Faculty of Engineering
School of Photovoltaic and Renewable Energy Engineering

UNSW SYDNEY

Global-Scale Non-Linear Modelling of Photovoltaic Module Degradation

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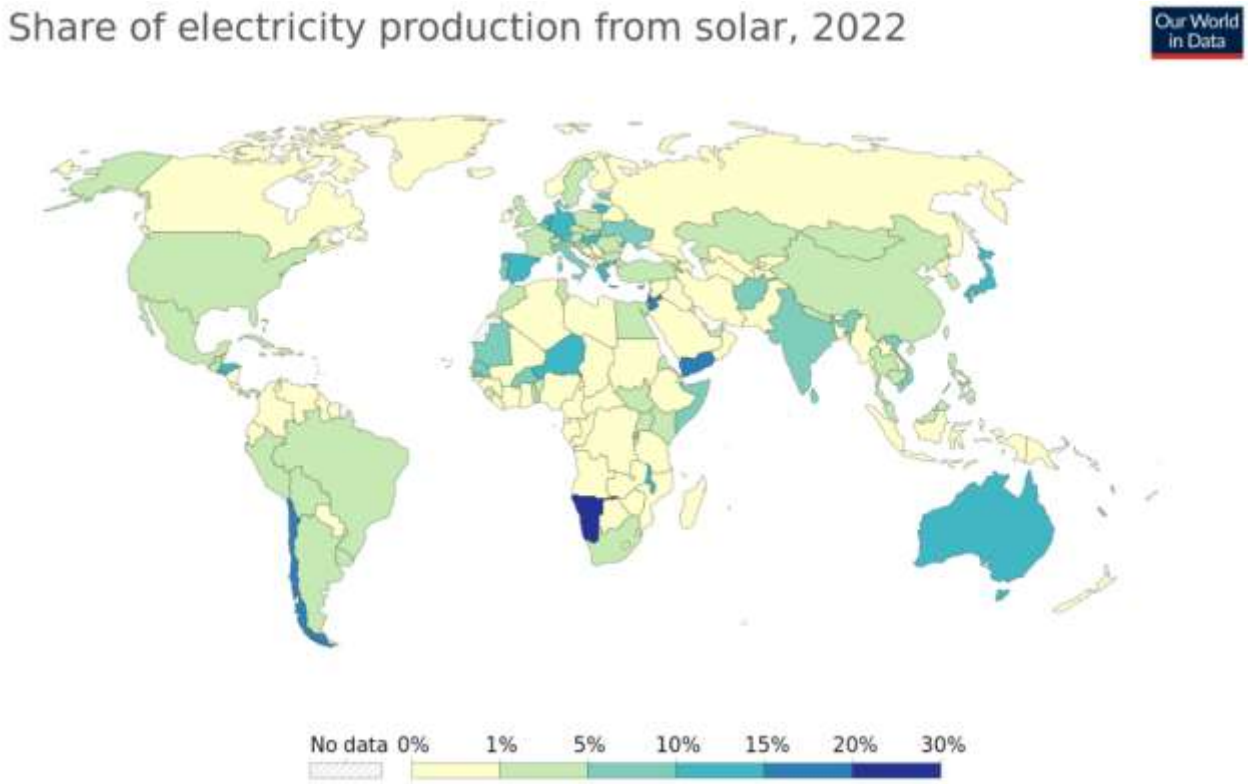
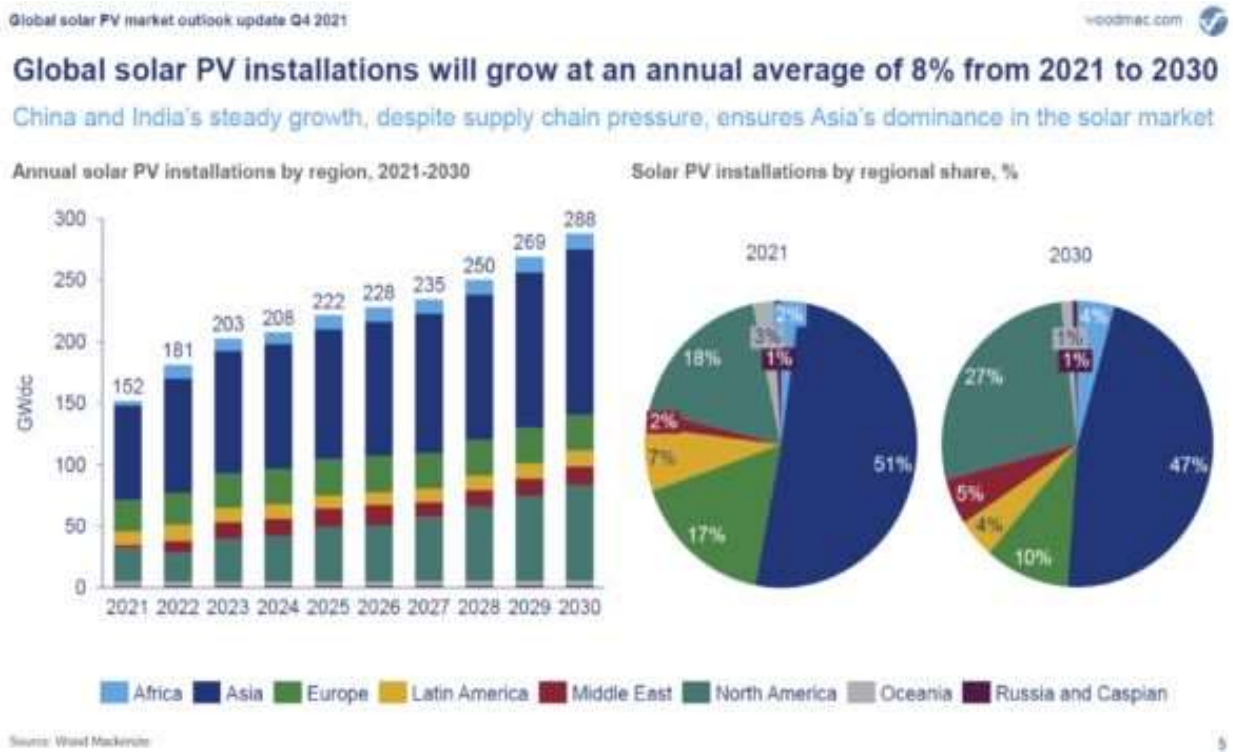
Solar PV: Exponential Growth





- PV warranties are usually for 25-30 years.
- Design, quantification and reliability standards have been highly dependent on the historical performance.
- Climate change and evolving operation strategies might accelerate module degradation.

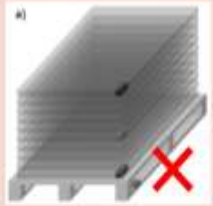
1. https://ourworldindata.org/grapher/share-electricity-solar
2. All I want for Christmas is 400 GW of solar installed in 2023, PV Magazine 2022, https://pv-magazine-usa.com/2022/12/23/all-i-want-for-christmas-is-400-gw-of-solar-installed-in-2023/

How can PV modules degrade?

Manufacturing & Installation

Manufacture QC

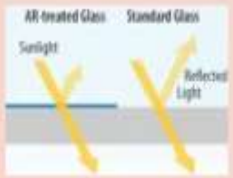
Transportation



Mounting

Packaging

AR-coating



Discoloration

Breakage

Delamination

Corrosion

Operational loading and environmental conditions

Thermal cycles

Wind

Snow

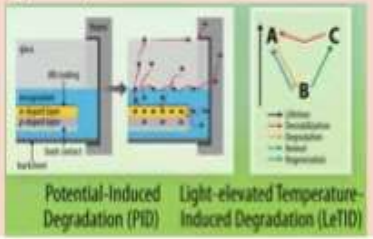
Cells

Cracks

Snail trails

Hot-spots

PID, LID, LeTID



Severe weather events

Hailstorm

Hurricane

Tornado

Interfaces

Solder Grid Finger, Diode Failures

Open Circuit Arcing

MC4 Failure

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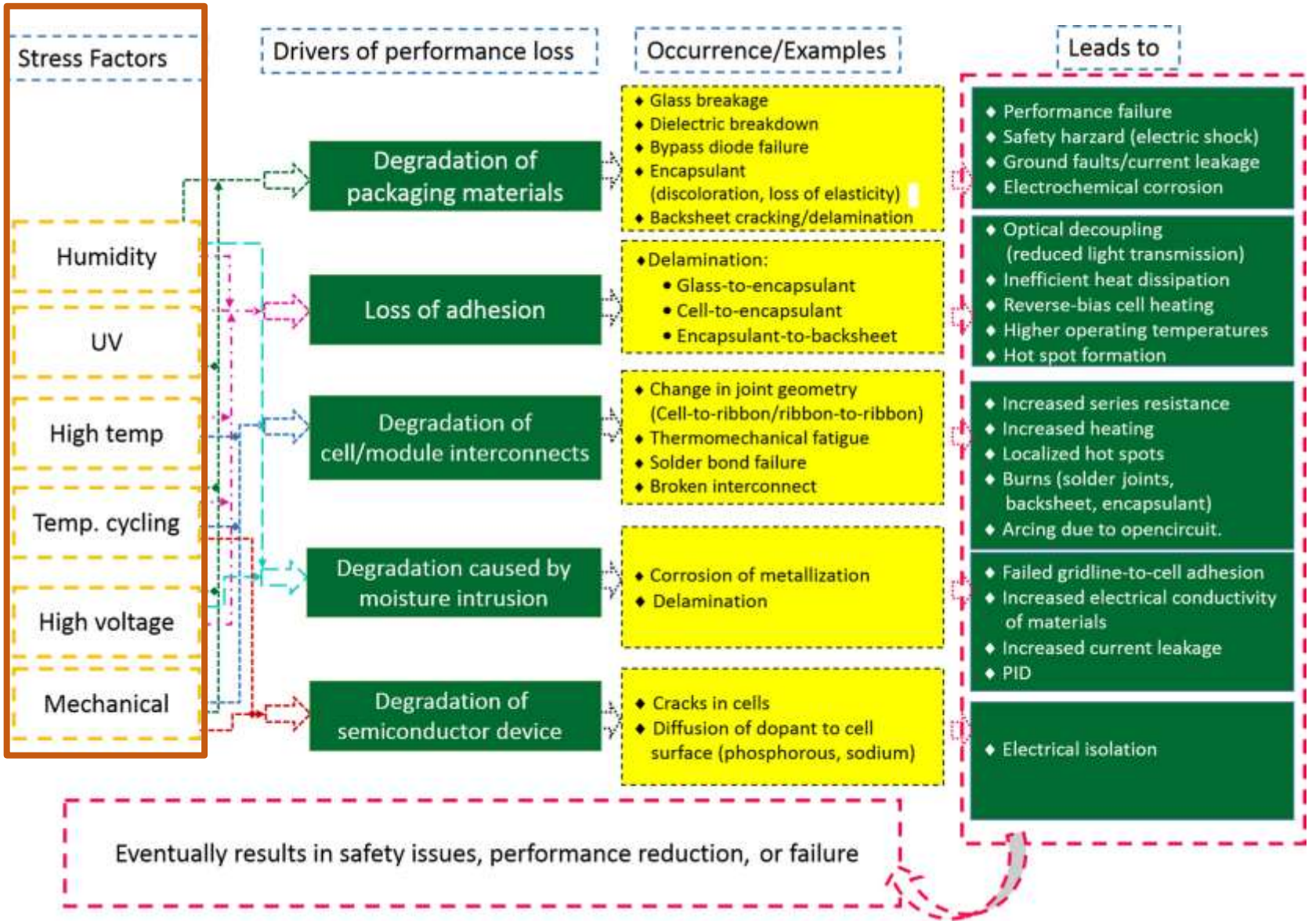
Impacts of Module Degradation

Stresses



Indicators

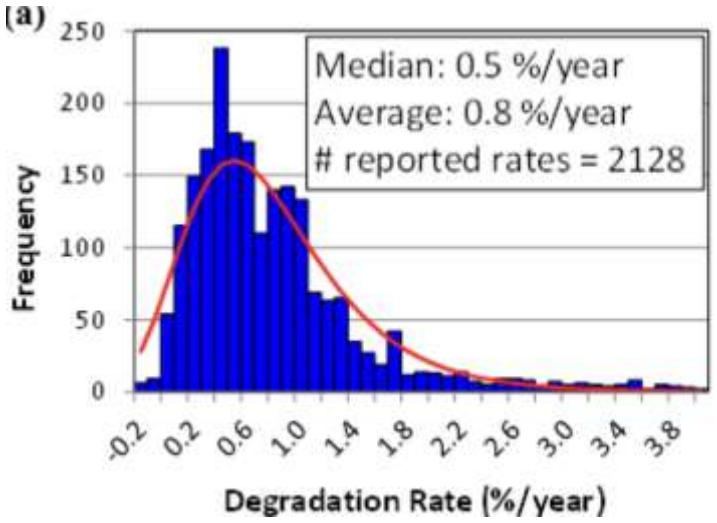
I-V Parameters

Power

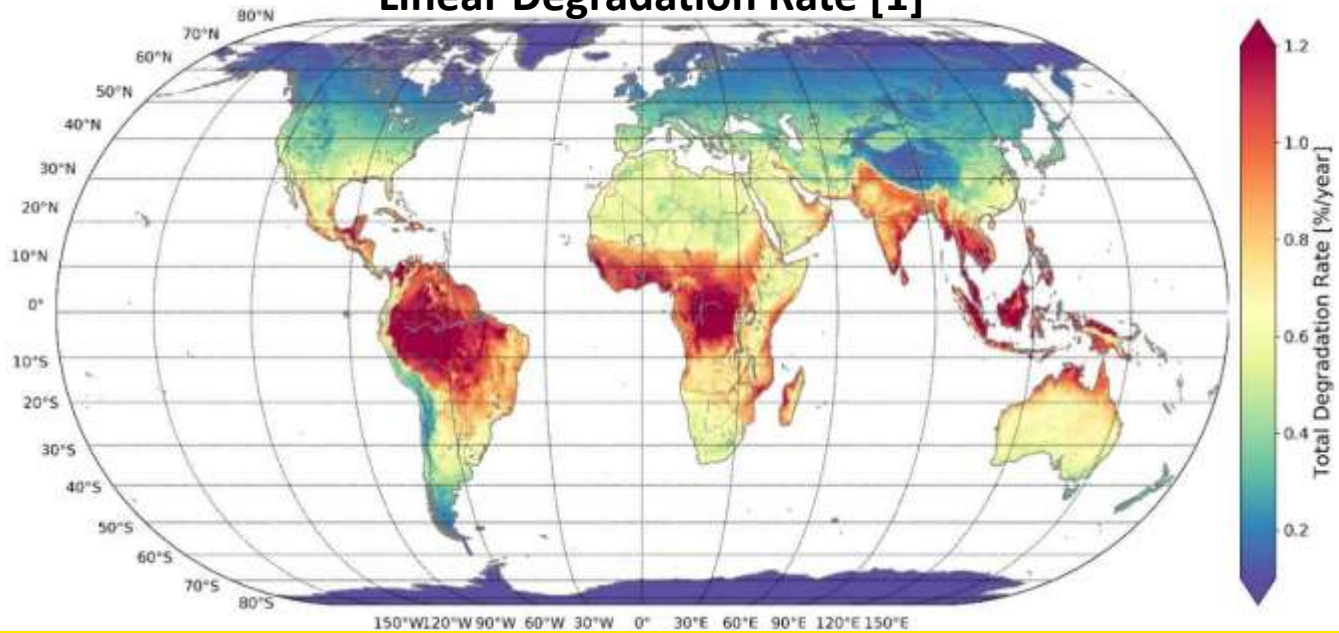
Research Gaps: Degradation Modelling

- Accelerated tests and lab experiments
- Site analysis year-to-year approach through performance modelling
- Linear total degradation
- Most literature discusses degradation for mono-Si modules

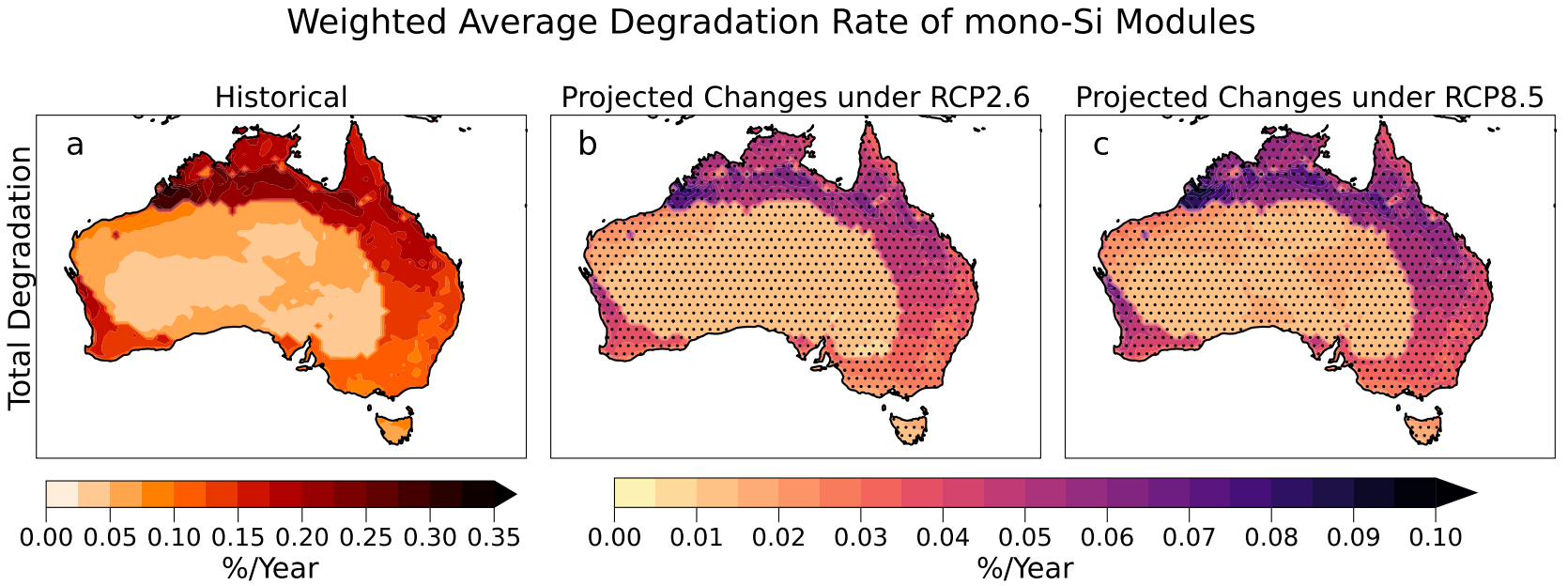
Based on PV System output [2]



Linear Degradation Rate [1]

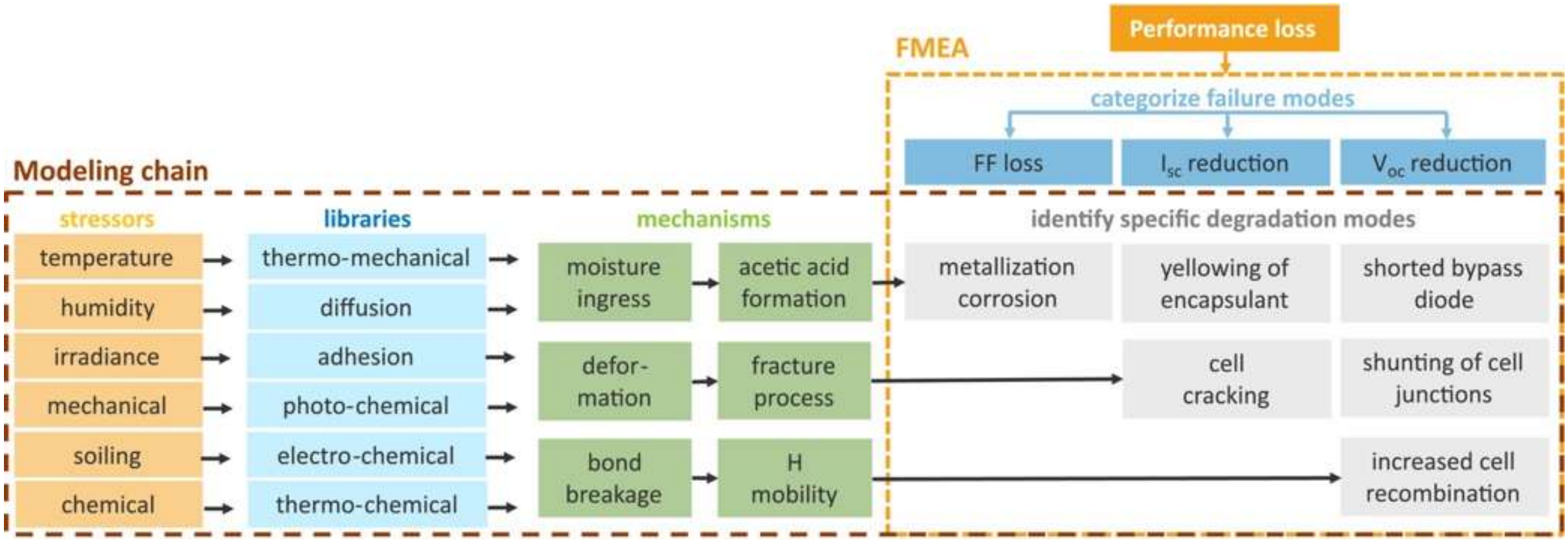


1. Ascencio-Vásquez, J.; Kaaya, I.; Brecl, K.; Weiss, K.-A.; Topič, M. Global Climate Data Processing and Mapping of Degradation Mechanisms and Degradation Rates of PV Modules. *Energies* **2019**, *12*, 4749. https://doi.org/10.3390/en12244749
2. Jordan, D., Wohlgemuth, J., Kurtz, S., 2012. Technology and Climate Trends in PV Module Degradation. 27th European hotovoltaic Solar Energy Conference and Exhibition



- Non-linear degradation rate
- Considers only delamination, encapsulant discoloration, internal circuit failure and cell ribbon corrosion

Research Gaps: Modelling Framework



- Lack of a robust modelling framework that considers physics-based models, lab test and accelerated tests

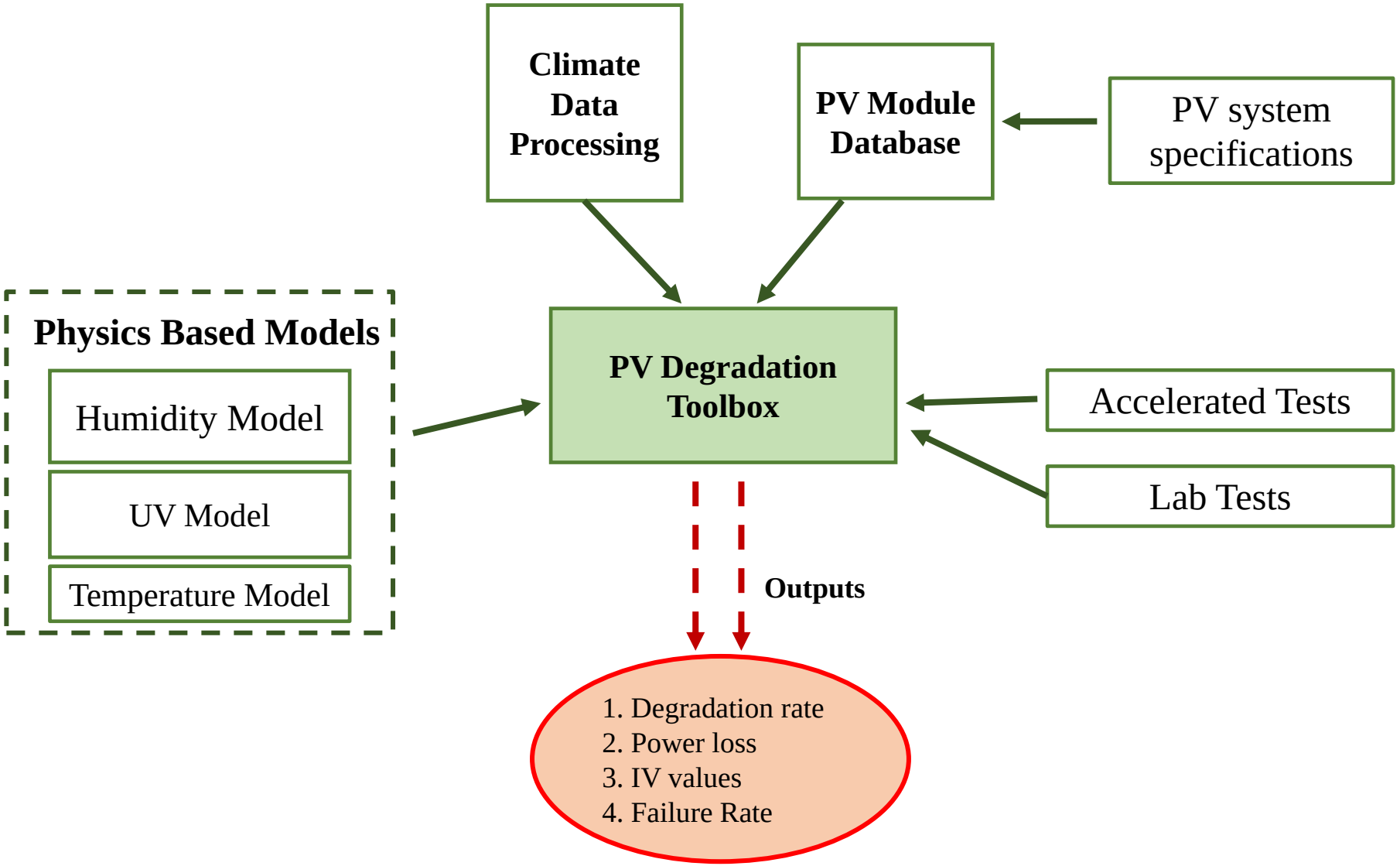
Research Goals for this project

- Create a simplified method to access and identify the meteorological stressors
    1. Pre-processing data to include all the missing variables like DNI, DHI, UV, etc.

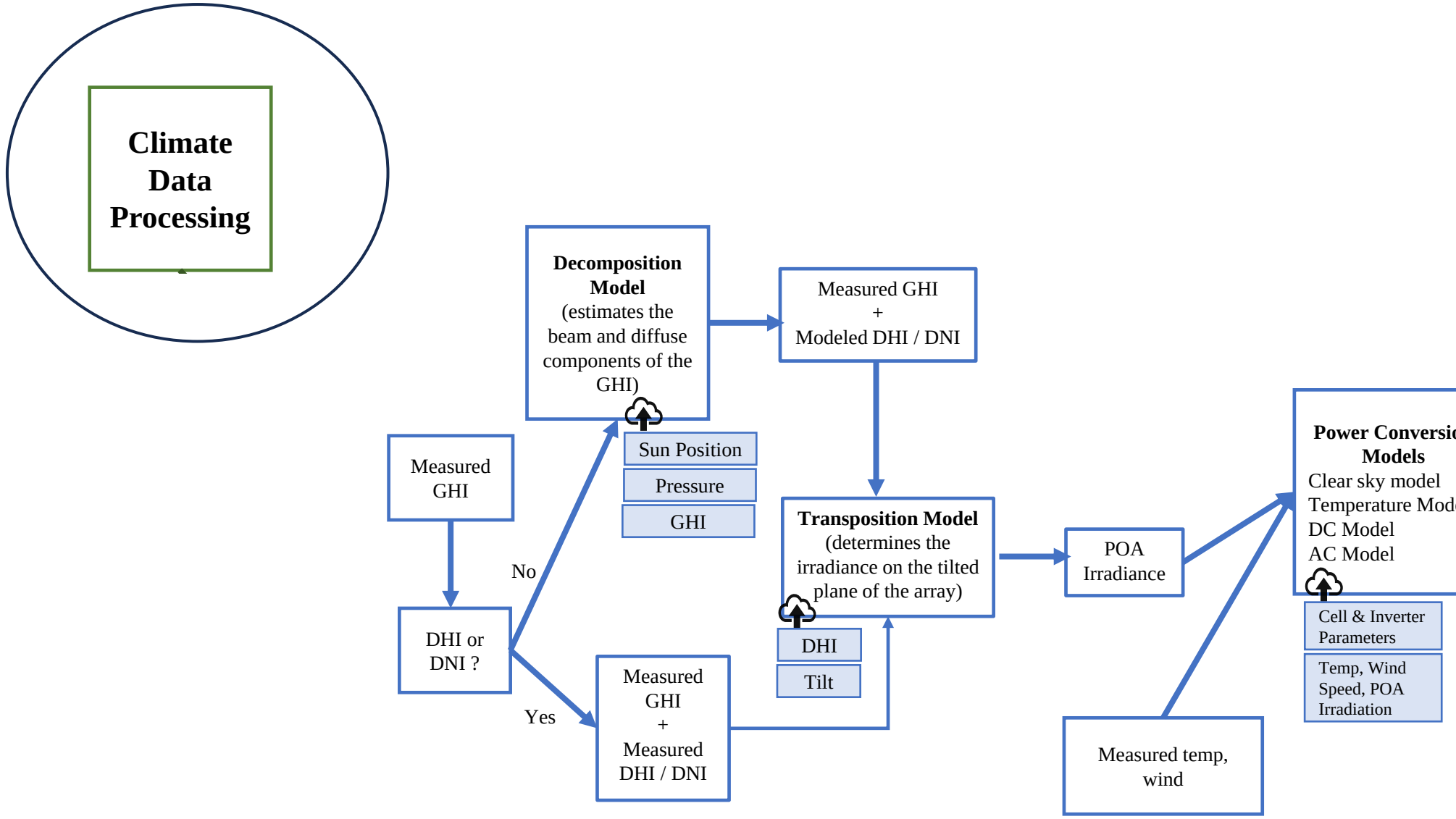
- Create a modelling framework that is able to calculate degradation based on physics-based models, laboratory tests and accelerated tests.

- Can span across different bill of materials and technologies.

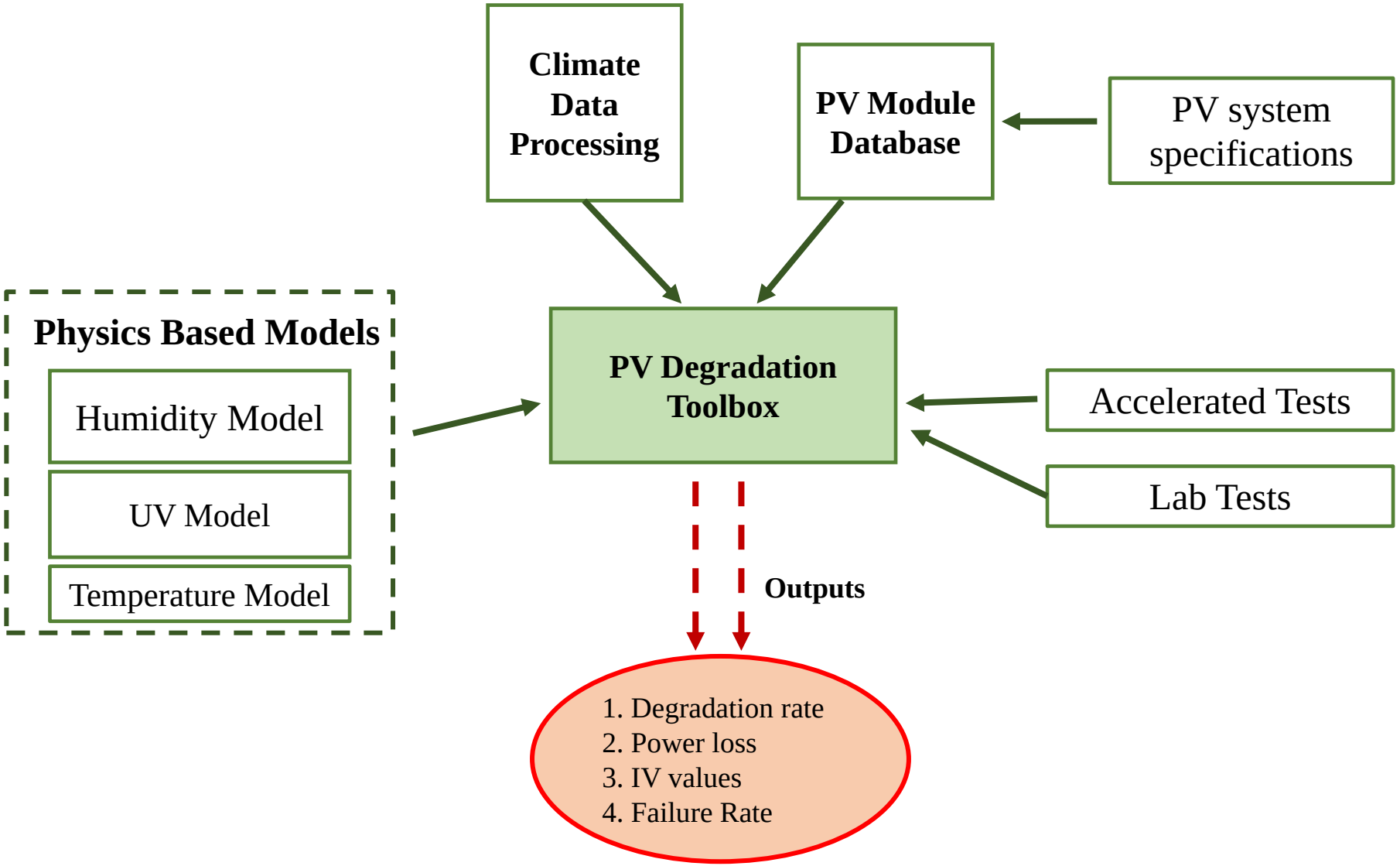
Methods


Climate Data Processing
PV Module Database
PV system specifications
Physics Based Models
Humidity Model
UV Model
Temperature Model
PV Degradation Toolbox
Accelerated Tests
Lab Tests
Outputs
1. Degradation rate
2. Power loss
3. IV values
4. Failure Rate

Methods


Climate Data Processing
Decomposition Model (estimates the beam and diffuse components of the GHI)
Measured GHI + Modeled DHI / DNI
Measured GHI
Sun Position
Pressure
GHI
No
DHI or DNI ?
Yes
Measured GHI + Measured DHI / DNI
Transposition Model (determines the irradiance on the tilted plane of the array)
DHI
Tilt
POA Irradiance
Measured temp, wind
Power Conversio Models
Clear sky model
Temperature Mod
DC Model
AC Model
Cell & Inverter Parameters
Temp, Wind Speed, POA Irradiation

Methods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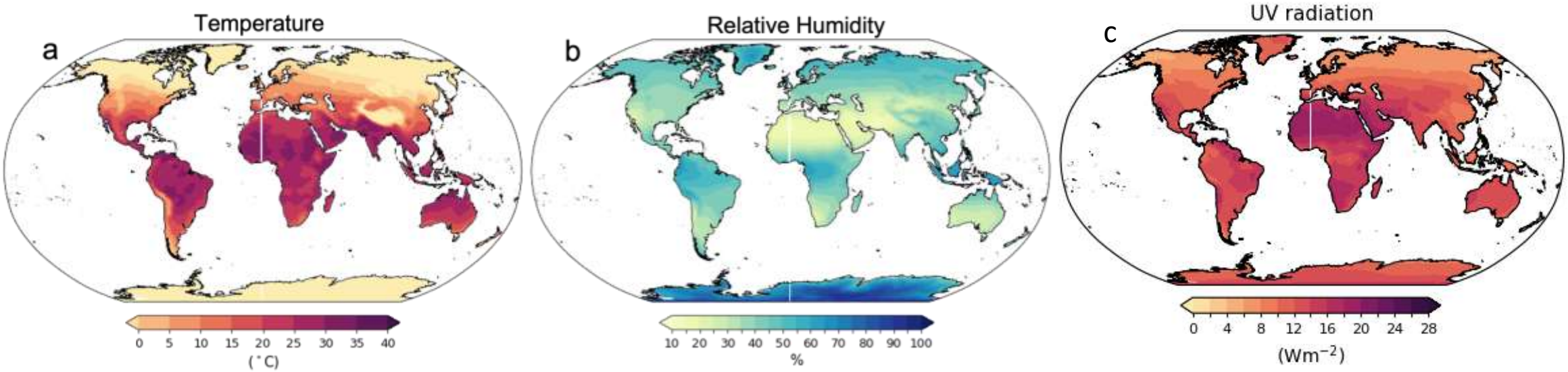
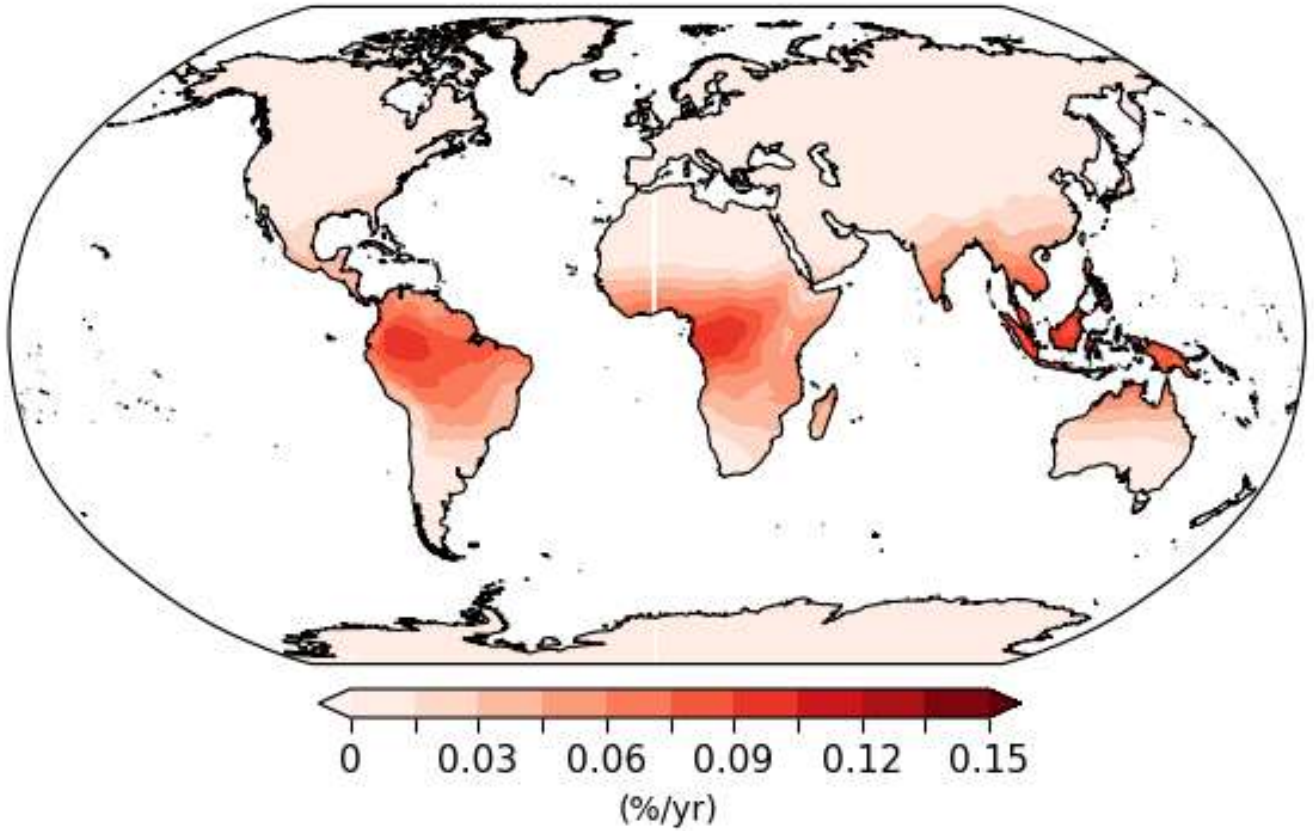
Climate Stressors



Analysis Period: 1985-2014

Photo-Degradation Mechanism



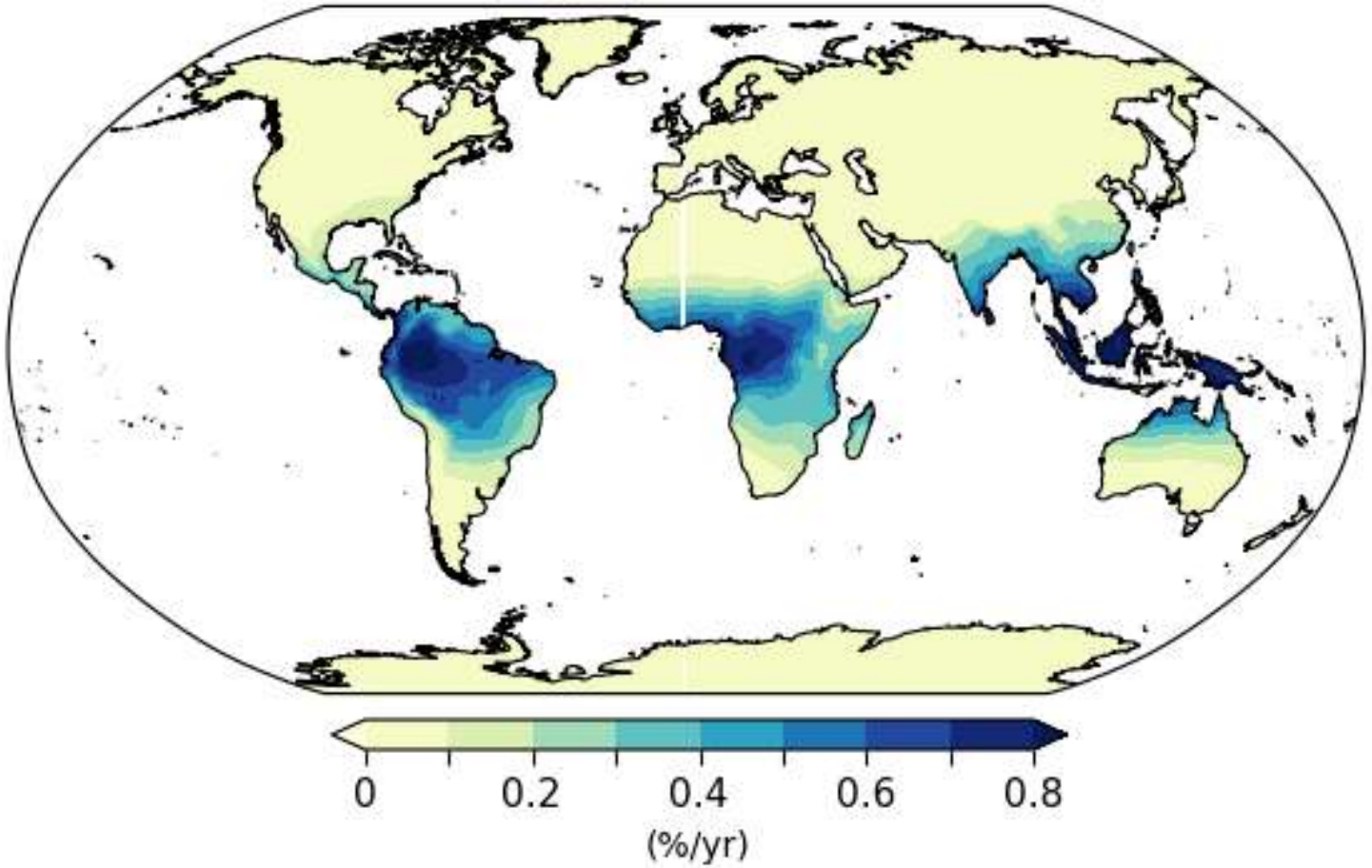
- Photo-Degradation mainly occurs due to UV radiation
- also dependent on humidity.

$$k_P = A_P \left((UV)^X \left(1 + {rh_{eff}}^X\right) \exp\left(-\frac{E_P}{k_B \times T_m} \right) \right.$$

Ap : pre-exponential constant;
Ep : activation energy;
K_B: Boltzmann Constant;
rh_{eff} : effective RH

- Tropical regions are the highest affected by photo-degradation degradation mechanism.
- Desert regions have relatively lower photo-degradation rates due to lower levels of humidity.

Encapsulant Discoloration



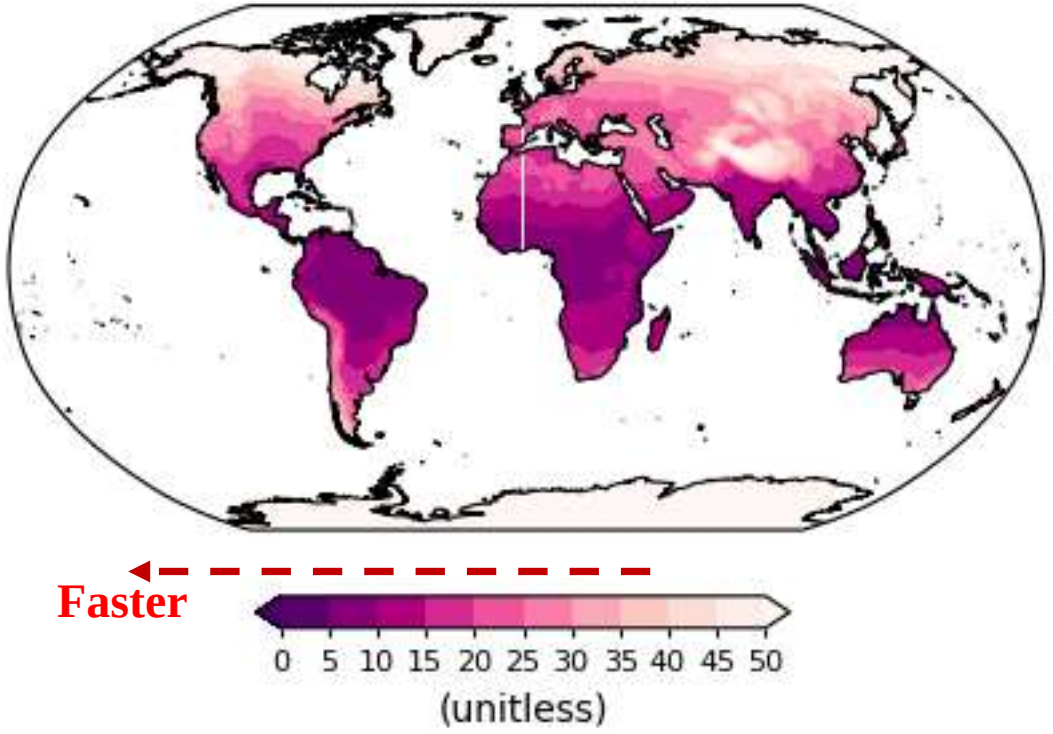
- Photo-Degradation and Hydrolysis are the main degradation mechanisms that lead to encapsulant discoloration
- Tropics show higher encapsulant discoloration.
- India, China, north Australia, central Africa, northern SA are highly affected by this mode.

$$Encapsulant\ discoloration = mean\ rate * \frac{(1+k_H)(1+k_P)-1}{(1+k_{H-base})(1+k_{P-base})-1}$$

K_H: hydrolysis degradation rate; Kp: Photo degradation

Accelerated Test

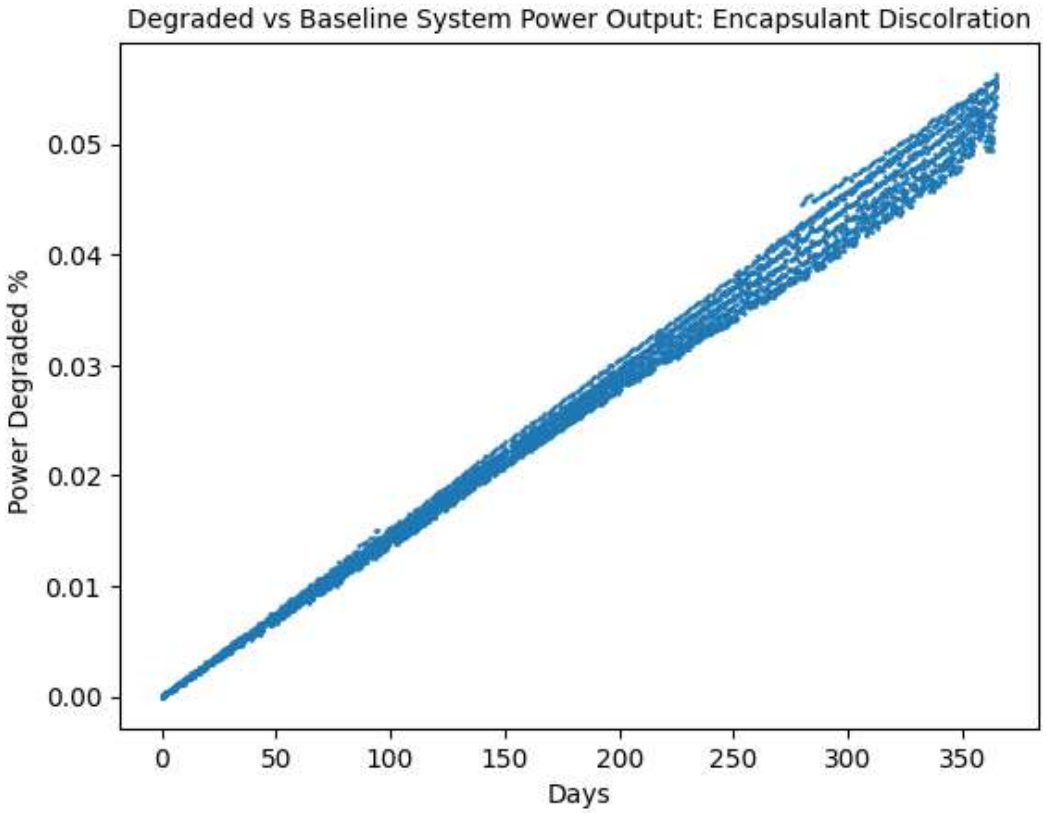
- Acceleration Factor between the rate of degradation of a modelled environment versus a modelled controlled environment.
- If the AF=25 then 1 year of Controlled Environment exposure is equal to 25 years in the field.

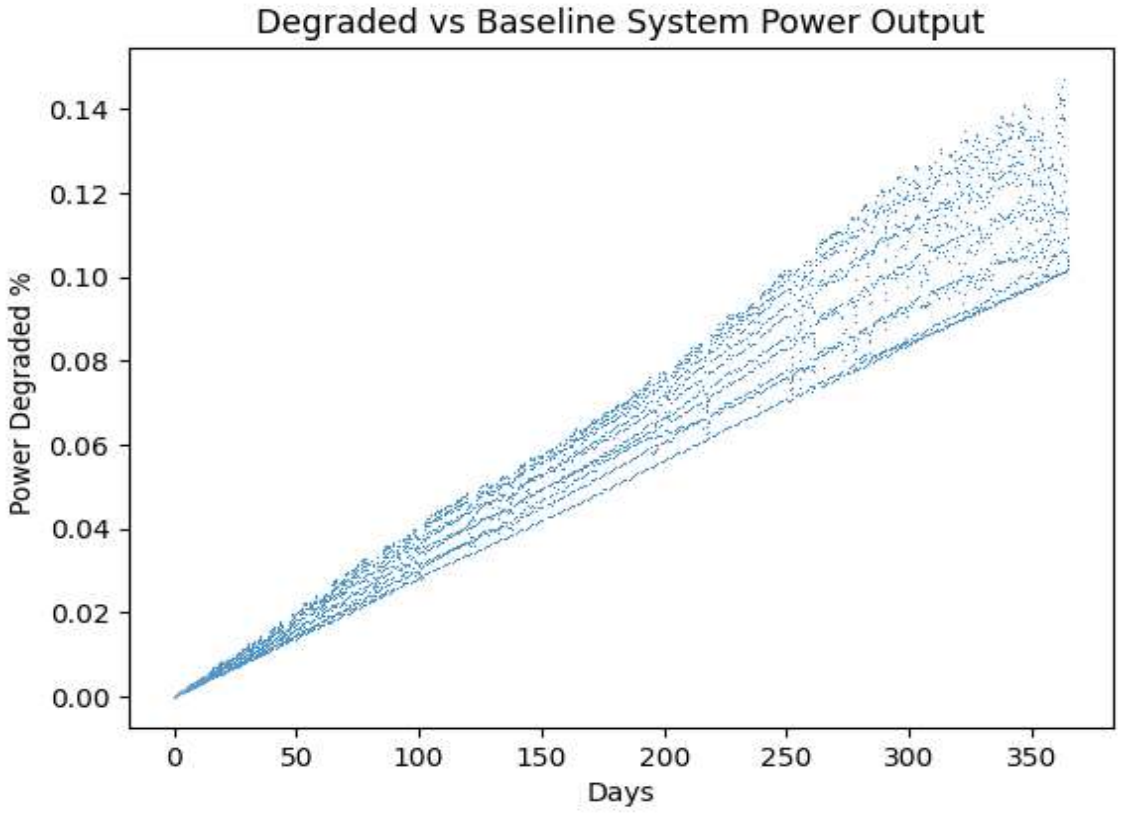


- Higher AF = Longer time to degrade
- Lower AF = **Faster degradation**

Modelled Control Conditions:
UV = 80 W/m^2
Chamber Temp = 80 °C
Chamber RH = 65%

Sensitivity Analysis





- Non-linear interaction among the degradation modes

Summary and Outlook

ADVANTAGES

- Robust Framework to model degradation
- Non-linearities in the degradation modes
- Modelling framework extends beyond PR modelling

CHALLENGES

- Each degradation mode depends on the specific climate type
- modes are completely dependent on either lab tests or visual inspection
- Observational data for model validations

CURRENT STATUS

FUTURE WORK

Proof of Concept

- Weather dependent
- Physics based models
- Accelerated Tests

Modelling Complex Degradation Modes

- PID
- LeTID

Failure Rate Analysis

Lifetime Prediction

Thank You

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