

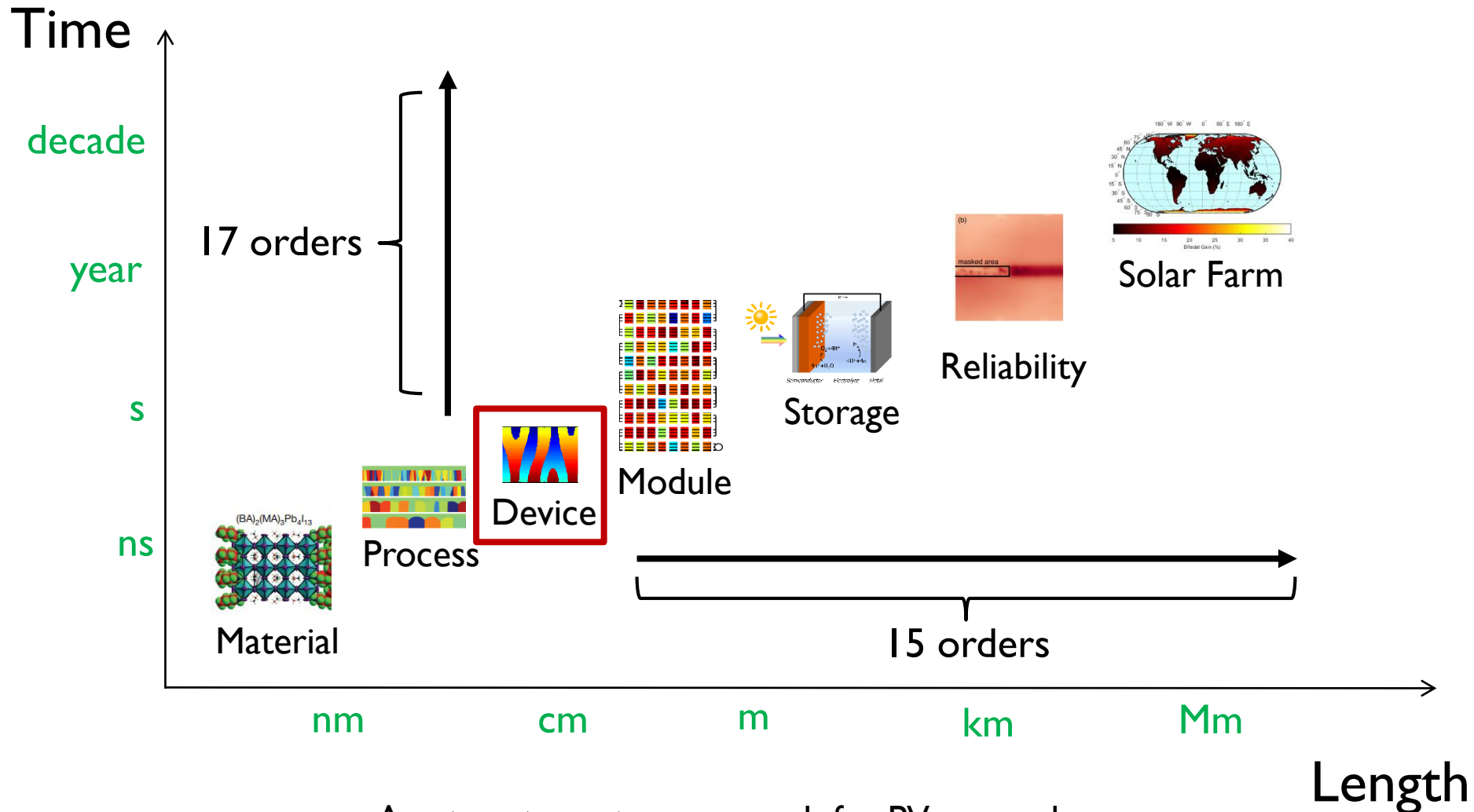


# Physics-based Machine Learning to Enable Reliable Modules & Sustainable Solar Farms

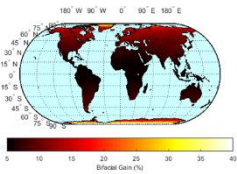
M. A. Alam, X. Sun, R. Khan, and T. Patel  
(alam@purdue.edu)



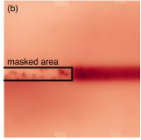
# A magnificent multiscale problem: Atom-to-farm perspective



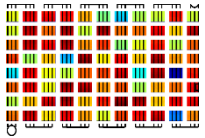
An atom-to-system approach for PV research.



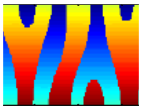
## Solar Farm



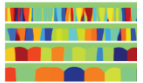
## Reliability



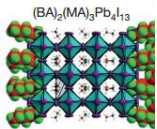
## Module



## Device



## Process



## Thermodynamic

### Vertical Bifacial Solar Farms: Physics, Design, and Global Optimization

M. Ryyan Khan <sup>b,1</sup>, Amir Hanna <sup>a,1</sup>, Xingshu Sun <sup>b,1</sup>, Muhammad A. Alam <sup>b,1\*</sup>



UPPSALA  
UNIVERSITET



IIT BOMBAY



جامعة الملك عبد الله  
للعلوم والتقنية  
King Abdullah University of  
Science and Technology



Muhammad A. Alam<sup>ab</sup> and M. Ryyan Khan  
School of Electrical and Computer Engineering, Purdue University, W  
(Received 15 September 2012; accepted 15 June 2013)

### Thermodynamic Efficiency Limits of Classical and Bifacial Multi-junction Tandem Solar Cells: An Analytical Approach

Muhammad A. Alam<sup>a)</sup> and M. Ryyan Khan  
School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN-47907,  
USA

SCIENTIFIC REPORTS

OPEN Directing solar photons to sustainably meet food, energy, and



BAPVC



anaphotronics 20

Peter Berm  
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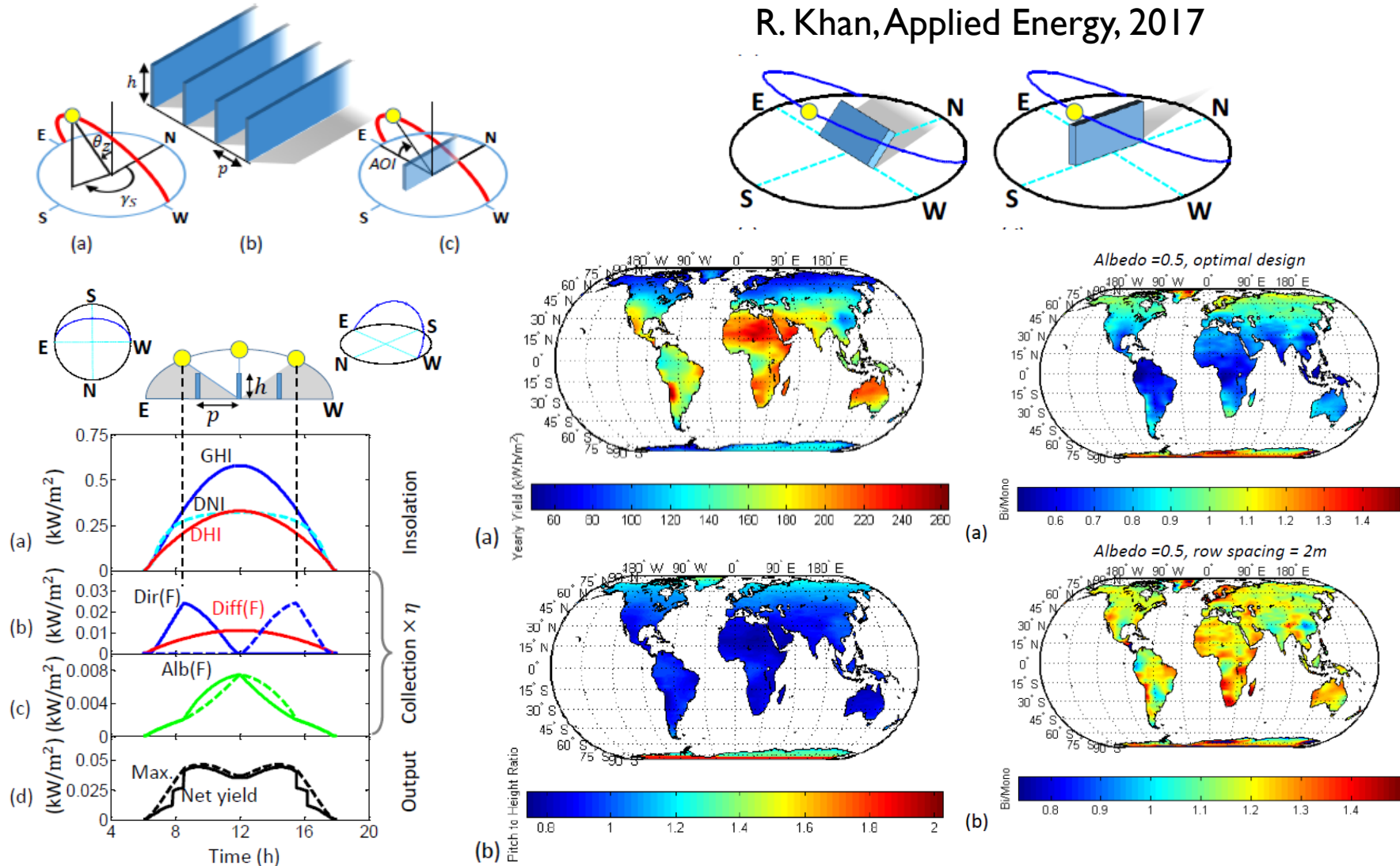
us  
Cells  
of.

4367

20

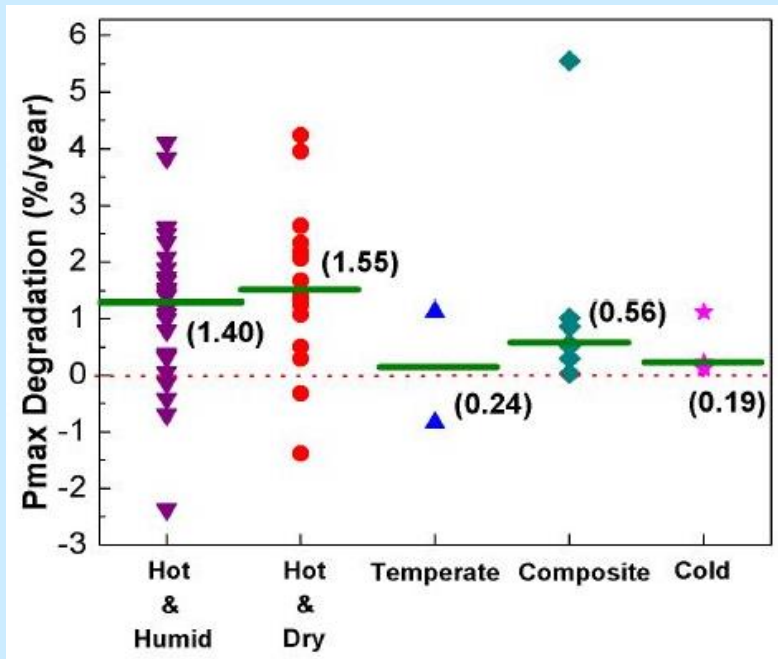
# Bifacial Farm: Global Optimization

R. Khan, Applied Energy, 2017

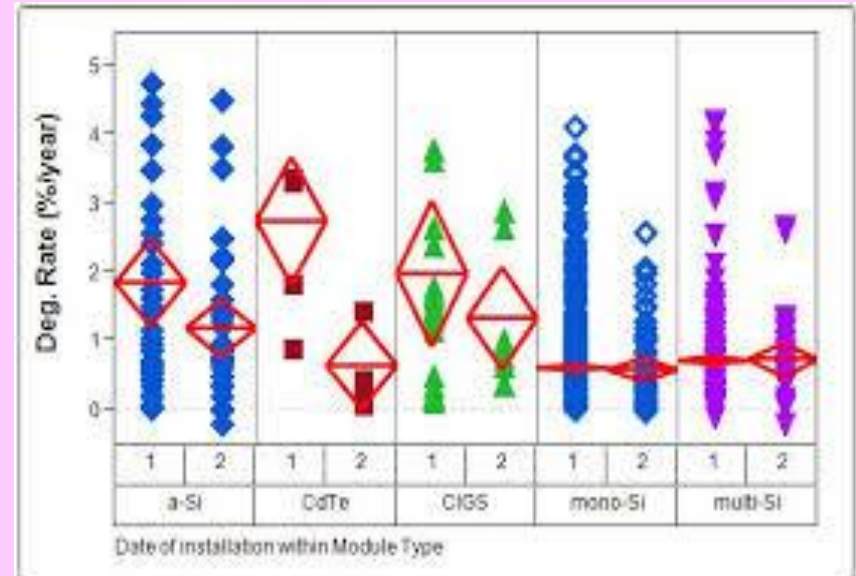


# Missing: Geography-specific Reliability

Degradation Rate: Hot = 8 × Cold



"All-India Survey of Photovoltaic Module Degradation : 2013."



Data is not information:

How did they fail? Hot-humid? Technology? Company?

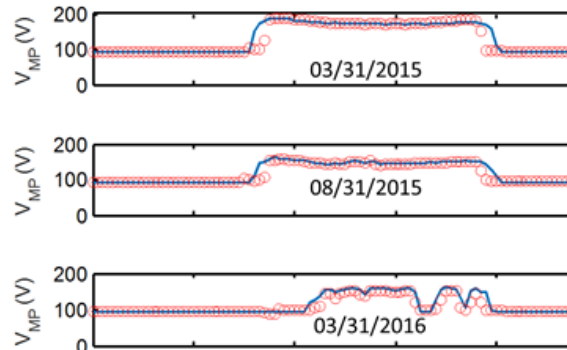
# Approach: PV Heartbeat interpreted by physics-based model



EKG Diagram

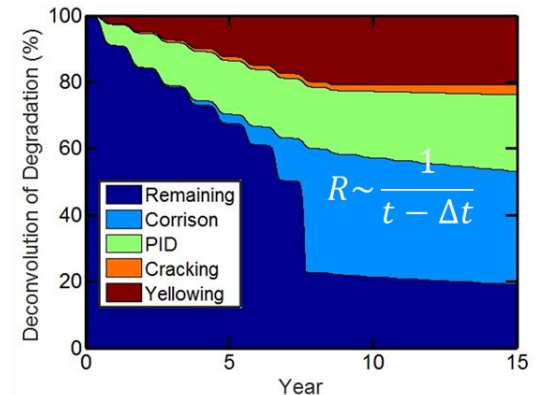
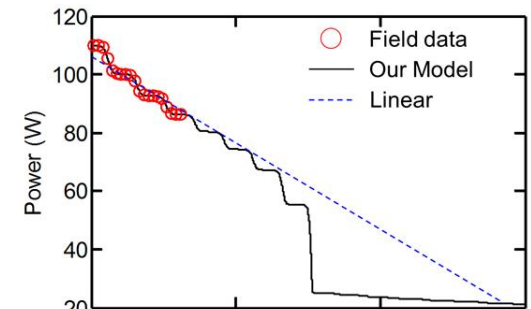


“Heartbeat” of PV



Solar Panels at Knoy Hall

X. Sun, PIP, 2018

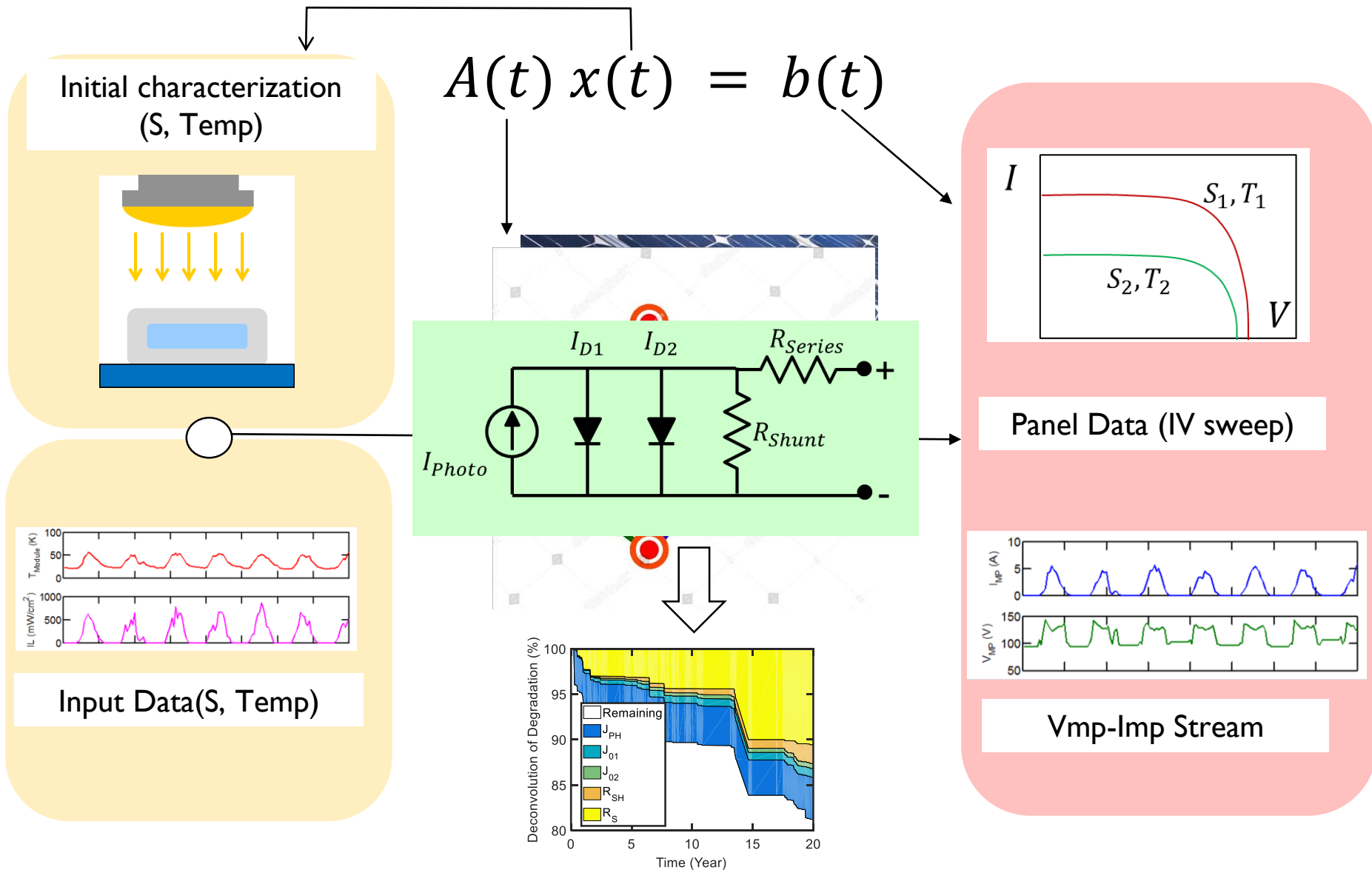


Can you hear the shape of a drum? ... M. Kac, 1966

# Outline

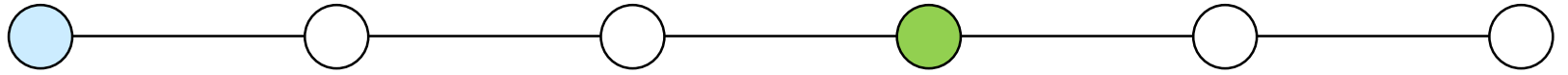
- Introduction: Atom-to-farm perspective
- Approach: Physics-based inverse modeling
  - Concept: Vmp-Imp as an in-situ EKG
  - Four steps for inverse modeling
  - Results: Parameter degradation
- Future prediction: physics-based degradation
- Conclusions: Data vs. Information

# Devices model as a “neural” network

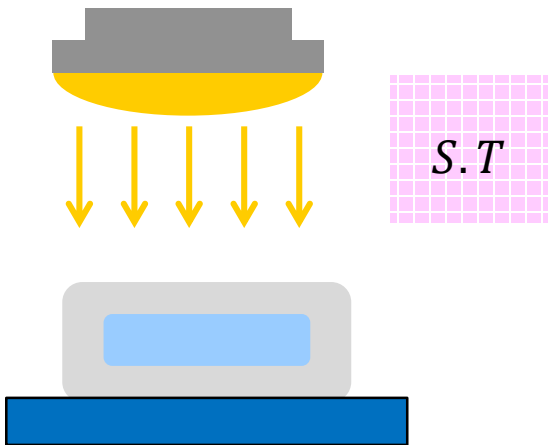




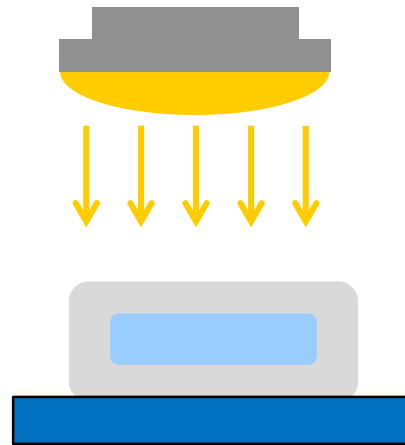
# Concept: In-situ parameter-extraction



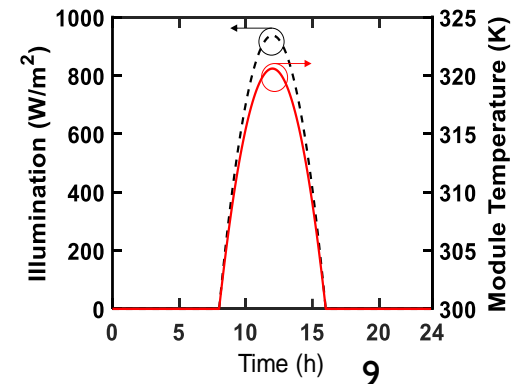
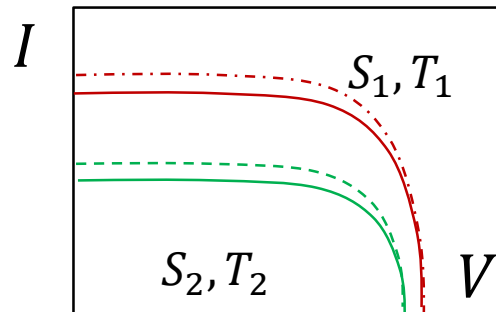
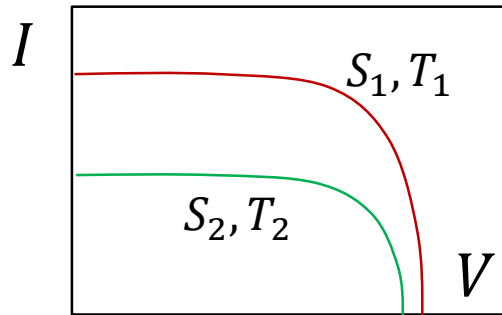
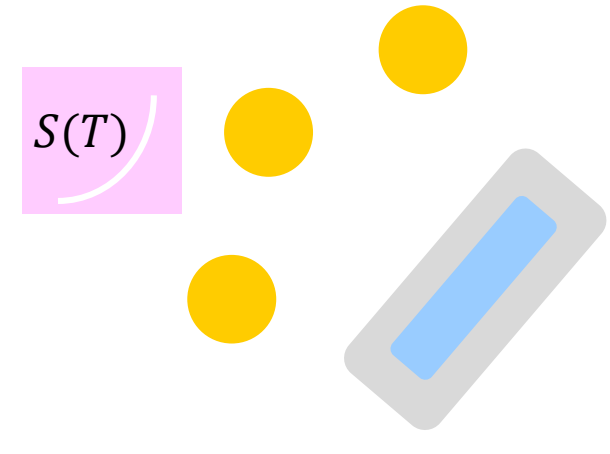
$t = 0$



$t = t_i$  (off-line)



$t = t_i$  (on-line)

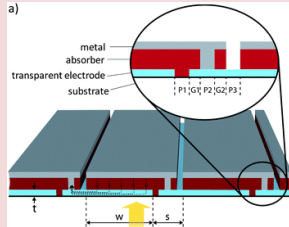

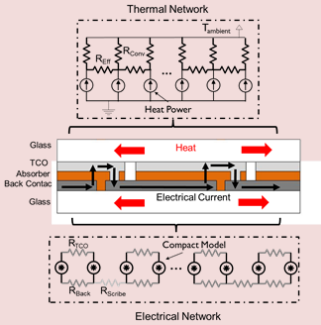
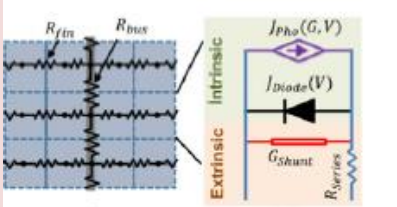


# Step 1: Physics-Based Compact Models

## Compact Model Library

		
Mono-Si	GaAs	p-n
		
a-Si	Perovskite	p-i-n
		
CIGS	HIT	heterojunction

## Circuit Network Library

	
monolithic solar module	Si-based solar module
	
	Sun, PVSC, 2015. Chavali, JPV, 2016.

<https://nanohub.org/publications/20/1>

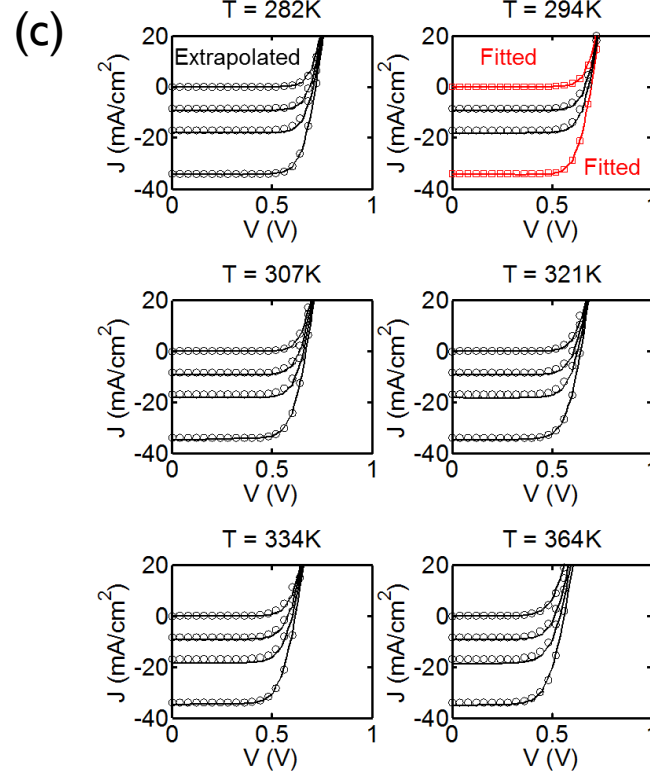
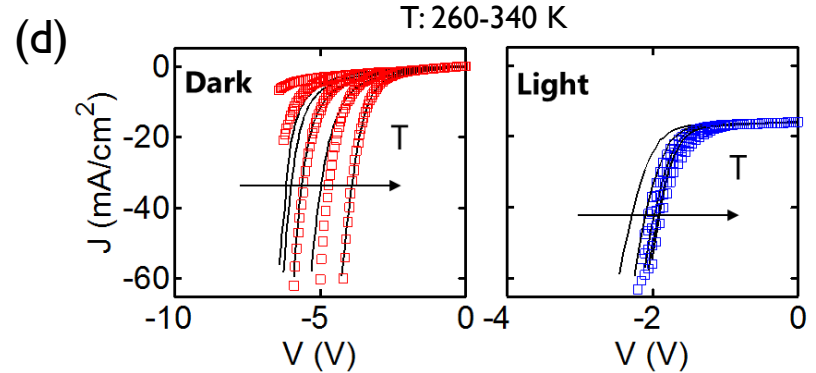
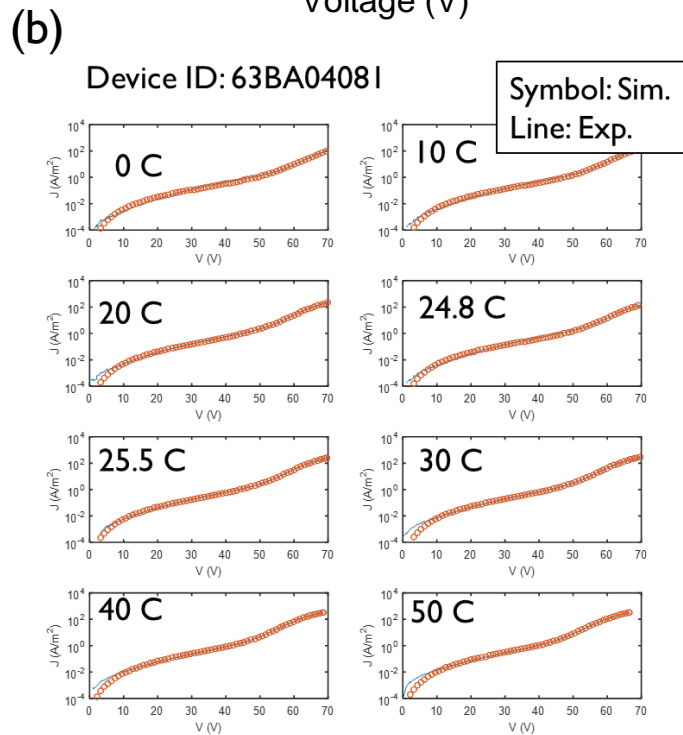
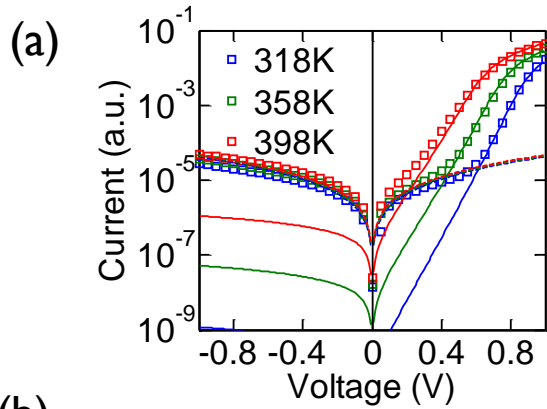
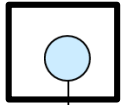
TAG Solar Cell Model (p-i-n thin film) 1.0.1

~5000 total views and ~1000 downloads



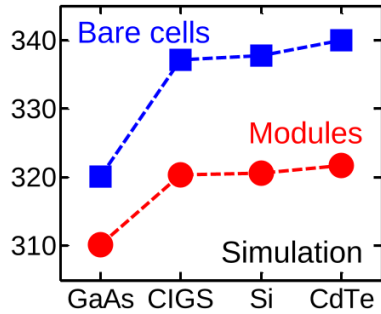
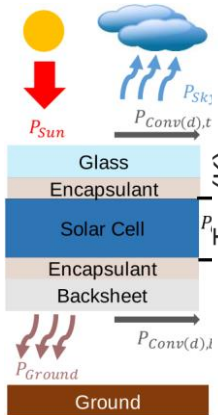
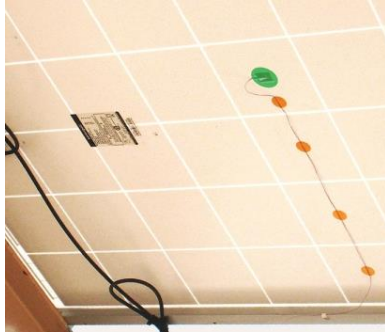
**Purdue Solar Cell Model  
(PSM)  
Version 2.0.0**

# Step 2: Time-zero model calibration



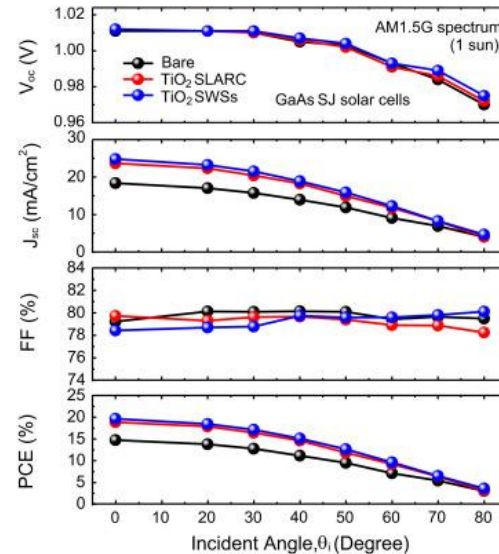
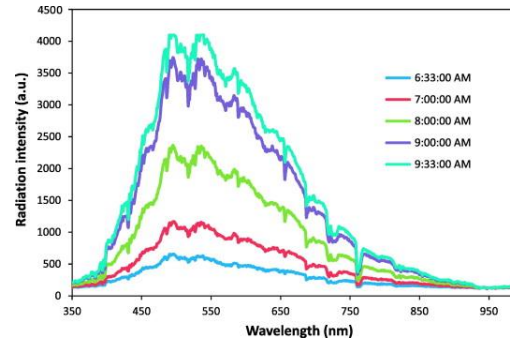
# Step 3: Preprocessing of weather data

## Module temperature



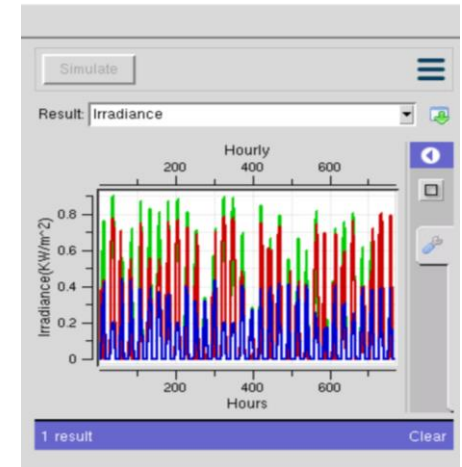
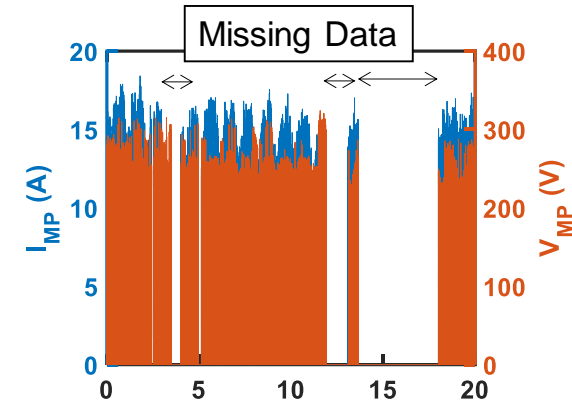
Faiman model

## Irradiance data



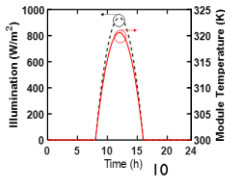
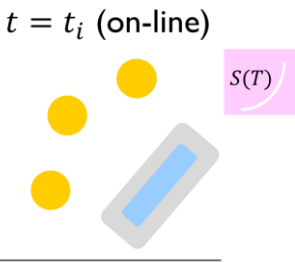
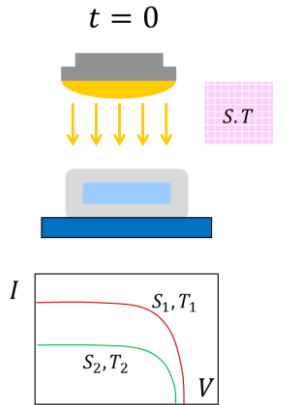
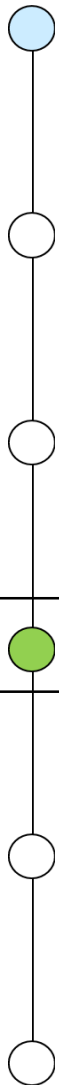
SAPM model

## Missing Data

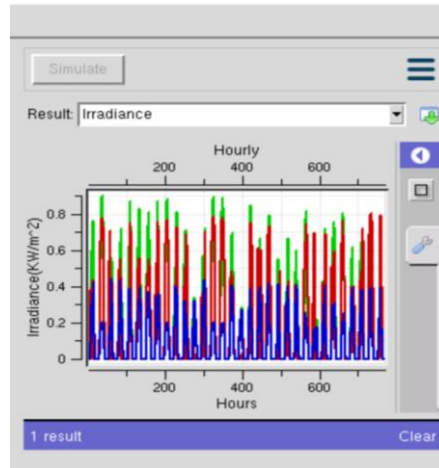


NSRDB  
PUMET model

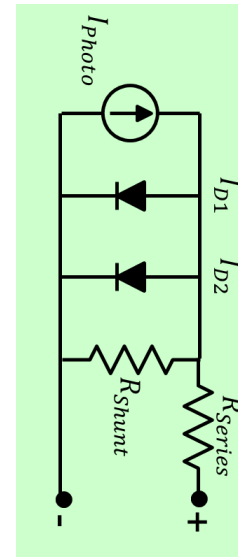
# Step 4: On-line characterization



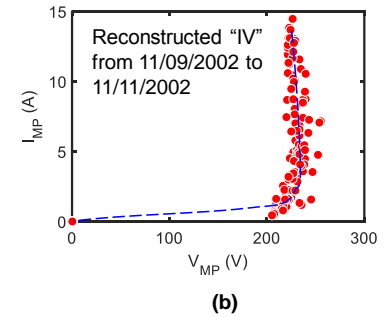
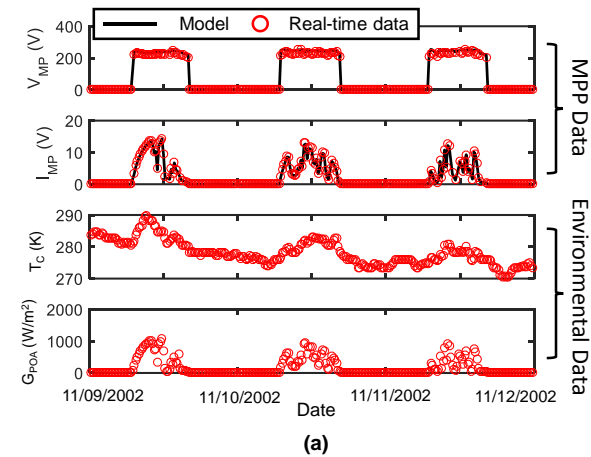
Weather information



T-dependent Comact model

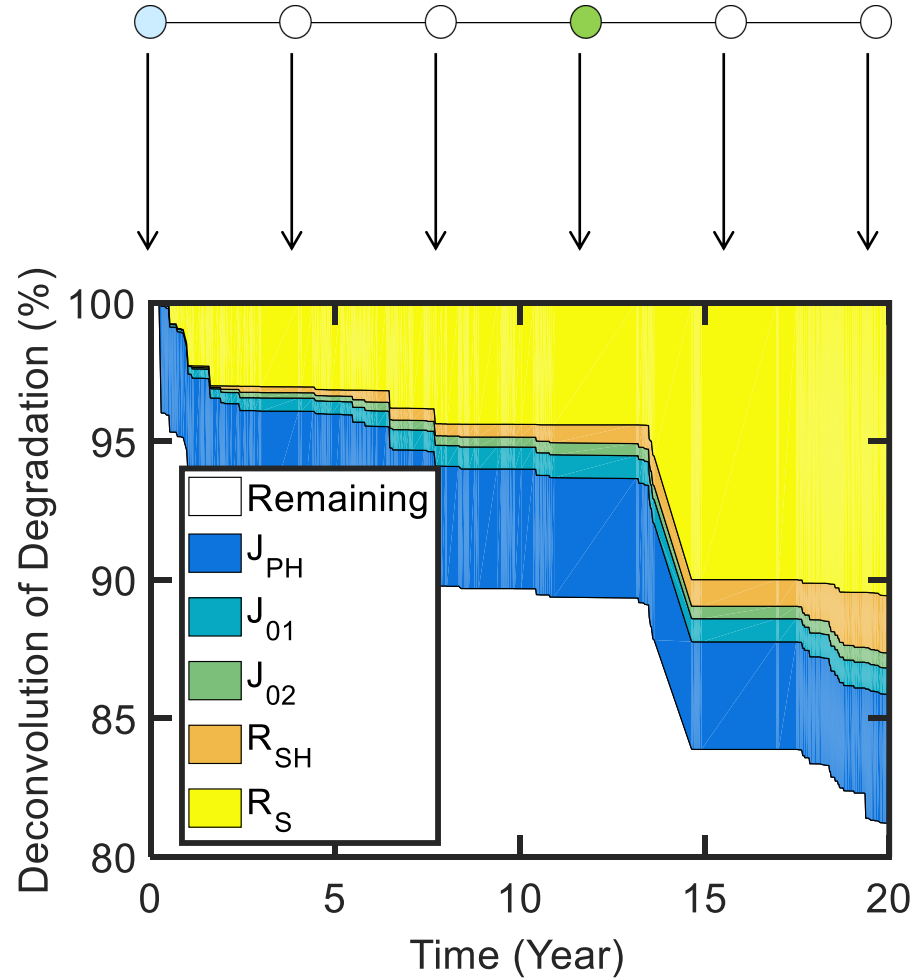
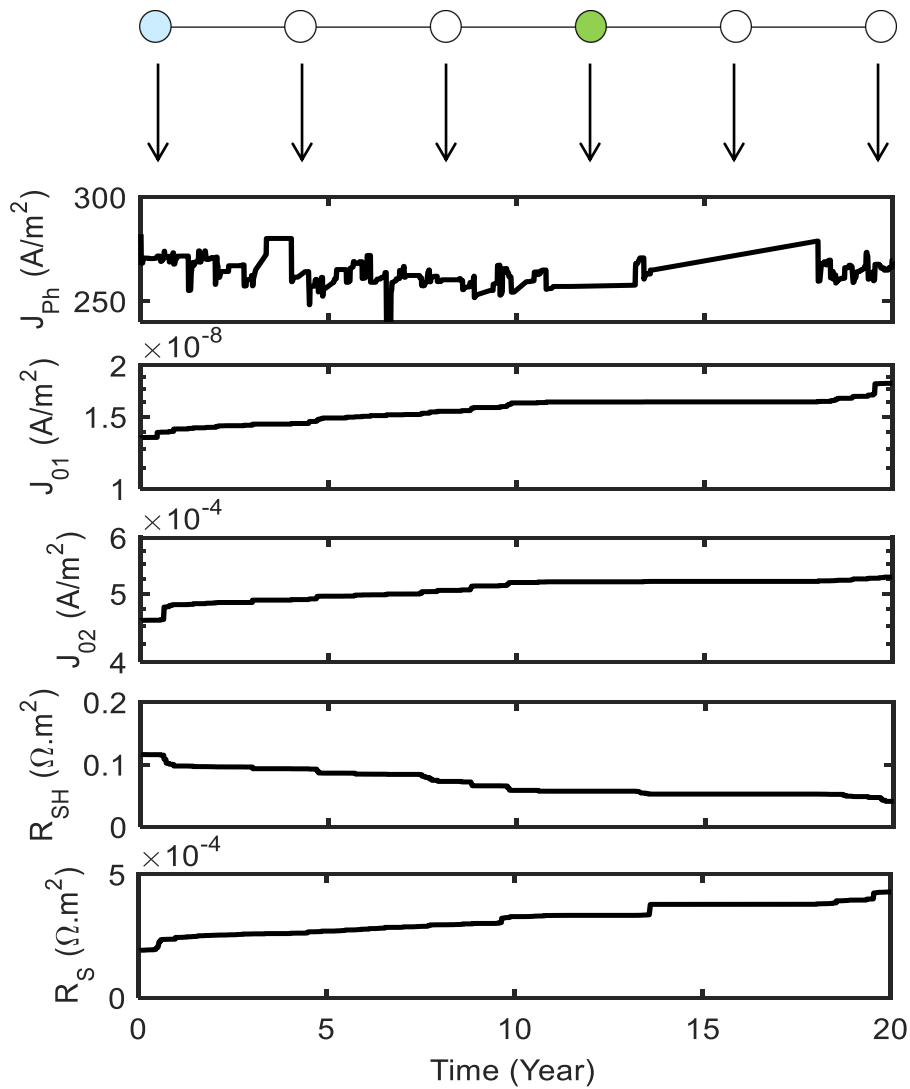


Suns-Vmp method

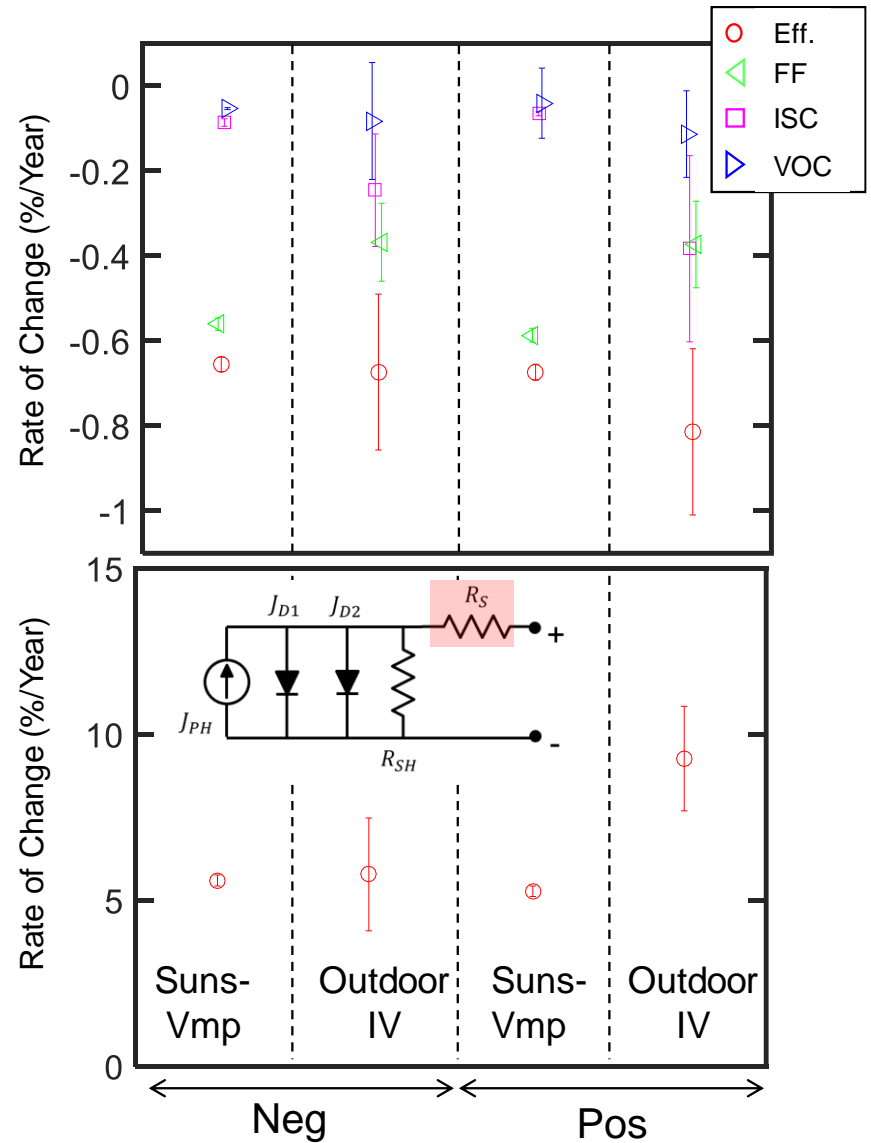
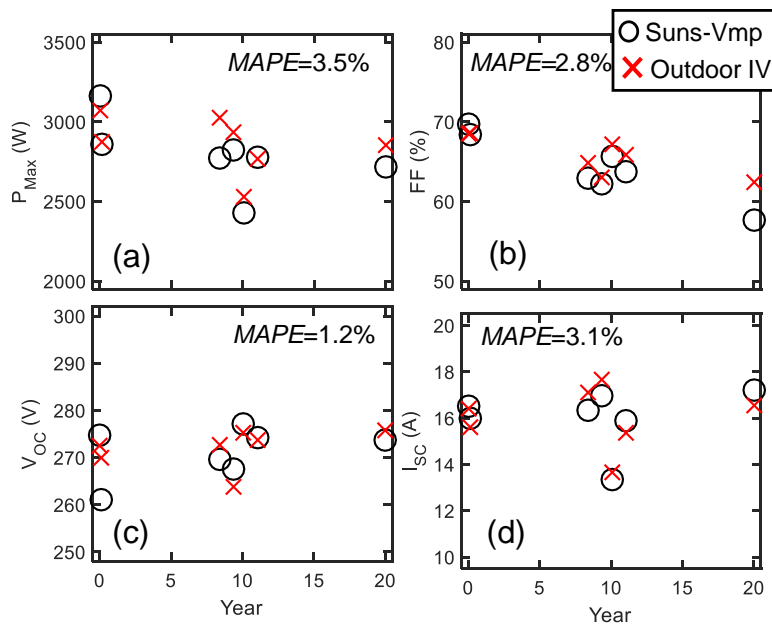
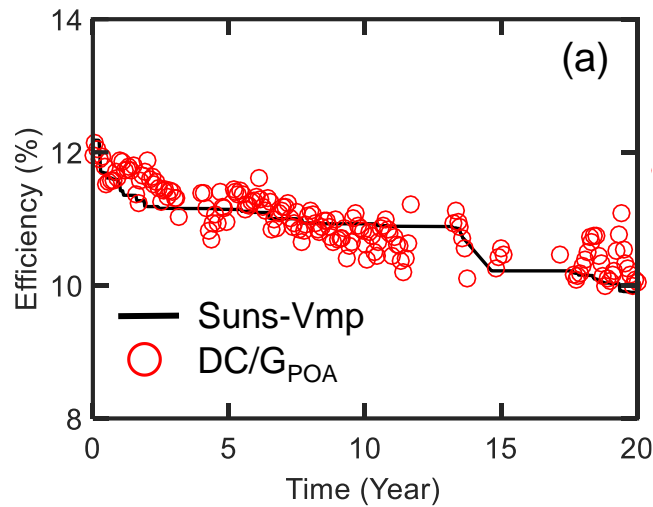
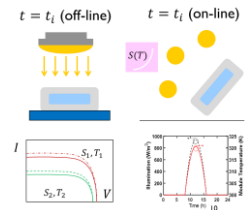


500 points to fit a dozen parameters

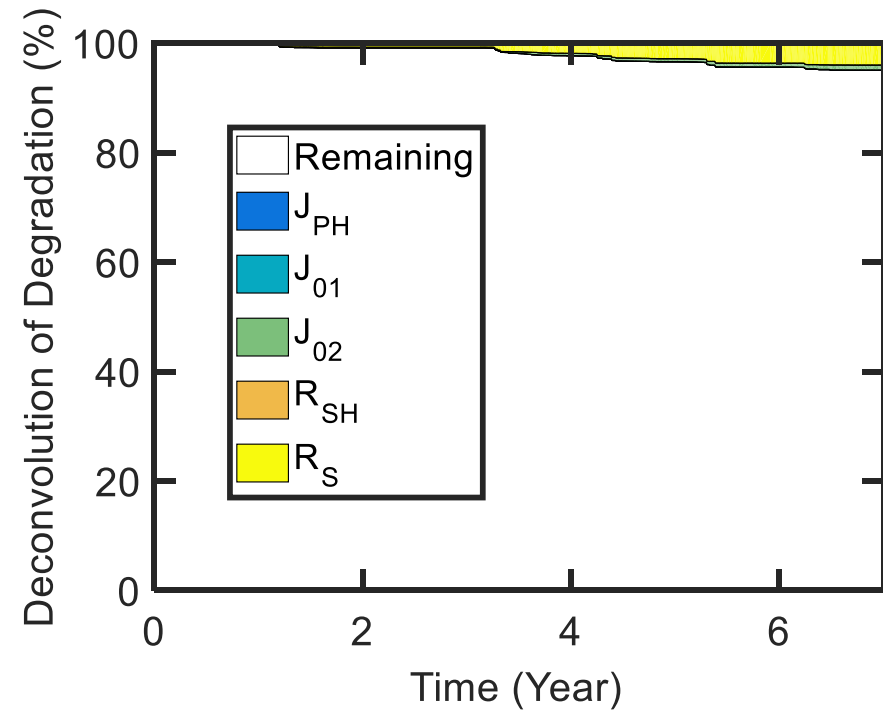
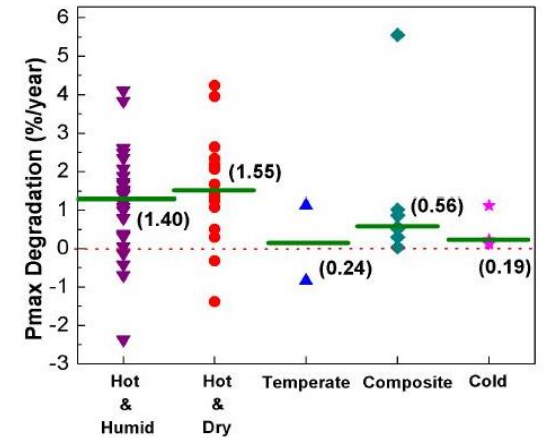
# Results: Extracted Model Parameters



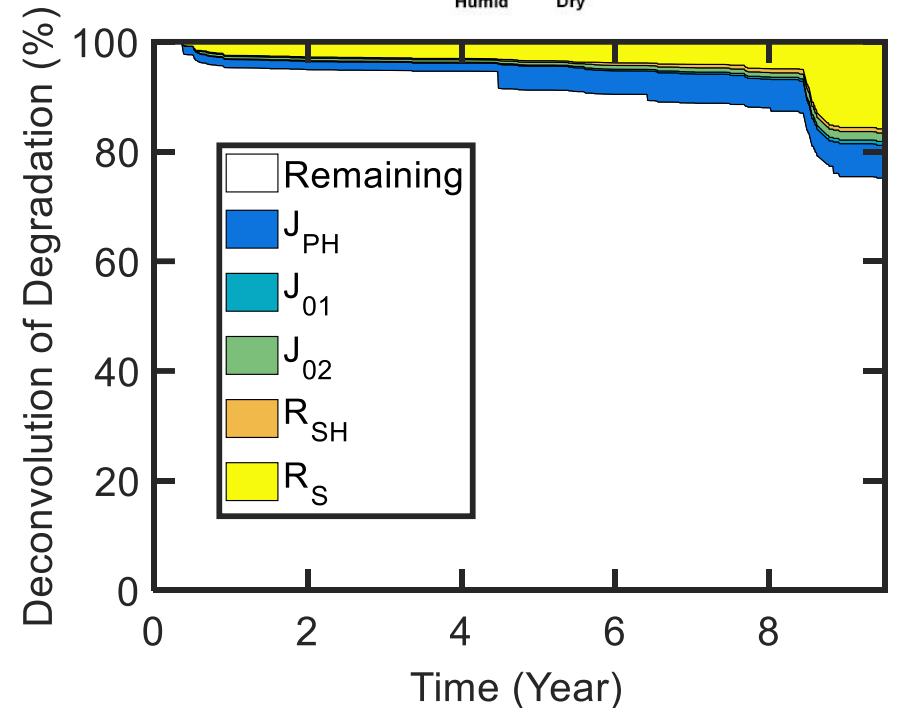
# Results: Independent Validation



# Results: multiple sites in close proximity



Sanyo HIT



SIEMENS X-Si

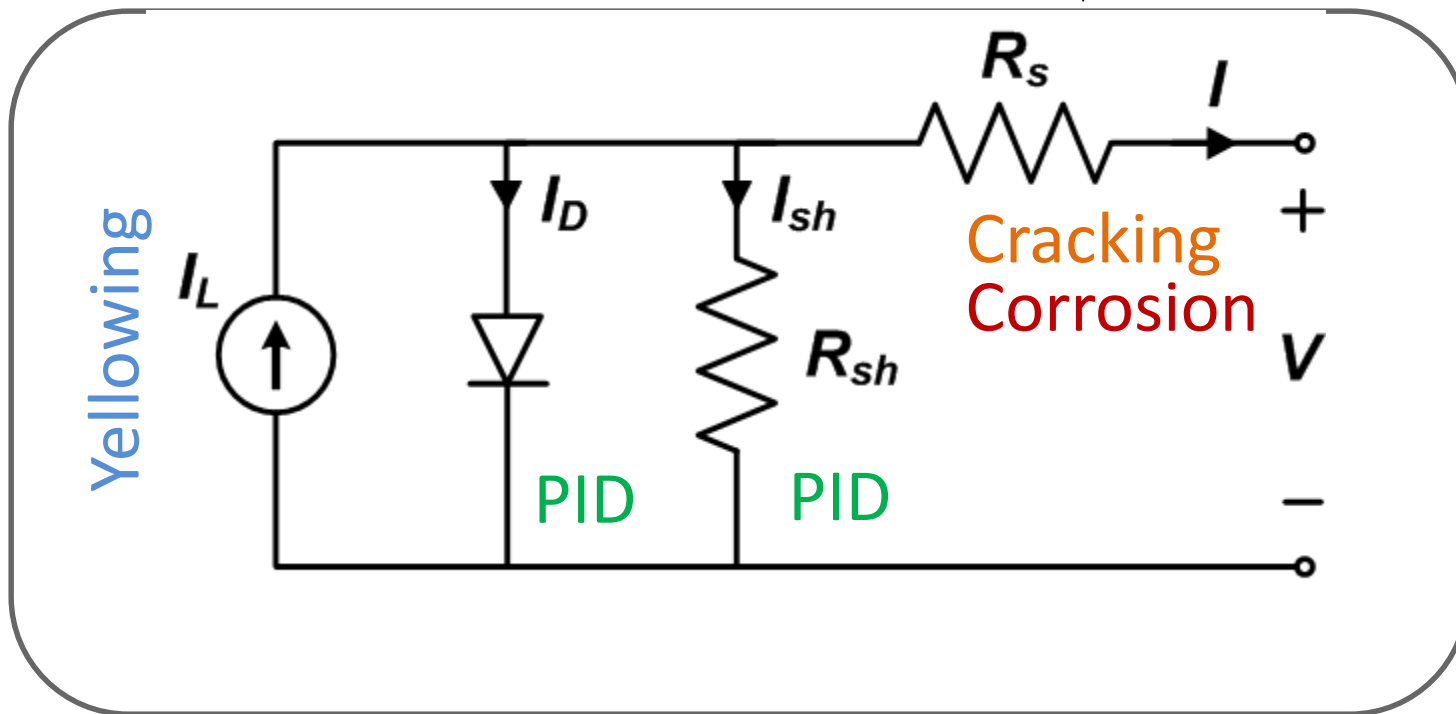
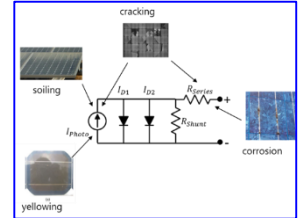


# Outline

- Introduction: Atom-to-farm perspective
- Approach: Physics-based inverse modeling
  - Concept: Vmp-Imp as an in-situ EKG
  - Four steps for inverse modeling
  - Results: Parameter degradation
- **Future prediction: physics-based degradation**
- Conclusions: Data vs. Information

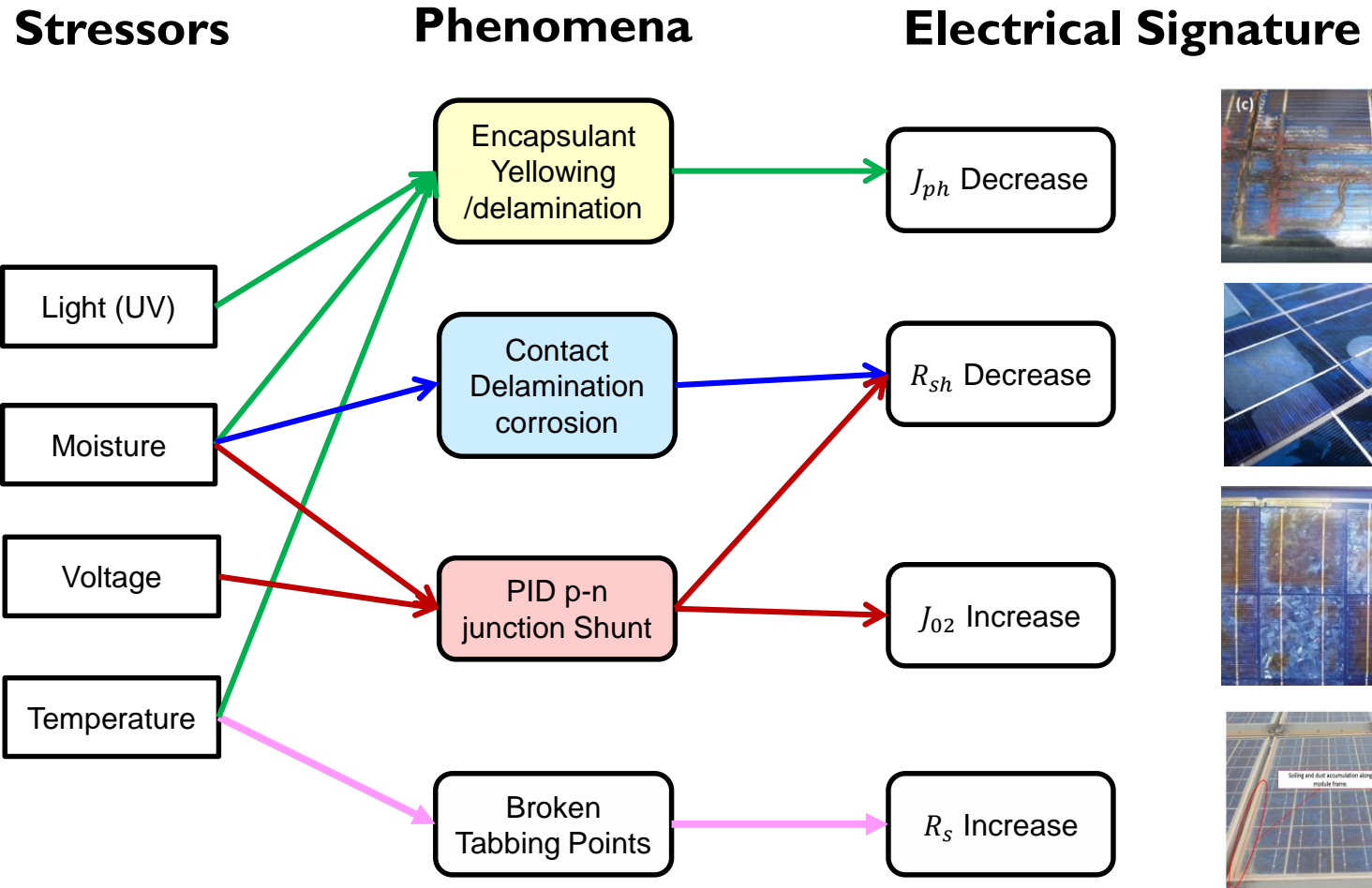
# Future performance: Fitting the degradation model

Weather & cell/module/farm configuration



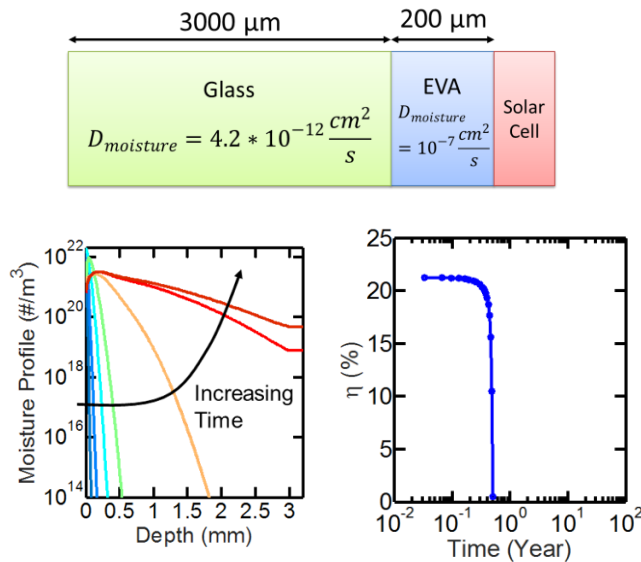
Time-dependent power output

# Electrical Signature Correlated to Degradation Phenomena



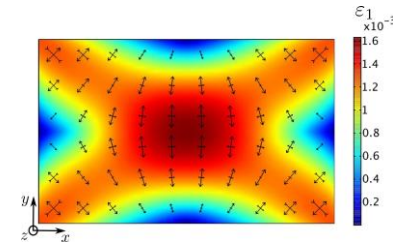
# Physics-based Degradation models

## Corrosion



$$R_S = f(T, E_A, k_M, RH, t)$$

## Cracking



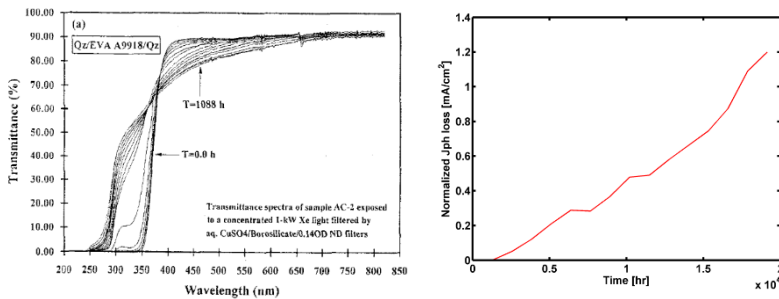
$$J_{O_2} = (1 + 2.5144 \times 10^{-6} t) J_{O_2}(0)$$

$$R_S = (1 - 1.5982 \times 10^{-6} t) R_S(0)$$

$$\Delta J_{ph} = (1 - 4.5662 \times 10^{-8} t) J_{ph}(0)$$

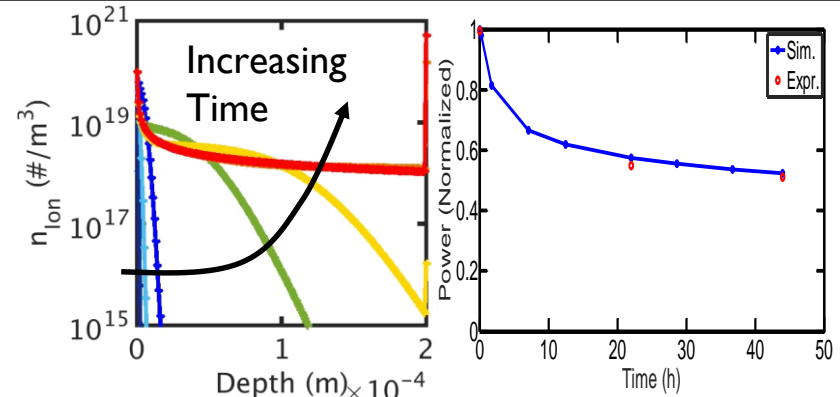
$$R_S = f(T, E_A, k_M, RH, t)$$

## Yellowing



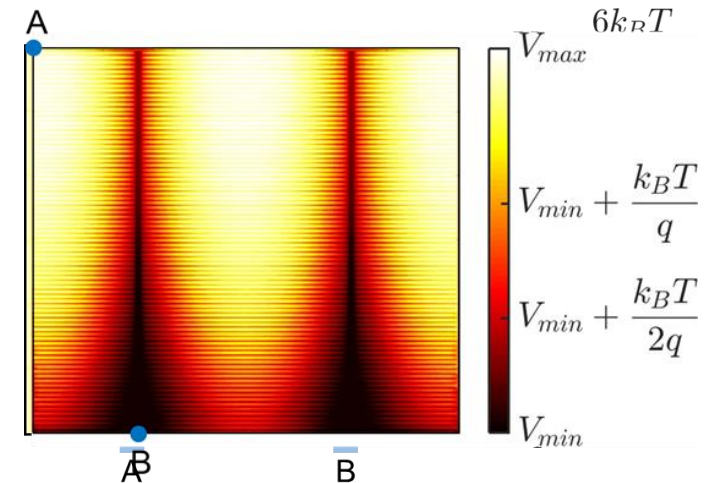
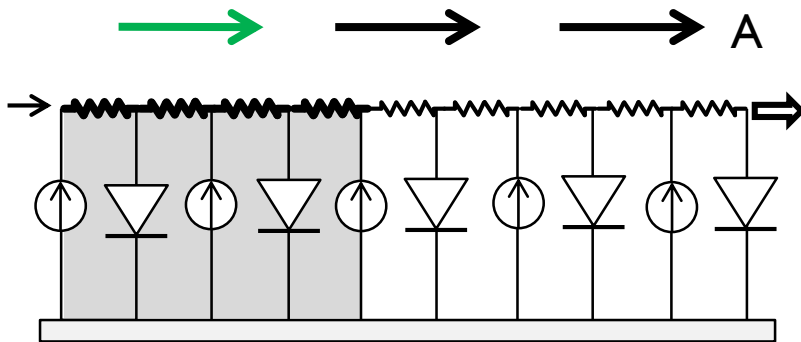
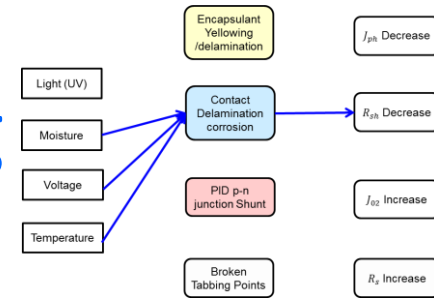
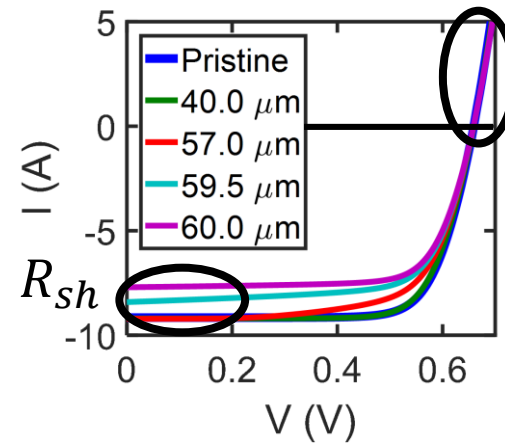
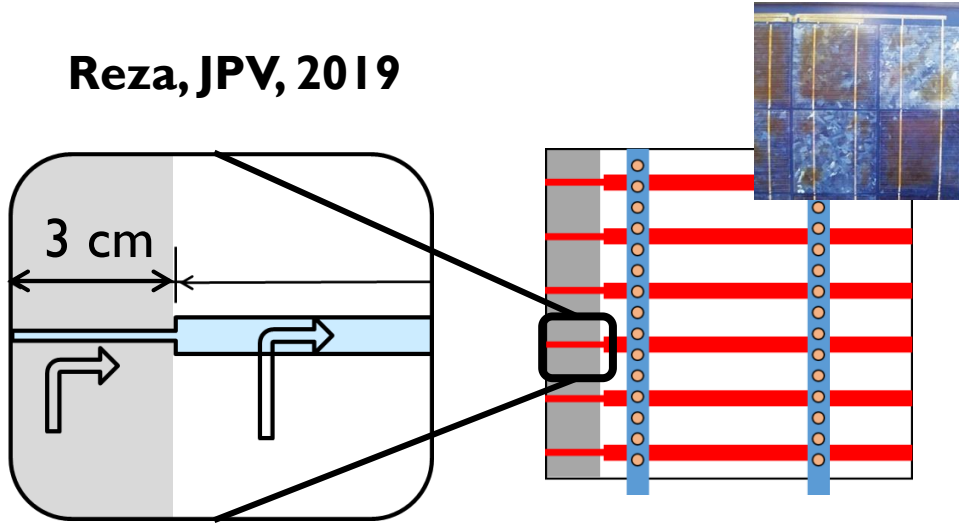
$$\Delta J_{ph}(t) = A \times 6.33 \times 10^{-5} t + 0.145$$

## PID



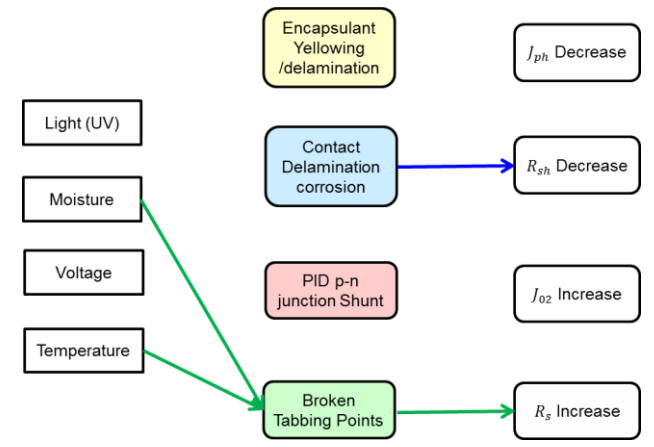
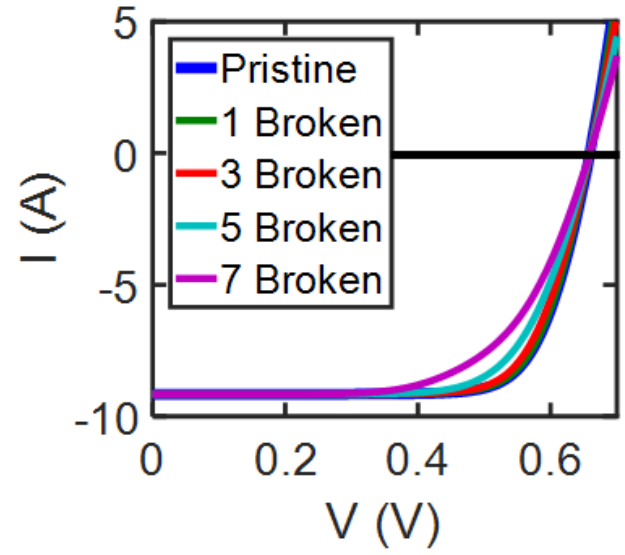
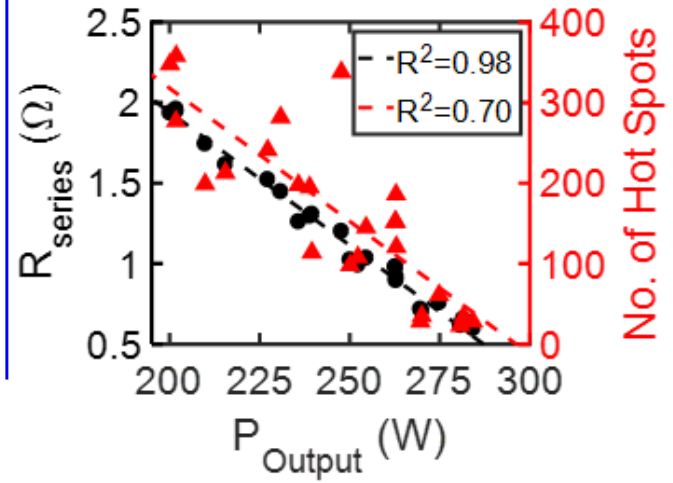
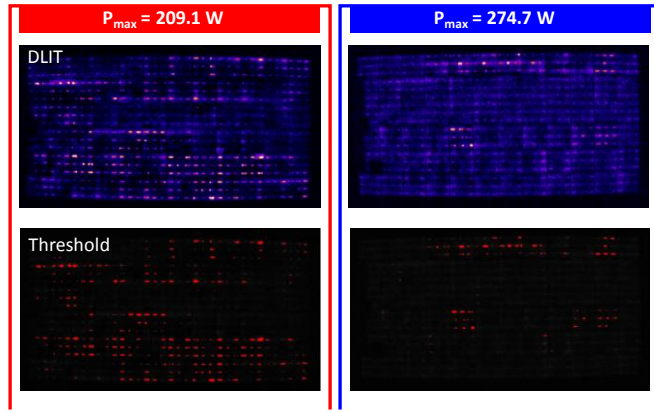
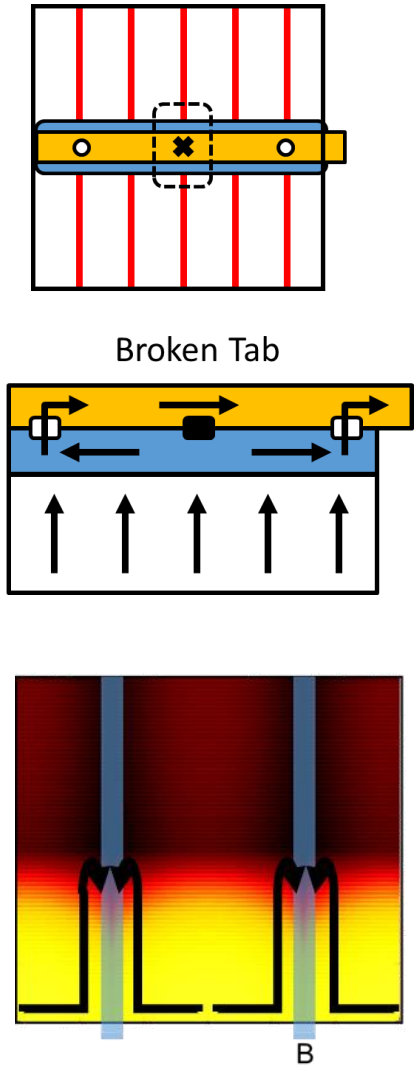
# (Fake) Shunt due to finger thinning

Reza, JPV, 2019



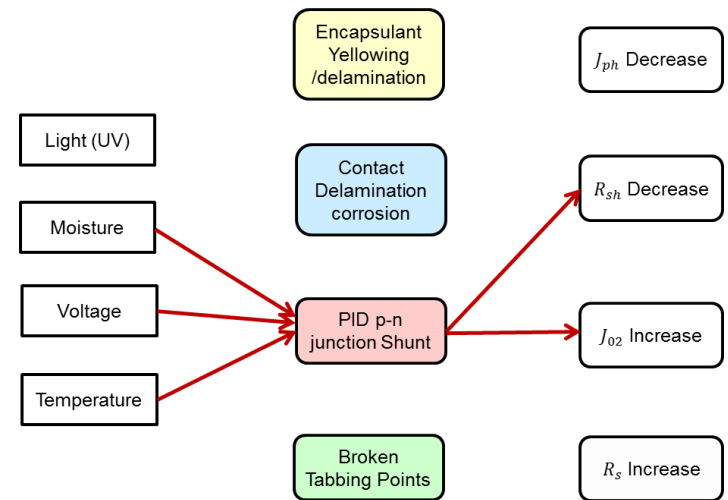
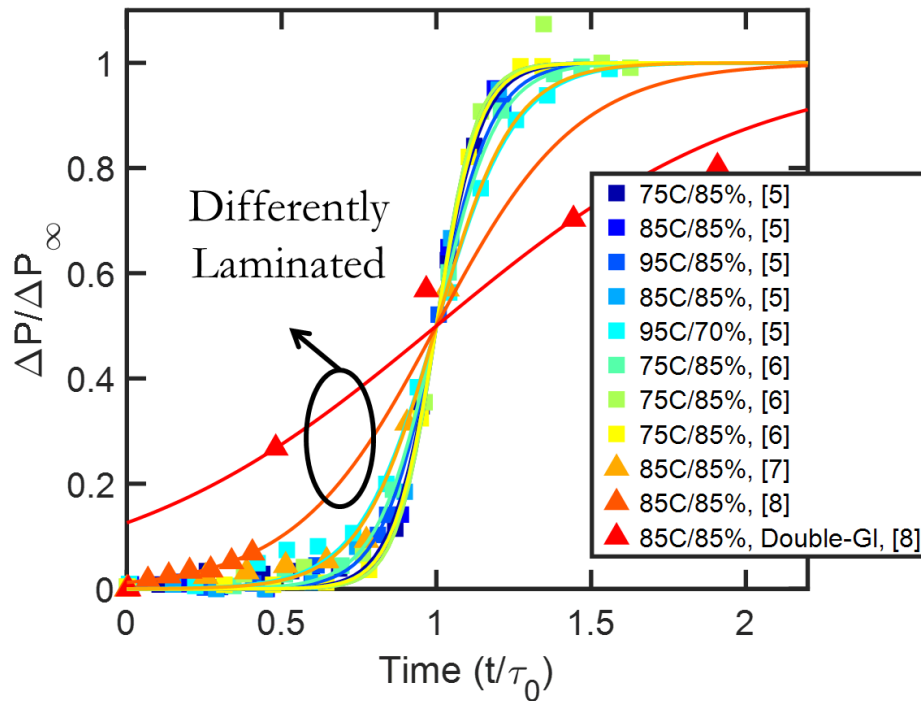
# Solder-Bond Failure Exclusively Correlated to Series Resistance Increase

Dana, Johnston, NREL

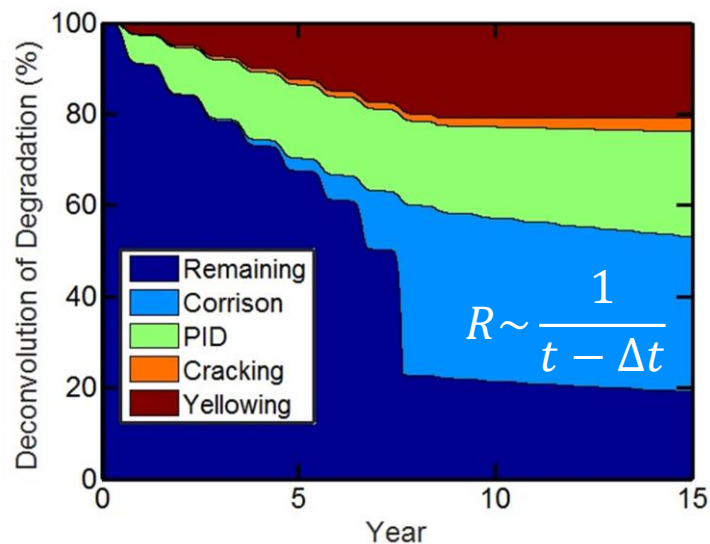
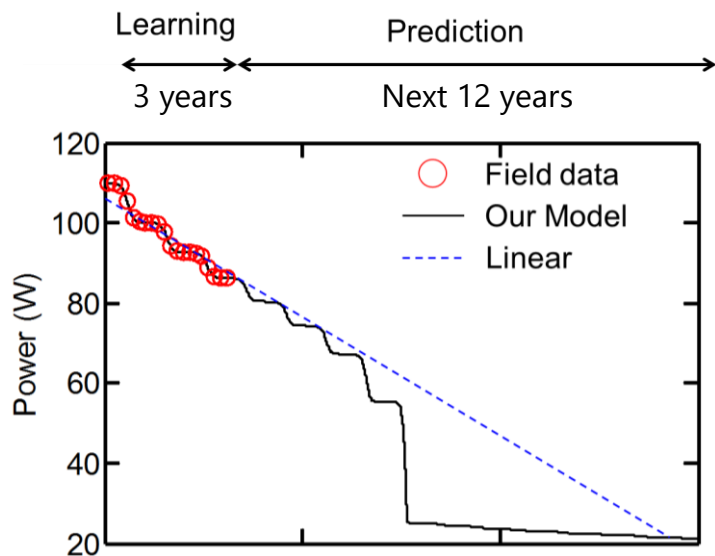


# PID affects Shunt Resistance

$$\Delta P(t) = \Delta P_{\infty} [1 + \exp(-(t - t_{0.5})R_D)^{-1}]$$



# Reliability prediction



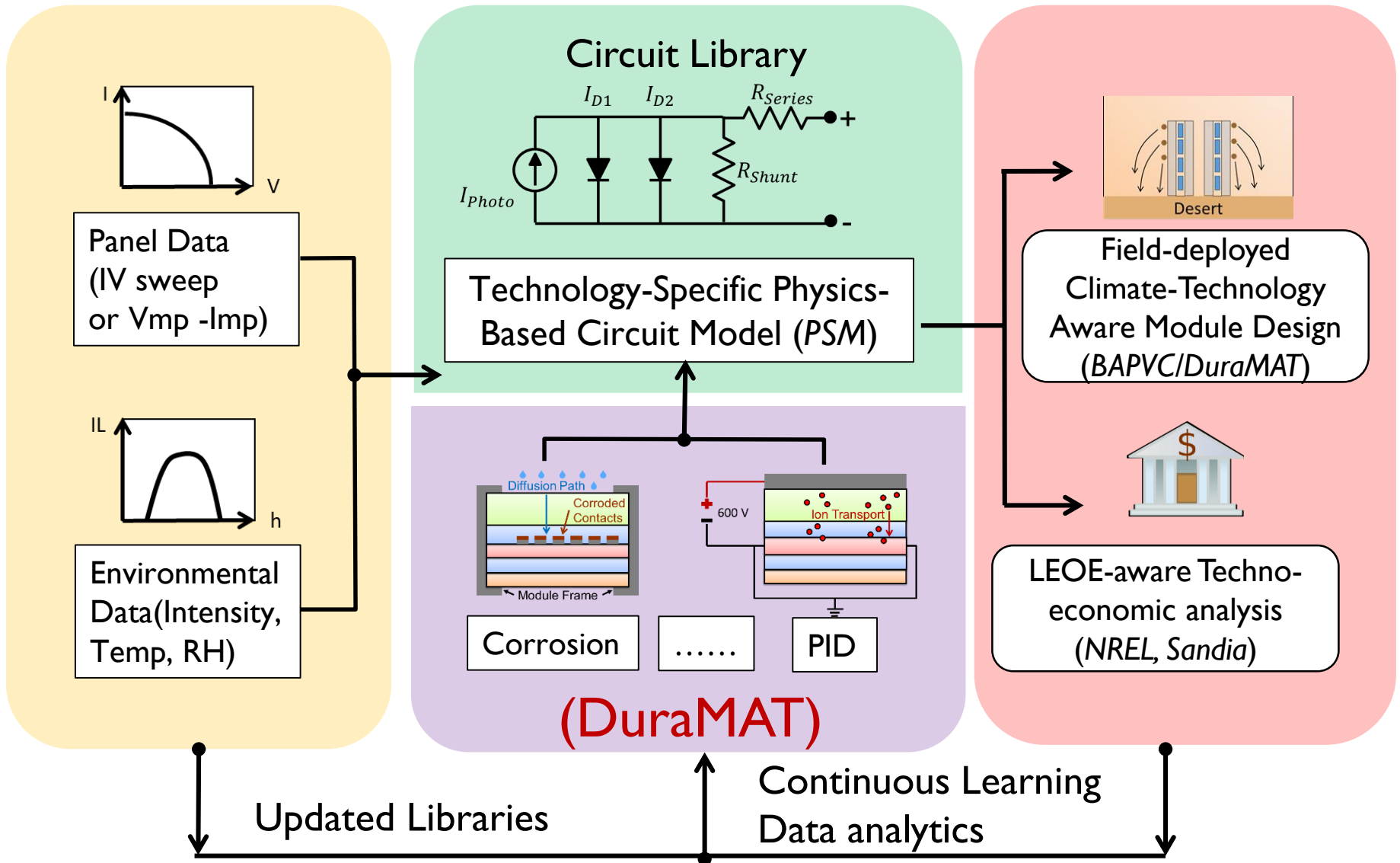
Our framework allows inverse modelling of **3-year** simulated field data, and predict the energy yield for total **15 years**.



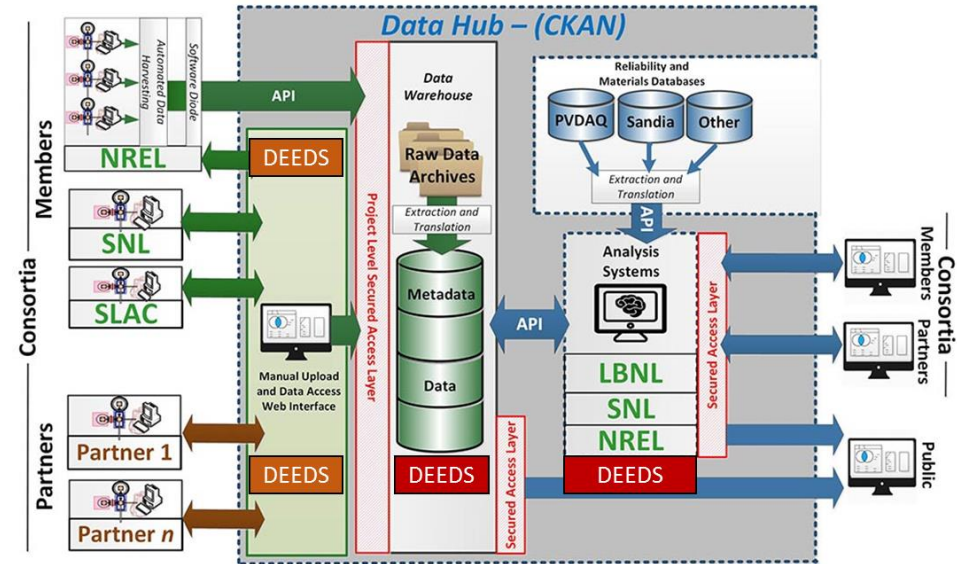
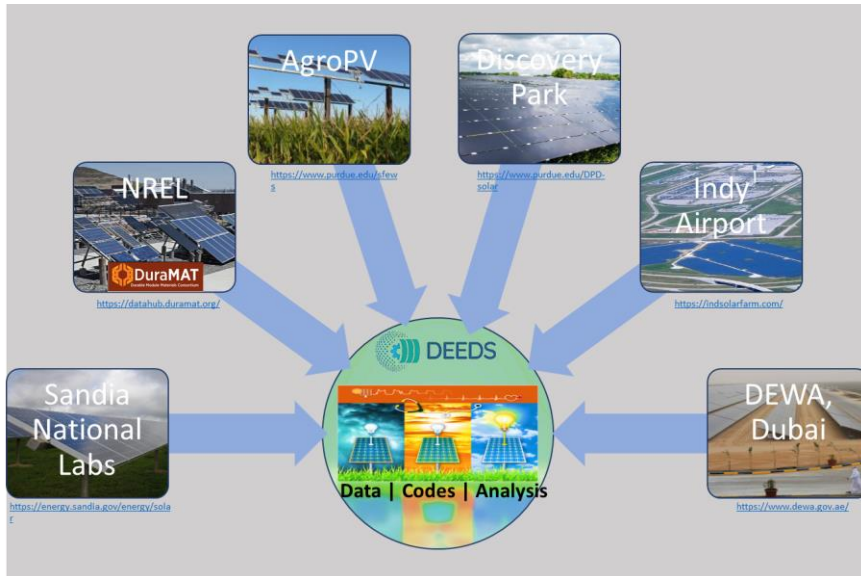
DataHUB

# Physics-based Learning

Industry



# DEEDS For Solar Farm EKG



DEEDS in a 4M NSF Data-Initiative at Purdue

Alam group's Physics-based PV Forensics is a key initiative

Builds on the DuraMAT Database

DEEDS

Solar PV Diagnosis: Real-time Monitoring of PV Systems using Suns-Vmp Method

Cases Files DataTables Tools Analytics

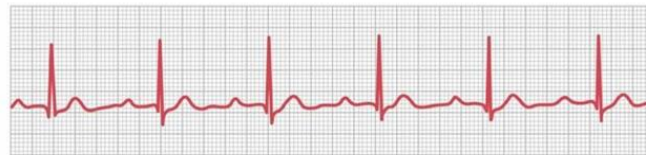
Case Information

ID	Case Name	Case ID	Description	Keywords	Source	Start Date	End Date	Latitude	Longitude	Technical Lead	Compiled By
639	NREL_System_51	System51	Solar farm in Golden Colorado, flat-plate ph...	solar photovoltaic system, N...	CEED Group	08/20/2017	12/31/2018	39.74160000	-105.23048400	Xingshu Sun	Xingshu Sun, Tahir Patel, F
640	NREL_System_50	System50	Solar farm in Golden Colorado, flat-plate ph...	solar photovoltaic system, N...	CEED Group	05/10/2018	12/31/2019	39.74160000	-105.23048400	Tahir Patel, Reza Asadpour	Tahir Patel, Reza Asadpour
874492	Sandia_Can_Poly	CP1_270P	Solar farm in Albuquerque, NM. Poly-Si. 12 ...	Sandia, efficiency degradatio...	CEED Group	02/01/2019	06/01/2020	37.34016560	-105.40162770	Tahir Patel, Reza Asadpour	Tahir Patel, Reza Asadpour
875416	DuraMat_MN_System_259472	MN_259472	Solar farm in Minneapolis MN, PV Module ...	solar photovoltaic system, et...	DuraMat	08/06/2019		44.89000000	-93.20000000	Tahir Patel, Reza Asadpour	Tahir Patel, Reza Asadpour
875417	DuraMat_MN_System_373938	MN_373938	Solar farm in Minneapolis MN, PV Module ...	solar photovoltaic system, et...	DuraMat	08/06/2019		44.94000000	-93.23000000	Tahir Patel, Reza Asadpour	Tahir Patel, Reza Asadpour
875418	DuraMat_MN_System_714162	MN_714162	Solar farm in Minneapolis MN, PV Module ...	solar photovoltaic system, et...	DuraMat	08/06/2019		45.01000000	-93.23000000	Tahir Patel, Reza Asadpour	Tahir Patel, Reza Asadpour

# Conclusions: PV Heartbeat interpreted by physics-based model

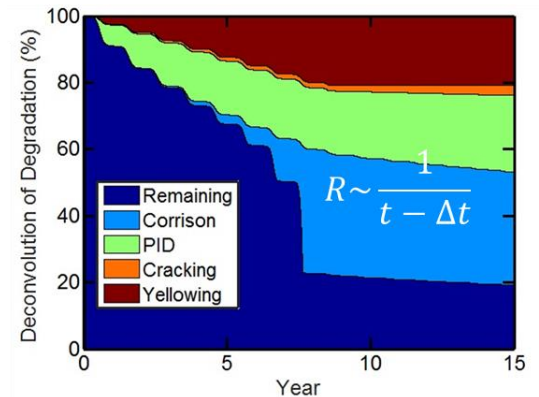
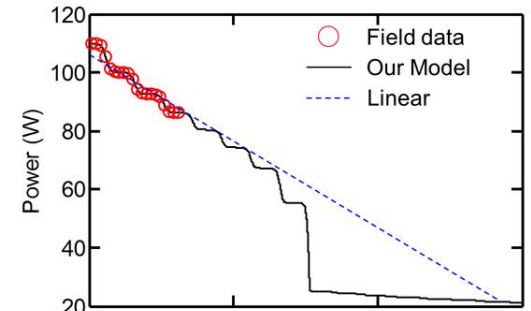
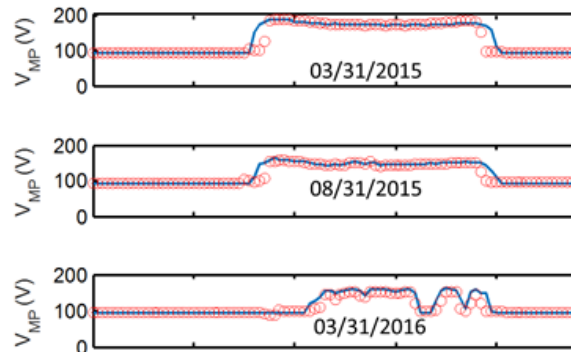


EKG Diagram



Solar Panels at Knoy Hall

“Heartbeat” of PV



Inverter as a Fitbit ...