pvdeg – Advanced Degradation Prediction Tool and Database

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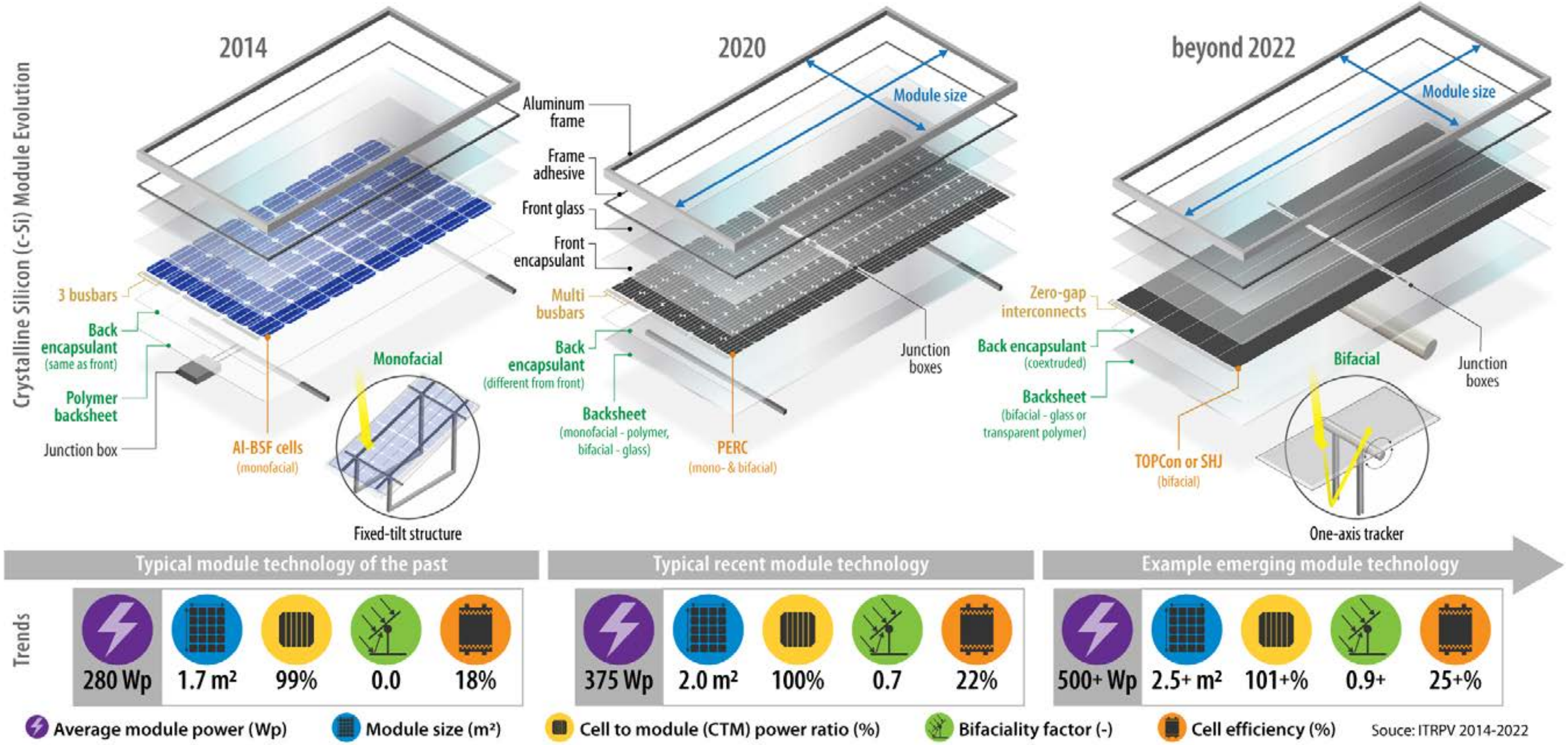
2023 NIST/UL Solutions Workshop on Photovoltaic Materials Durability

Photo by Dennis Schroeder, NREL 55200

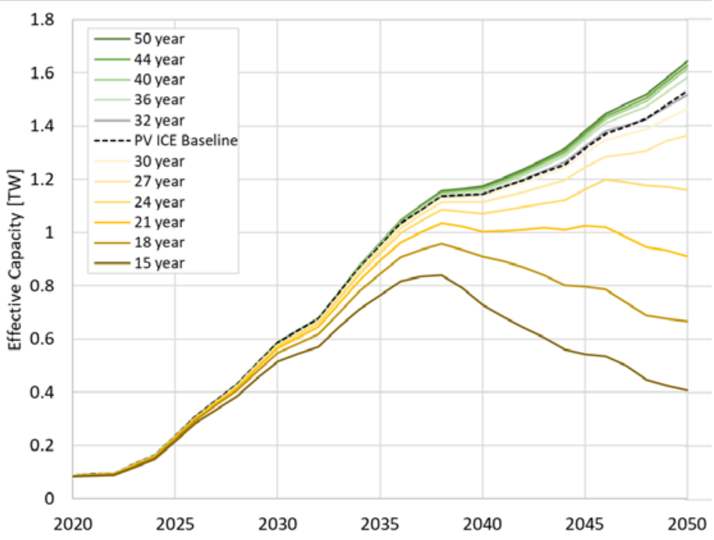
Technological evolution of PV modules



[Zuboy, Jarett et al., Getting Ahead of the Curve: Assessment of New Photovoltaic Module Reliability Risks Associated with Projected Technological Changes (November 3, 2022). http://dx.doi.org/10.2139/ssrn.4273054]

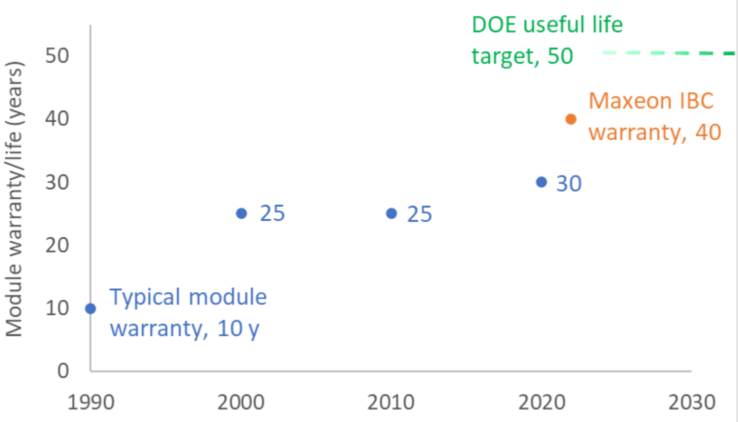
How do we get the long life that is desired?

longer lifetimes increase capacity



[S. Ovaitt, **et. al.**, "PV in the Circular Economy, A Dynamic Framework Analyzing Technology Evolution and Reliability Impacts," *ISCIENCE*, 2021

module warranties

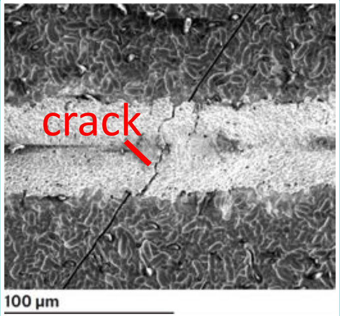


[Modified from Jordan et al., "Photovoltaics module reliability for the terawatt age". Progress in Energy (2022)]

- It is extremely difficult to know a design will last 50 years.
- There is a need to simplify and improve the predictive capability of PV tests.

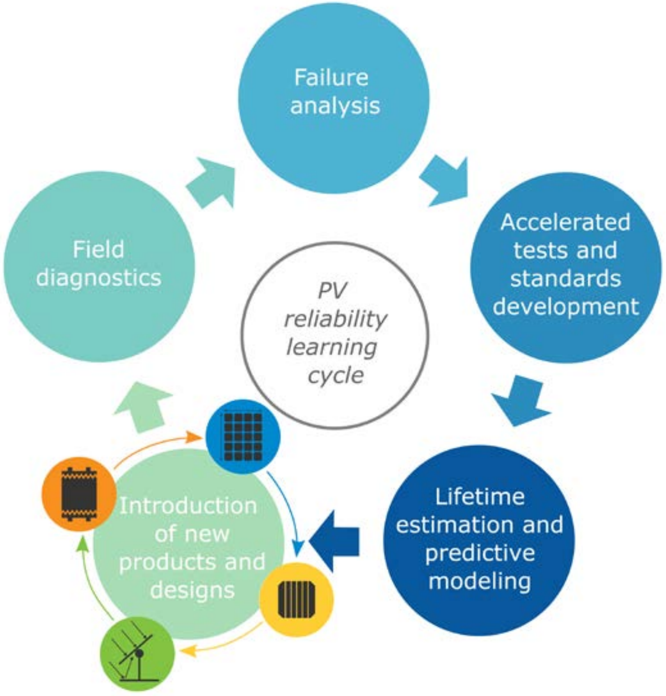
DESIGN-FOR-RELIABILITY

Challenge: *Design-for-reliability needs to keep with rapid change and scaling of industry.*

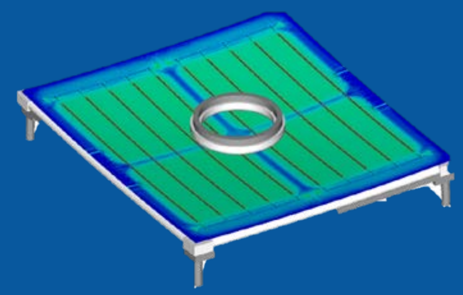


[Image by Tim Silverman / NREL]

[Photo by Dennis Schroeder / NREL]



[P. Hacke, et al., (2019) In Advanced Micro-and Nanomaterials for Photovoltaics]



[Owen-Bellini, *et al. Sci Rep* **11,** (2021).]

[M. Springer, **et. al.**, *Prog Photovolt Res Appl.* 2022;1–8., doi: DOI: 10.1002/pip.3645]

Goals for this project

Python code library to simplify repetitive tasks

- access meteorological data, perform geospatial analysis or monte-carlo simulations…
- allow for easy extensibility to add new degradation related functions
- Standardize variable names and code communication.

Create living databases of information on degradation and material properties

- pre-defined set of material and degradation properties
- allow users to add their own

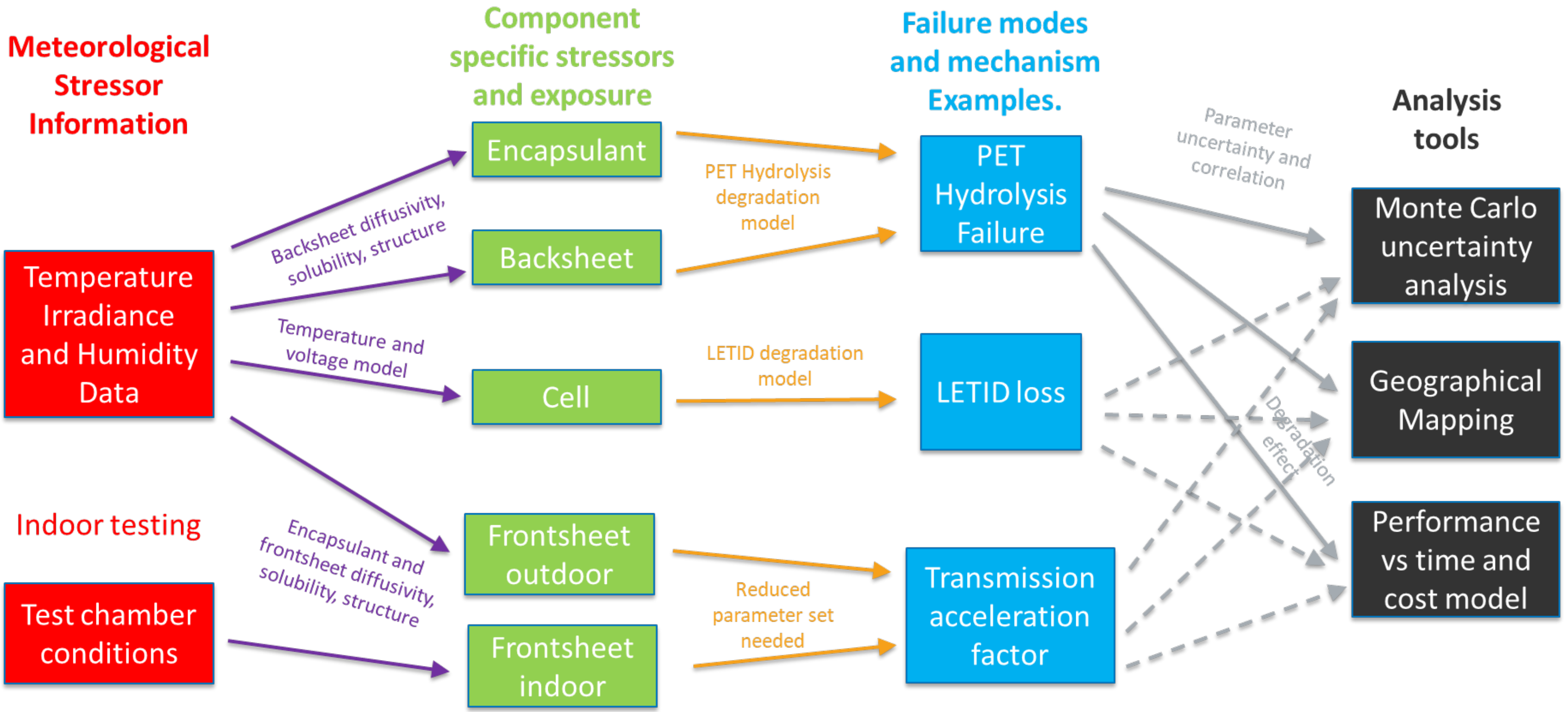
Focus user experience

- tutorials – based on Jupyter notebooks
- Create simple interfaces such that one does not need to be a Python expert to use the code.
- scalability – from laptop to HPC for production of maps.

PVDEG

Set of tools to calculate degradation responses and degradation related parameters for PV.

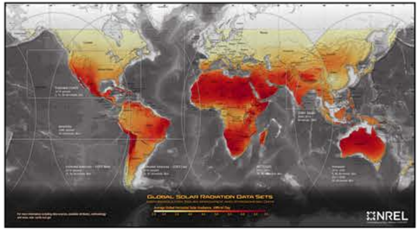
Degradation pathways and analysis



PV Degradation Tools

The integration pipeline for PV degradation analysis!

Stressors – NSRDB



Material Libraries

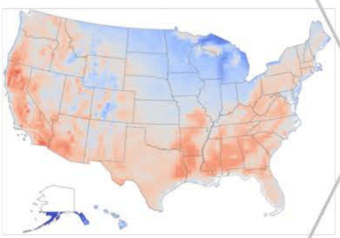
DuraMAT DataHub

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

Code library

- Peer-reviewed functions
- Auxiliary data handling and calculations functions
- Open-source
- Flexibility for Parallelization

https://github.com/NREL/PVDegradationTools

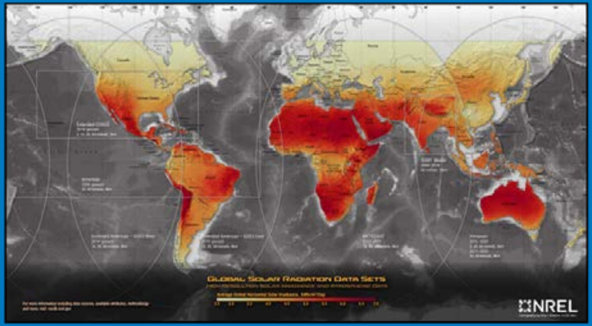
API

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 transitions
`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.

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

Weather Database



- NSRDB for geospatial analysis
- Any pvlib compatible database/format possible

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

Region	Model Name	Satellite	Temporal Resolution	Spatial Resolution
Europe, Africa, & Asia	PSM V3	METEOSAT IODC	15, 30, 60-minute	4km
USA & Americas	PSM V3	GOES	30, 60-minute	4km
USA & Americas	PSM V3	GOES	10, 30, 60-minute	4km
USA (Continental) & Mexico	PSM V3	GOES	5, 30, 60-minute	2km
South Asia	SUNY	METEOSAT IODC	60-minute	10km
Asia, Australia & Pacific	PSM V3	Himawari	10, 30, 60-minute	2km
Asia, Australia & Pacific	PSM V3	Himawari	30, 60-minute	4km

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)

Material Libraries

- 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:


```json
{
    "quantity": [
        {
            "name": "Young's Modulus",
            "identifier": "https://www.nist.gov/example/ontology/matsci.owl#123",
            "value": 179,
            "unit": "GPa"
        },
        {
            "name": "Ultimate Tensile Strength",
            "identifier": "https://www.nist.gov/example/ontology/matsci.owl#234",
            "value": 855,
            "unit": "MPa"
        },
        {
            "name": "Yield Strength",
            "identifier": "https://www.nist.gov/example/ontology/matsci.owl#345",
            "value": 494,
            "unit": "MPa"
        }
    ]
}
```

Parallel computation

aws

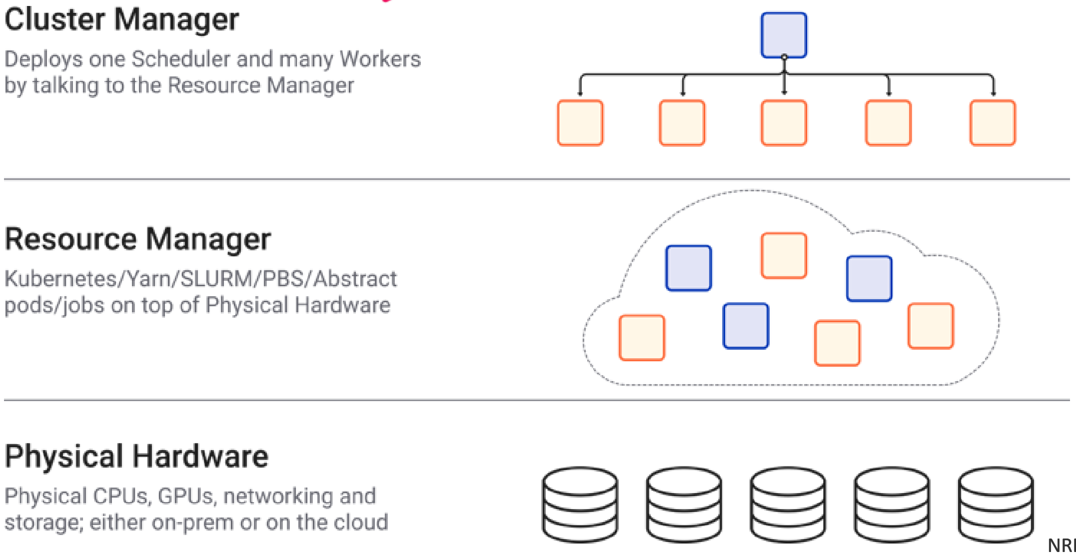
-Run in NREL's HPC and AWS
-Flexible
-As intuitive as possible

Allow single location calculations through webpage typically locally on a laptop computer.

binder jupyter

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

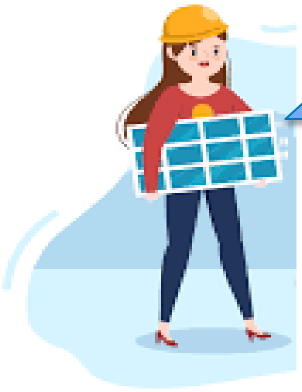
dask



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

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



What standoff distance do I need for a 70°C (level 0) rated module?

$X_0 = 6.1$ cm

$T_{98} = 70°C$

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

How can pvdeg help?

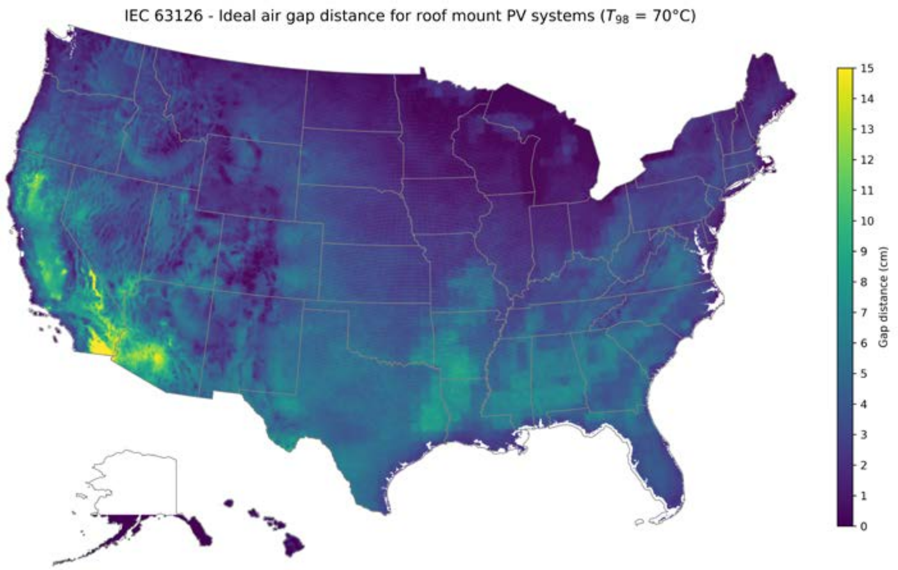
Translate into python

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

```python
def standoff(
    weather_df=None,
    meta=None,
    ...
    ):
    '''
    Calculate a minimum standoff distance for roof mounded PV systems.

    ...

    '''

    x, T98_0, T98_inf = eff_gap(T_0, T_inf, level=level, T98=T98, x_0=x_0)

    res = {'x': x,
           'T98_0': T98_0,
           'T98_inf': T98_inf}
    df_res = pd.DataFrame.from_dict(res, orient='index').T

    return df_res
```

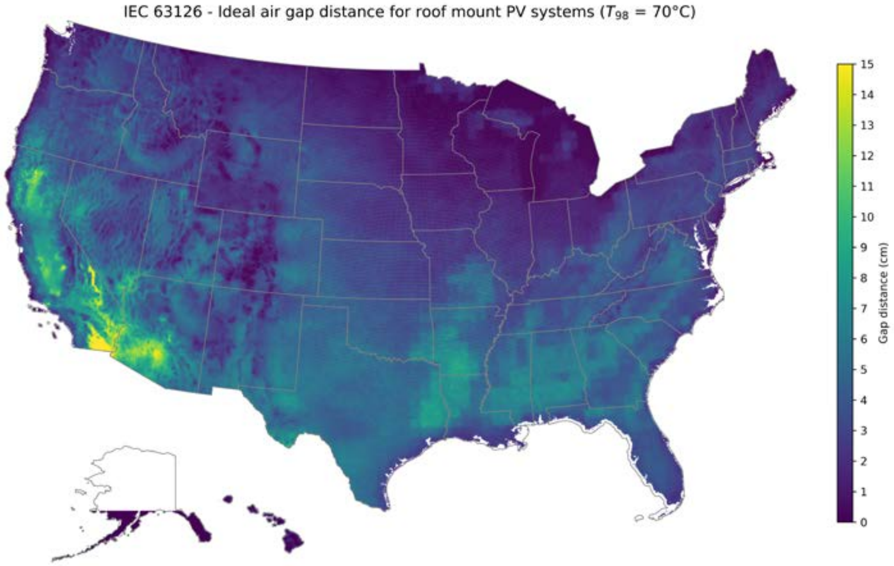
Geospatial analysis

```
# Import package
import pvdeg

# Start compute cluster
pvdeg.geospatial.start_dask()

# Get weather data
weather_db = 'NSRDB'
weather_arg = {'satellite': 'Americas',
               'names': 2022,
               'NREL_HPC': True,}
weather_ds, meta_df = pvdeg.weather.get(
    weather_db, geospatial=True, **weather_arg)

# Specify function and input parameters
geo = {'func': pvdeg.standards.standoff,
       'weather_ds': weather_NM_sub,
       'meta_df': meta_NM_sub}

# Perform calculation
standoff_res = pvdeg.geospatial.analysis(**geo)

# Post process results
fig, ax = pvdeg.geospatial.plot_USA(standoff_res['x'],
                  cmap='viridis', vmin=0, vmax=None,
                  title='Minimum estimated air standoff',
                  cb_title='Standoff (cm)')
```

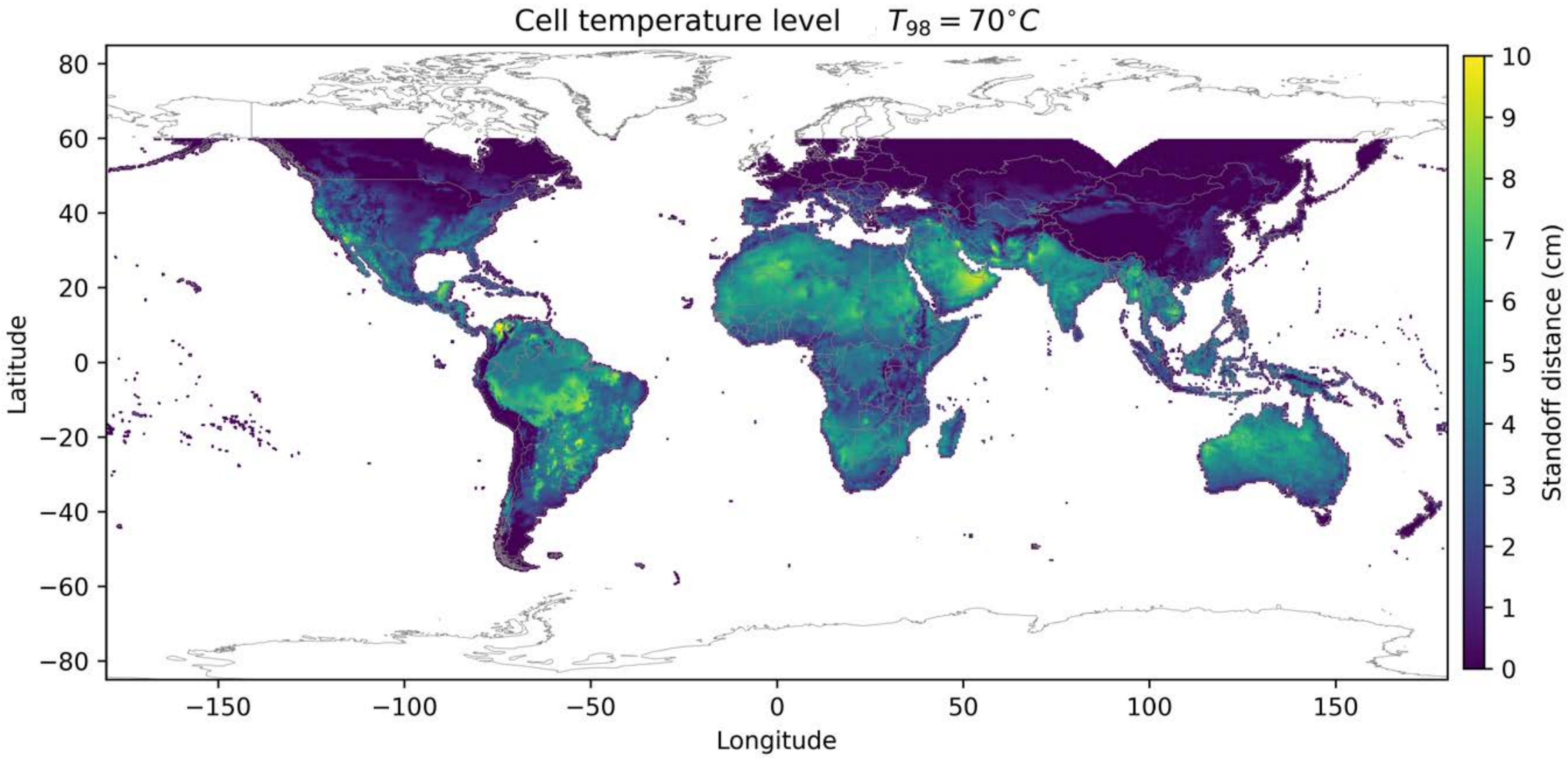


Geospatial analysis

- 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.

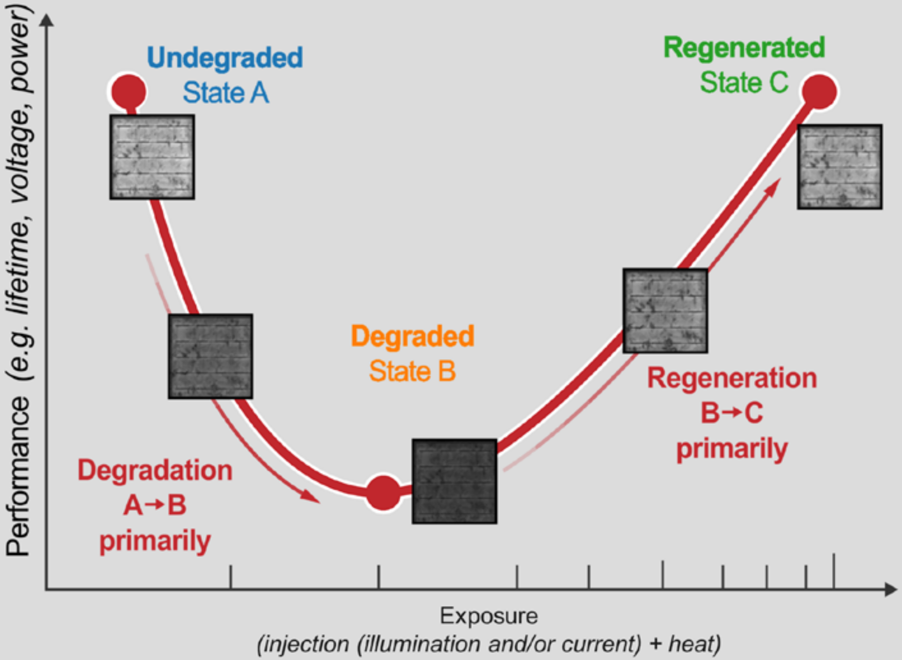


Extension to world map



NEW! – LETID implementation

Review of LETID and B-O LID



J. Karas *et al.*, *Progress in Photovoltaics: Research and Applications*, 2022, doi: 10.1002/pip.3573.
I. L. Repins *et al.*, *MRS Bulletin*, 2023, doi: 10.1557/s43577-022-00438-8.

- Light- and elevated temperature-induced degradation (LETID)
  - Relatively recently-discovered degradation mode in silicon
  - Some early cases showed ~10% degradation; more typically 0-3%
  - Losses will eventually "regenerate", but this may take decades, depending on climate and technology
- Boron-oxygen light-induced degradation (B-O LID)
  - More well-known and better understood defect in mono c-Si
  - Motivated the industry transition to Ga-doped wafers
  - Compared to LETID: faster and less severe. Often accounted for by "First Year" losses in warranties and financial models.
- Both LETID and B-O LID can be described by a 3-state model
  - Degradation (A → B) followed by regeneration (B → C)
  - Kinetics and time constants are different in LETID and B-O LID, but they can be modeled similarly.
- Progression between states depends on time, carrier injection (either illumination or electrical current), and temperature.

NEW! – LETID implementation

LETID and B-O LID Modeling

Performance loss is a function of the number of defects in state B. → $Degradation \propto N_B$

Defect state transitions depend on simultaneous, competing reaction rates

$$\frac{dN_A}{dt} = k_{AB} \cdot N_A + k_{BA} \cdot N_B$$

$$\frac{dN_B}{dt} = k_{AB} \cdot N_A + k_{CB} \cdot N_C - (k_{BA} + k_{BC}) \cdot N_B$$

$$\frac{dN_C}{dt} = k_{BC} \cdot N_B - k_{CB} \cdot N_C$$

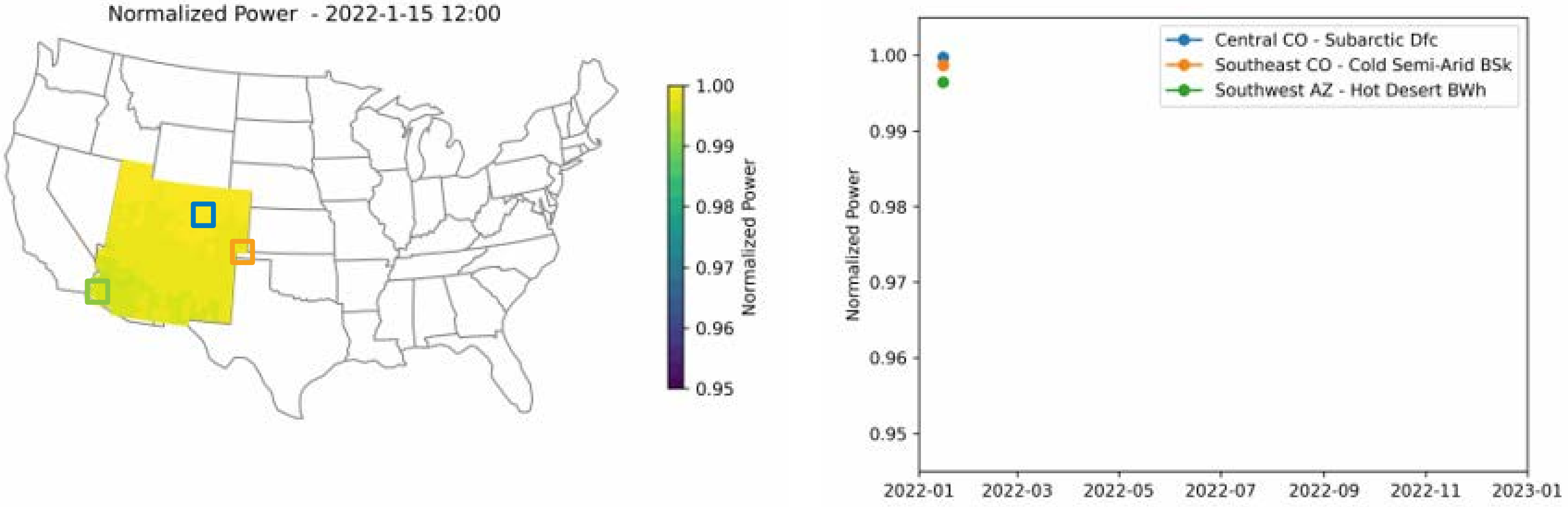
Reaction rates (k_{ij}) have Arrhenius behavior, with modification for injection (excess electronic carrier density in the device)

Kinetic parameters compiled from literature: $E_{a,ij} \mid v'_{ij} \mid x_{ij}$

$$k_{ij} = v_{ij} \cdot \exp\left(\frac{E_{a,ij}}{kT}\right)$$

$$v_{ij} = v'_{ij} \cdot \Delta n^{x_{ij}}$$

NEW! – LETID implementation



Credit: Joseph F. Karas

I. L. Repins *et al.*, "Long-term impact of light- and elevated temperature-induced degradation on photovoltaic arrays," *MRS Bull.*, 2023, doi: 10.1557/s43577-022-00438-8.

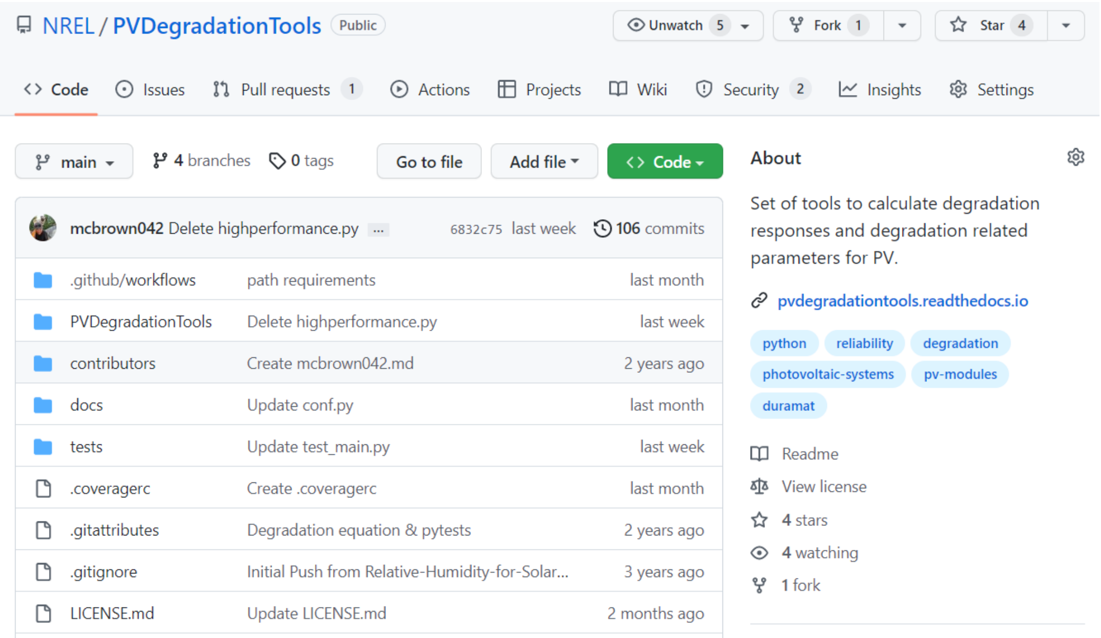
Summary

Current status

- Collection of degradation functions
- Establish open-source software best practice compliant repository
- Define framework for weather and material data

Shooting for the Sun

- Becoming the umbrella of many old and new developed scripts on degradation, like PVlib but for degradation (PVdeg!)



https://github.com/NREL/PVDegradationTools

Thank you!

Publication Number: NREL/PR-5K00-88250

github.com/NREL/PVDegradationTools

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