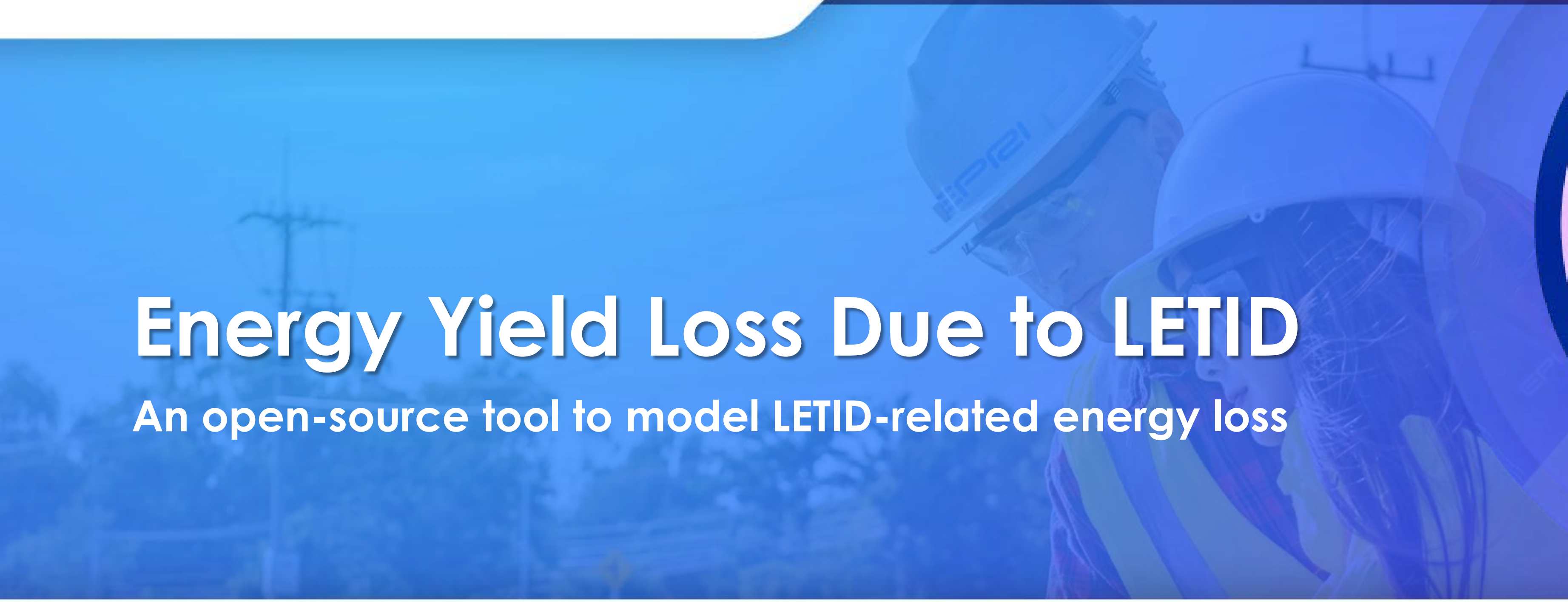

Energy Yield Loss Due to LETID

An open-source tool to model LETID-related energy loss

Together…Shaping the Future of Energy

Joe Karas
Electric Power Research Institute (EPRI) (formerly of NREL)

Martin Springer, Michael Kempe, Silvana Ovaitt, Ingrid Repins
National Renewable Energy Laboratory (NREL)

Transforming ENERGY

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SiliconPV 2024
Chambery, France
15 April, 2024

EPRI Research & Development

Together…Shaping the Future of Energy

TECHNOLOGY INNOVATION

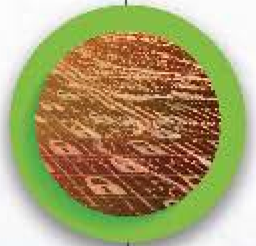
Driving thought leadership, advanced R&D, and technology scouting and incubation to sustain a full pipeline of solutions

Nuclear Power

Energy Supply and Low-Carbon Resources

Electrification and Sustainable Energy Strategy

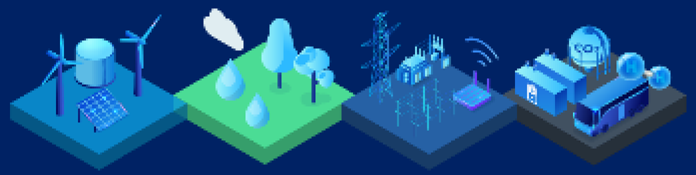
Transmission and Distribution Infrastructure



Integrated Grid and Energy Services

STRATEGIC RESEARCH

- Low-Carbon Resources
- End-Use/ Economy-Wide Carbon Reduction
- Electric System Reliability/Resilience
- Electric System Flexibility
- Market Transformation/ Policy/Regulatory Education



EPRI Solar Generation Research

Mission

Reduce levelized cost of electricity while increasing reliability, dispatchability, grid service, and sustainability of large-scale solar PV plants

Why EPRI Solar Generation Research?

Value of Collaboration

Leading Solar Research Together With:

Internal: EPRI's Grid Ops & Planning, Environment, Climate, Materials & Repair, Asset Management, Storage, IT, Legal, and Cyber Security.

External: Solar Owners and EPRI Members, National Labs, Universities, Standard Orgs, and Governments.

Research Focus Areas

Plant Design & Development

Performance & Reliability

Operations & Maintenance

Program Manager

Robert Flottemesch
(845)-430-6478
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www.epri.co/solar

Unique Insights

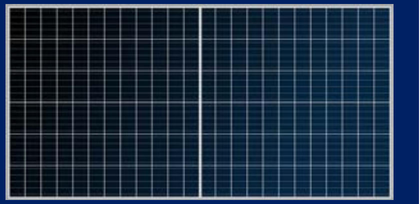
- > 80 Years Combined Solar Industry Experience
- > 60 Large-scale PV plants Performance Database (SUPER)
- PV Technology Testing Capability in Field and Laboratory

Impactful Content

- **Solar Power Fact Book** (3002026675)
- **Plant Monitoring & Diagnostics** (3002020233, 3002013617)
- **PV Plant Design Specification** (3002017648)

Technology Application

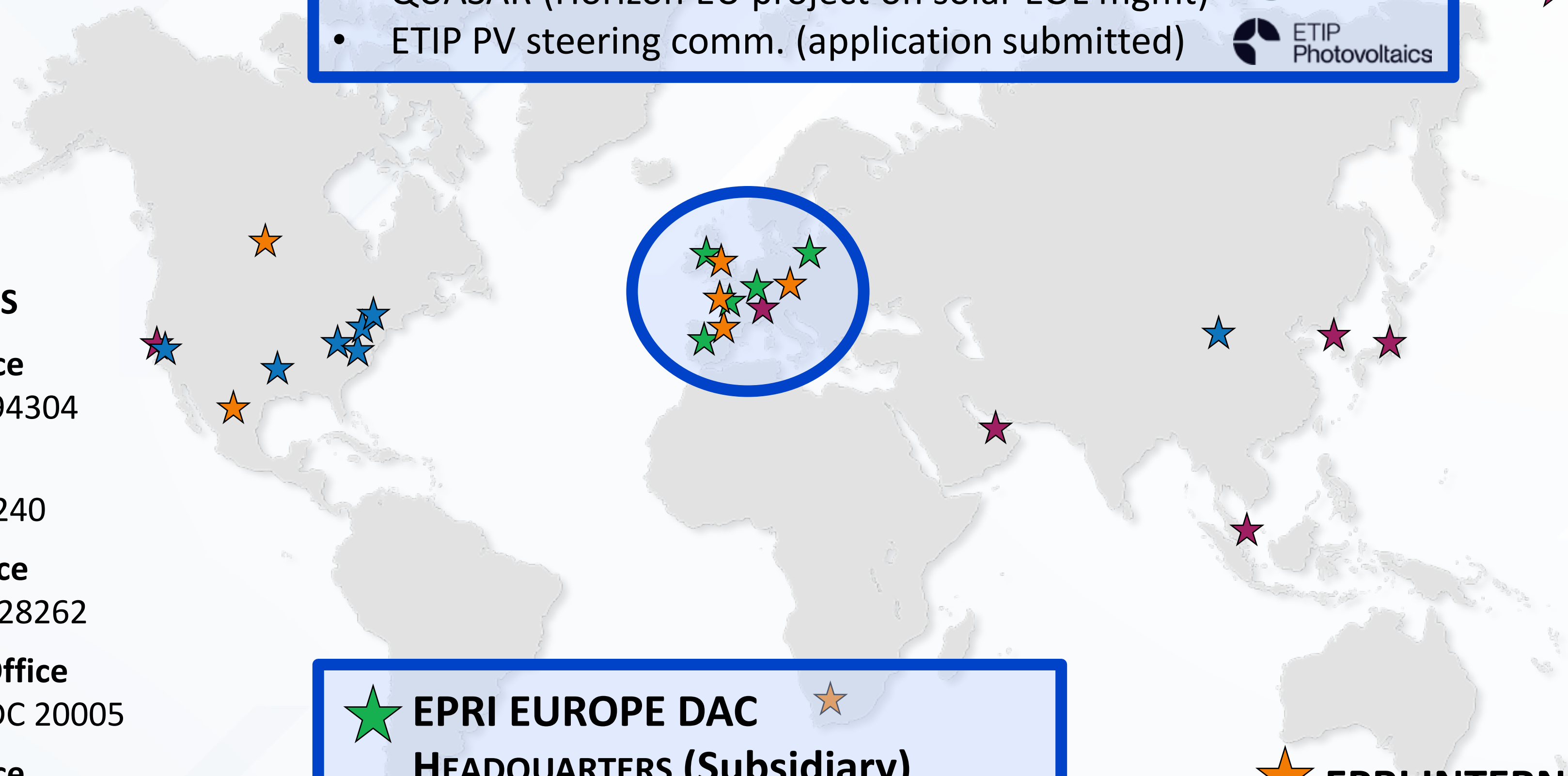
- Performance Loss Rate Analysis
- Sub-hourly Clipping Losses
- Bifacial Module Field Characterization



EPRI Offices

EPRI Europe Solar work

- QUASAR (Horizon EU project on solar EOL mgmt)
- ETIP PV steering comm. (application submitted)



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Motivation

- ~**10 years** between the discovery of LETID and codification of a formal test for it:
  - Early reports (~2015) of LETID showed >10% power loss! [1]
  - Today's products likely have little LETID susceptibility
    - Engineering and testing; B → Ga p-type wafers; n-type wafers
  - Future products can be tested according to IEC TS 63342 (modules) and or IEC TS 63202-4 (cells)

- This 10-year period also coincides with transition of industry from primarily **BSF** to primarily Cz-Si **PERC** cells.

- During this time, **many GW** of LETID-sensitive modules (both BSF ***and*** PERC) may have been deployed.
  - BSF cells can be LETID-sensitive too! [2]

- It's **reasonably likely that LETID is an ongoing cause of underperformance** in currently-deployed systems

➢ Can we develop <u>a kinetic model</u> of LETID to understand how LETID-sensitive systems will behave for the rest of their lives?

[1] D. Chen *et al*., Prog. Photovoltaics Res. Appl., 2021, doi: 10.1002/pip.3362.
[2] M. Deceglie *et al*., IEEE J. Photovoltaics, 2020, doi: 10.1109/JPHOTOV.2020.2989168.

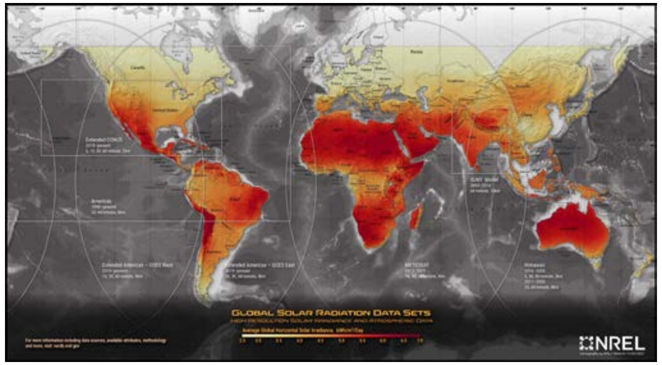
Outline

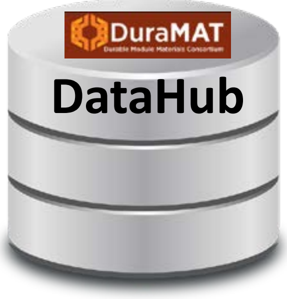
- Open-source LETID modeling tool is part of the **PVDegradationTools** library
- Quick review of LETID kinetics
  - How does lifetime loss manifest as performance loss?
- Comparing **modeled LETID** to **outdoor LETID** datasets
- LETID energy yield loss

PV Degradation Tools – The PV focused, open-source, integration pipeline for PV degradation analysis!

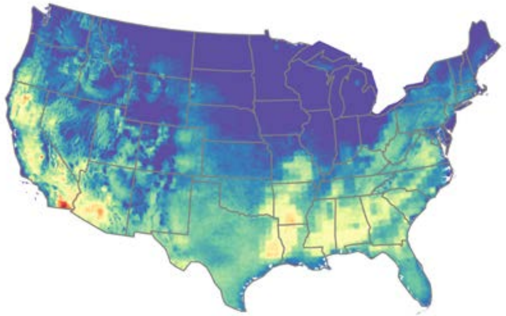
PVDEG

Stressors – NSRDB | **Material Libraries** | **Degradation models** | **Geospatial Analysis**





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



powered by

reV &gaps, pvlib, python, jupyter, The HDF Group, aws, binder, DuraMAT

Check out the GitHub repository!

https://github.com/NREL/**PVDegradationTools**

GitHub

…and example Jupyter notebooks in the tutorials folder!

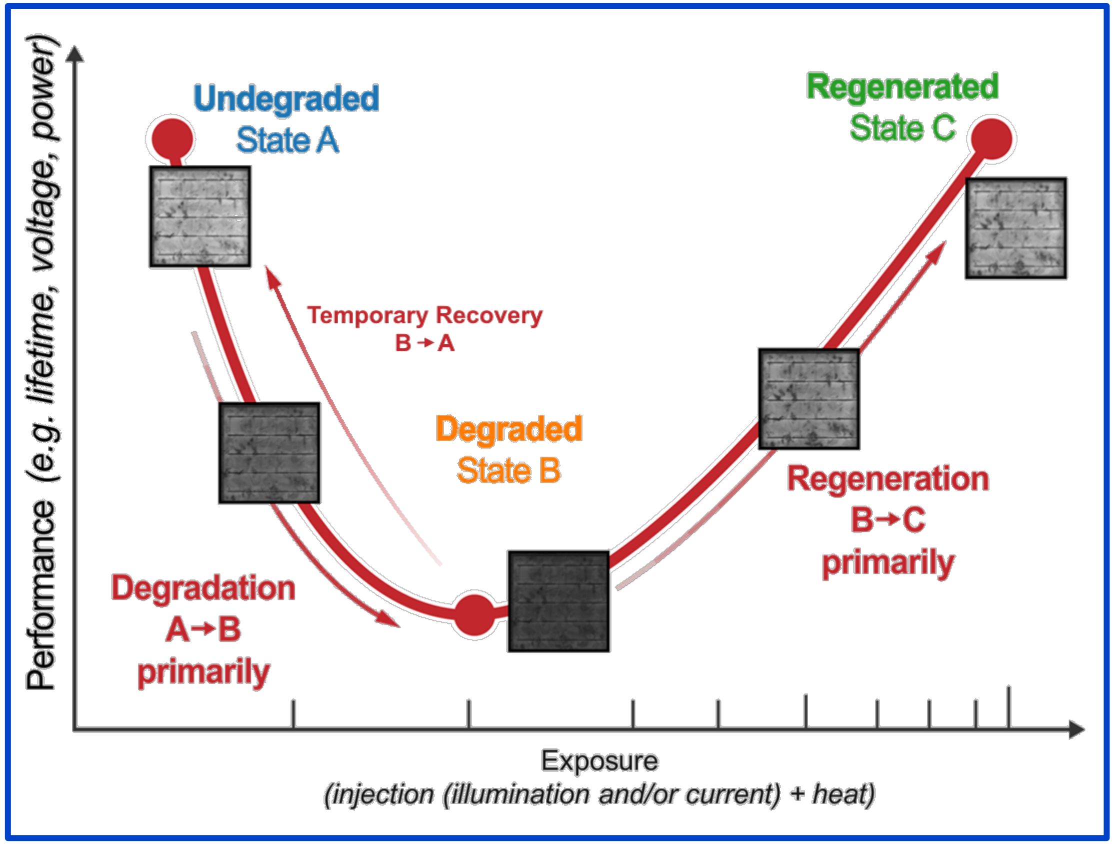
Project Highlights

- Open-source library of functions for **specific degradation** mechanisms
- JSON databases of PV-related **degradation parameters**
- **User-friendly web notebooks** for single locations
- **Geospatial analysis** via high-performance parallel computing (NREL Kestrel HPC) and in aws (under development)

LETID kinetics

Performance loss is a function of the number of defects in ***state B***

$$Degradation \propto \boldsymbol{N_B}$$



Defect state transitions depend on simultaneous, competing reaction rates

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

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

$$\frac{d\boldsymbol{N_C}}{dt} = k_{BC} \cdot \boldsymbol{N_B} + k_{CB} \cdot \boldsymbol{N_C}$$

Reaction rates (k_{ij}) have Arrhenius behavior, with modification for injection ($\Delta n^{x_{ij}}$)

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

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

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

I. Repins *et al.*, MRS Bulletin, 2022, doi: 10.1557/s43577-022-00438-8

Lifetime loss results in power loss

Carrier lifetime is proportional to the # of defects in state B: $\boldsymbol{N_B}$

$$\tau(t) \propto 1/\boldsymbol{N_B}\,(t)$$

Minority carrier lifetime loss results in:

- **Voltage loss:**

$$\tau \propto \frac{1}{J_0} \qquad V = \frac{kT}{q}\ln\left(\frac{J}{J_0}\right)$$

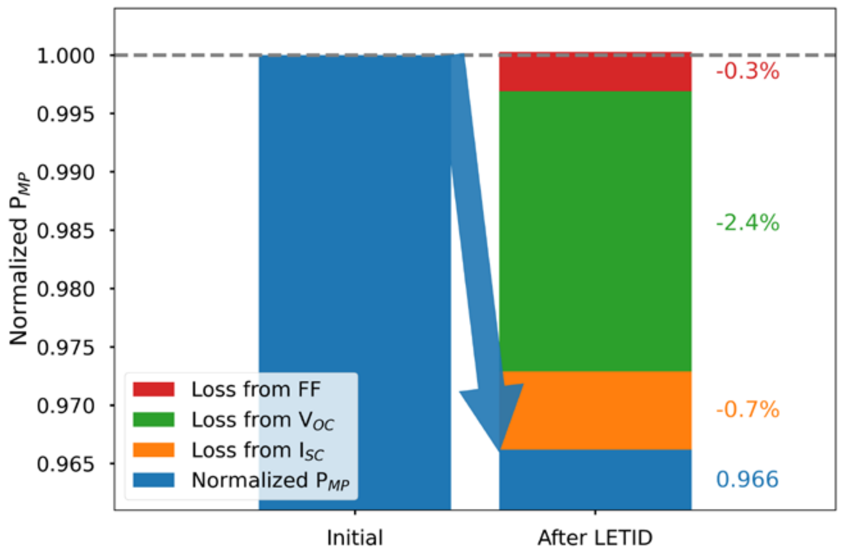
- **Fill factor (FF) loss:**

$$FF = \frac{v_{oc} - \ln(v_{oc} + 0.72)}{v_{oc} + 1}$$

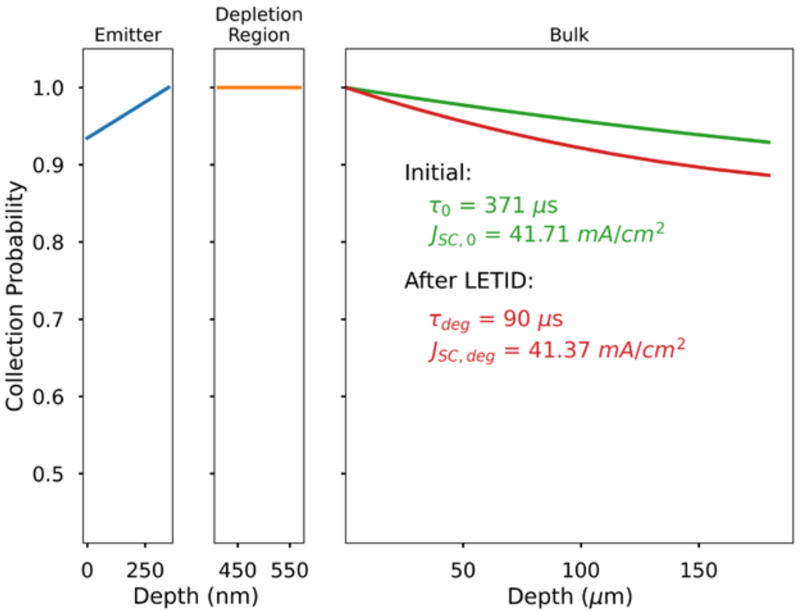
- **Current loss**

$$\tau \propto CP(z) \qquad J_{SC} = q\int_0^W CP(z)G(z)dz$$

Power loss components:



Current loss model:



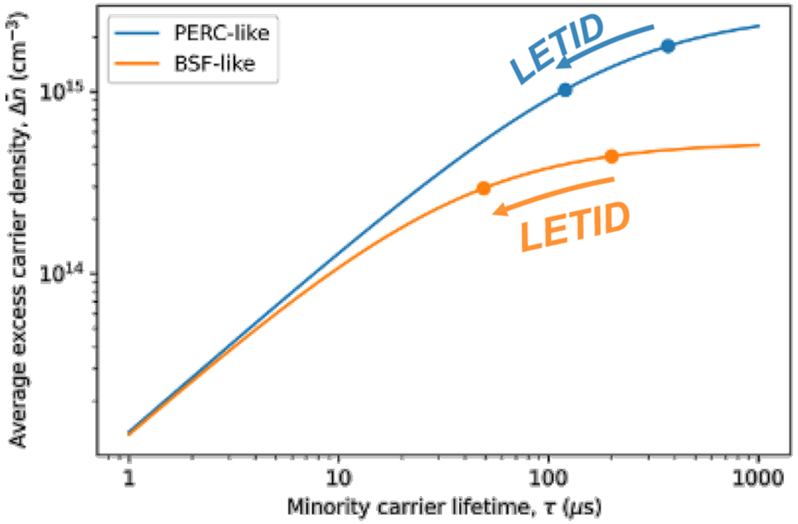
A. McPherson *et al.*, MRS Adv., 2022, doi: 10.1557/s43580-022-00222-5.\
I. Repins *et al.*, MRS Bulletin, 2022, doi: 10.1557/s43577-022-00438-8

Modeling PERC-like vs. BSF-like devices

- Reasonable assumptions about device parameters suggest ***Δn*** **will be ~4x higher in PERC devices**, both before and after LETID related lifetime loss

- Therefore, each transition $i \rightarrow j$ will **proceed faster by a factor of** $\mathbf{4^{x_{ij}}}$ in PERC devices

- In this simple implementation, devices are characterized by **lifetime** (τ_0 and τ_{deg}) and **rear surface recombination** (S_{rear}).
  - τ_{deg} selected to result in ~2.5% P_{MP} loss

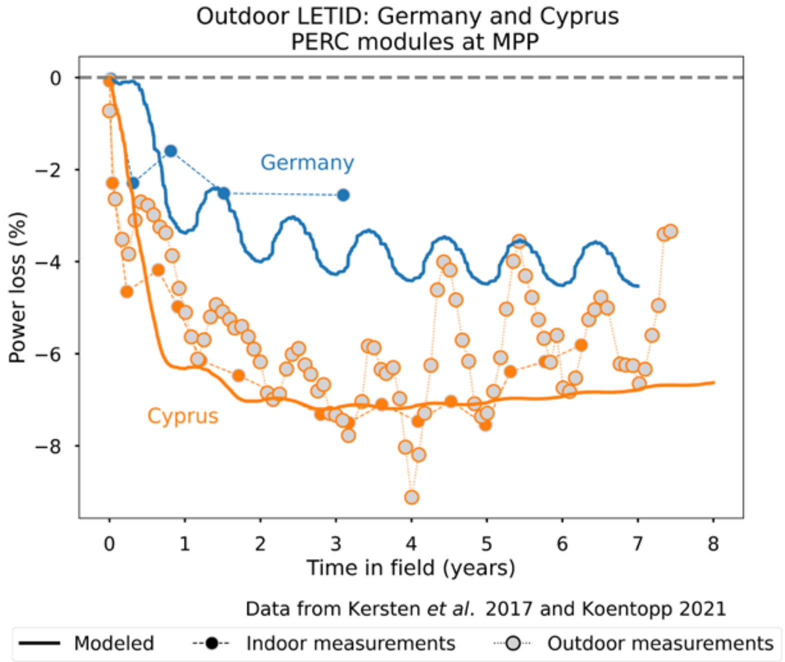


Device parameters:

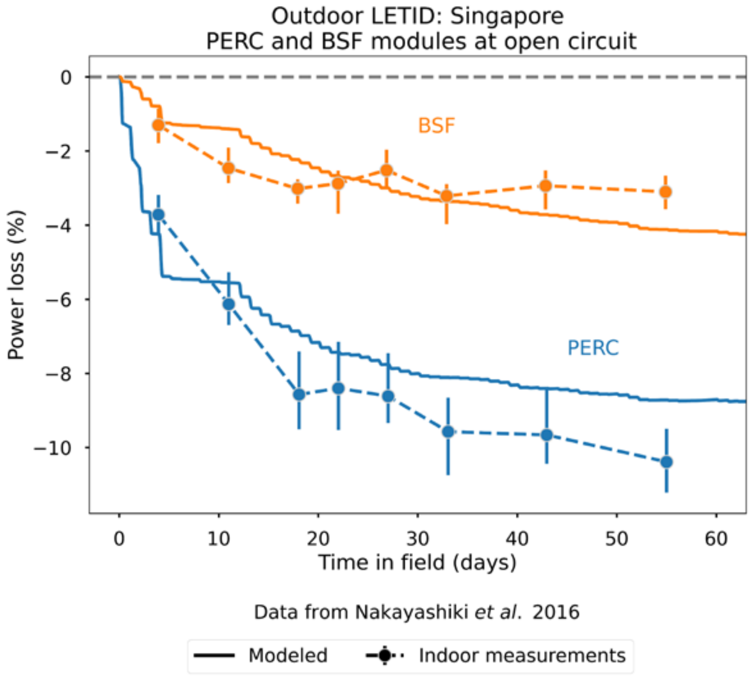
PERC-like module		
τ_0 (μs)	τ_{deg} (μs)	S_{rear} (cm/s)
371	120	90 (effective)

BSF-like module		
τ_0 (μs)	τ_{deg} (μs)	S_{rear} (cm/s)
200	49	500

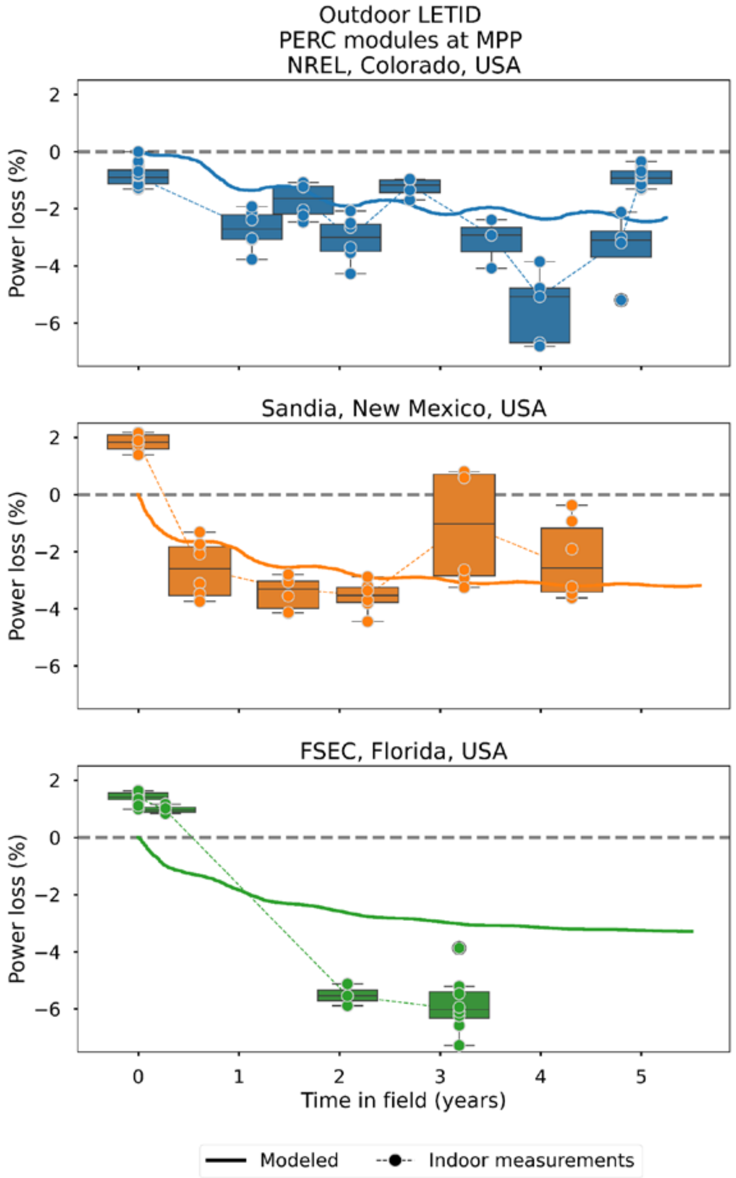
Validation on known LETID-sensitive outdoor datasets



Data from Kersten *et al.* 2017 and Koentopp 2021



Data from Nakayashiki *et al.* 2016

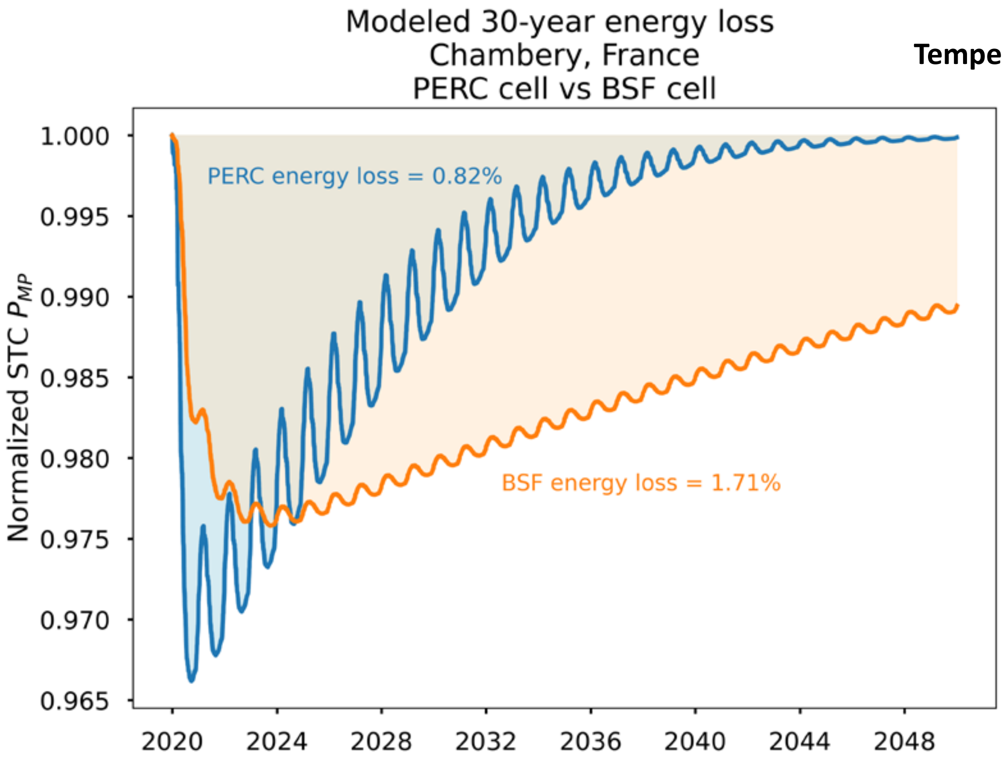


Model compares reasonably well with lab-generated data on known LETID-sensitive modules:

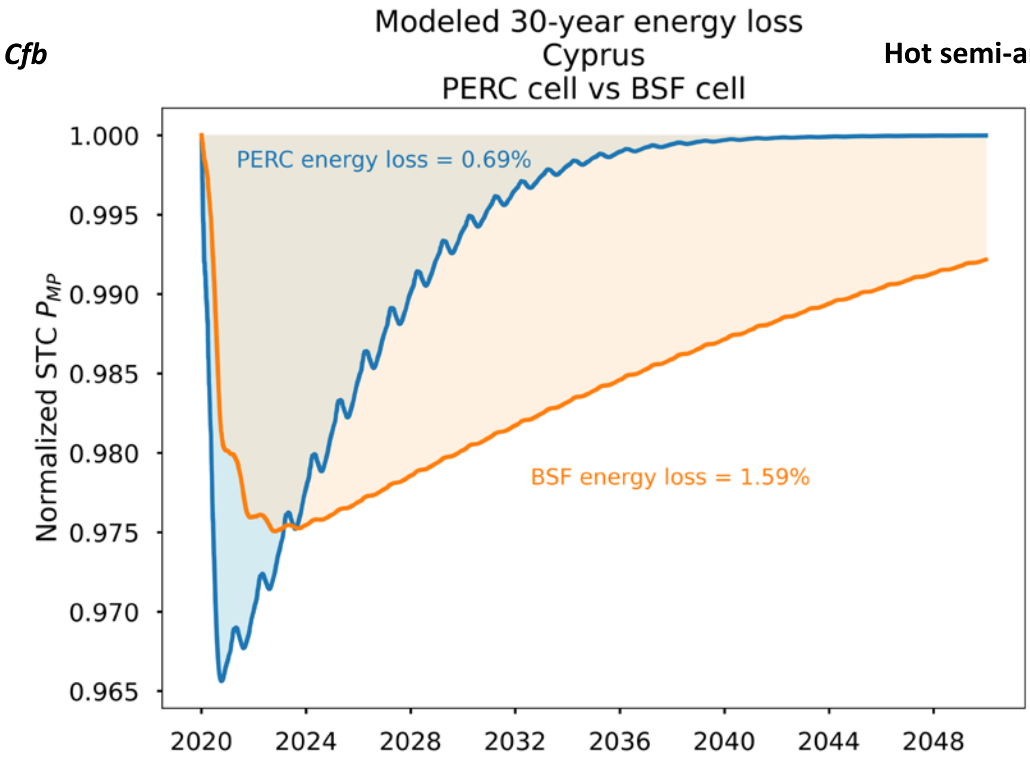
- **Qcells:** Germany and Cyprus, PERC modules at MPP
- **SERIS:** Singapore, PERC and BSF modules at open-circuit
- **NREL/Sandia/FSEC:** different USA climates, PERC modules at MPP

F. Kersten *et al.*, Energy Procedia, 2017, doi: 10.1016/j.egypro.2017.09.260
M. Köentopp, Photovoltaic Reliability Workshop, 2021
K. Nakayashiki *et al.*, IEEE J. Photovoltaics, 2016, doi: 10.1109/JPHOTOV.2016.2556981
I. Repins *et al.*, MRS Bulletin, 2022, doi: 10.1557/s43577-022-00438-8

Modeled LETID energy yield loss in different climates



Temperate climate *Cfb*



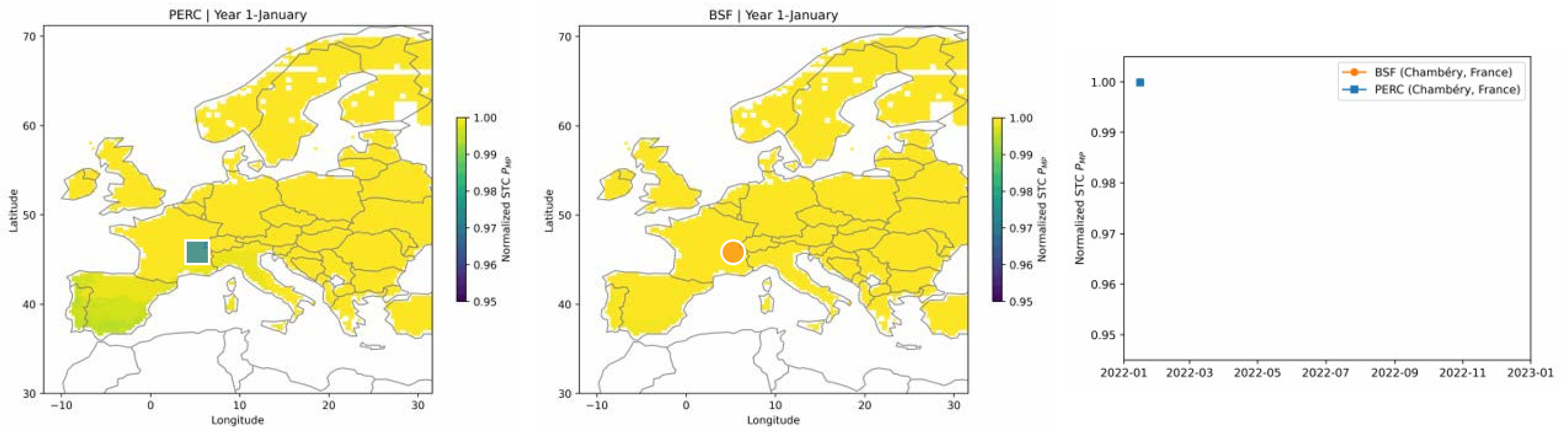
Hot semi-arid climate *BSh*

- TMY weather data via NSRDB PSM3 API → Meteosat (EU)
- POA irradiance, cell temperature, DC operating point via pvlib
- System assumptions:
  - Fixed latitude tilt
  - SAPM temperature model for open rack glass-polymer module

Takeaways:

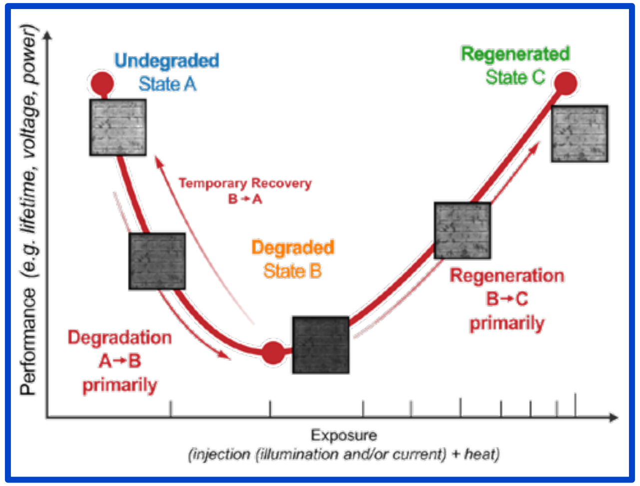
- PERC modules fully regenerate in ~20 years
- BSF modules **never** regenerate completely
- Energy yield loss is ~**2x greater in BSF modules**
- Seasonal Temporary Recovery of ~1% P_{MP} possible in cooler climates

Geospatial modeling shows differences in LETID across device types and climates

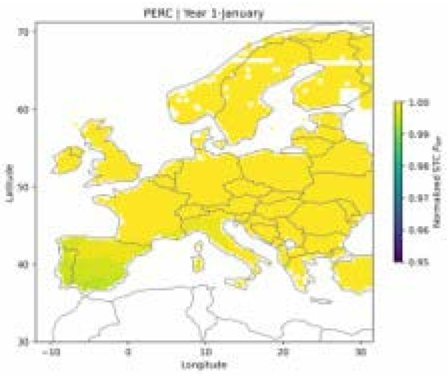


One year of LETID power loss, PERC vs. BSF

Conclusions



- LETID is a **uniquely intricate** degradation mechanism:
  - Degradation, seasonal temporary recovery, and permanent regeneration



- LETID degradation is particularly **site**-specific, **system**-specific, and **device**-specific
- **Modeling is necessary** to understand energy yield loss over system life
- Open-source LETID modeling tool available with **PVDeg**

PVDEG

https://github.com/NREL/PVDegradationTools

Thank you!

jkaras@epri.com

www.epri.co/solar

https://github.com/NREL/**PVDegradationTools**

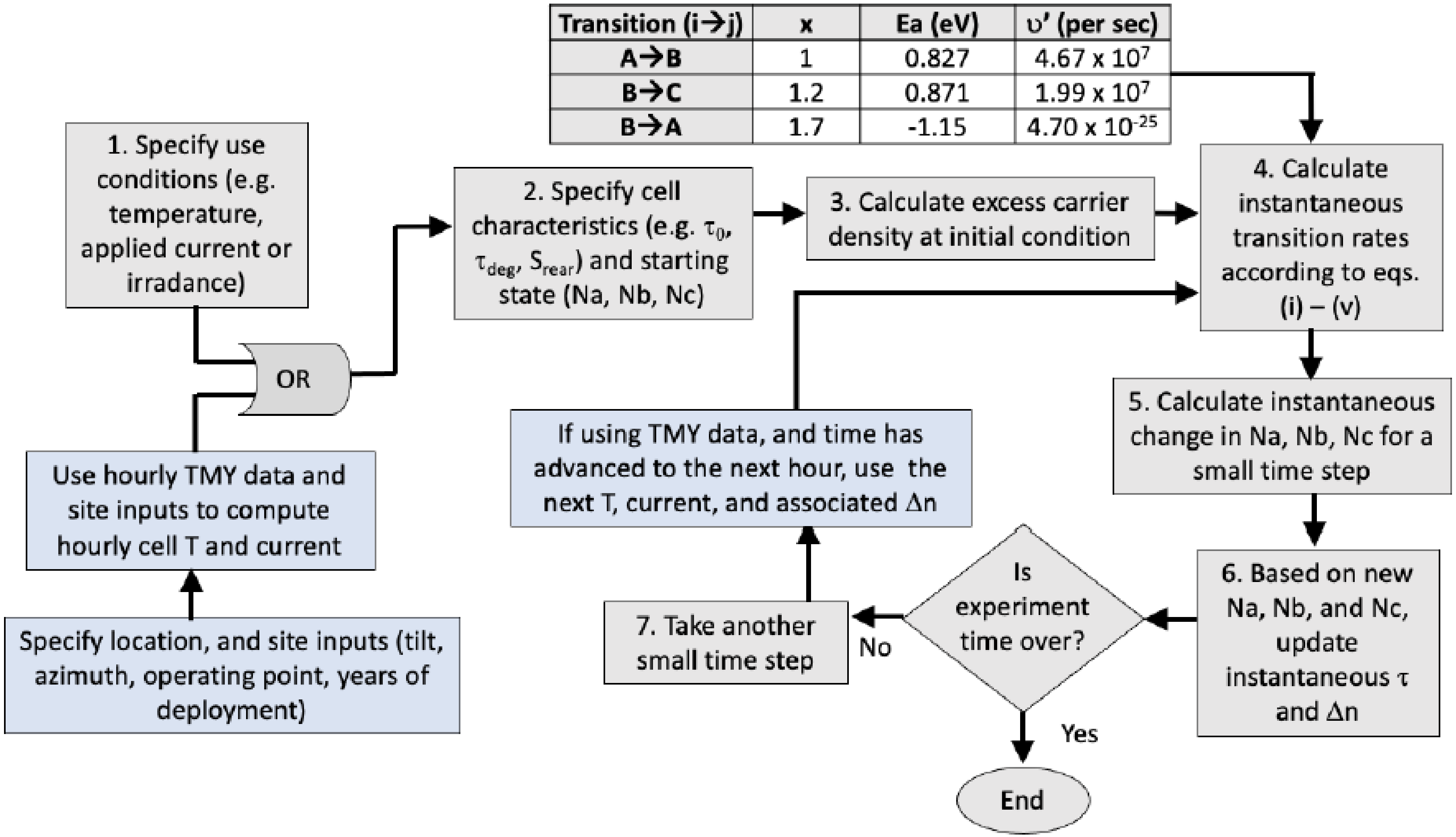
NREL/PR-5K00-89630

DuraMAT
Durable Module Materials Consortium

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided in part by the Durable Modules Consortium (DuraMAT) funded by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office, agreement numbers 32509 and 38263. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

Backup slides

Modeling details



Transition (i→j)	x	Ea (eV)	υ′ (per sec)
A→B	1	0.827	4.67 x 10^{7}
B→C	1.2	0.871	1.99 x 10^{7}
B→A	1.7	-1.15	4.70 x 10^{-25}

1. Specify use conditions (e.g. temperature, applied current or irradiance)

OR

Use hourly TMY data and site inputs to compute hourly cell T and current

Specify location, and site inputs (tilt, azimuth, operating point, years of deployment)

2. Specify cell characteristics (e.g. τ_0, τ_{deg}, S_{rear}) and starting state (Na, Nb, Nc)

3. Calculate excess carrier density at initial condition

4. Calculate instantaneous transition rates according to eqs. (i) – (v)

5. Calculate instantaneous change in Na, Nb, Nc for a small time step

6. Based on new Na, Nb, and Nc, update instantaneous τ and Δn

Is experiment time over?

No

7. Take another small time step

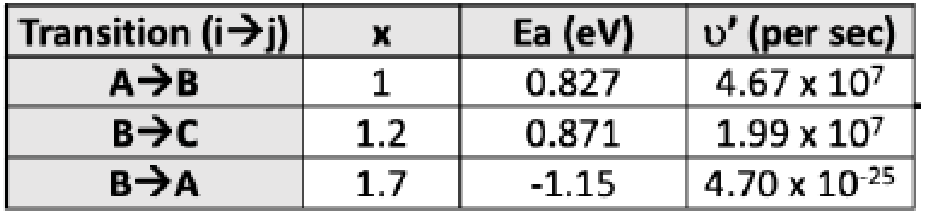
If using TMY data, and time has advanced to the next hour, use the next T, current, and associated Δn

Yes

End

I. Repins *et al.*, MRS Bulletin, 2022, doi: 10.1557/s43577-022-00438-8

Modeling details



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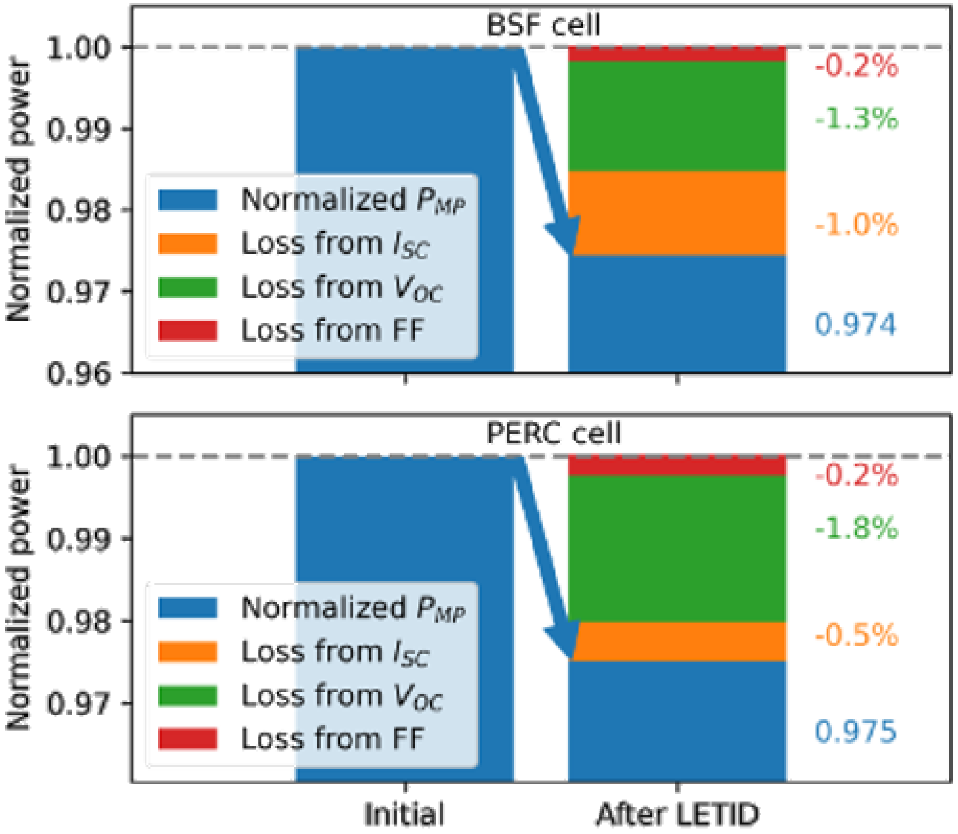
"The values are taken directly from the literature for the A→B [29] the B→C [35] and B→A [49] transitions. Activation energies and attempt frequencies for the A→B and B→C transitions are taken from within the ranges bounded by the literature. Values were chosen such that a wide set of published data, gathered via experiments at modest temperature and irradiance, show reasonable agreement with the model."

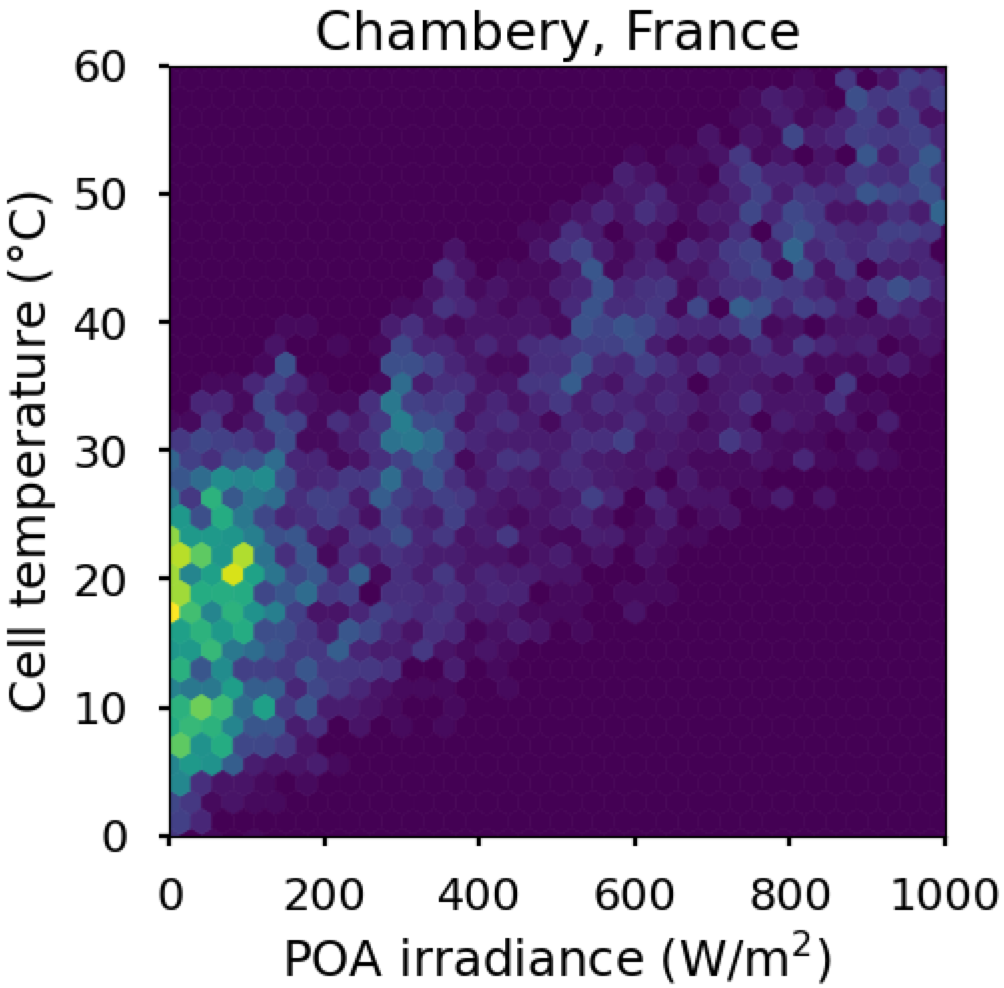
I. Repins *et al*., MRS Bulletin, 2022, doi: 10.1557/s43577-022-00438-8

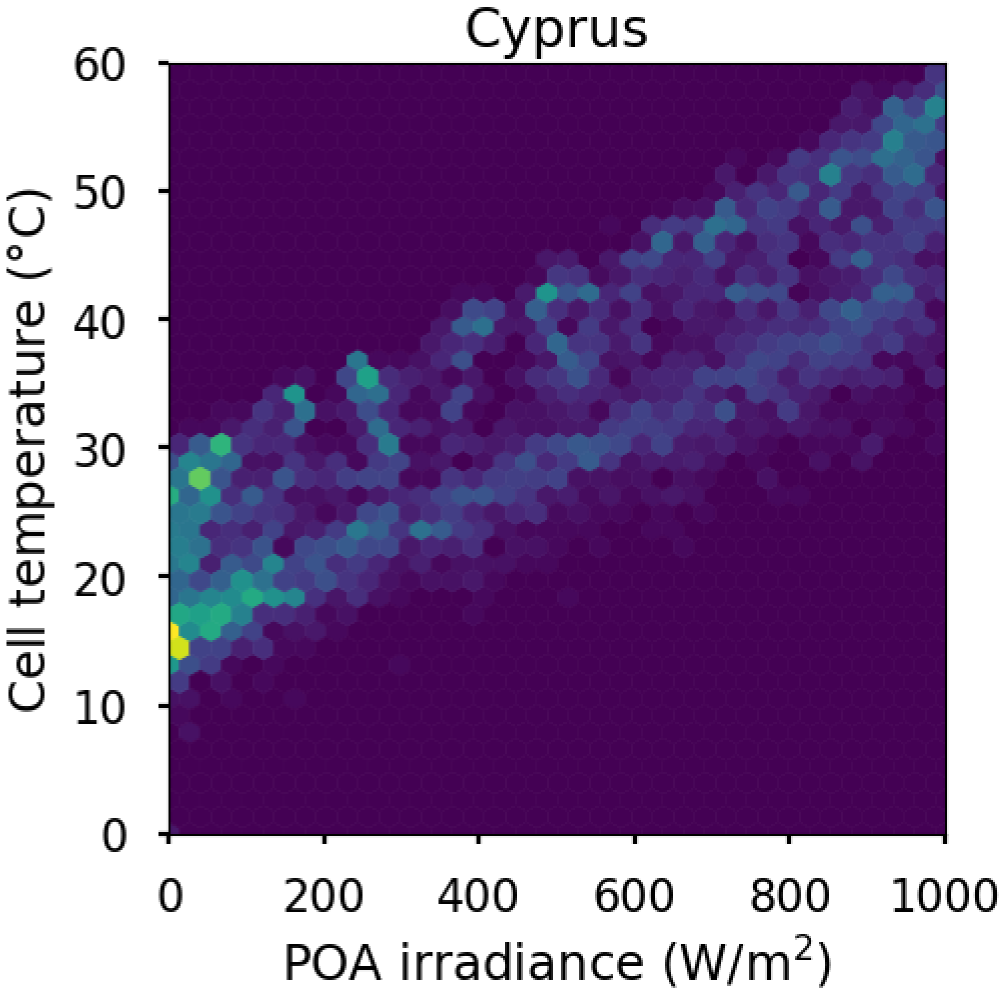
[29] D. Bredemeier, D.Walter, and J. Schmidt, "Light-induced lifetime degradation in high-performance multicrystalline silicon: Detailed kinetics of the defect activation," Sol. Energy Mater. Sol. Cells, vol. 173, pp. 2–5, 2017.
[35] Guro Marie Wyller , Marie Syre Wiig , Ida Due-Sørensen , Rune Søndenå, "The Influence of Minority Carrier Density on Degradation and Regeneration Kinetics in Multicrystalline Silicon Wafers," IEEE JOURNAL OF PHOTOVOLTAICS, VOL. 11, NO. 4, JULY 2021.
[49] Wolfram Kwapil , Jonas Schön , TimNiewelt , and Martin C. Schubert, "Temporary Recovery of the Defect Responsible for Light- and Elevated Temperature-Induced Degradation: Insights Into the Physical Mechanisms Behind LETID," IEEE JOURNAL OF PHOTOVOLTAICS, VOL. 10, NO. 6, NOVEMBER 2020

Power loss components are different in BSF vs PERC devices

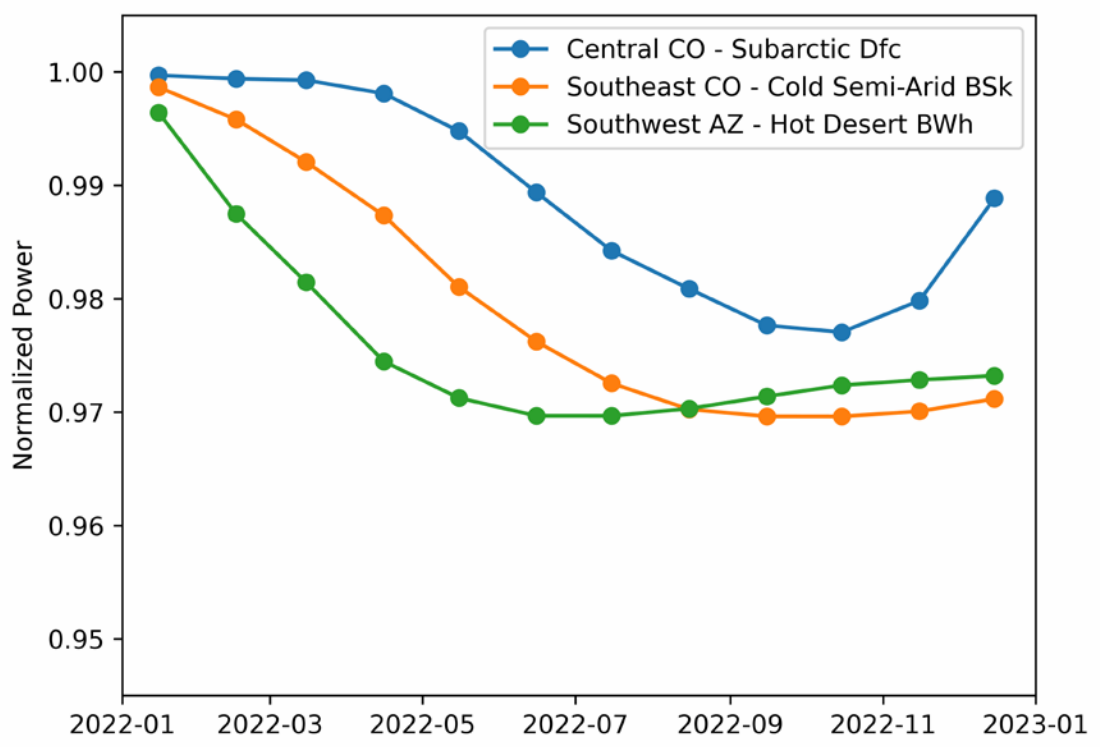


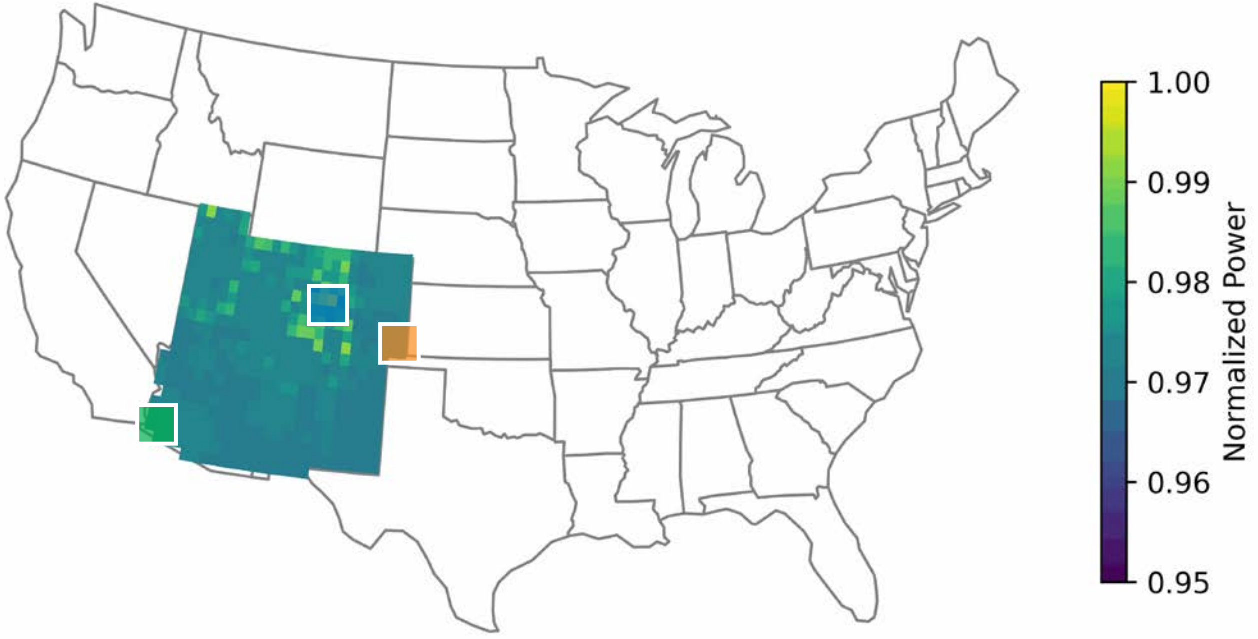
Climate differences





Geospatial modeling shows differences in LETID across climates

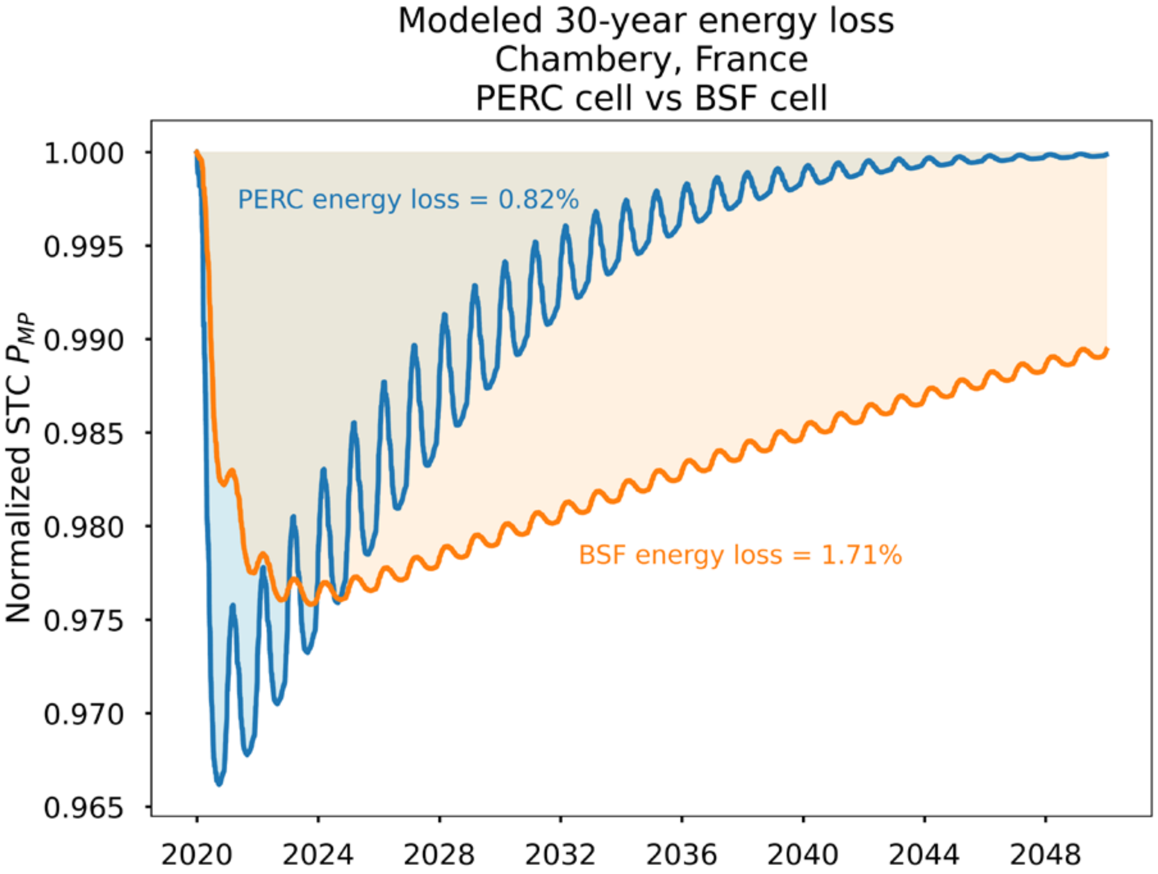




Different temperature models

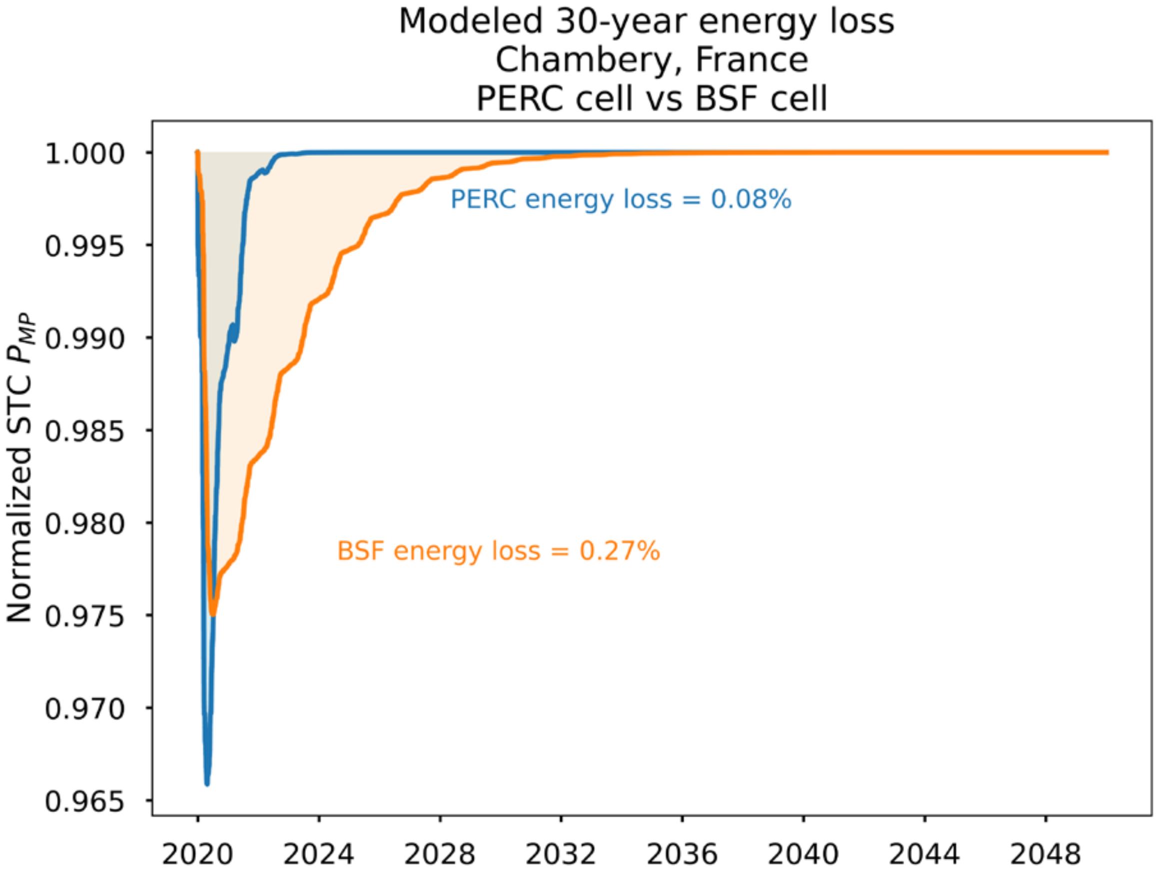
SAPM “open-rack glass-polymer”
Ground-mount

median T_{cell} = 27.3°C
mean T_{cell} = 28.8°C



PVSyst “insulated”
Roof-mount?

median T_{cell} = 33.8°C
mean T_{cell} = 38.9°C



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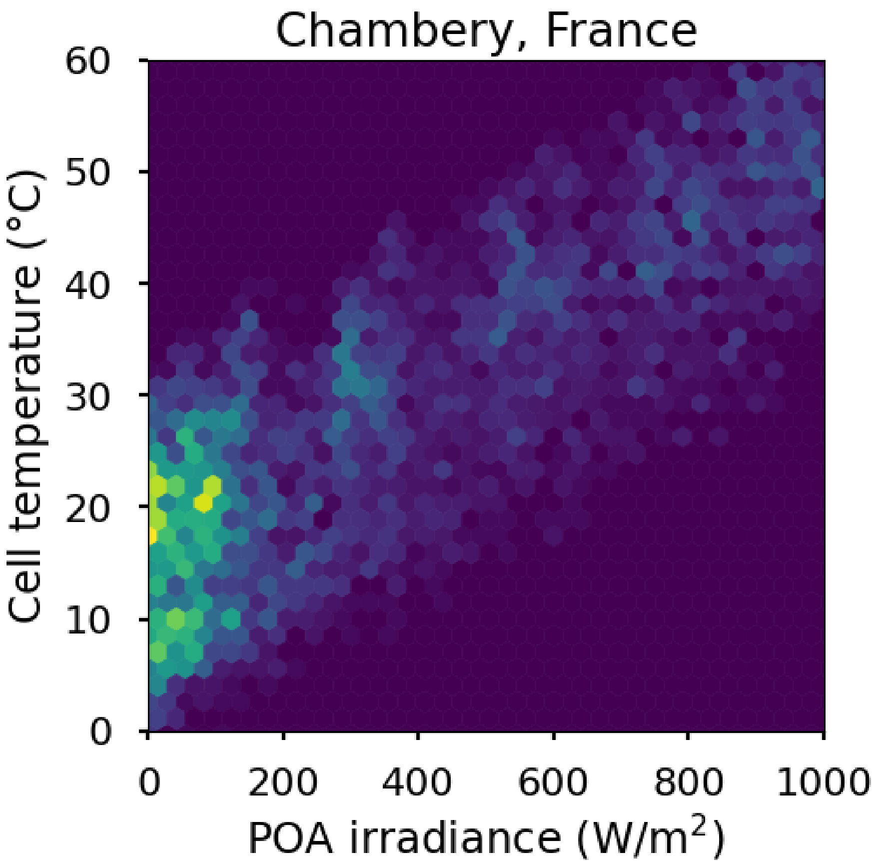

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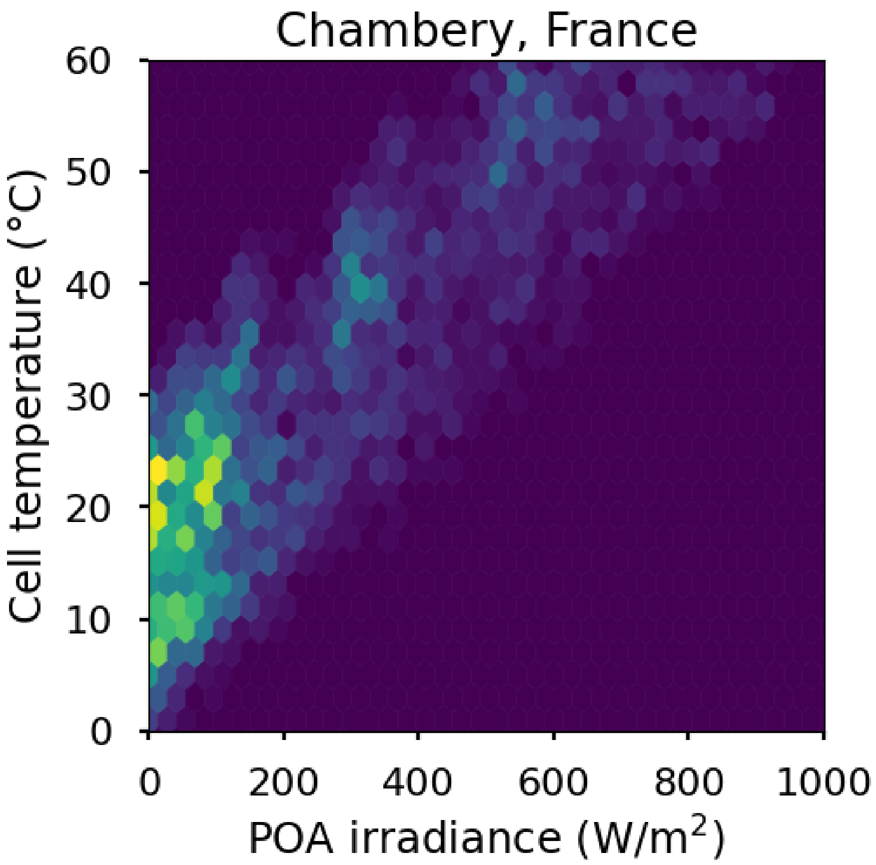
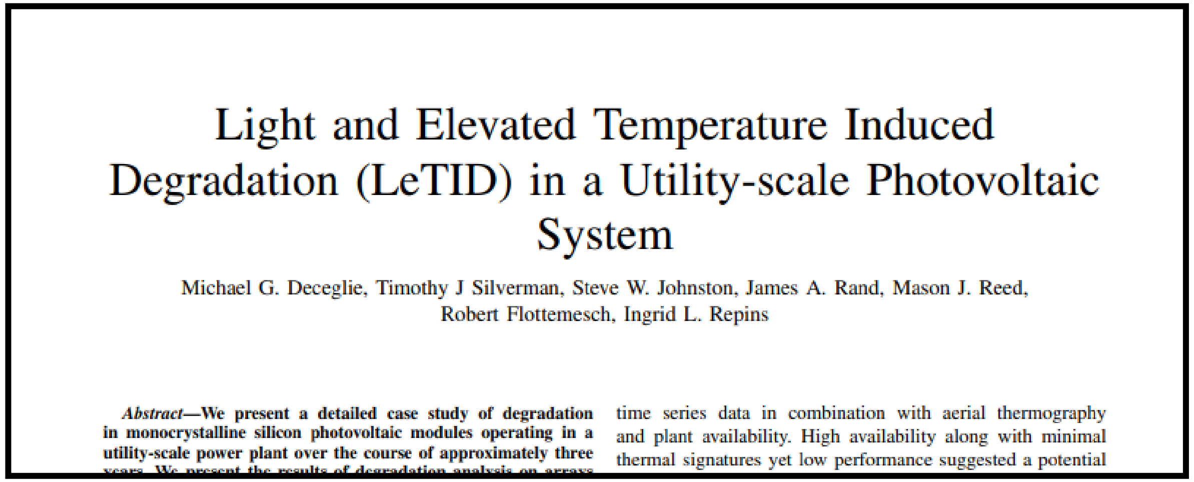


LETID in the field



Light and Elevated Temperature Induced Degradation (LeTID) in a Utility-scale Photovoltaic System

Michael G. Deceglie, Timothy J Silverman, Steve W. Johnston, James A. Rand, Mason J. Reed,
Robert Flottemesch, Ingrid L. Repins

***Abstract*—We present a detailed case study of degradation in monocrystalline silicon photovoltaic modules operating in a utility-scale power plant over the course of approximately three**

time series data in combination with aerial thermography and plant availability. High availability along with minimal thermal signatures yet low performance suggested a potential

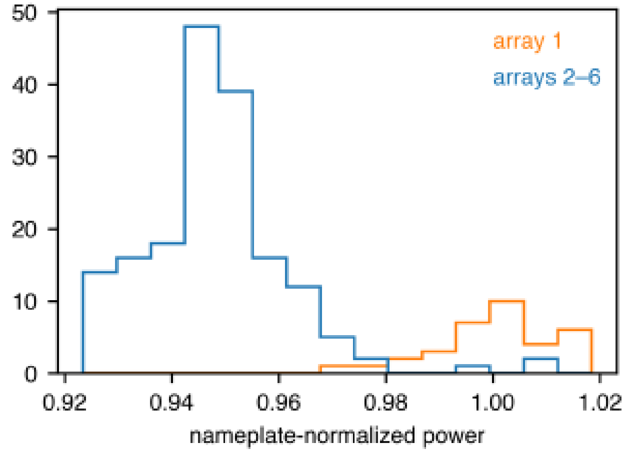


Fig. 1. Histograms of normalized power for modules from array 1 (orange) and arrays 2–6 (blue) based on corrected field I-V curves. The modules in arrays 2–6 tend to be more degraded than those in array 1.

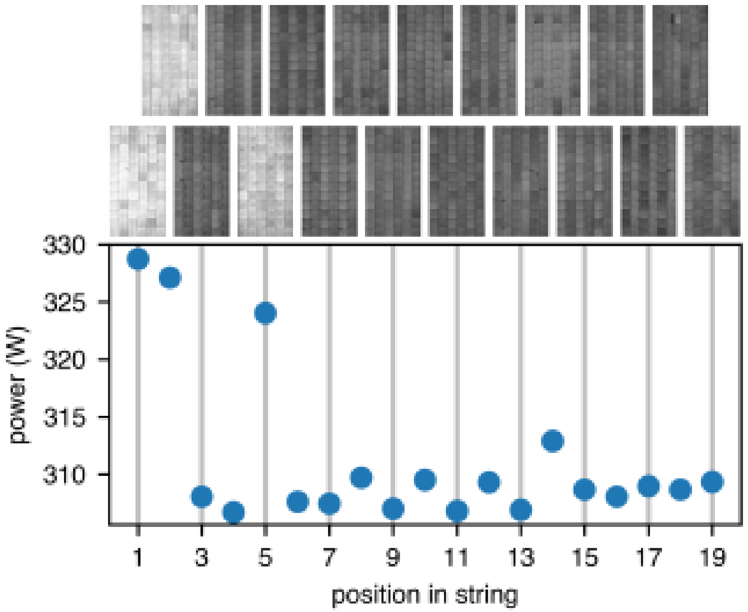


Fig. 2. Module power as a function of electrical position in a string from array 2 along with field EL images. EL images are centered on the x axis with respect to their electrical position. Modules in position 1, 2, and 5 have both higher power and brighter EL images. Correlation between EL and I-V measurements further supported the conclusion that degradation was affecting some modules in the array, but not others.