Industry Facing PV Degradation Prediction Tool and Database to Enable a 50-Year Life Module

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Photo from iStock-627281636

Outline

1 PV Industry projected growth and reliability challenges

2 Ensuring quality of PV: standards, accelerated testing, and modeling

3 Capturing degradation with PV Degradation Tool

4 Example of PVDeg: rooftop installation distance

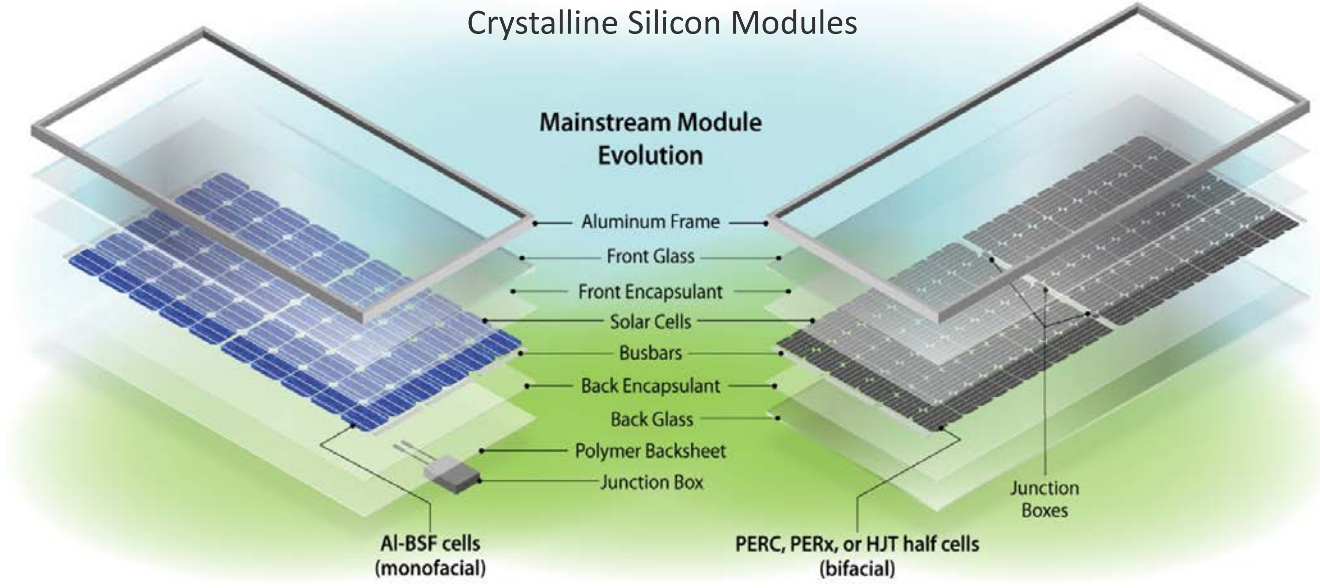
5 Live Demo

6 Summary

PV Industry projected growth and reliability challenges

Modules Continuously Evolve

Crystalline Silicon Modules



Mainstream Module Evolution

Aluminum Frame
Front Glass
Front Encapsulant
Solar Cells
Busbars
Back Encapsulant
Back Glass
Polymer Backsheet
Junction Box
Junction Boxes

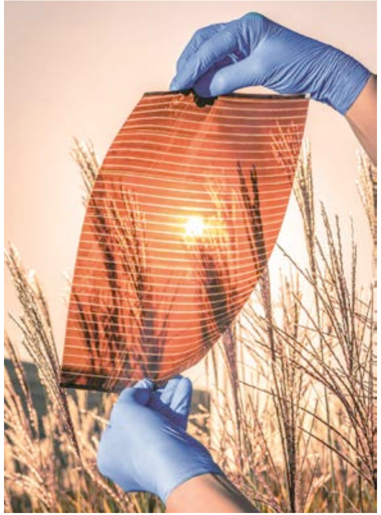
Al-BSF cells (monofacial)

PERC, PERx, or HJT half cells (bifacial)

Pre-2015 module, 20-25 year life

2022 module, 35 year life

Electricity is a commodity therefore cost pressures are driving innovation to untested materials and processes to reduce costs wherever possible.



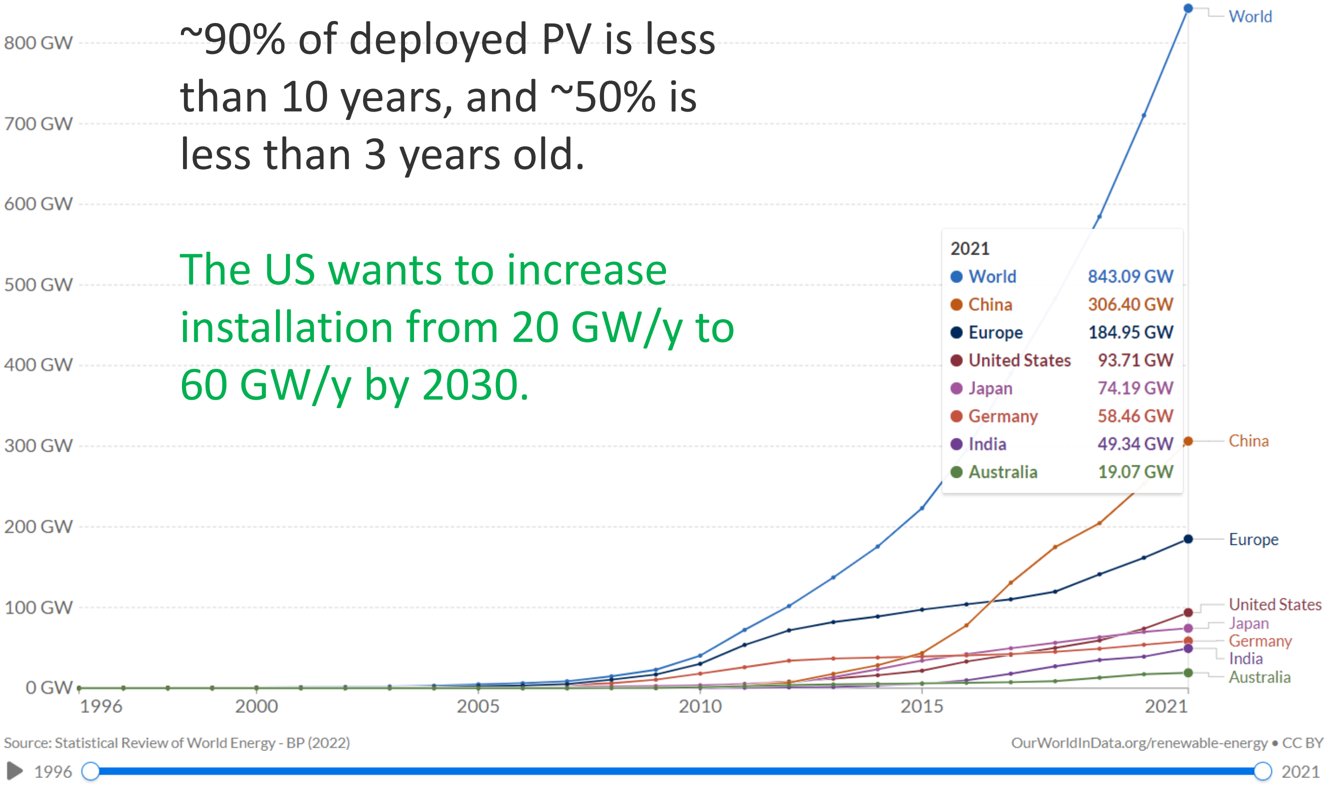
Emerging Products – flexible, non-CdTe thin film, BIPV, Etc.

Modules collect light from both sides

Ovaitt & Mirletz et al, 2022. “PV in the Circular Economy, A Dynamic Framework Analyzing Technology Evolution and Reliability Impacts.” *ISCIENCE* https://doi.org/10.1016/j.isci.2021.103488.

Exponential Growth in PV

- PV warranties are for 25 to 35 years.
- Designs and qualification testing is highly dependent on historical performance.
- We can’t wait 10 to 20 years to determine if current testing and manufacturing processes are adequate.
- Warranties are based on market demands, not on robust scientific understanding.



Source: Statistical Review of World Energy - BP (2022)

OurWorldInData.org/renewable-energy • CC BY

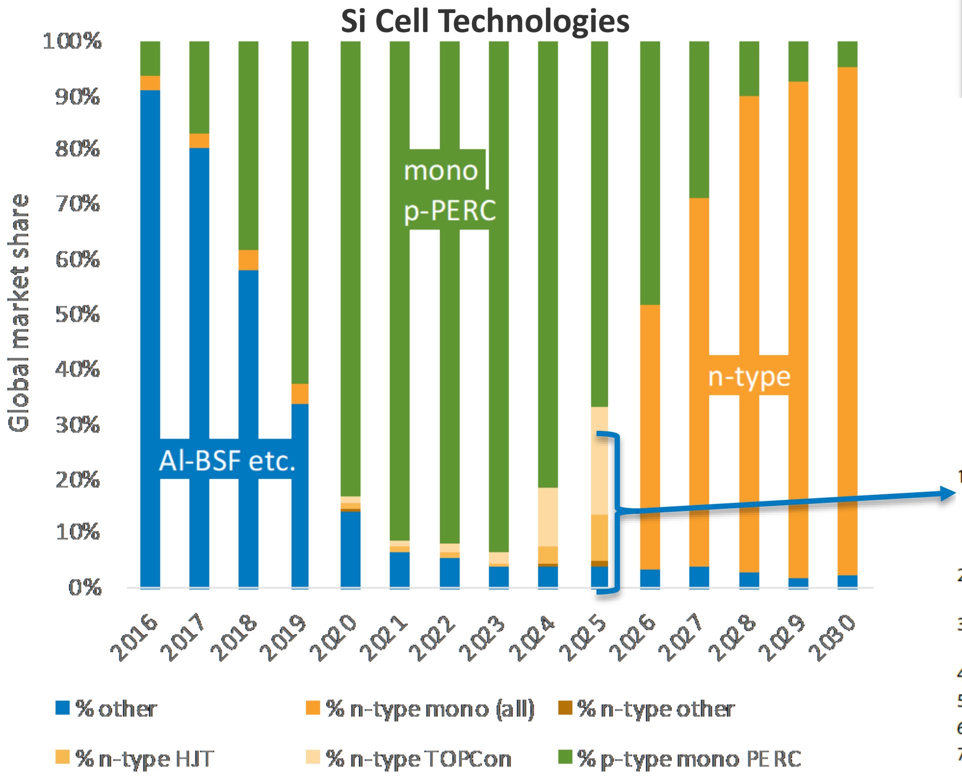
~90% of deployed PV is less than 10 years, and ~50% is less than 3 years old.

The US wants to increase installation from 20 GW/y to 60 GW/y by 2030.

https://ourworldindata.org/

New Technology + Explosive Growth

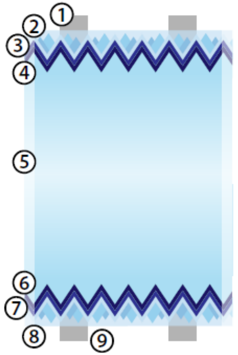
Module bifaciality factor $\phi = \frac{P_{Rear}}{P_{Front}}$



HJT

23-25% cell efficiency

ϕ ~0.85 – 0.95

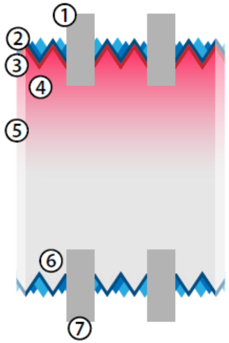


1. Frontside fingers (busbars optional) compromised of low-temperature screen-printed Ag pastes or electroplated Ni/Cu/Sn/Ag
2. TCO by PVD (typically ITO for high optical transmission and low sheet resistance)
3. p^+ doping and full-area emitter formation by PECVD of a-Si:H
4. Intrinsically doped a-Si:H by PECVD
5. High lifetime n-type base wafer
6. Intrinsically doped a-Si:H by PECVD
7. n^+ doping and full-area BSF formation by PECVD of a-Si:H
8. TCO by PVD (typically ITO for high optical transmission and low sheet resistance)
9. Backside fingers (busbars optional)

TOPCon

21-23% by SP, 21-26% by PVD

ϕ ~0.8



1. Ag and Al front metallization by screen-printing or PVD
2. SiN$_x$ ARC and passivation layer by PECVD
3. PECVD or ALD of AlO$_x$ surface passivation layer
4. p^+ doping and full-area emitter formation by ion implantation or BBr$_3$ diffusion
5. High lifetime n-type base wafer
6. Tunnel oxide passivated contact (TOPCon) layer formed by PECVD or LPCVD of doped a-Si or poly-Si layers
7. Ag rear metallization (sometimes full-area) by screen-printing or PVD

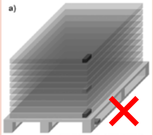
Jarett Zuboy. DuraMAT Tech Scouting 2022

How do PV Systems Degrade

Manufacturing & Installation

Manufacture QC

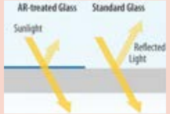
Transportation



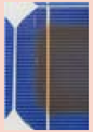
Mounting

Packaging

AR-coating



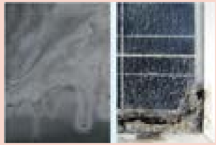
Discoloration



Breakage

Delamination

Corrosion



Operational loading and environmental conditions

Thermal cycles

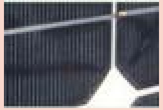
Wind

Snow

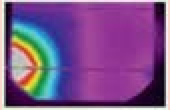
Cells

Cracks

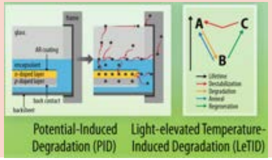
Snail trails



Hot-spots



PID, LID, LeTID



Severe weather events

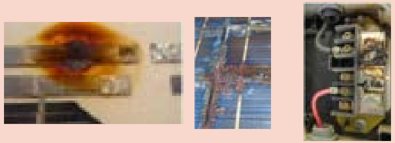
Hailstorm

Hurricane

Tornado

Interfaces

Solder Grid Finger, Diode Failures



Open Circuit Arcing

MC4 Failure

Mechanical stress may produce latent damage which is manifest after environmental exposure. This is in addition to reliability issues and other long-term degradation modes.

Ensuring quality of PV: standards, accelerated testing, and modeling

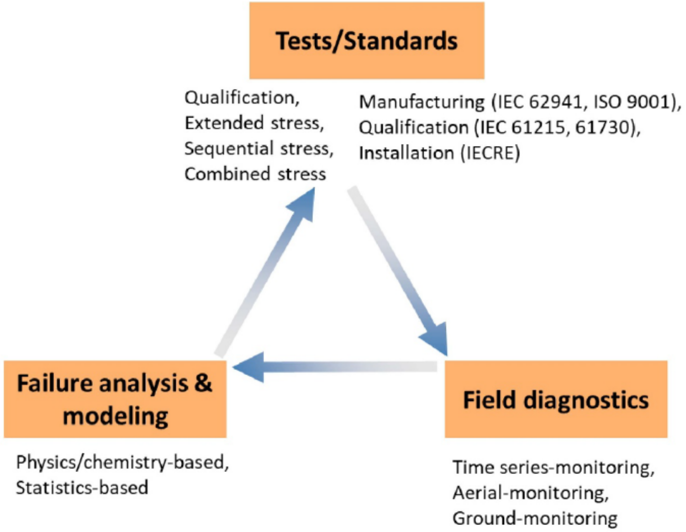
Standardized Testing is Highly Empirical

Challenge: rapidly changing BOM, design and manufacturing process with unknown capacity to meet adequate degradation rate targets. We can't rely upon empirical field data to create at 50-year module.

Solution:

1. Continue the empirical process as a long-term feedback assessment augmented by tracking the BOM of fielded modules.
2. Identify all the major failure modes
    a) Develop tests that are equivalent to well over 50 years or that can guarantee the problem cannot occur.
    b) Determine which failure modes can be assessed with only a few year's equivalent exposure and extrapolated accurately.
    c) More emphasis on coupon testing and prequalifying materials
3. Better fundamental understanding of the mechanisms of failure for testing design.
4. More coordinated industry-wide collection of degradation data in easily used formats.

PV reliability learning cycle
slow process



Tests/Standards

Qualification,
Extended stress,
Sequential stress,
Combined stress

Manufacturing (IEC 62941, ISO 9001),
Qualification (IEC 61215, 61730),
Installation (IECRE)

Field diagnostics

Time series-monitoring,
Aerial-monitoring,
Ground-monitoring

Failure analysis & modeling

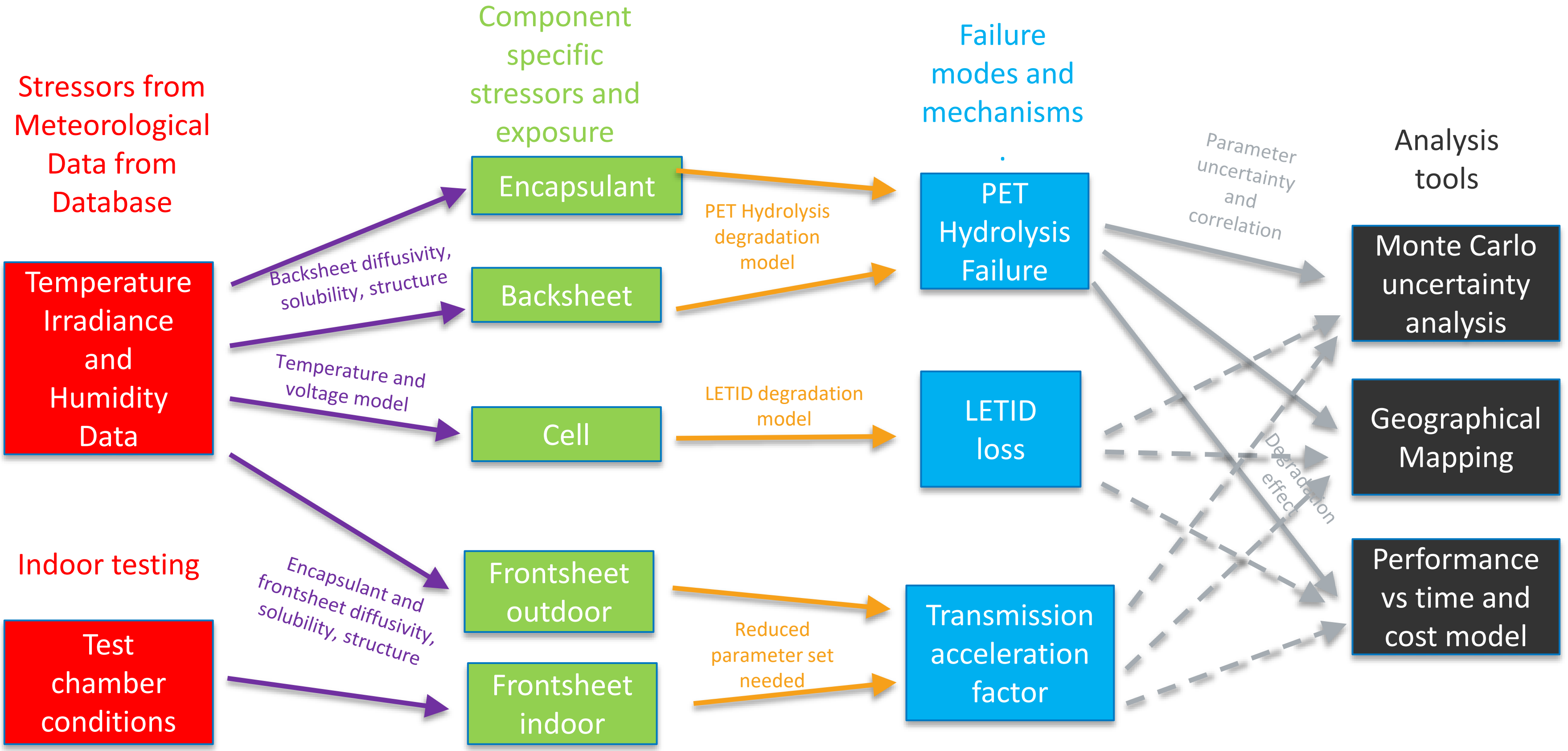
Physics/chemistry-based,
Statistics-based

[Jordan and TamizhMani, J. Phys. D: Appl. Phys. 53 (2020)]

Goals for this project

- **Create a simplified method to extrapolate laboratory data to the field.**
  - Develop python code to accomplish repetitive tasks. (e.g. access meteorological data, determine field stressors…)
  - Establish protocols for software such that new degradation functions can be implemented using only a few lines of code.
- **Create living databases of information on degradation and material properties that are needed for extrapolation**
- **The Python code will be written to be utilized by three levels of users:**
  - Experts who are developing the core procedures of the project
  - Experienced Python coders who will write their own functions and add them to the database
  - People with almost no Python experience who will just want to run common (e.g. Arrhenius) or industry standard degradation functions.

Block diagram of python code structure



Stressors from Meteorological Data from Database

Temperature Irradiance and Humidity Data

Indoor testing

Test chamber conditions

Backsheet diffusivity, solubility, structure

Temperature and voltage model

Encapsulant and frontsheet diffusivity, solubility, structure

Component specific stressors and exposure

Encapsulant

Backsheet

Cell

Frontsheet outdoor

Frontsheet indoor

PET Hydrolysis degradation model

LETID degradation model

Reduced parameter set needed

Failure modes and mechanisms

PET Hydrolysis Failure

LETID loss

Transmission acceleration factor

Parameter uncertainty and correlation

Degradation effect

Analysis tools

Monte Carlo uncertainty analysis

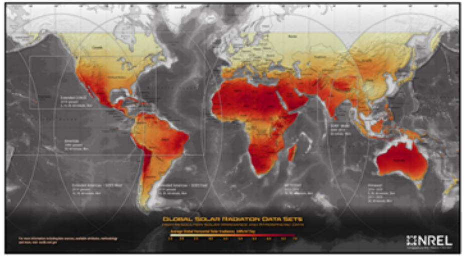
Geographical Mapping

Performance vs time and cost model

Capturing degradation with PV Degradation Tool

PV Degradation Tools
The integration pipeline for PV degradation analysis!

Stressors – NSRDB



Material Libraries

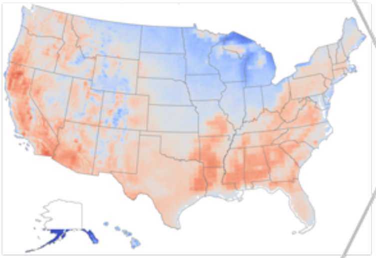
DuraMAT
DataHub

Degradation models

PVD

$$R_D = R_o G^p e^{\left(\frac{-E_a}{RT}\right)}$$

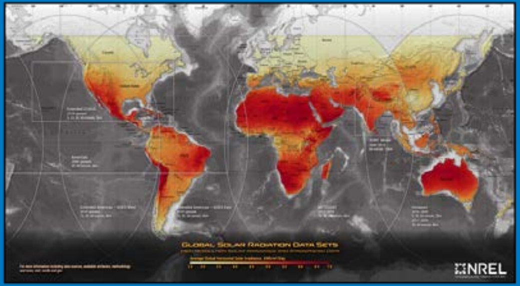
Parallel Analysis



powered by

reV &gaps pvlib python™ jupyter The HDF Group aws binder

1) Weather Database



Needs:

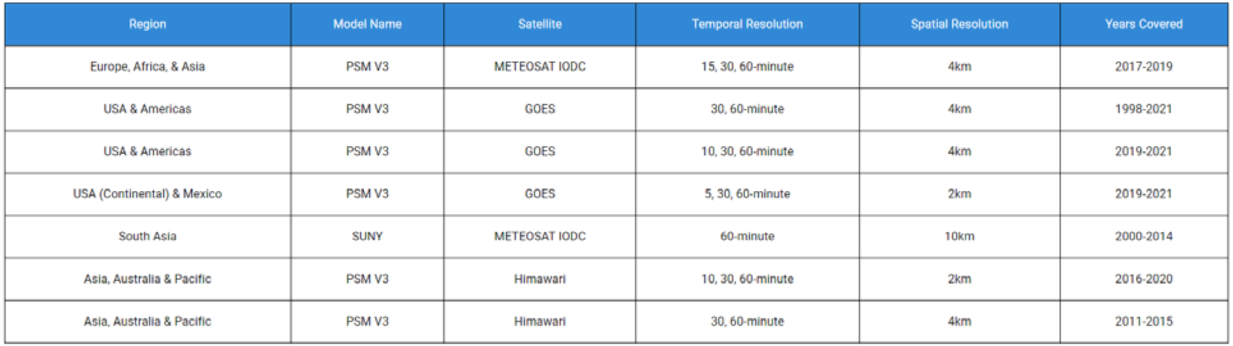
-High quality

-Open Access

-High Resolution and locations captured

National Solar Radiation Database: https://nsrdb.nrel.gov/

- Satellite data of cloud properties, atmospheric and aerosol properties, surface albedo, and solar radiation measurements
- +20 years of data for many global locations; TMYs
- Online viewer/downloader
- API to download data from AWS
- Facilitated use through the NREL-rex package to use internally on HPC or in AWS

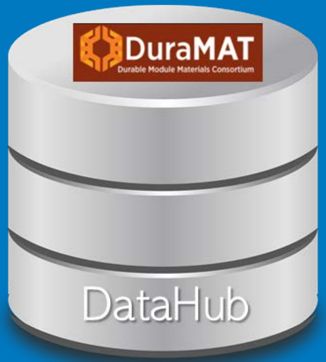


Region	Model Name	Satellite	Temporal Resolution	Spatial Resolution	Years Covered
Europe, Africa, & Asia	PSM V3	METEOSAT IODC	15, 30, 60-minute	4km	2017-2019
USA & Americas	PSM V3	GOES	30, 60-minute	4km	1998-2021
USA & Americas	PSM V3	GOES	10, 30, 60-minute	4km	2019-2021
USA (Continental) & Mexico	PSM V3	GOES	5, 30, 60-minute	2km	2019-2021
South Asia	SUNY	METEOSAT IODC	60-minute	10km	2000-2014
Asia, Australia & Pacific	PSM V3	Himawari	10, 30, 60-minute	2km	2016-2020
Asia, Australia & Pacific	PSM V3	Himawari	30, 60-minute	4km	2011-2015

PVDeg can also intake from some others open-source formats:

- Energy Plus website (.EPW format; world)
- PVGis (.CSV format, mostly Europe)
- Local files (SAM format)

2) Material Libraries



Needs:

Searchable database of PV related degradation parameters.

Comprehensive literature search for most common values already included

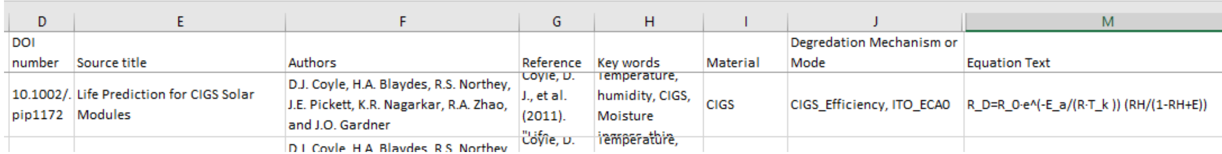
User contributions

Proposed taxonomy

Includes:

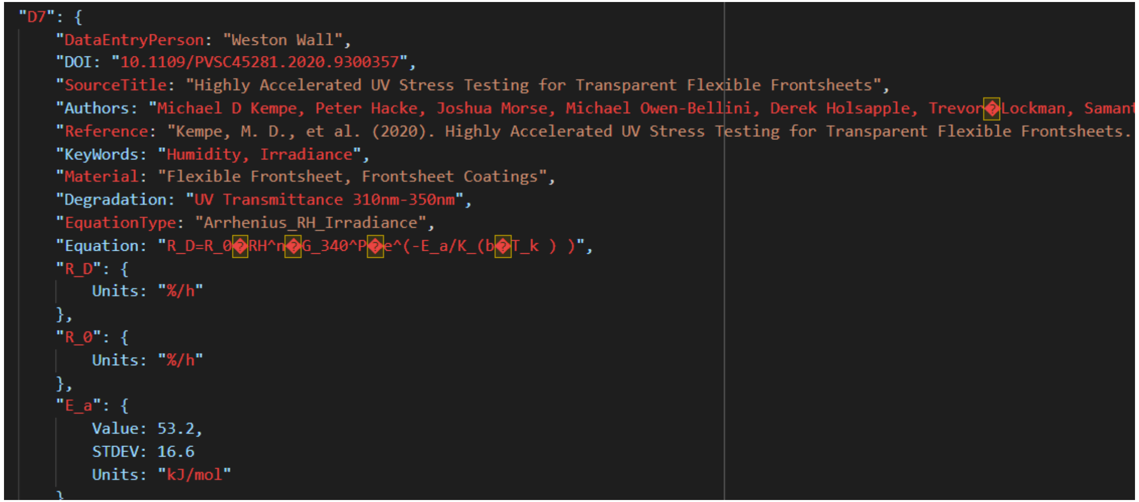
- material properties
- parameters for degradation calculations
- Known constants and other empirical factors
- equations

Data Gathering:



D	E	F	G	H	I	J	M
DOI number	Source title	Authors	Reference	Key words	Material	Degredation Mechanism or Mode	Equation Text
10.1002/. pip1172	Life Prediction for CIGS Solar Modules	D.J. Coyle, H.A. Blaydes, R.S. Northey, J.E. Pickett, K.R. Nagarkar, R.A. Zhao, and J.O. Gardner	Coyle, D. J., et al. (2011).	Temperature, humidity, CIGS, Moisture	CIGS	CIGS_Efficiency, ITO_ECA0	R_D=R_0·e^(-E_a/(R·T_k)) (RH/(1-RH+E))
		D.J. Coyle, H.A. Blaydes, R.S. Northey	Coyle, D.	Temperature,			

Structured proposed in JSON format (taxonomy still in development):

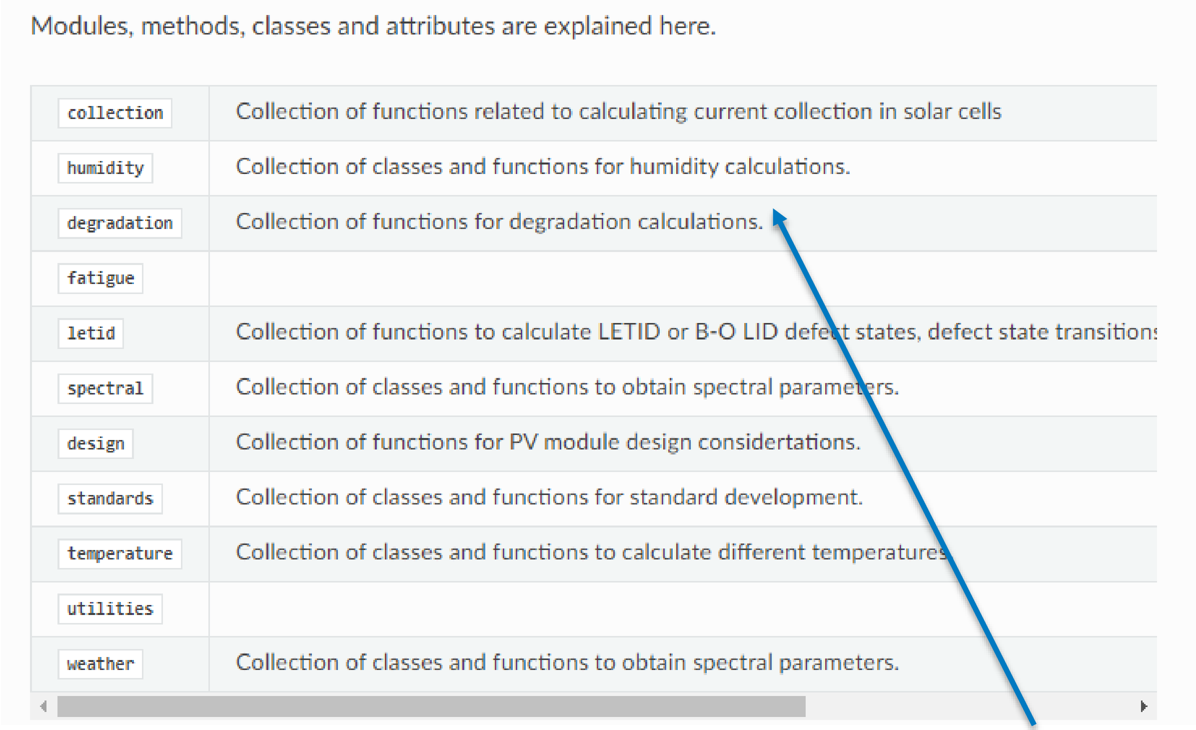


```
"D7": {
    "DataEntryPerson: "Weston Wall",
    "DOI: "10.1109/PVSC45281.2020.9300357",
    "SourceTitle: "Highly Accelerated UV Stress Testing for Transparent Flexible Frontsheets",
    "Authors: "Michael D Kempe, Peter Hacke, Joshua Morse, Michael Owen-Bellini, Derek Holsapple, Trevor�Lockman, Samant
    "Reference: "Kempe, M. D., et al. (2020). Highly Accelerated UV Stress Testing for Transparent Flexible Frontsheets.
    "KeyWords: "Humidity, Irradiance",
    "Material: "Flexible Frontsheet, Frontsheet Coatings",
    "Degradation: "UV Transmittance 310nm-350nm",
    "EquationType: "Arrhenius_RH_Irradiance",
    "Equation: "R_D=R_0�RH^n�G_340^P�e^(-E_a/K_(b�T_k ) )",
    "R_D": {
        Units: "%/h"
    },
    "R_0": {
        Units: "%/h"
    },
    "E_a": {
        Value: 53.2,
        STDEV: 16.6
        Units: "kJ/mol"
    }
```

3) Degradation Functions

Needs:
-Peer-reviewed functions
-Auxiliary data handling and calculations functions
-Open-source
-Flexibility for Paralelization

https://github.com/NREL/PVDegradationTools



Modules, methods, classes and attributes are explained here.

`collection`	Collection of functions related to calculating current collection in solar cells
`humidity`	Collection of classes and functions for humidity calculations.
`degradation`	Collection of functions for degradation calculations.
`fatigue`	
`letid`	Collection of functions to calculate LETID or B-O LID defect states, defect state transition
`spectral`	Collection of classes and functions to obtain spectral parameters.
`design`	Collection of functions for PV module design considertations.
`standards`	Collection of classes and functions for standard development.
`temperature`	Collection of classes and functions to calculate different temperatures.
`utilities`	
`weather`	Collection of classes and functions to obtain spectral parameters.

$$R_D = R_o G^p e^{\left(\frac{-E_a}{RT}\right)}$$

4) Parallel Analysis

Needs:

-Run in NREL’s HPC and AWS

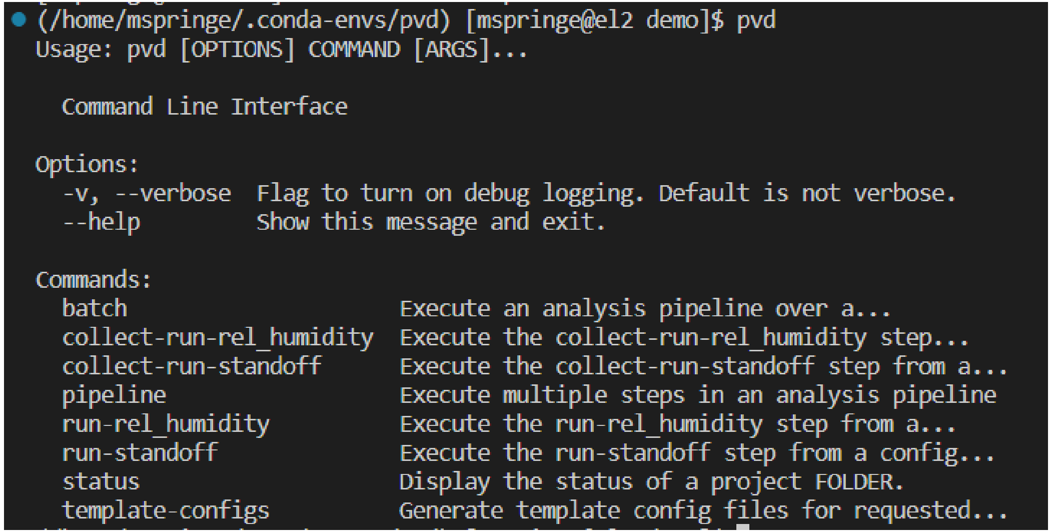
-Flexible

-As intuitive as possible

- Allow single location calculations through webpage

- Allow parallelized geospatial world map calculations through AWS cloud (external) and Eagle (internal)

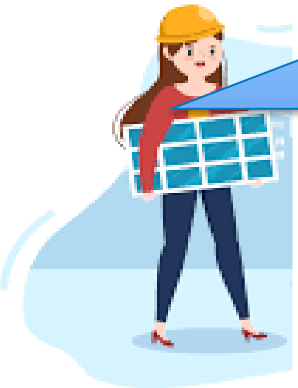
https://github.com/NREL/gaps



```
(/home/mspringe/.conda-envs/pvd) [mspringe@el2 demo]$ pvd
Usage: pvd [OPTIONS] COMMAND [ARGS]...

  Command Line Interface

Options:
  -v, --verbose  Flag to turn on debug logging. Default is not verbose.
  --help         Show this message and exit.

Commands:
  batch                      Execute an analysis pipeline over a...
  collect-run-rel_humidity   Execute the collect-run-rel_humidity step...
  collect-run-standoff       Execute the collect-run-standoff step from a...
  pipeline                   Execute multiple steps in an analysis pipeline
  run-rel_humidity           Execute the run-rel_humidity step from a...
  run-standoff               Execute the run-standoff step from a config...
  status                     Display the status of a project FOLDER.
  template-configs           Generate template config files for requested...
```

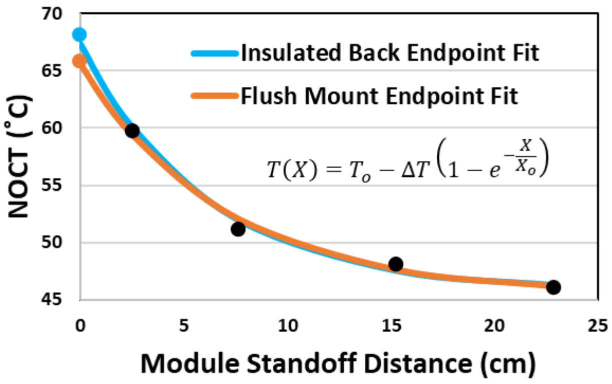
Example of PVDeg: rooftop installation distance

Example Use Case:
IEC 63126



I want the panels I install to be safe,
but I don’t want to spend more money than necessary on racking.
I know hot panels are no-bueno,
and that the closer they are to the roof the hotter they’ll be.
How do I know the right distance for my city, i.e. Phoenix?

Standoff images for distances of (A) flush mount (B) 2.5 cm, and (C) 10 cm.

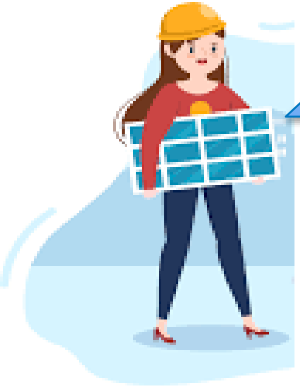


M. K. Fuentes, "A simplified thermal model for Flat-Plate photovoltaic arrays," United States, 1987-05-01 1987. [Online]. Available: https://www.osti.gov/biblio/6802914

Example Use Case: IEC 63126

IEC 63126 specifies more rigorous testing for modules deployed in combinations of locations and racking that result in **high temperatures** defined as the 98th percentile temperature of 70°C, 80°C or 90°C

$$X_{eff} = -X_o \ln\left(1 - \frac{T_o - T_{98}}{\Delta T}\right)$$



My Module is rated for the 70°C high temperature

$X_0 = 6.1$ cm
$T_{98} = 70°\text{C}$
T_0 = Insulated back module temperature
ΔT = Difference between insulated back and open rack modules

M. K. Fuentes, "A simplified thermal model for Flat-Plate photovoltaic arrays," United States, 1987-05-01 1987. [Online]. Available: https://www.osti.gov/biblio/6802914

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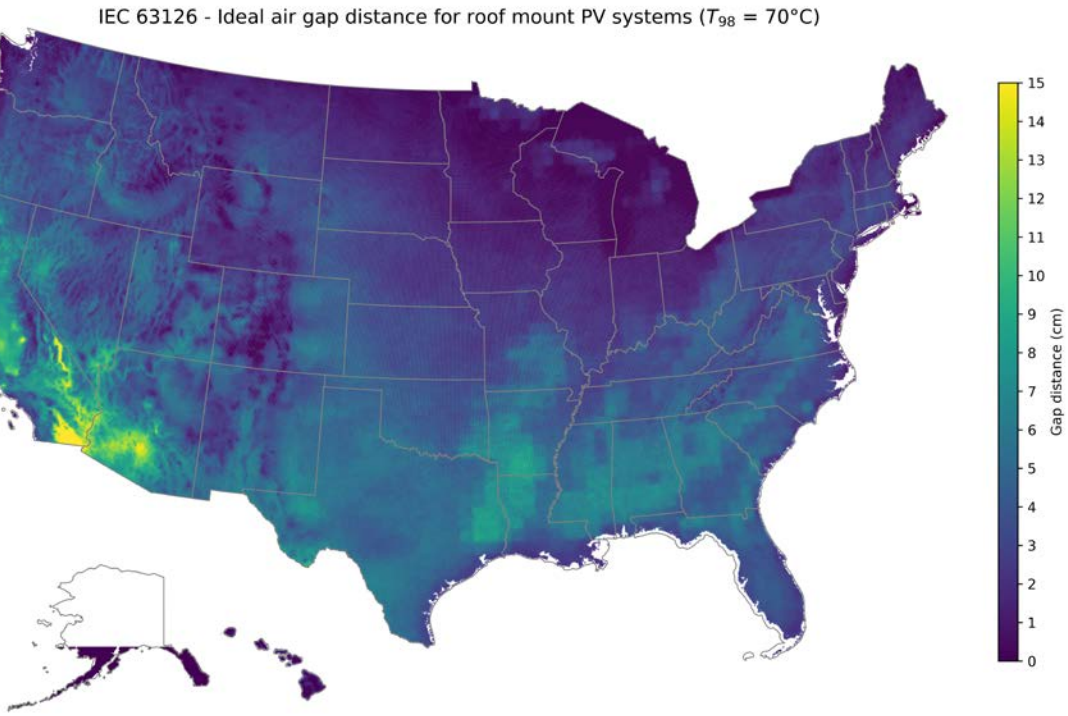
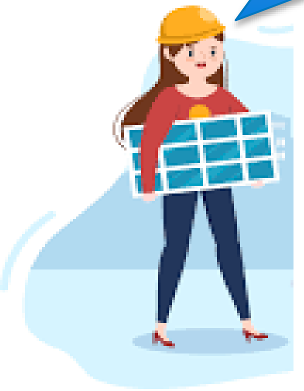
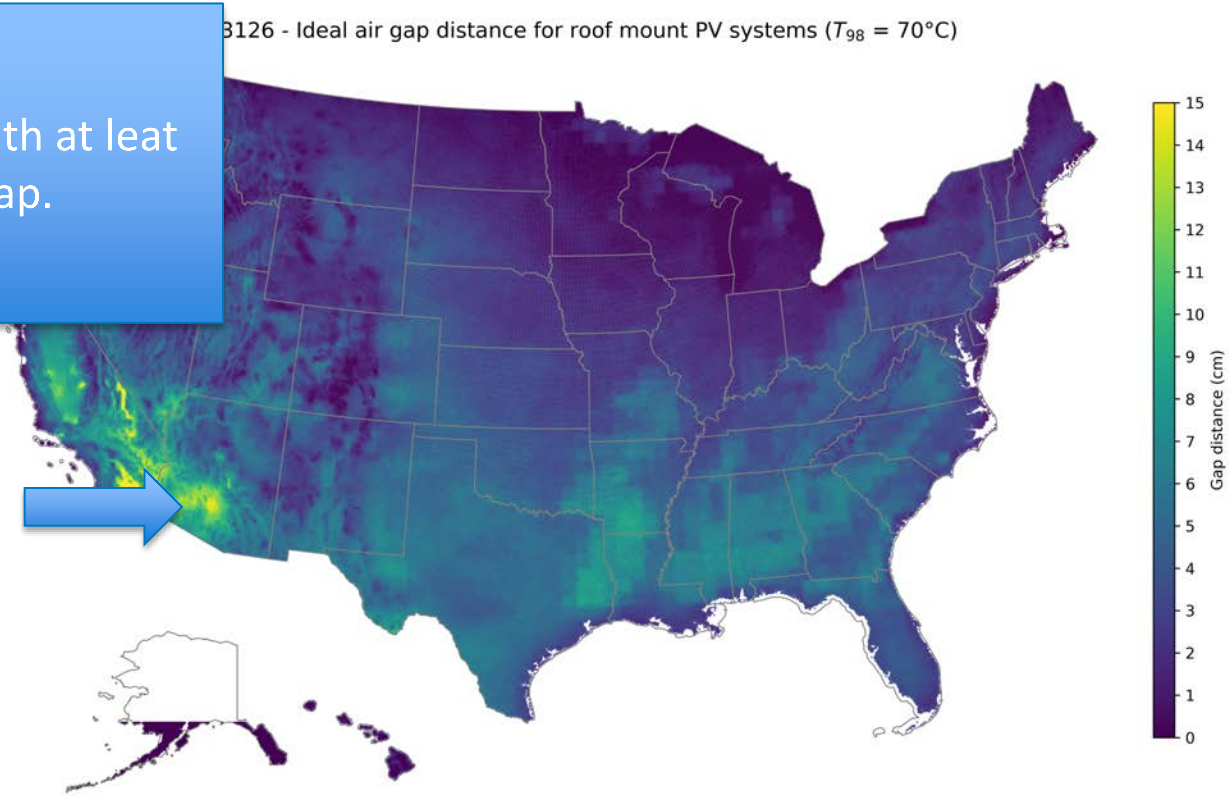

IEC 63126 - Ideal air gap distance for roof mount PV systems (T_{98} = 70°C)

M. K. Fuentes, "A simplified thermal model for Flat-Plate photovc

Example Use Case: IEC 63126

I should install with at leat 15 cm of gap.





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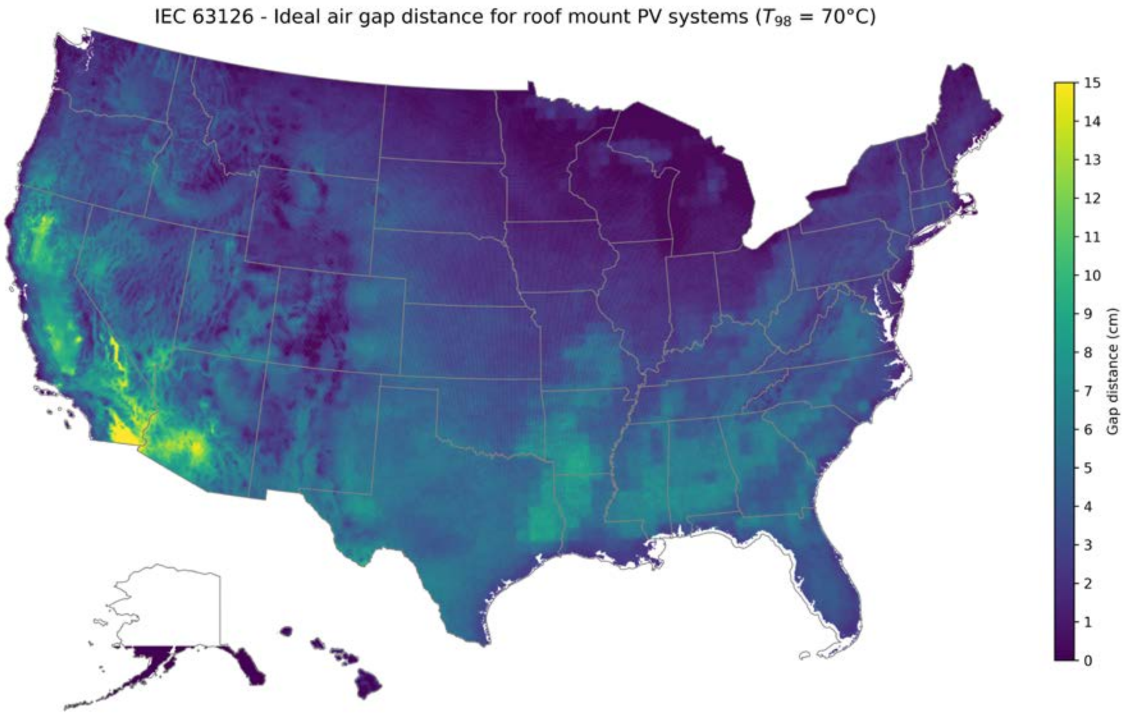
Example Use Case: IEC 63126

- Large amounts of calculation with minimal effort
- Integrates the NSRDB data, module temperature models, and the PVDeg functions in the GitHub repository.
- <1 hour (with parallelization)
- Single-location calculations easily accessible through the journals
- Similar maps will be used in the new version of IEC 63126.



IEC 63126 - Ideal air gap distance for roof mount PV systems (T_{98} = 70°C)

M. K. Fuentes, "A simplified thermal model for Flat-Plate photovoltaic arrays," United States, 1987-05-01 1987. [Online]. Available: https://www.osti.gov/biblio/6802914

Live demo

tinyurl.com/ASTMDemo

Summary

- PV deployment is growing and evolving exponentially, and we can't wait many years to know if things are durable and might last 50 years; therefore, a very robust understanding of the modes and mechanisms for failure is needed.
- Open source and flexible Python code is being developed to help with this long-term extrapolation to the field.
- Extrapolation to the field involves a lot of repetitive process which we are automating enabling users to focus on the unique and fundamental aspects of a given degradation.
- We are also creating living libraries of data to facilitate understanding of the complex and multi-faceted degradation of PV modules.

github.com/NREL/PVDegradationTools

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