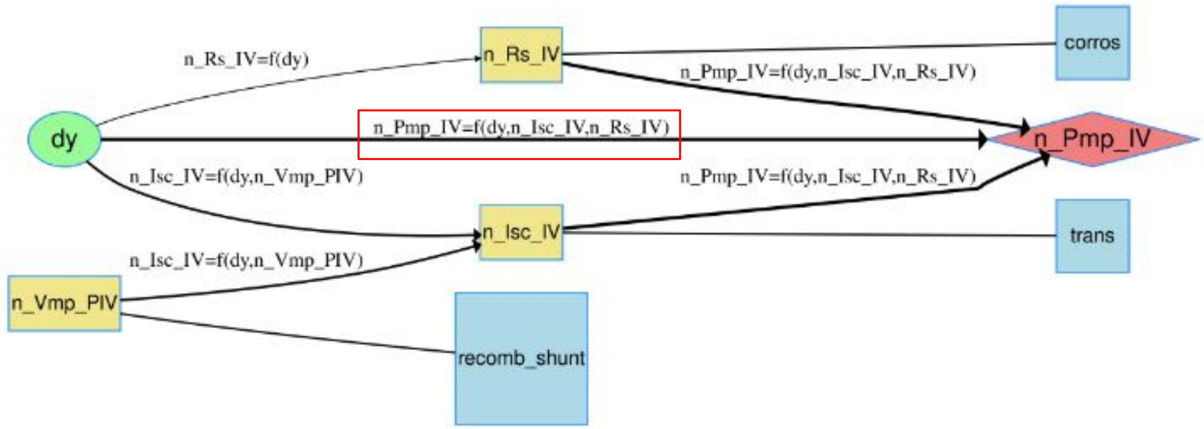
Indoor accelerated exposures:
- mDH
- mDH + Full Spectrum Light

Outdoor exposure:
CWRU Sunfarm, Cleveland, OH

\+

Evaluations:
- *I-V* (Multiple Irradiance levels)
- *Suns-*V_{oc}
- EL & PL
- 4-pt bending proof loading
- Time-series *I-V* & P_{mp}

Principle 2 <$S|M|R$> Model: Multiple Regression by Step AIC



$^nP_{mp,IV} = f(dy, {}^nI_{sc,IV}, {}^nR_{s,IV})$

↓

$^nP_{mp,IV} = 1.26 + 0.11\,dy^2 + 1.68\log({}^nI_{sc,IV}) - 0.26({}^nR_{s,IV}) - 0.11({}^nR_{s,IV} - 1)_c$

Before breakpoint:

$^nP_{mp,IV} = 1.26 + 0.11\,dy^2 + 1.68\log({}^nI_{sc,IV}) - 0.26({}^nR_{s,IV})$

After breakpoint:

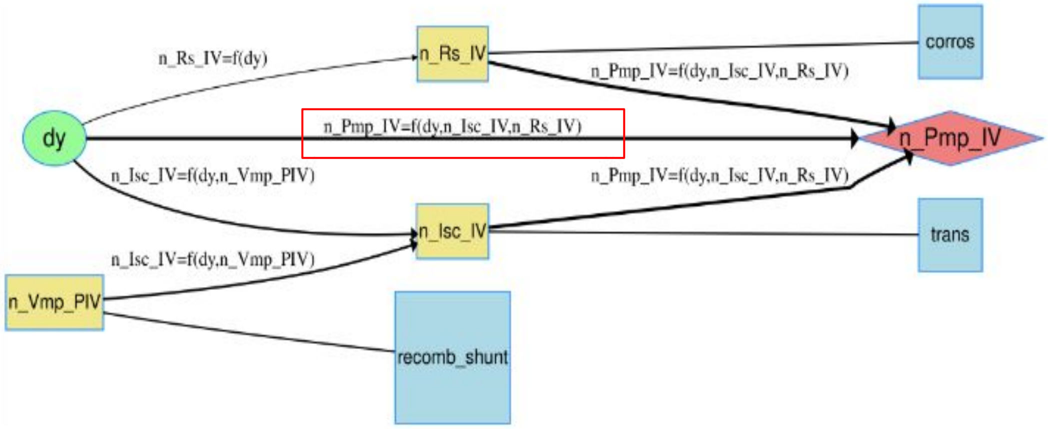
$^nP_{mp,IV} = 1.26 + 0.11\,dy^2 + 1.68\log({}^nI_{sc,IV}) - 0.26({}^nR_{s,IV}) - 0.11({}^nR_{s,IV} - 1)$

Multiple regression equations

- Relating $^nP_{mp,IV}$ and other stressor/mechanistic variables
    - High R_{adj}^2

From $^nP_{mp,IV}$ equation: power loss due to dy, $^nI_{sc,IV}$, $^nR_{s,IV}$

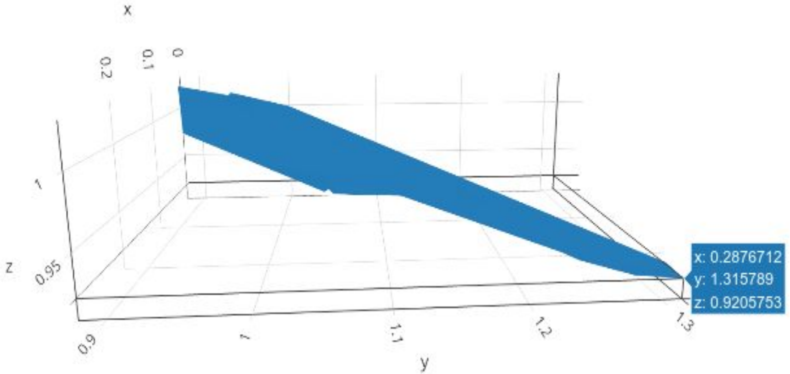
Principle 2 <*S*|*M*|*R*> Model: Multiple Regression by Step AIC



With ↑dy, ↓$^{n}P_{mp,IV}$

↑$^{n}R_{s,IV}$ at ↓$^{n}P_{mp,IV}$ and ↑dy

$^{n}I_{sc,IV}$ does not vary so much (range: 0.99-1)

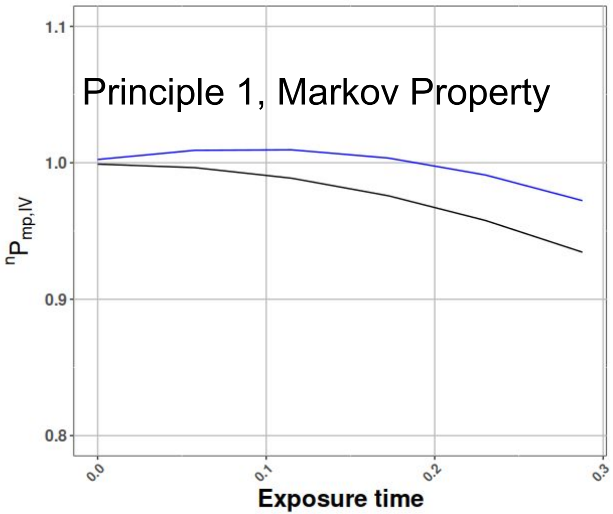


Multiple regression equations

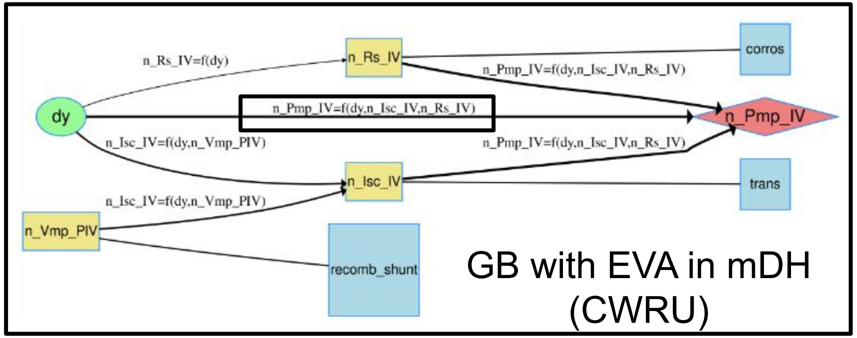
- Relating $^{n}P_{mp,IV}$ → z and other stressor/mechanistic variables
    - High R_{adj}^{2}

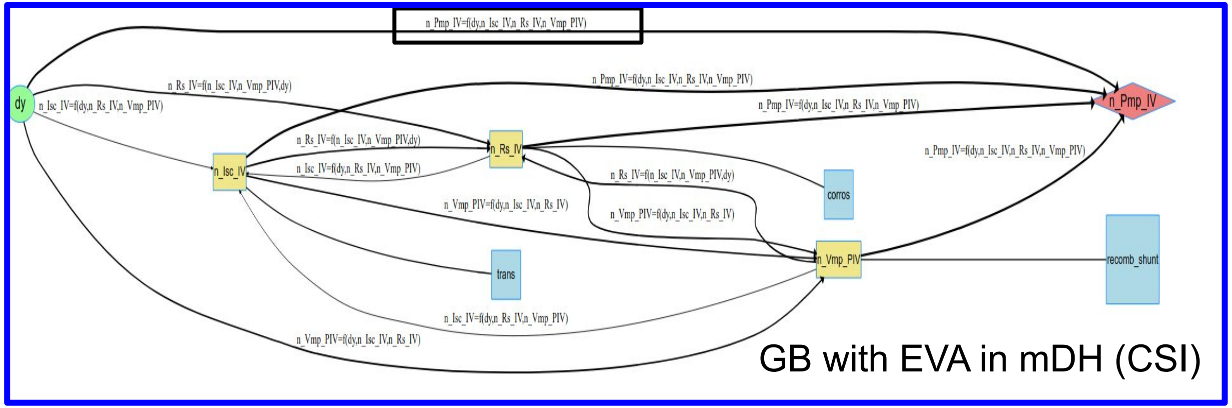
From $^{n}P_{mp,IV}$ equation: power loss due to *dy* (→ x), $^{n}I_{sc,IV}$, $^{n}R_{s,IV}$ (→ y)

Comparison of Principles 1 & 2 <*S*|*M*|*R*> Modeling



Principle 2, Multiple Regression by Step AIC





Field SLP

Study protocol framework

- **Module**:
  - **2** types (brand, architecture), **8** modules
- **Aging**:
  - **3 different climates** (Köppen-Geiger climate zones), for **3** to **9** years
- **Data collection**:
  - Datastreams of P_{mp} every **1** min
  - Datastreams of ***I-V*** every **5** min
  - **POA & T_{module}** every **1** min

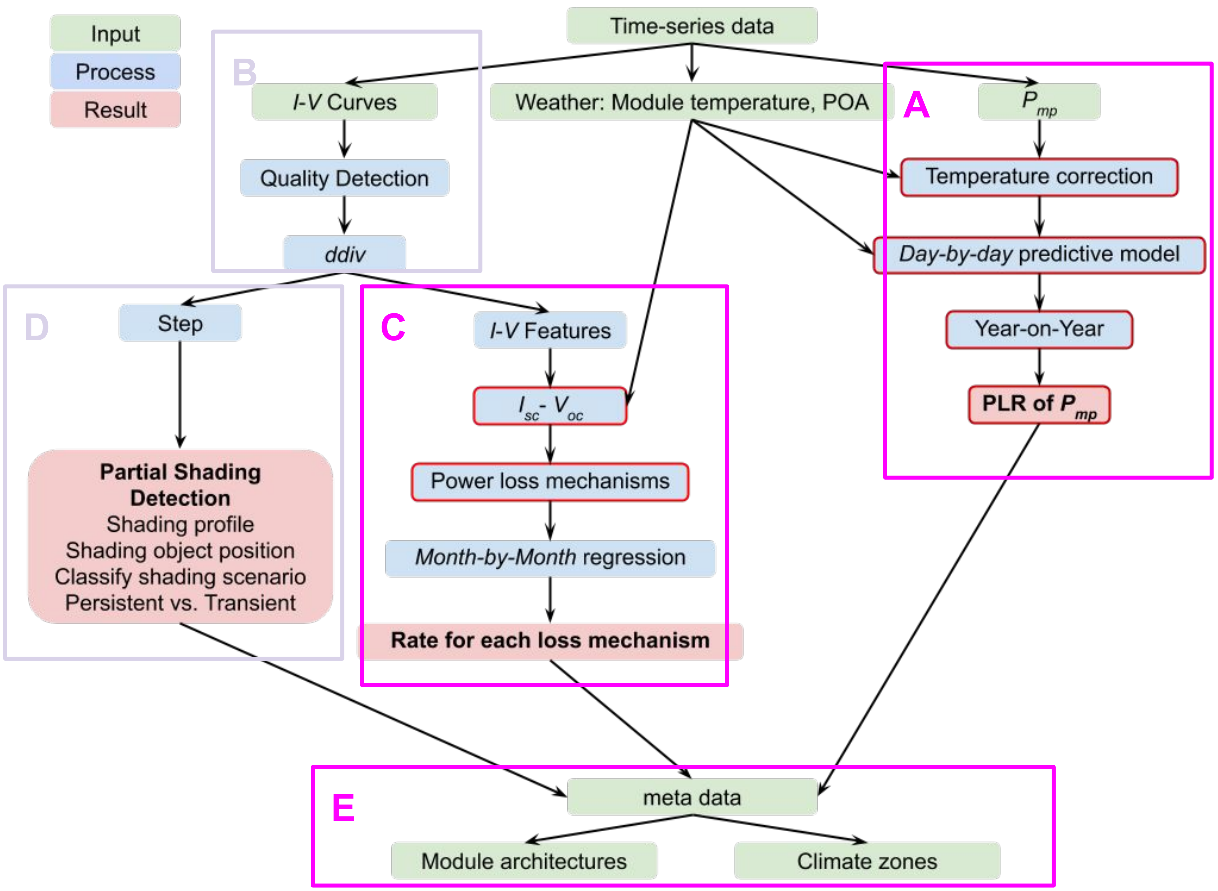
Results	Degradation mode
ΔP_{Isc}	Optical transmission loss
ΔP_{Rs}	Corrosion
ΔP_{Voc}	Recombination
ΔP_{Imis}	Current mismatch

Network model

- **PVplr**: performance loss rate analysis pipeline
  - *Month-by-month* regression infer the domain degradation modes
  - Power loss rate prediction

[1]Bryant, Chelsey, Nicholas R. Wheeler, Franz Rubel, and Roger H. French. Kgc: Koeppen-Geiger Climatic Zones (version 1.0.0.2), 2017. https://CRAN.R-project.org/package=kgc.
[2]Google Maps. "Google Maps." Accessed May 8, 2020. https://www.google.com/maps.

Flowchart of the Study Process



Input:

- Time-series P_{mp}, *I-V*, POA & MT
- Meta data

Analysis & Result:

- P_{mp} -> PLR
- *I-V* curves -> *I-V* features & Steps
- -> Outdoor I_{sc}-V_{oc} analysis & Shading
- Comparison across climate zones & module architectures

Advantages:

- Partial shading detection based on time-series *I-V* curves
- Degradation study include general performance and degradation mode by converting the *I-V* features' changes to their contribution in power loss

Performance Loss Rate Calculation[1,2]

Filtering by POA >= 200W/m^2

↓

Temperature coefficient Linear model *Pmp* vs. MT (890 W/m^2 - 910 W/m^2)

↓

Temperature correction to *Pmp (MT = 40 °C)*

$$P_{mp,corrected} = \frac{P_{mp}}{1+\gamma_T(T_{obs}-T_{ref})\times(\frac{POA}{900})}$$

↓

Day-by-Day Predictive method of corrected *Pmp* vs. POA

$$P_{mp,corrected} = \beta_0 + \beta_1 \times POA$$

↓

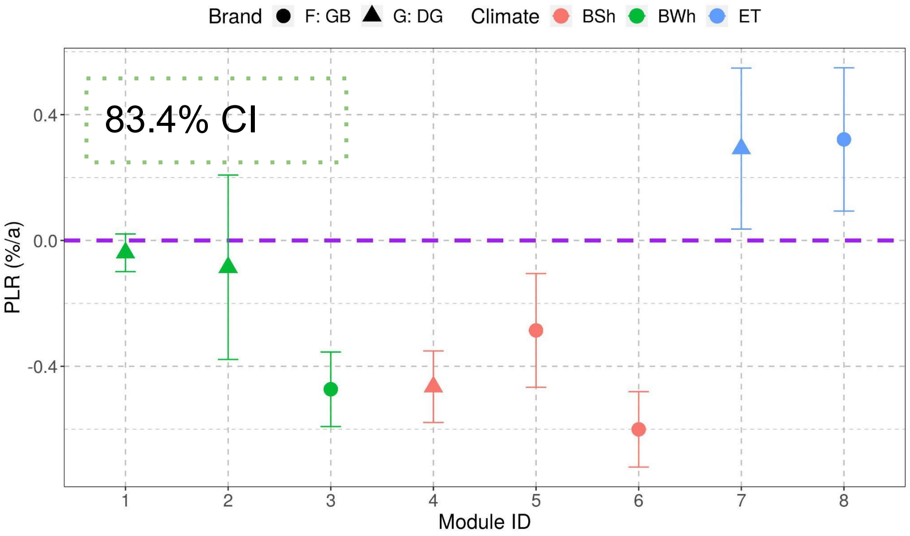
Predicted *Pmp* at 900 W/m^2 POA

$$P_{mp,predicted} = \beta_0 + \beta_1 \times 900$$

↓

Year-on-Year Linear Regression[2] PLR

PLR processing pipeline



Brand F (Glass-Backsheet)

- **BWh ~ BSh > ET**

Brand G(Double Glass)

- **BSh > BWh > ET**

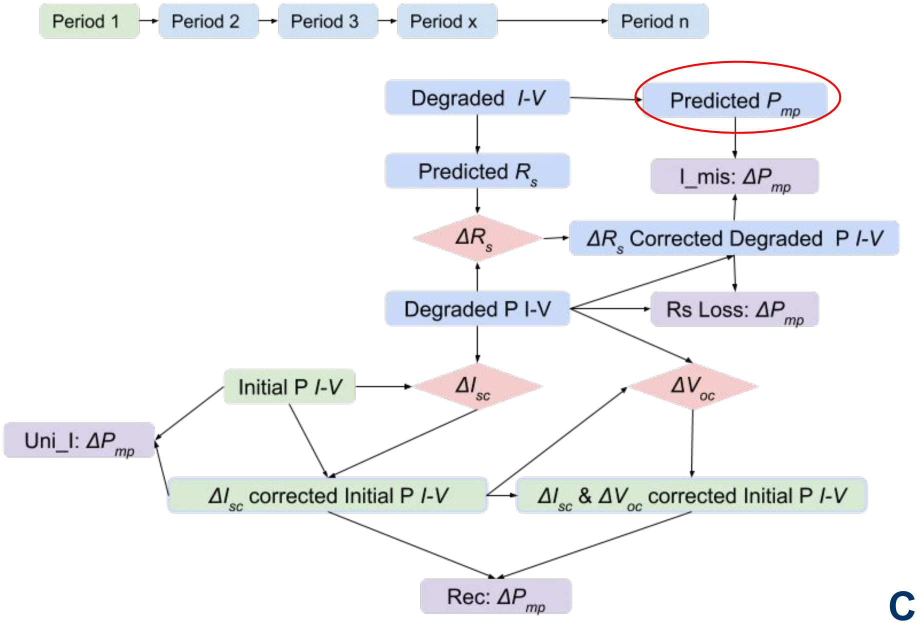
Due to lower degradation rate for DG module in BW

- **Brand G(DG) has higher weather resistance**

Modules under ET have positive PLR

[1]Liu, Jiqi, Menghong Wang, Alan J. Curran, Ahmad Maroof Karimi, Wei-heng Huang, Erdmut Schnabel, Michael Köhl, Jennifer L. Braid, and Roger H. French. "Real-World PV Module Degradation across Climate Zones Determined from Suns-Voc, Loss Factors and I-V Steps Analysis of Eight Years of I-V, Pmp Time-Series Datastreams." In 2019 IEEE 46th Photovoltaic Specialists Conference (PVSC), 0680–86, 2019. https://doi.org/10.1109/PVSC40753.2019.8980541.
[2]Curran, Alan J., C. Birk Jones, Sascha Lindig, Joshua Stein, David Moser, and Roger H. French. "Performance Loss Rate Consistency and Uncertainty Across Multiple Methods and

Outdoor I_{sc}-V_{oc} & Loss Factor Calculation[1]

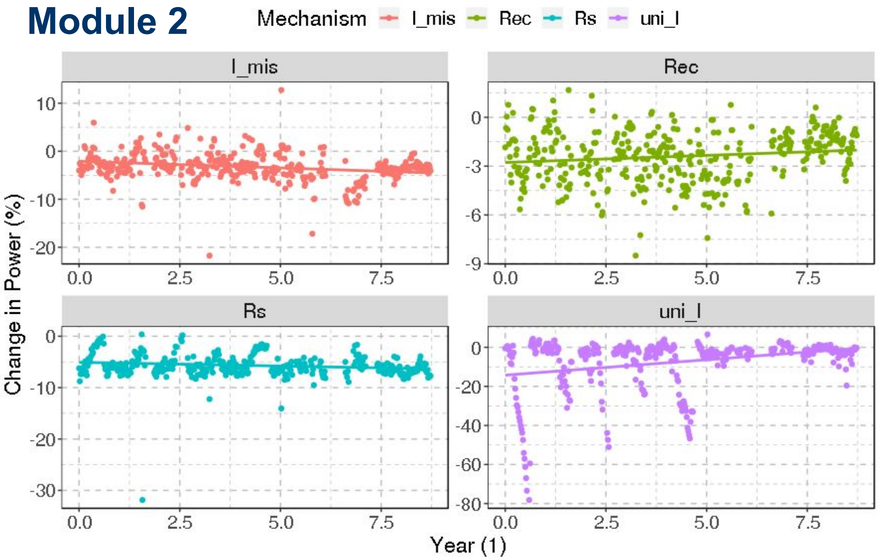


Reference Condition

Outdoor I_{sc}-V_{oc} & loss factor pipeline[1]

$$V_{oc}(I_{sc}, T_m) = \alpha_0 + \alpha_1 \cdot (T_m + 273.15) \cdot ln(I_{sc}) + \alpha_2 \cdot (T_m + 273.15) + \varepsilon$$

$$I_{psd}(V_{psd}) = I_{sc}^0 - I_{sc}(V_{oc})$$



Current mismatch(I_mis): partial shading, cracking

Recombination(Rec): Cells carrier recombination

Series resistance loss(Rs): corrosion

Uniform current: Soiling, yellowing in encapsulant

[1]Wang, Menghong, Xuan Ma, Wei-Heng Huang, Jiqi Liu, Alan J. Curran, Erdmut Schnabel, Michael Köhl, et al. "Evaluation of Photovoltaic Module Performance Using Novel Data-Driven I-V Feature Extraction and Suns-VOC Determined from Outdoor Time-Series I-V Curves." In 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC 34th EU PVSEC), 0778–83, 2018. https://doi.org/10.1109/PVSC.2018.8547772.

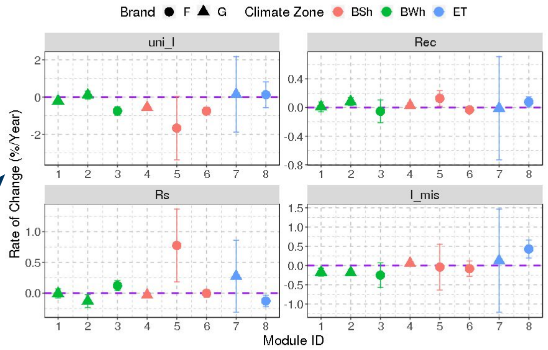
Rate of Change for Outdoor I_{sc}-V_{oc} & Loss Factor

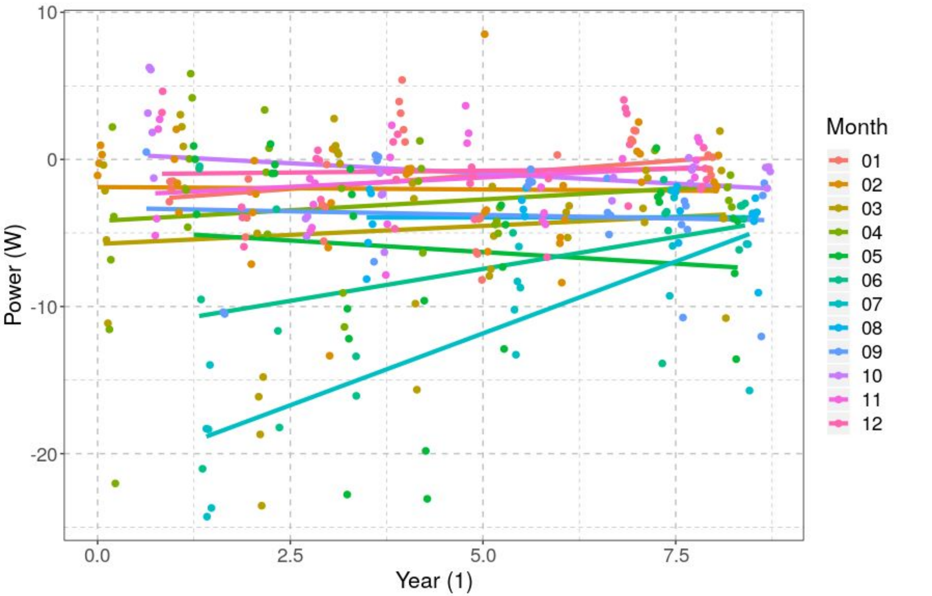
Month-by-Month **linear regression**

- **Fit linear model by observations of each month across all years**
- **Extract slopes from each model**
- **Remove the one from the month that does not include**
  - the begin and the end year
  - miss over 2 years observations

Average + 95% confidence interval of the rate of change for each power loss mode of each module

Outdoor I_{sc}-V_{oc} result





Month-by-month **Regression for Uniform Current Loss in Module 2**

Result from July and August will be removed

Outdoor I_{sc}-V_{oc} & Power Loss & Regression

Module 5 & 7 has too high standard error, due to very short system age (< 3)

Domain Degradation Mode chosen by

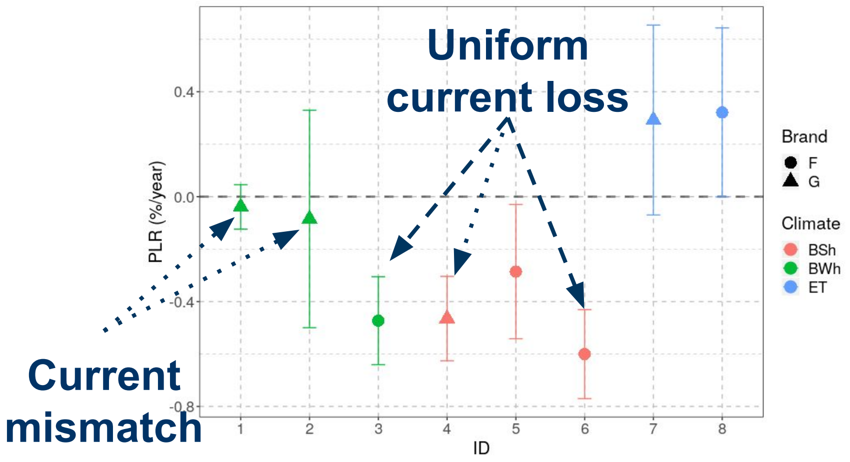
- **Most negative rate of change**

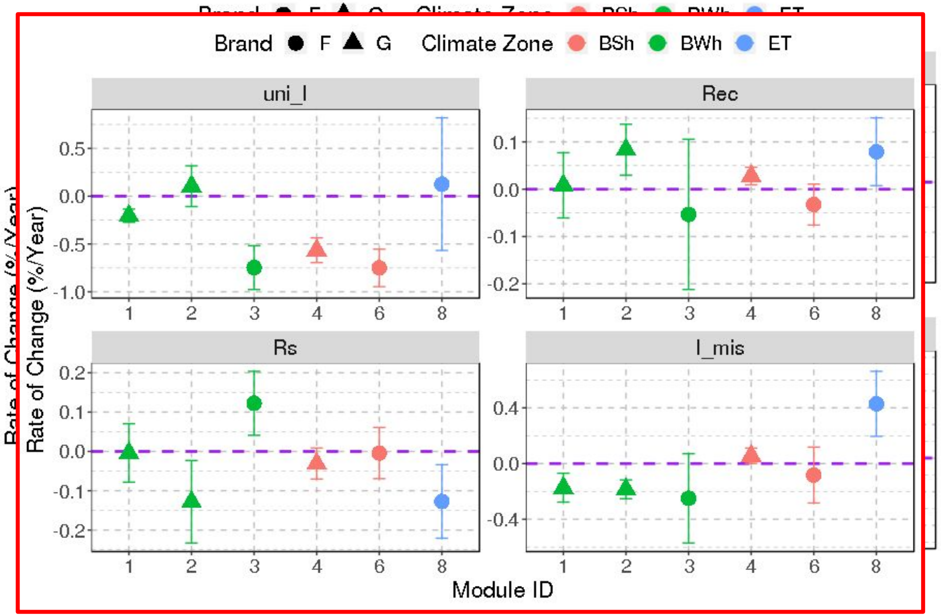
Uniform current Loss: BWh + F, BSh + F/G

Current mismatch: BWh + G,

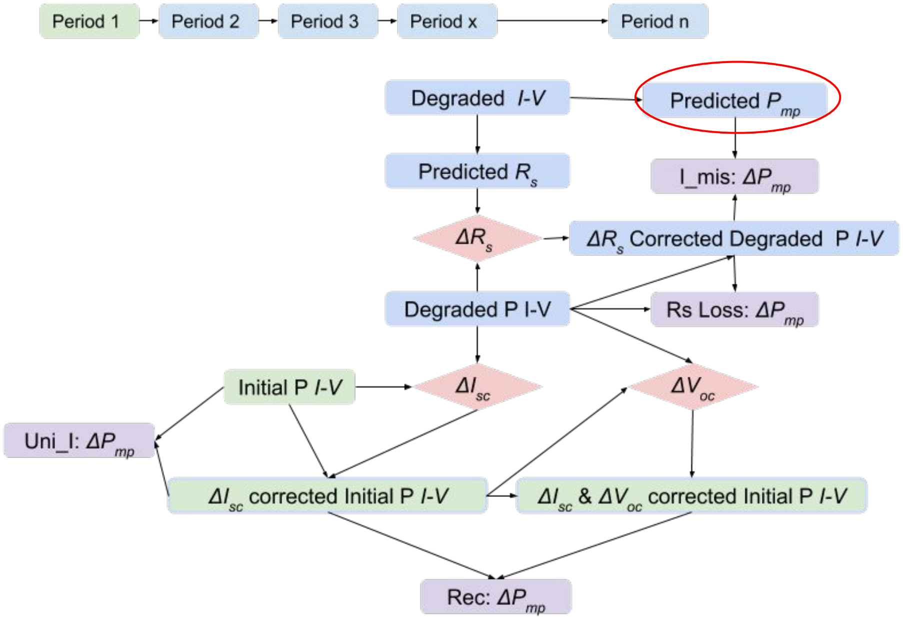
Series resistance loss: ET + F

Climate Zone	Brand	uni_I(%/year)	Rec(%/year)	R_s(%/year)	I_mis(%/year)
BWh	G:DG	-0.0495	0.0458	-0.0660	**-0.179**
BWh	F:GB	**-0.747**	-0.0532	0.1220	-0.250
BSh	G:DG	**-0.565**	0.0278	-0.0308	0.0560
BSh	F:GB	**-0.750**	-0.0325	0.0042	-0.0825
ET	F:GB	0.1261	0.0792	**-0.1272**	0.4289





B,C.Outdoor I_{sc}-V_{oc} & Power Loss Factors[1]

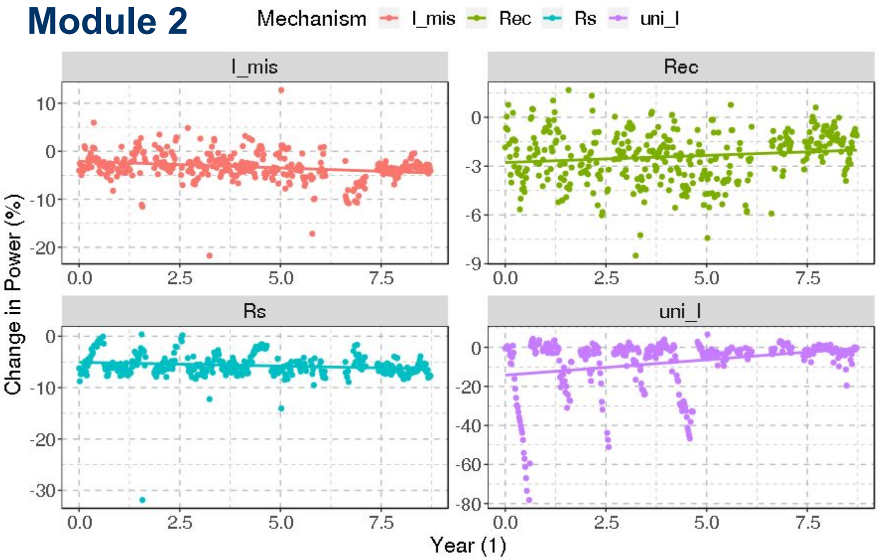


Reference Condition

Outdoor I_{sc}-V_{oc} & loss factor pipeline[1]

$$V_{oc}(I_{sc}, T_m) = \alpha_0 + \alpha_1 \cdot (T_m + 273.15) \cdot ln(I_{sc}) + \alpha_2 \cdot (T_m + 273.15) + \varepsilon$$

$$I_{psd}(V_{psd}) = I^0_{sc} - I_{sc}(V_{oc})$$



Power Loss Factors, due to

- **Current mismatch**(I_mis): partial shading, cracking
- **Recombination**(Rec): Cells carrier recombination
- **Series resistance loss**(Rs): corrosion
- **Uniform current**: Soiling, yellowing in encapsulant

[1]Wang, Menghong, Xuan Ma, Wei-Heng Huang, Jiqi Liu, Alan J. Curran, Erdmut Schnabel, Michael Köhl, et al. "Evaluation of Photovoltaic Module Performance Using Novel Data-Driven I-V Feature Extraction and Suns-VOC Determined from Outdoor Time-Series I-V Curves." In 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC 34th EU PVSEC), 0778–83, 2018. https://doi.org/10.1109/PVSC.2018.8547772.

D.Percentage of Multiple Steps *I-V* Curves(MS)

Percentage of Multiple steps *I-V* curves(MS) is calculated for each module:

- Because **AS** is about **80%**
- Only for module has MS >= 20%

Next:

- Time dependence of MS occurrence -> shading profile
- Solar angle dependence -> orientation of obtable
- Voltage of "steps" cluster -> shading scenarios
- Classification & density plot -> duration of partial shading

Table 5.1. PERFORMANCE IN TRAINING AND TESTING DATASET FOR THE BEST TWO SET OF PARAMETERS

k	$slop_{diff}$	Training AS (%)	Training AM (%)	Training Accuracy (%)	Testing AS (%)	Testing AM (%)	Testing Accuracy (%)
7	0.018	79.3	77.7	78.5	94.2	71.1	82.7
8	0.018	77.8	78.9	78.4	91.2	74.7	83.0

D.Obstacle Orientation

MS occurrence: when the shadow on the module

- Obstacle and Module are stationary
- Sun is scanning everyday

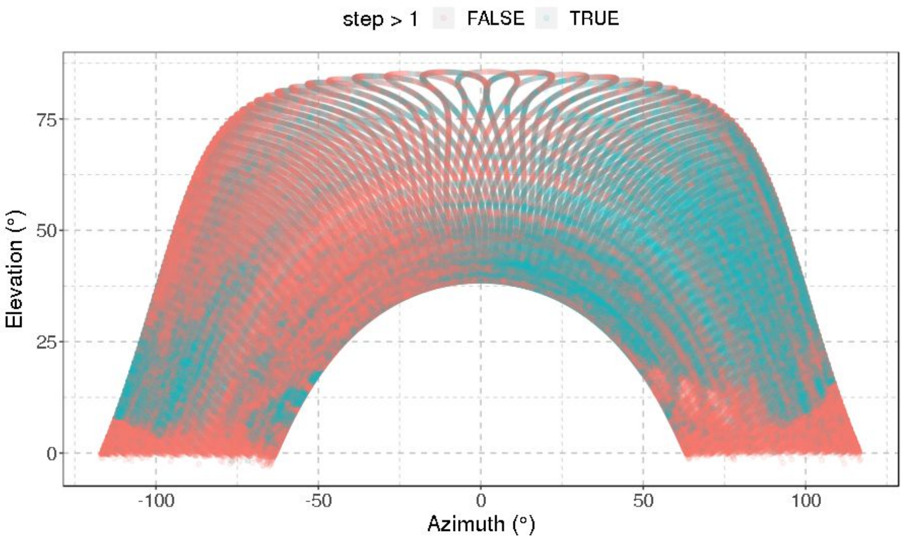
Input **longitude & latitude** of location

Convert data & time

- **into solar elevation & azimuth** (Suncalc[1])

"elevation" : sun angle above the horizon, e.g. 0 at the horizon and 90° at the zenith (straight over your head)

"azimuth" : sun azimuth in (direction along the horizon, measured from south to west), e.g. 0 is south and 75° is northwest



Solar elevation vs. solar azimuth for occurance of MS for Module 3
-99°, 35°, 87°

[1]interface), Benoit Thieurmel (R, and Achraf Elmarhraoui (R interface). Suncalc: Compute Sun Position, Sunlight Phases, Moon Position and Lunar Phase (version 0.5.0), 2019. https://CRAN.R-project.org/package=suncalc.

D.Duration of Partial Shading

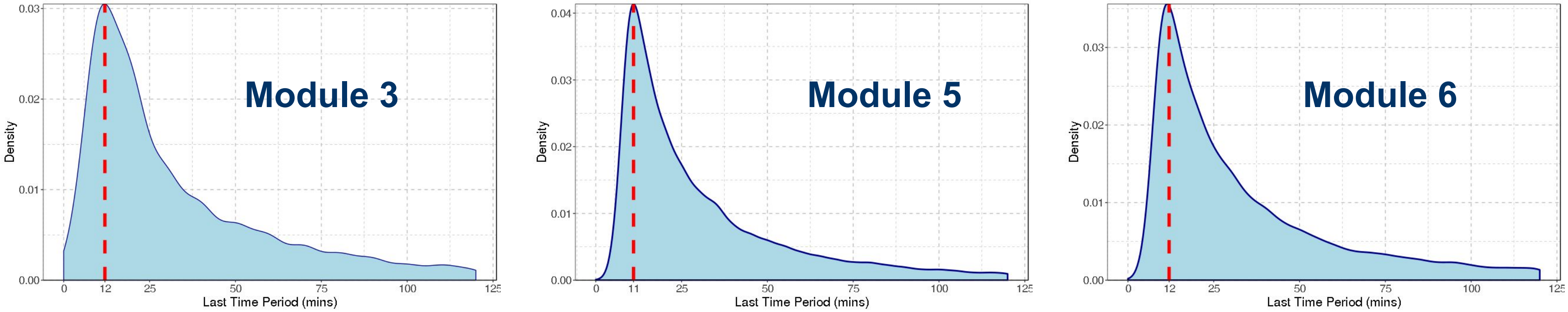
Table 5.18. Classification of persistent and transient multiple steps I-V curves

Module ID	Persistent (%)	Transient(%)
3	89.9	10.1
5	92.0	8.0
6	95.2	4.8

Measurement time interval enough to capture continuation in partial shading

Duration peak of Persistent Steps

- Module 3: 12min
- Module 5: 11min
- Module 6: 12min



Duration of persistence multiple steps *I-V* curves

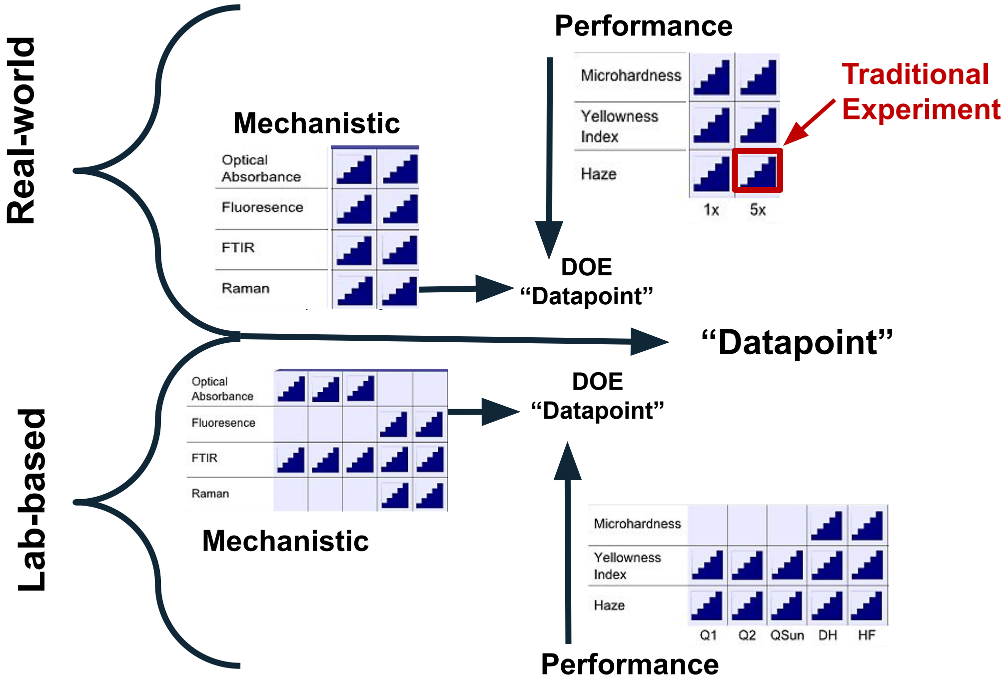
Building a Study Protocol

Statistically Informed Study

- Metadata
- Large Volume of Samples
  - All samples are measured
- Diverse Exposures
  - Real-world & Accelerated
- Many Evaluations
  - Mechanistic & Performance
  - Through time or exposure
  - Multiple datapoints and types
    - Spectra, Images, etc.
- Retained Sample Library

Holistic approach

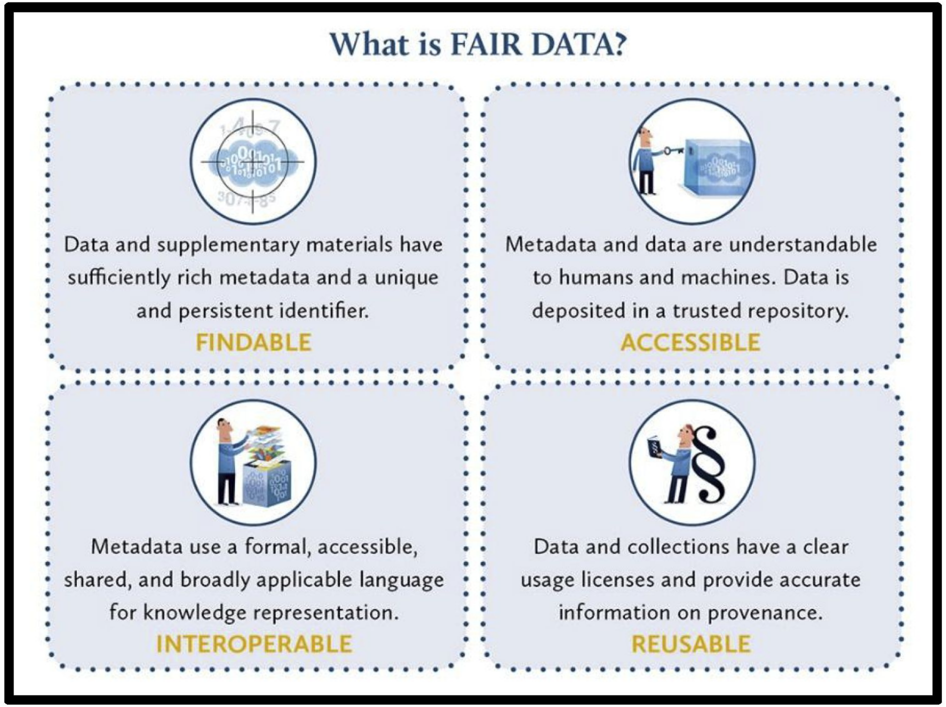
- Central Limit Theorem



Integrating multiple datasets

FAIRification

- **F**indable
  - ‘Like’ measurements line up
- **A**ccessible
  - Data sources share information
  - Able to read information
- **I**nteroperable
  - Data uses the same terminology
  - Data is comparable, standards
- **R**eusable
  - Able to be stored and used by multiple integration
  - Join by common language in data



A. Nihar *et al.*, "Toward Findable, Accessible, Interoperable and Reusable (FAIR) Photovoltaic System Time Series Data," *2021 IEEE 48th Photovoltaic Specialists Conference (PVSC)*, 2021, pp. 1701-1706, doi: 10.1109/PVSC43889.2021.9518782.

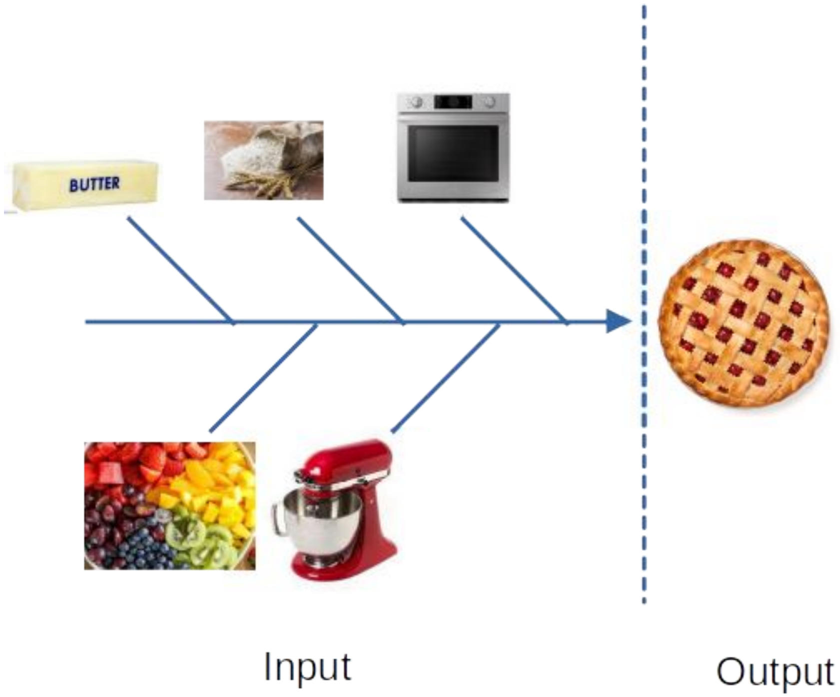
Design of Experiment (DOE)

Systematic approach

- Determine the relationship between
    - input variables and output variables
- Least data for maximum results
- Attempt to define parameter space

Multiple variables

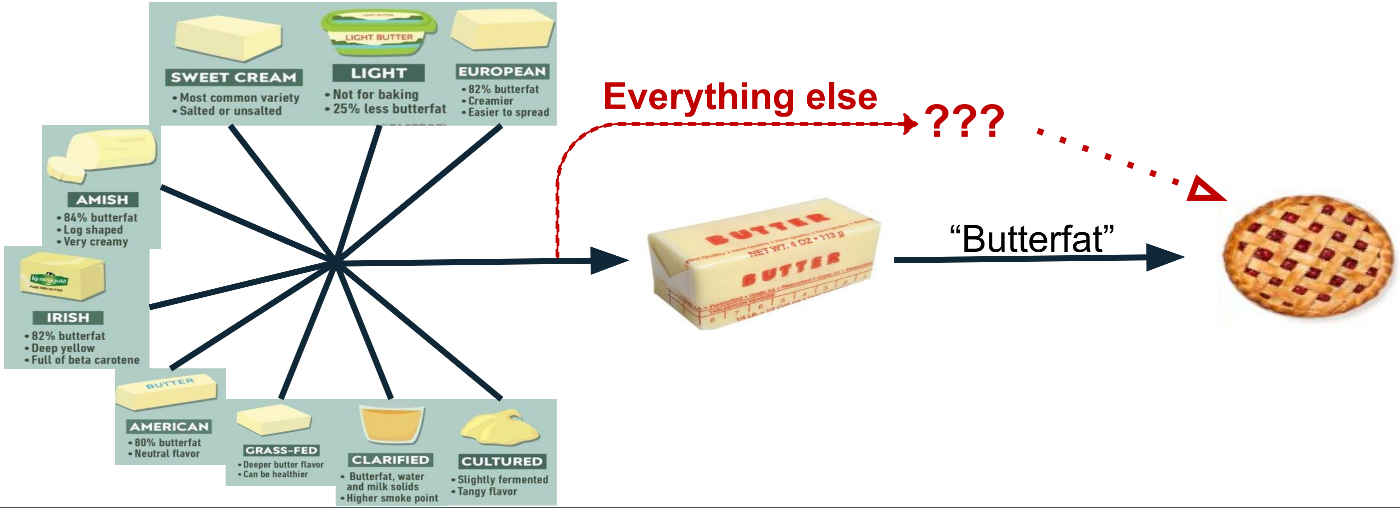
- Kept constant to isolate the effect of a variable of interest (limited)
- Multivariate relationships aren't considered
- Additive



Design of Experiment (DOE) Problem

Limitations of DOE

- Assumes all variables are isolated
  - Inputs are only factor with given output
  - Inputs are not influenced by another input
  - Assumes linear input
- Assumes only variable of interest is evaluated
- Full parameter space isn't considered



Design of Experiment (DOE)

Systematic approach

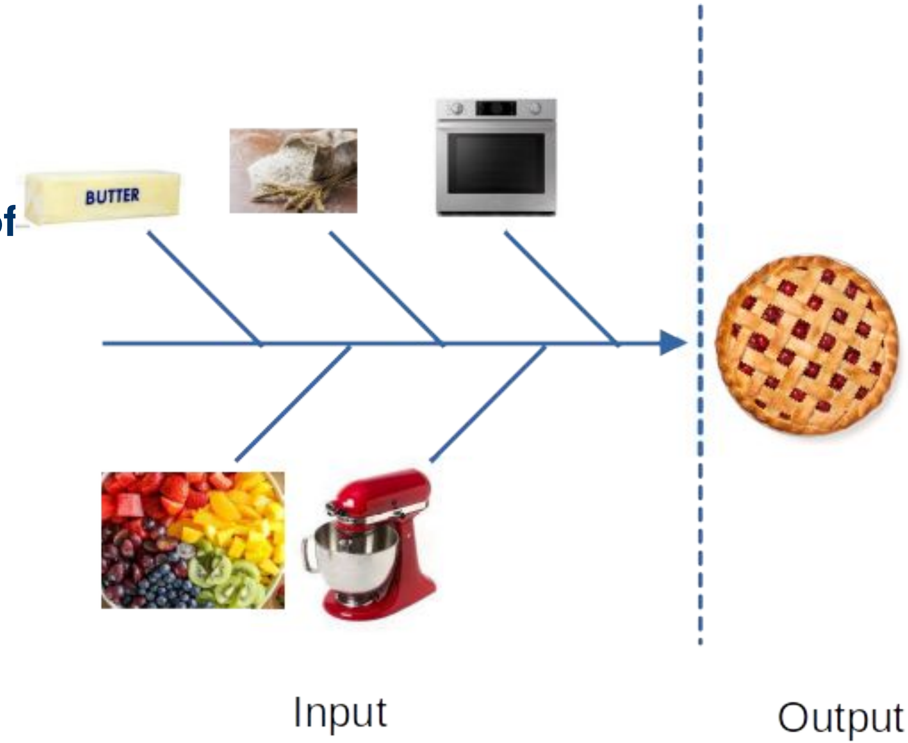
- to determine the relationship between
- input variables and output variables

Multiple variables

- are kept constant to isolate the effect of a variable of interest

Relationships

- designed around a central hypothesis



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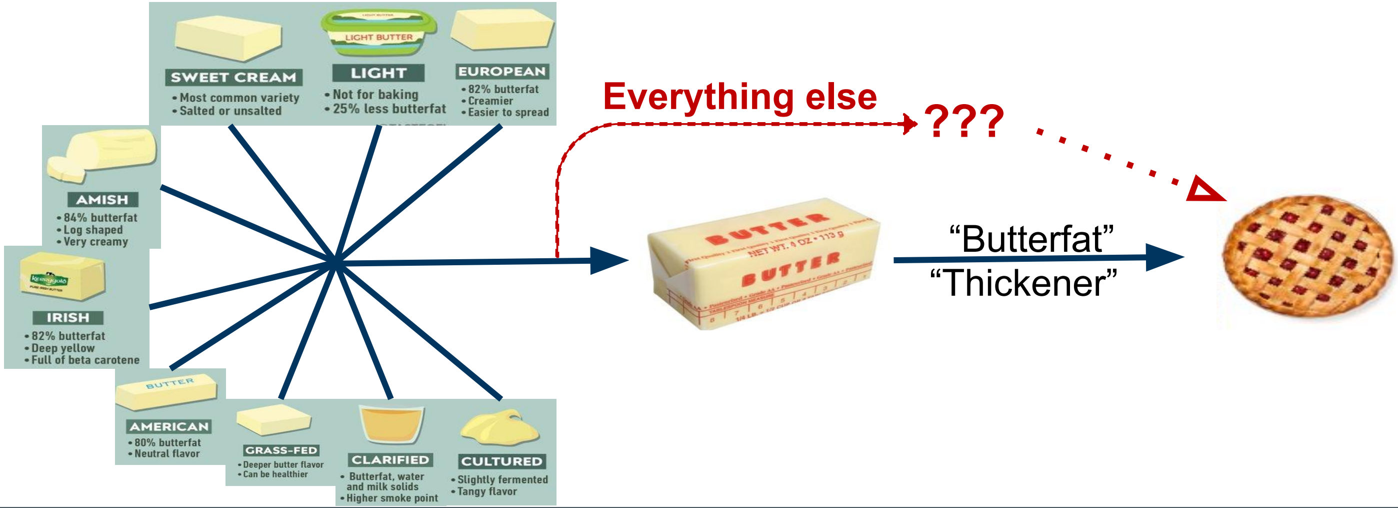
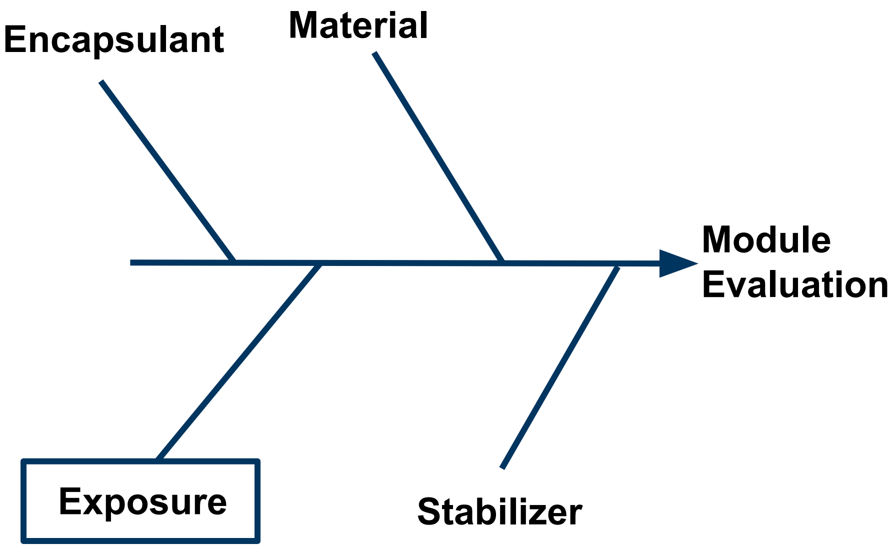


Re-examining the Design of Experiment

What is meant by ‘experiment’?

- **Academia**
  - Making discovery/ testing hypothesis
    - Multiple tests
    - Multiple measurements
- **Industry**
  - Performing a procedure to determine something
  - Any procedure measurement is an experiment

DOE represents a datapoint in larger question



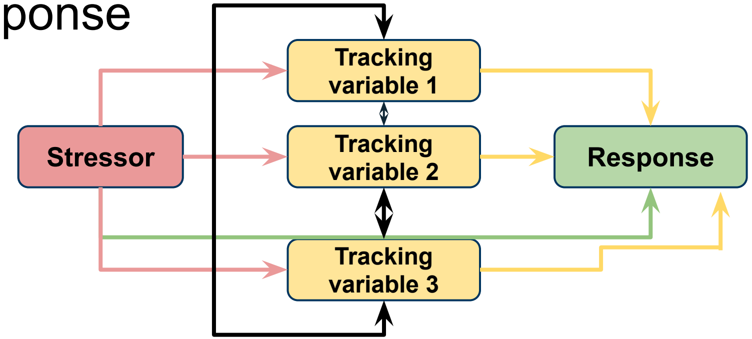
Network Structural Equation Modeling (netSEM)[6]

netSEM: mapping of stressor mechanisms and response

- <*S*|*M*|*R*> modeling

Dominant and sequential/parallel pathways

- Pairwise relationships: <*S*|*R*>, <*S*|*M*|, |*M*|*R*>



Includes nonlinear relationships

- To understand complex forms of degradation

Model	Equation
Simple linear (SL)	$y = \beta_0 + \beta_1 x$
Quadratic (Quad)	$y = \beta_0 + \beta_1 x + \beta_2 x^2$
Simple quadratic (SQuad)	$y = \beta_0 + \beta_2 x^2$
Nonlinearizable exponential (nls)	$y = \beta_0 + \beta_5(1 \pm exp(\beta_6(x - \beta_7))$
Exponential (Exp)	$y = \beta_0 + \beta_3 e^x$
Logarithmic (Log)	$y = \beta_0 + \beta_4 logx$
Change point (CP)	$y = \beta_0 + \beta_1 x + \beta_2(x - c)$

Two principles

- Principle 1: Markov property
  - **Except the two considered variables: rest are constant**
- Principle 2: Multiple Regression by Step AIC
  - **Response impacted by several variables**

6. Yang, H. E., French, R., & Bruckman, L. (Eds.). (2019). *Durability and Reliability of Polymers and Other Materials in Photovoltaic Modules.* William Andrew. DOI: 10.1016/C2016-0-01032-X.
21. Bruckman, L. S., Wheeler, N. R., Ma, J., Wang, E., Wang, C. K., Chou, I., ... & French, R. H. (2013). Statistical and domain analytics applied to PV module lifetime and degradation science. *IEEE Access*, *1*, 384-403. DOI: 10.1109/ACCESS.2013.2267611.

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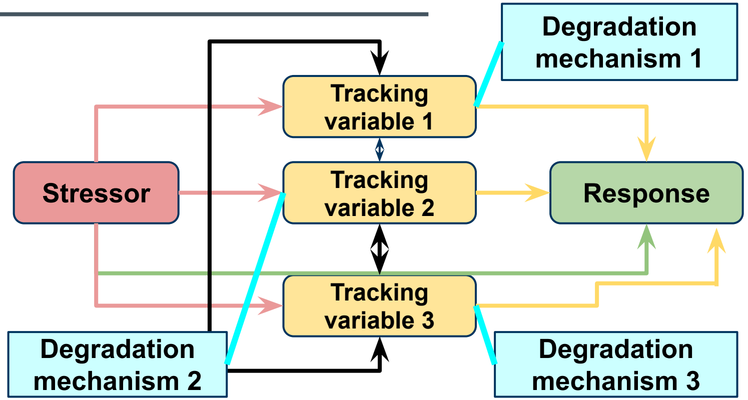

Two principles

- Principle 1: Markov property
  - **Univariate relationships between variables**
- Principle 2: Multiple Regression by Step AIC
  - **Multiple regression of variables**

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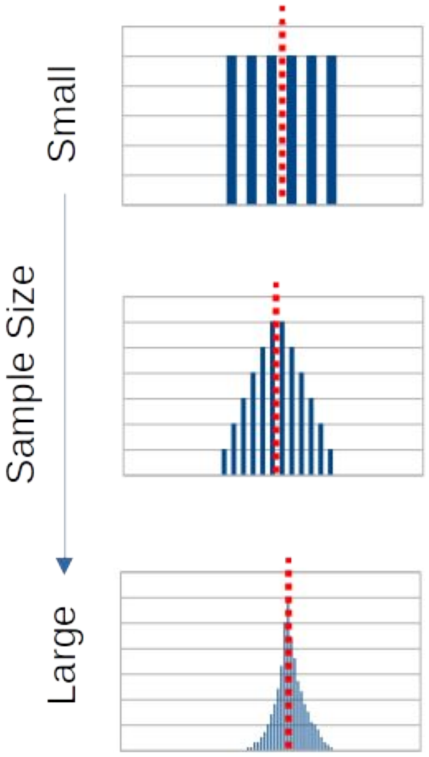

Law of Large Numbers
Probability Theory