NATIONAL RENEWABLE ENERGY LABORATORY

PV reliability and resilience in challenging climates

KAUST Workshop

KAUST, Saudi Arabia

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4/24/2024

Outline

- Introduction
- Performance loss rates caused by extreme weather (hail & high wind)
- Visible damage caused by extreme weather
- Impact of physics-based degradation science
- Conclusion

Photovoltaics: a comparable amount of energy

Ghawar oil field, Saudi Arabia

Discovered: 1948

Commercial start: 1951

Size: ≈ 280 km x 27km = 7660km^2

PV land use:

0.35 MWdc/acre fixed tilt

0.25 MWdc/acre 1-axis tracked Bolinger et al., JPV, 2022.

PVWatts includes now Saudi Arabia

https://pvwatts.nrel.gov/

3.8 – 5 mill barrels/day oil

2.5 – 8 bill ft^3/day natural gas

850 – 1350 TWh/yr* oil/gas ⟷ **970 – 1240 TWh/yr solar**

- Conversion: 0.08 oil gal/kWh, 7.42 gas ft3/kWh
- US Energy Information administration

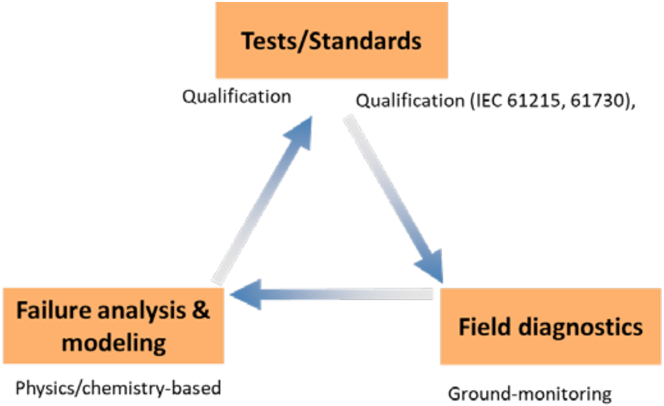
Comparable annual electricity production but there are also challenges

PV Reliability Science: ≈50 years

"You have to understand the past to understand the present."

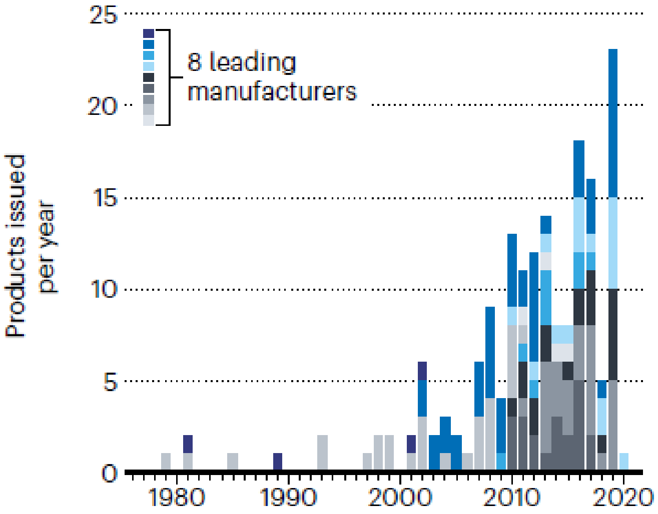
Carl Sagan

PV Reliability Learning Cycle



JPL Block Buy program (late 1970s-early 1980s)

Jordan et al., Progress in Energy, 2022.



Jordan et al., Nature, 2021.

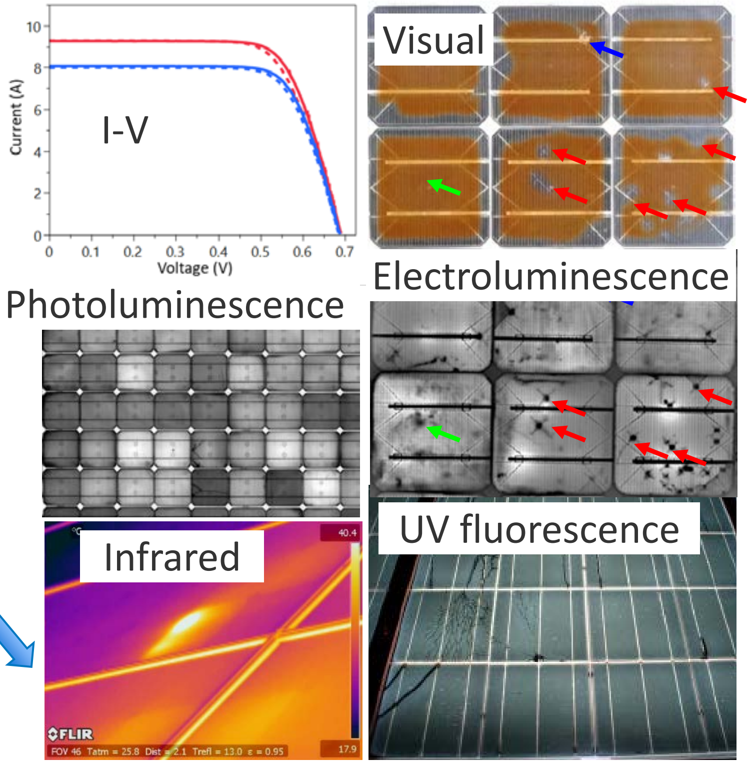
Majority of PV systems are new & product development cycle measured in months!

Need to accelerate the learning cycle.

PV Reliability Science Challenge

Plato's cave allegory

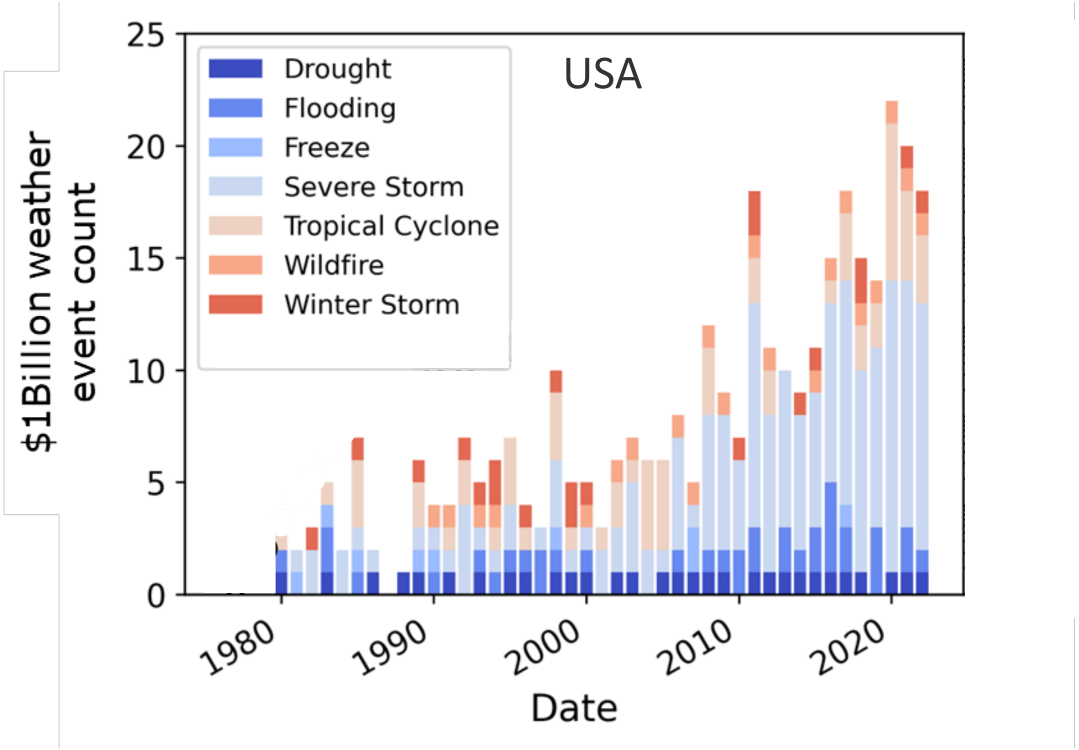
"Shadows" = **Degradation modes**



Degradation mechanisms:

- Debonding/Decomposition
- Corrosion
- Cell cracking
- Fatigue
- Ion mobility

Extreme Weather is increasing



NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2023).

Inflation-adjusted

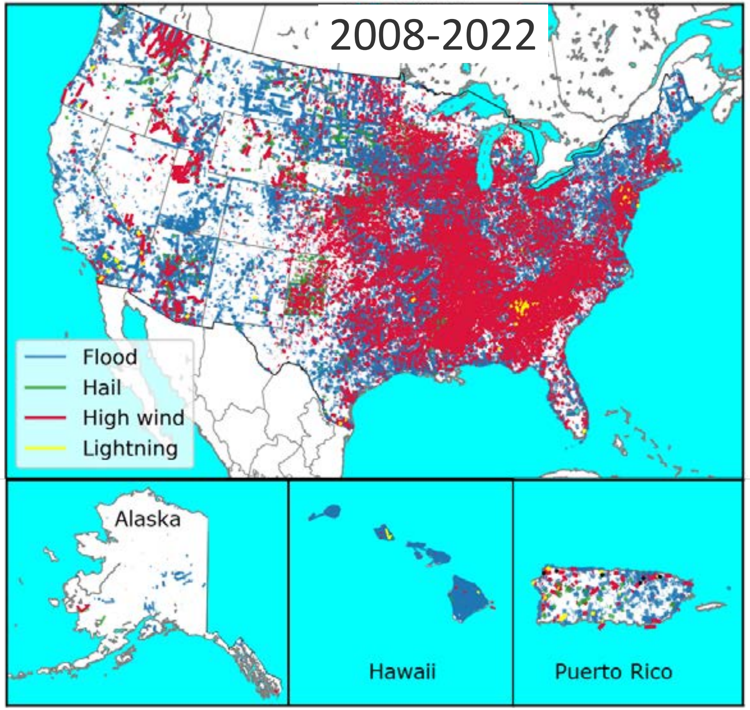
Challenge: Understanding the PV system impact & making them more resilient

Opportunity: PV & storage can provide power in the aftermath of extreme weather

https://www.ncei.noaa.gov/access/billions/

National Oceanic and Atmospheric Administration (NOAA)

Weather phenomena causing loss of life, property damage, injuries, or disruption of commerce.

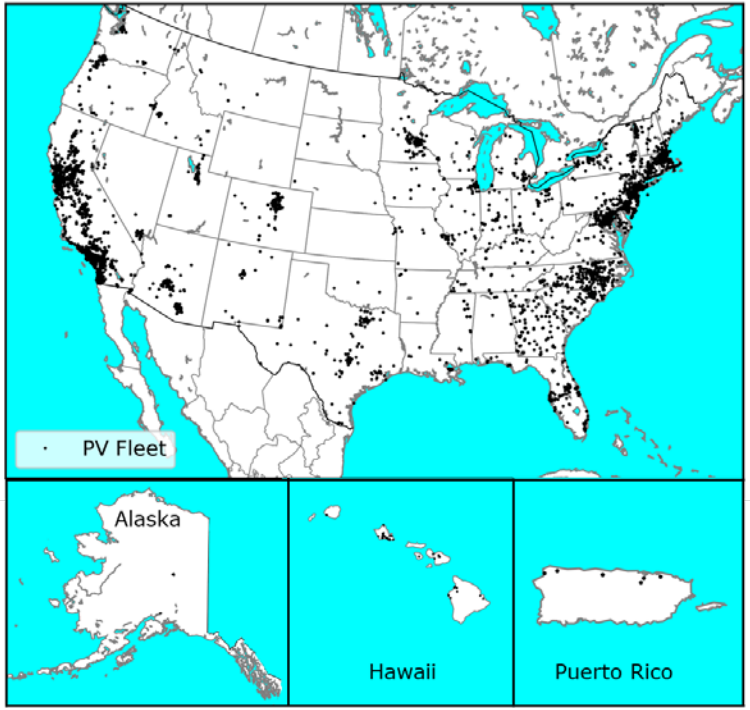


- Time & date
- Type of event
- Latitude/longitude (county)
- Magnitude
- Description
- .
- .

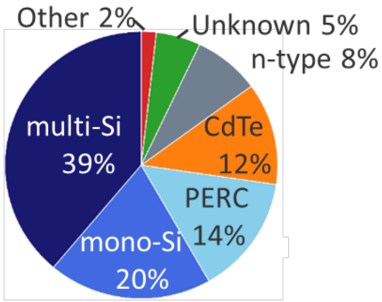
https://www.ncei.noaa.gov/products/severe-weather-data-inventory

PV Fleet Data Initiative

- > 25,000 inverter data
- Typically, 15 min data
- 8.3 GW capacity
- Mean age: 5+ years
- Mean size: 3.8 MW

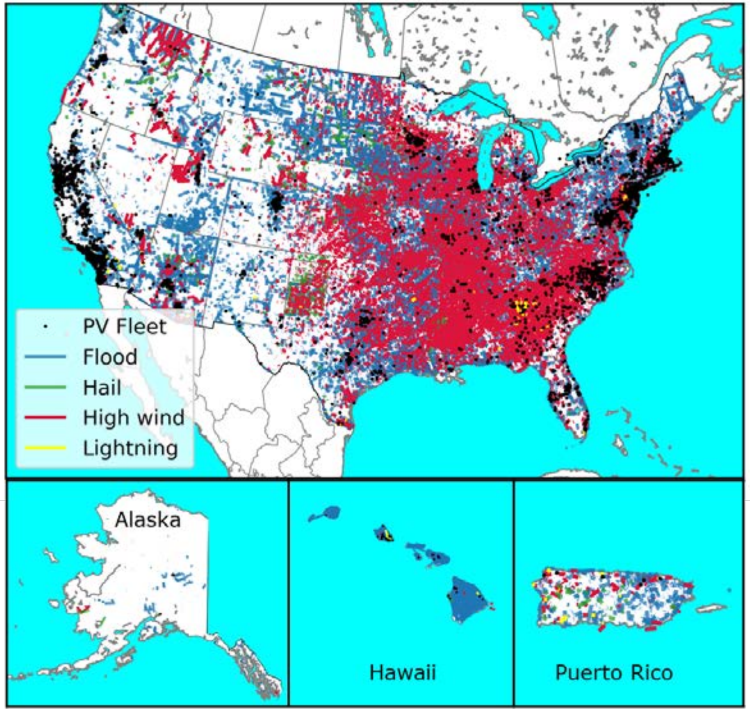


Technology breakdown



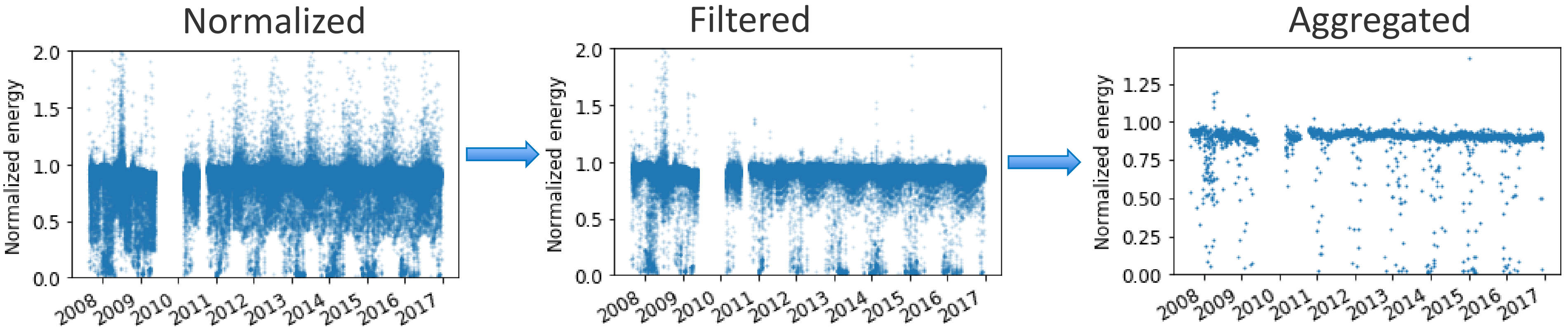
https://www.nrel.gov/pv/fleet-performance-data-initiative.html

Extreme Weather & PV Systems



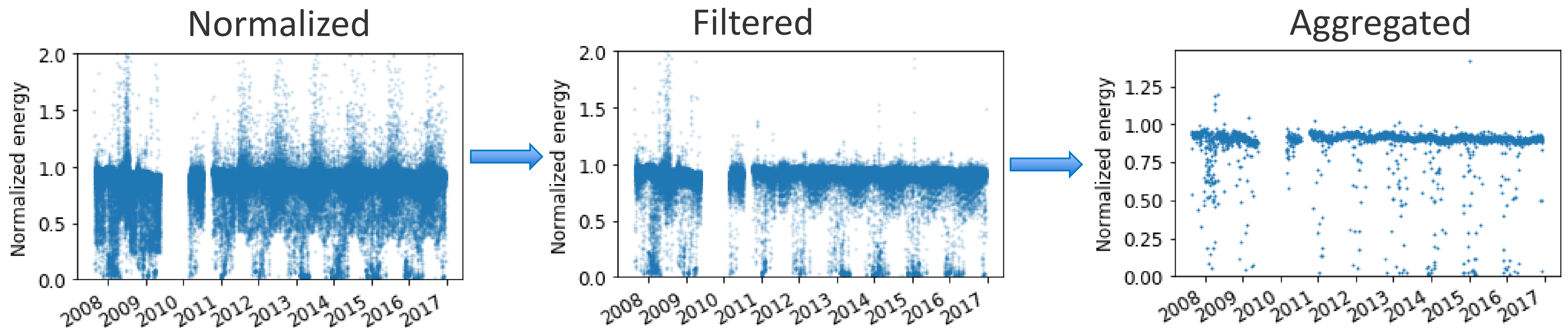
Determined events that came within 10 km of an existing PV system

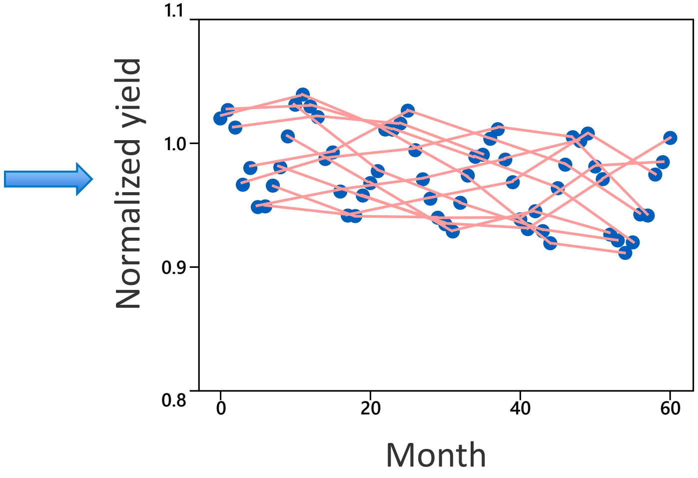
Performance Loss Rates (PLR) - RdTools

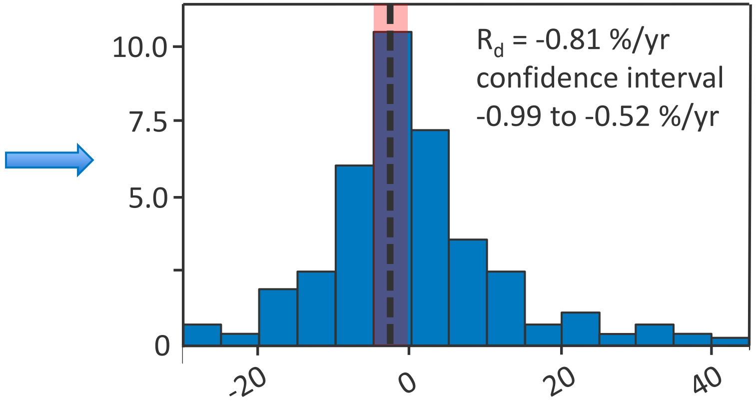


https://github.com/NREL/rdtools

Performance Loss Rates (PLR) - RdTools







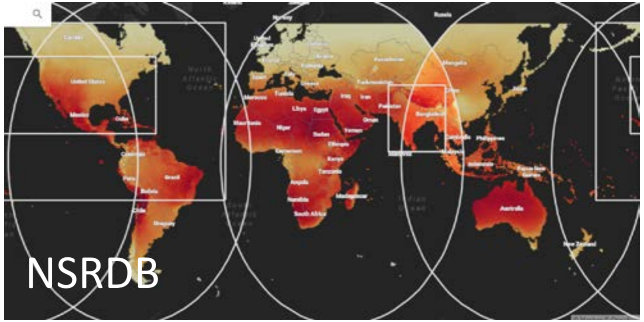
RdTools

https://github.com/NREL/rdtools

Performance Loss Rates (PLR) - RdTools

Additional modifications to obtain more accurate results

1. Used National Solar Radiation Database (NSRDB), satellite irradiance data



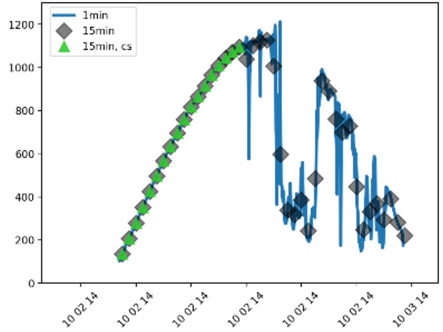
https://nsrdb.nrel.gov/

2. Filter for clear sky periods only using pvlib detect_clearsky function*

pvlib

https://github.com/pvlib/pvlib-python

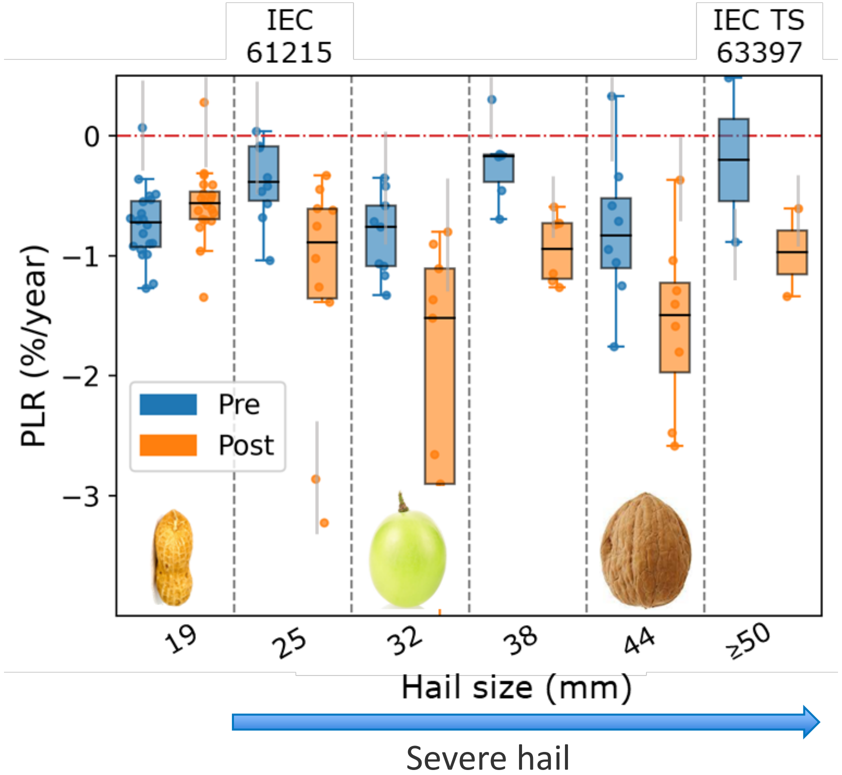
*Reno, Hansen, Ren. Energy, 2016.
*Jordan, Hansen, Ren. Energy, 2023.



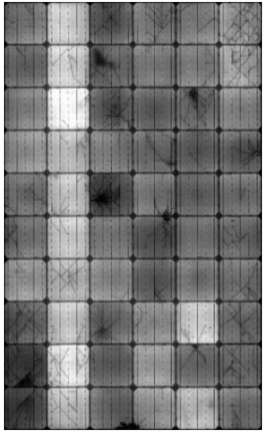
Performance Loss Rates – Hail

Pre: PLR before hail
Post: PLR after hail

Gray vertical bar: uncertainty



Possible cause: cracked cells

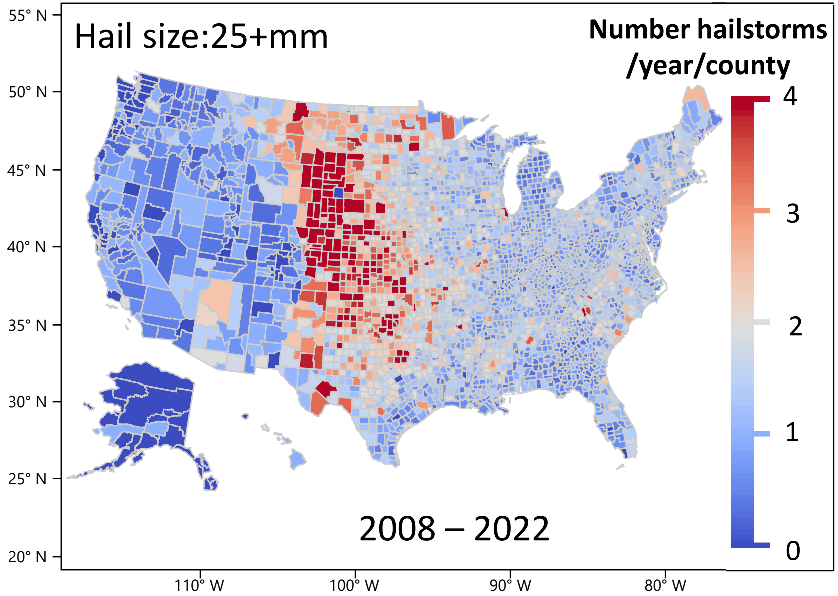


Electroluminescence

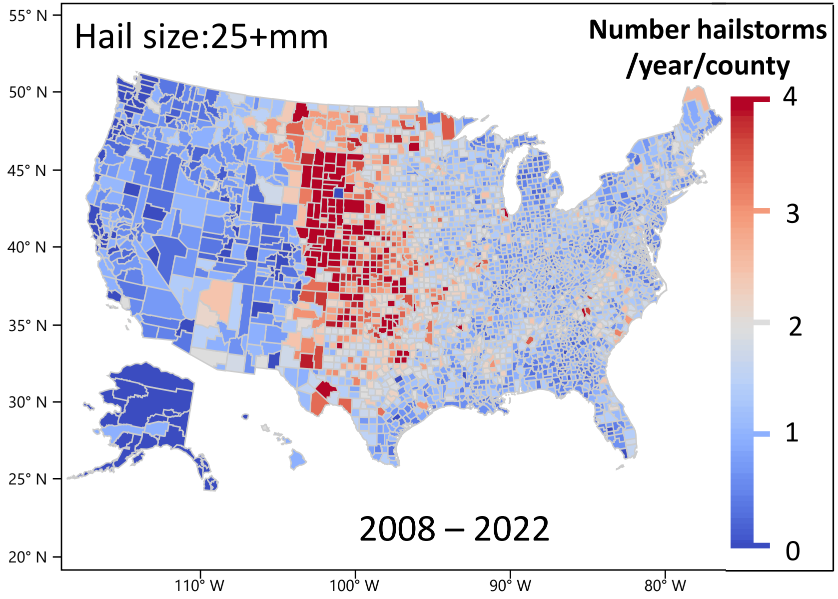
Higher performance losses after hail ≥ 25mm

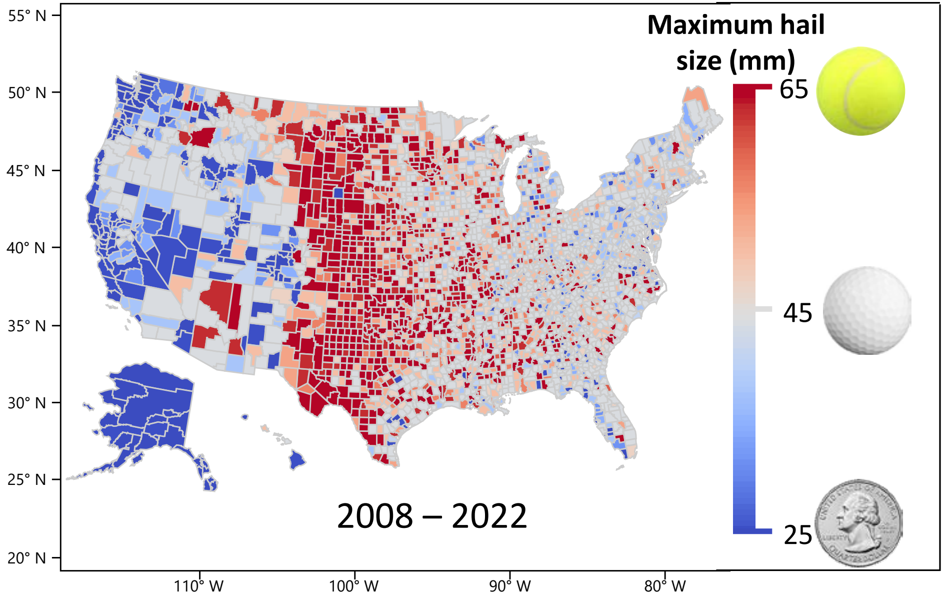
More stringent newer hail certification—IEC TS 63397 should be utilized!

Mapping hail events in the USA



Mapping hail events in the USA

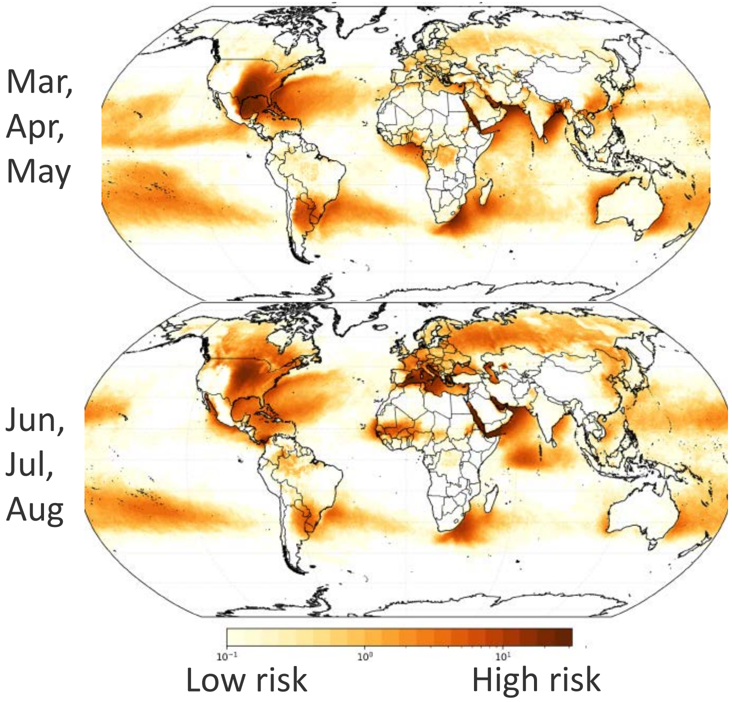




Many counties outside "hail alley" experience potentially hail-damaging events

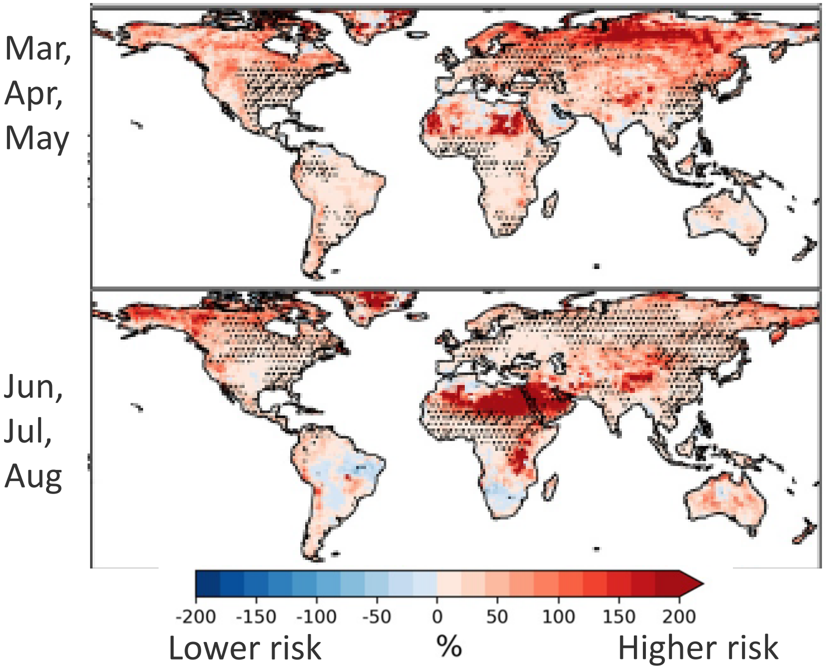
Hail is a Global Problem

Historical data (1980-2019)



John T. Allan et al., PVRW, 2024.

Projections (1.5ºC)



Lepore et al., Adv. Earth & Space Sci., 2021.

If climate projections are right hail will become a problem in many locations

Examples of Extreme Weather in Saudi Arabia

Medina, Feb 24/25, 2018.
Source: Gulf news

Hail Event in Italy

different tilt

https://www.pv-magazine.com/2023/08/01/smart-om-platform-detects-hail-related-damages-in-pv-systems/

Damage depends on many factors such hail size, wind speed, mounting, technology.
Hail stow for trackers is an option.

Industry Trends that may jeopardize Reliability

To reduce (installation) costs

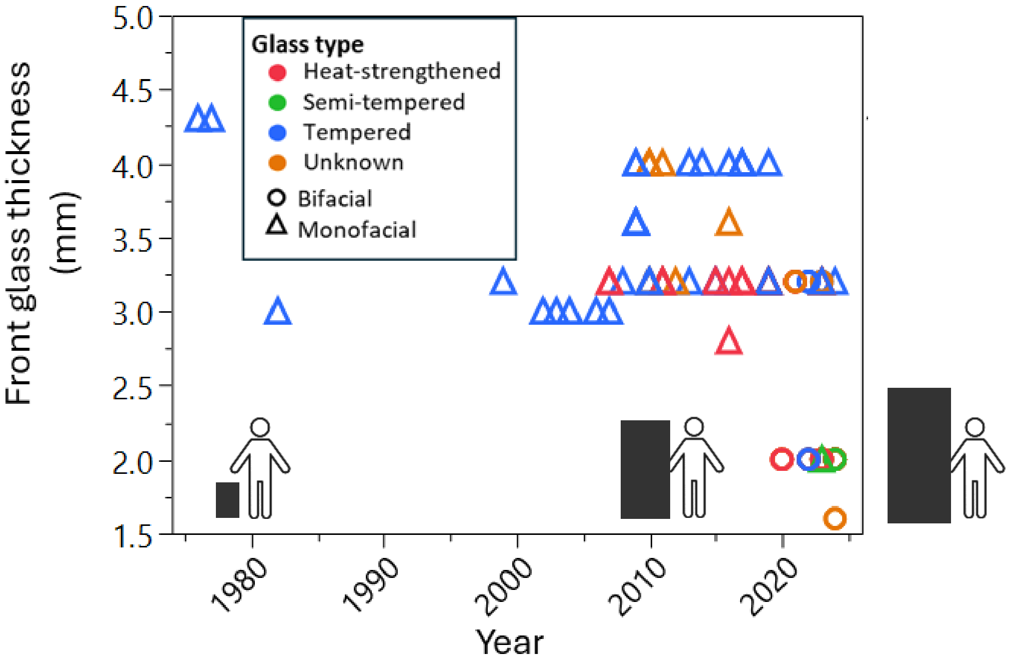
Larger modules

Bifacial modules with glass/glass

Glass thickness decreased to reduce weight

Glass cannot fully tempered

Commercial module datasheets

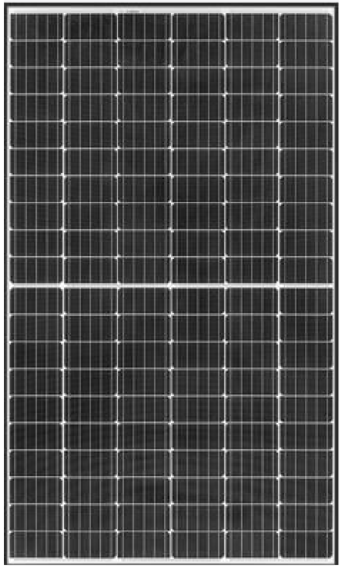


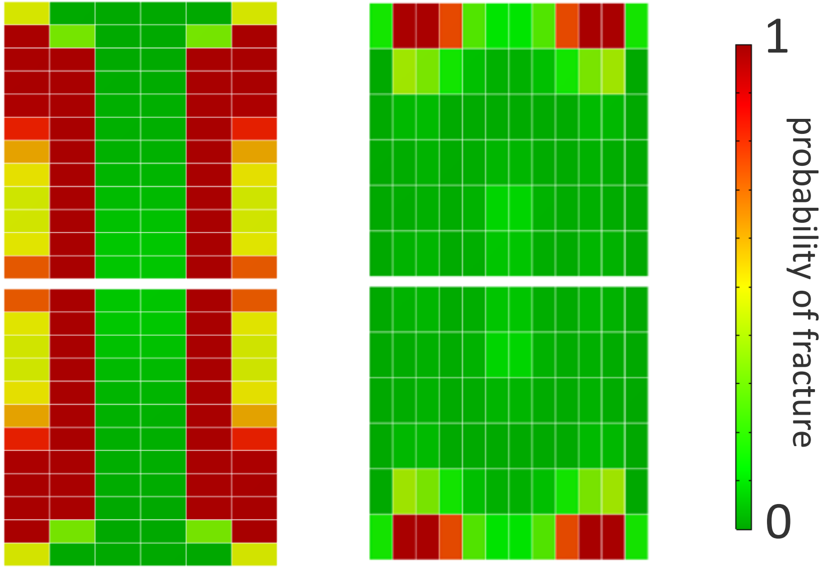
Bifacial modules with glass/transparent backsheet can use tempered glass

Structural Mechanics Modeling

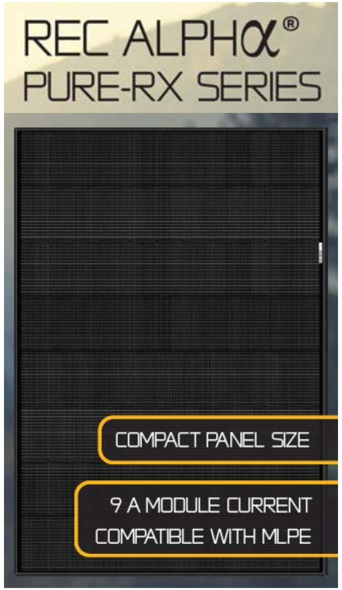
Same mechanical load: 5,400 Pa

Conventional module





Commercial module



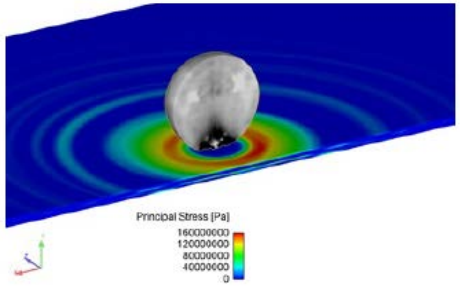
Rectangular cell orientation relative to bracketing-- resilience to static load

Physics-based modeling can improve reliability

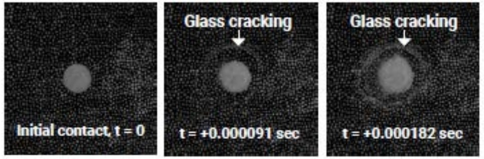
Bosco, JPV, 2022.

Physics-based Degradation Science

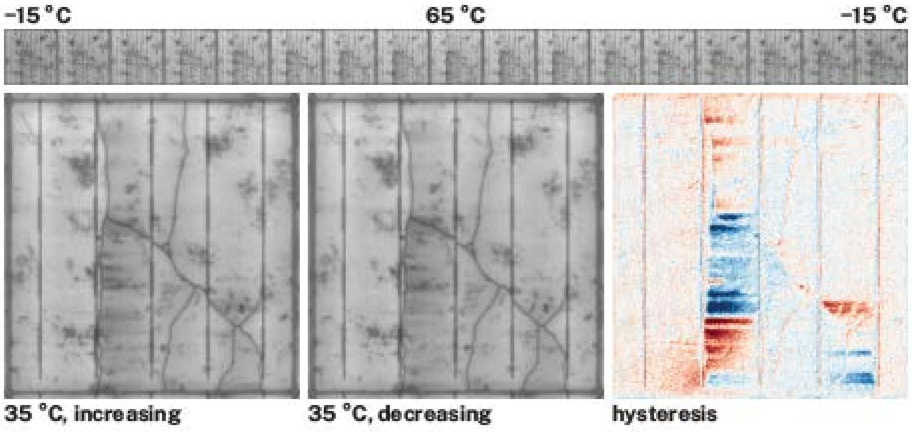
Hail impact study



Simulated glass stresses during ice ball impact, 75 microseconds post-contact. Predicted stresses are influenced by both ice fracture behavior and modeled module design.



Temperature-dependent Electroluminescence



Performance impact depends on the module temperature

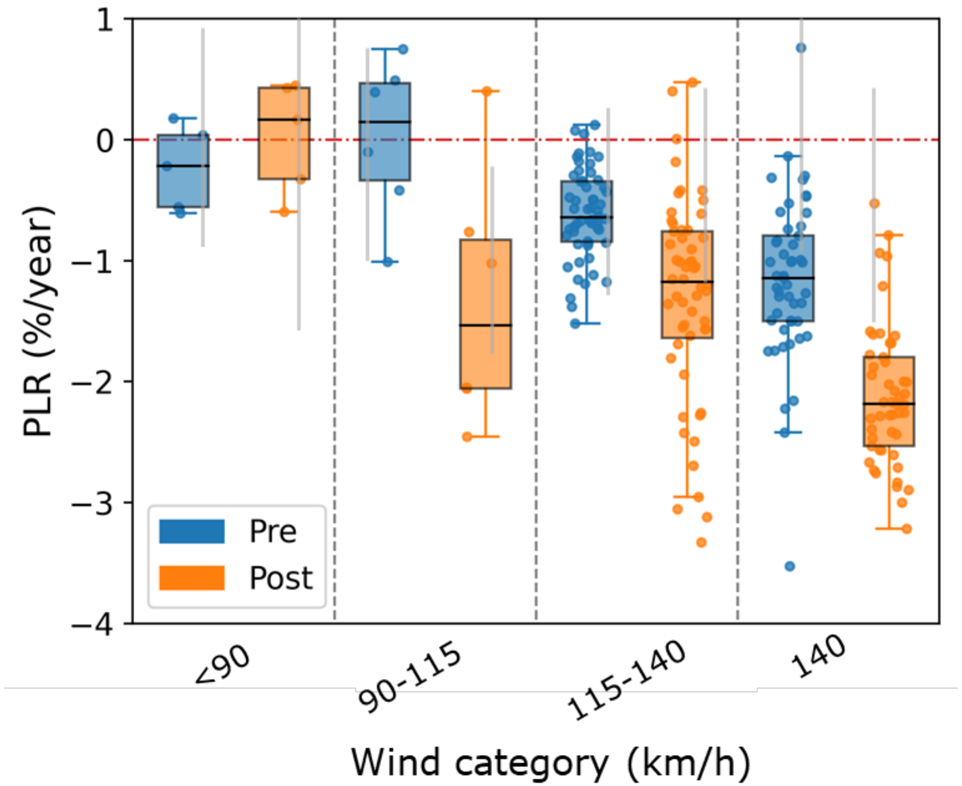
Hartley et al., Duramat workshop, 2023

Silverman et al., PVSC, 2021

Performance Loss Rates – high wind

Pre: PLR before the storm
Post: PLR after the storm

Gray vertical bar:
representative uncertainty



Wind speeds 90+ km/h higher loss after storm in almost all inverters

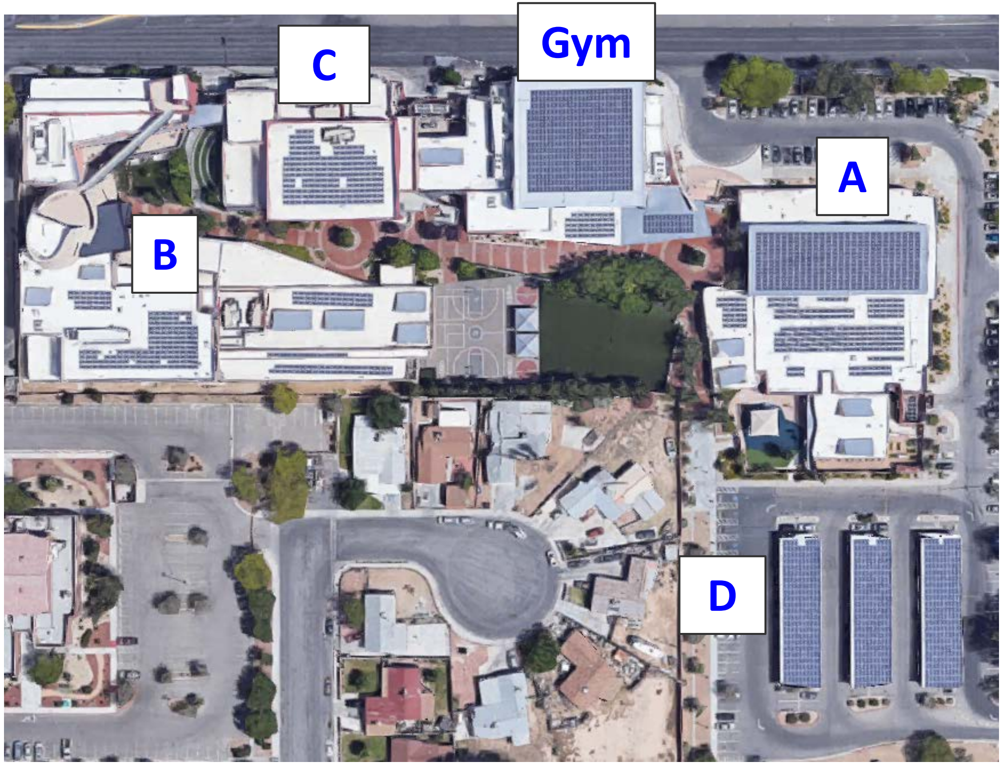
A few inverters were wind sheltered by building

High wind event—case study 1

Desert location, Las Vegas

All buildings:

- Same modules, c-Si (Al-BSF)
- Different mounting
- 4 years data before storm
- 6 years data after storm



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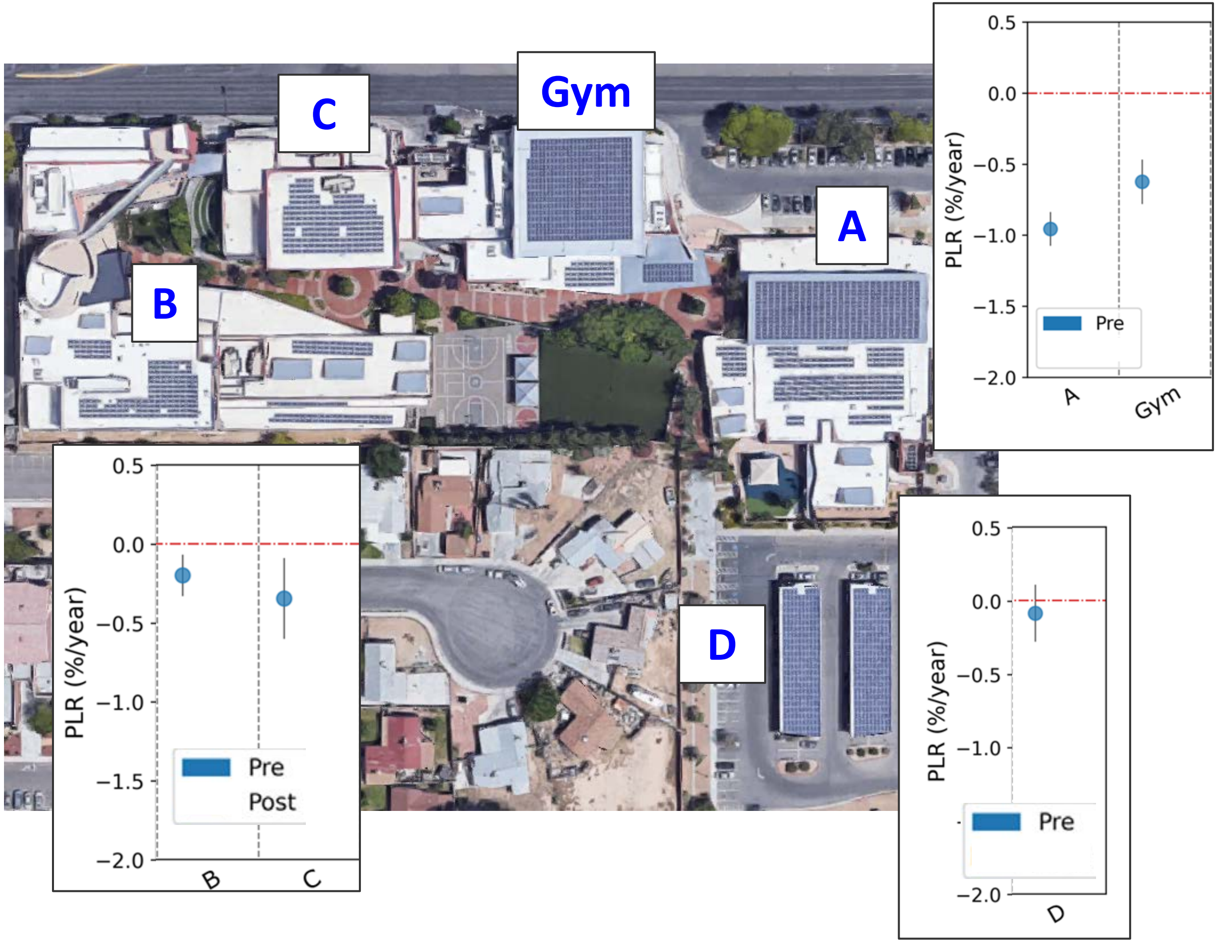

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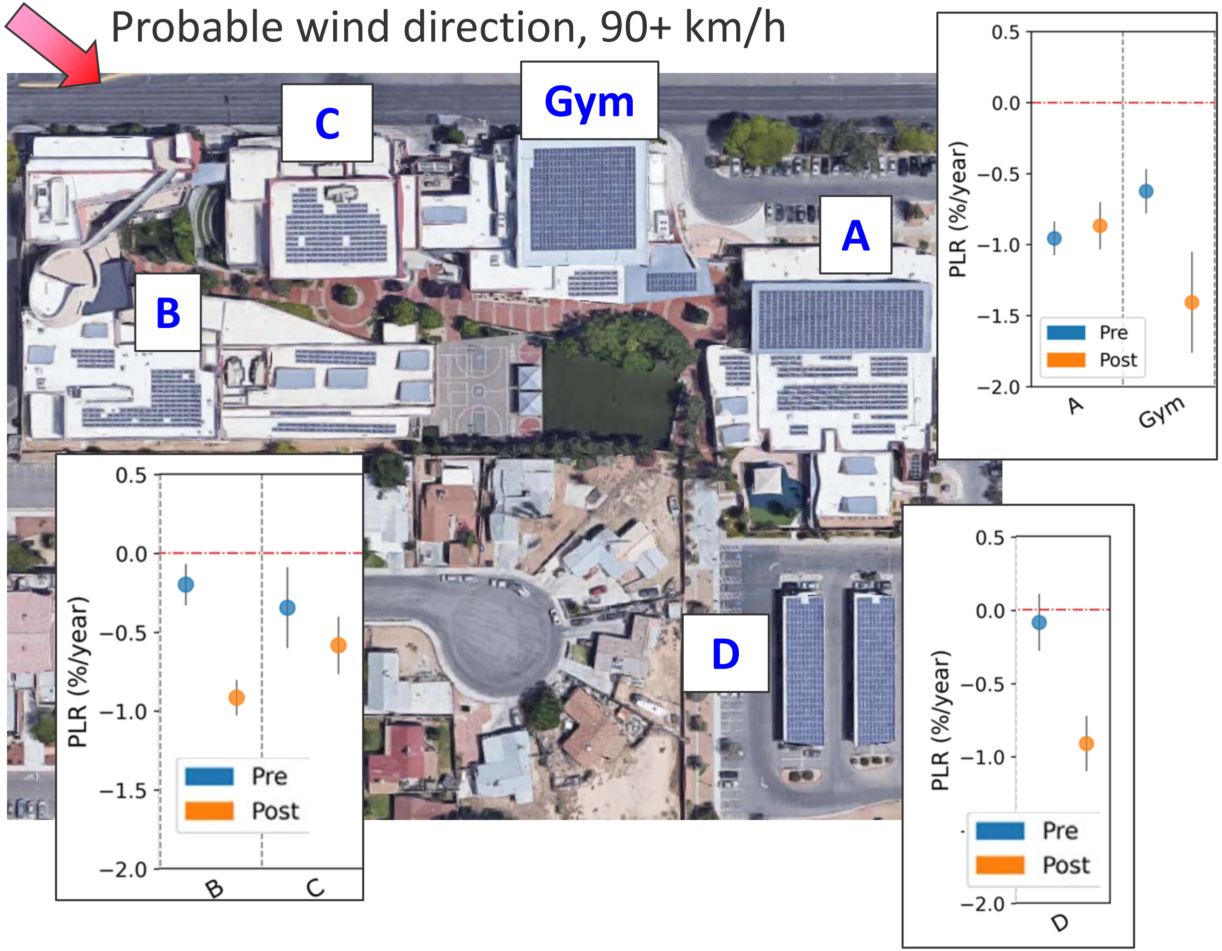
Only buildings A & C show no higher PLR after storm

A was sheltered by gym.



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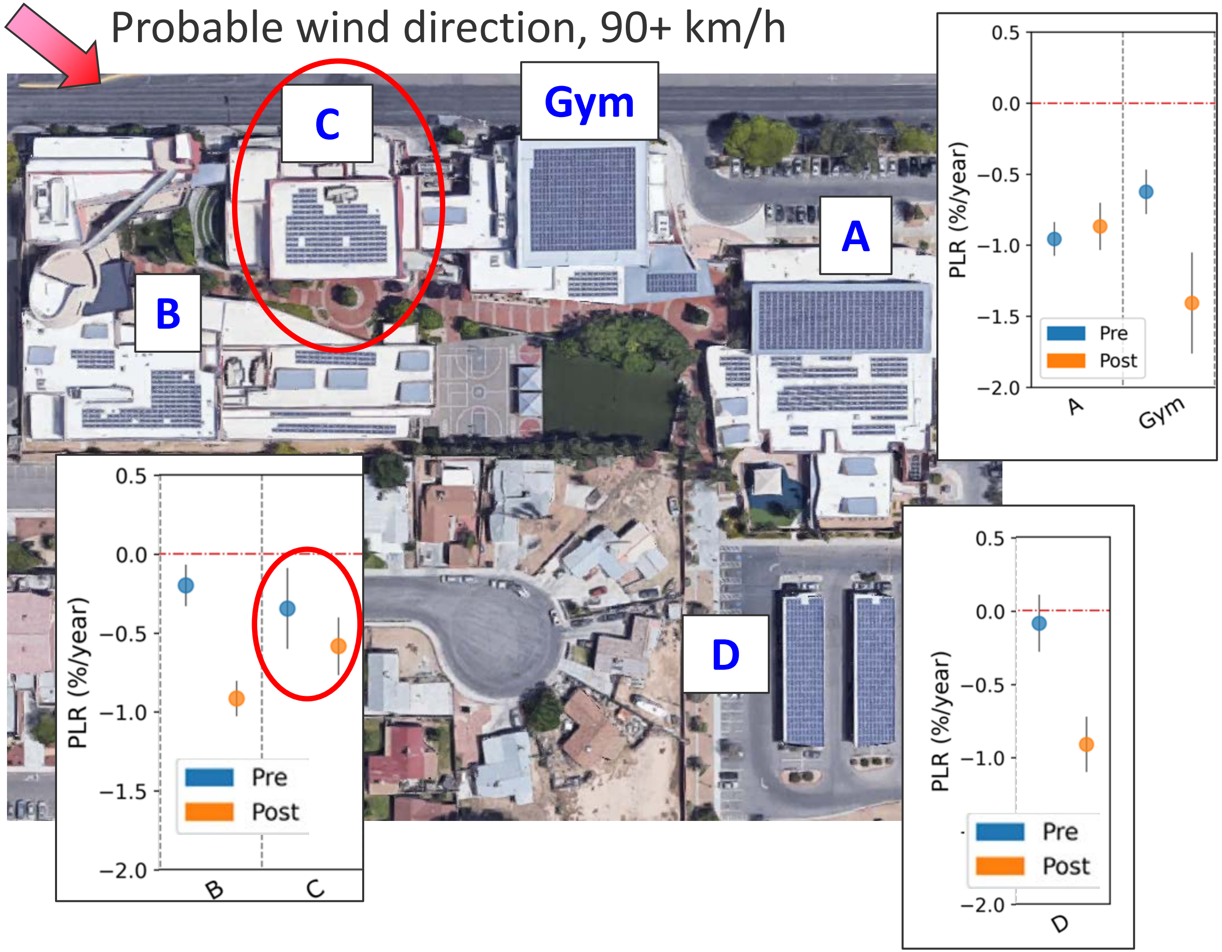
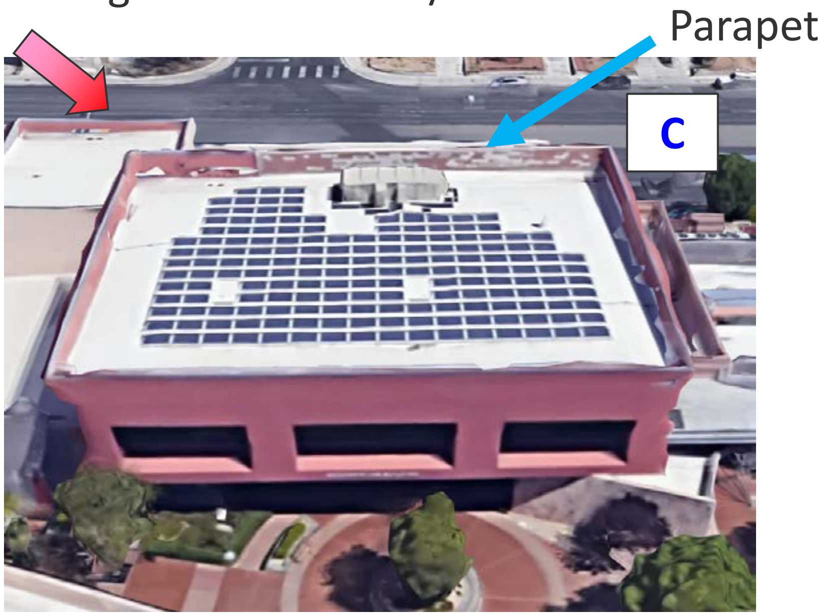
A was sheltered by gym.

What about building C?

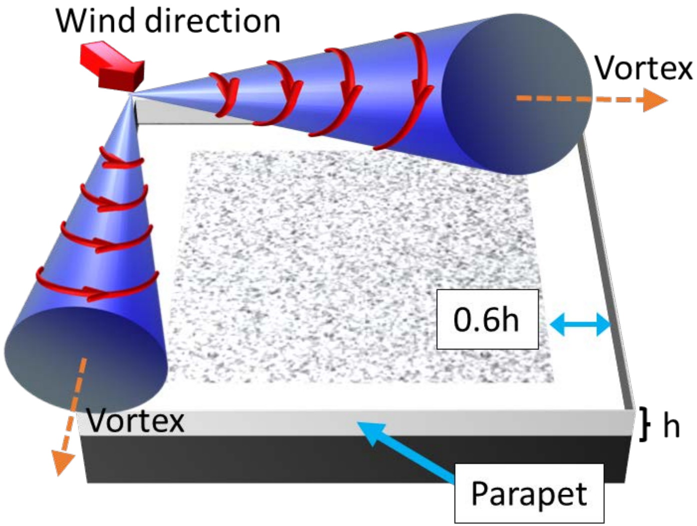


High wind event—case study 1

Wind gusts: 90-115km/h



Structural Engineers Association of California (PV2-2017)



- Vortex formation leads to strong uplift
- Wind uplift depends on wind speed, parapet height etc.

Parapet probably sheltered system
No modules in the vortex region

High wind event—case study 2

Wind gusts: 90-115km/h

High wind event—case study 2

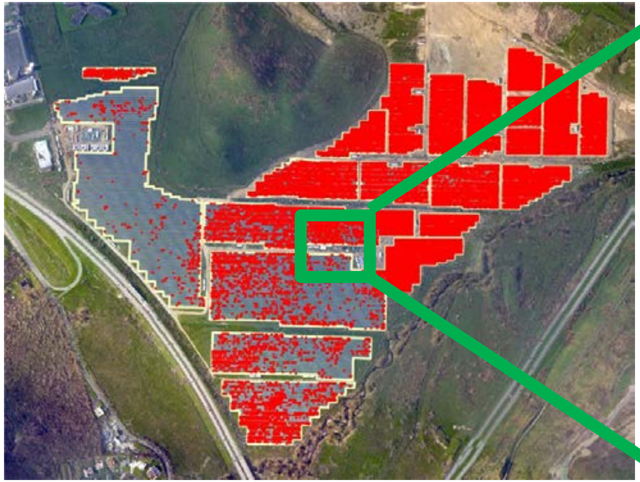
Wind gusts: 90-115km/h

Installer training can prevent design & installation issues
USA: North American Board of Certified Energy Practitioners (NABCEP)

Wind damage through satellite imagery

Hurricane (category 5) damage, Puerto Rico, 2017. > 170 km/hr wind gusts

Satellite image

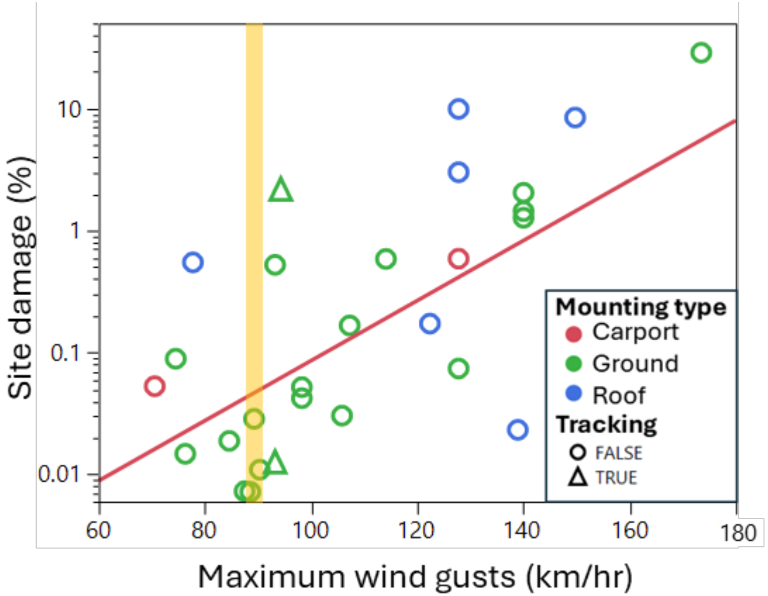


Red label: physical damage to plant (missing modules)

Analyzed ca. 50 sites → relationship between wind speed, damage, system configuration

Quantifying Wind Damage

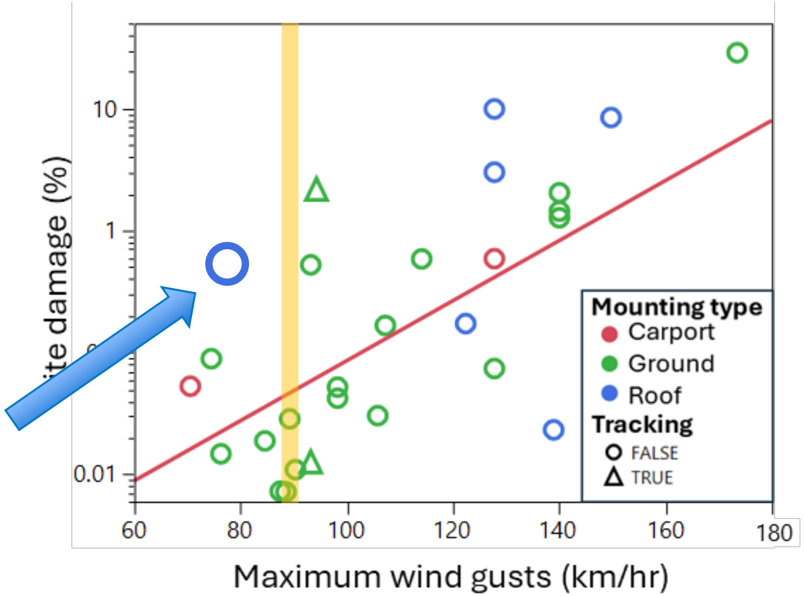
Yellow bar: Threshold above which we detected higher degradation



General trend: higher wind gusts more damage

Quantifying Wind Damage

Yellow bar:
Threshold above which we detected higher degradation



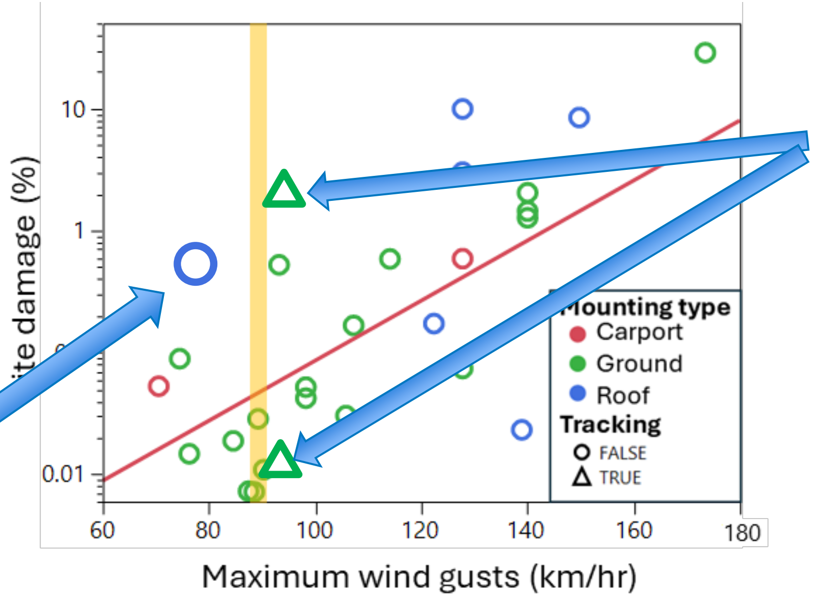
Modules mounted flush with building edge

General trend: higher wind gusts more damage

Quantifying Wind Damage

Yellow bar: Threshold above which we detected higher degradation

Modules mounted flush with building edge



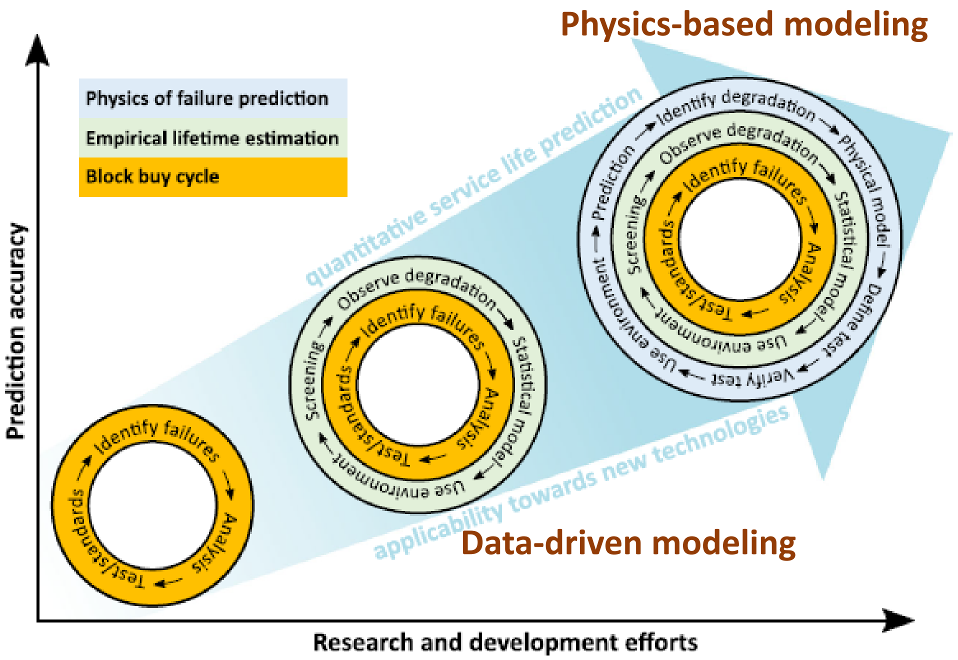
Same location (across the street) but one had known mounting issues

General trend: higher wind gusts more damage

But installation practices have substantial impact

PV Reliability & Degradation Science Today

Connecting materials science & field observations



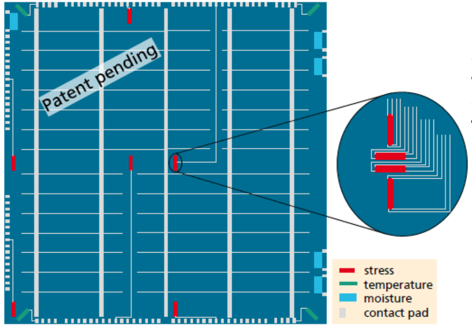
Springer et. al. Progress in PV, 2022.

Reliability Data - Becoming More Predictive

PV modules are complex systems

Interactions between different degradation mechanisms

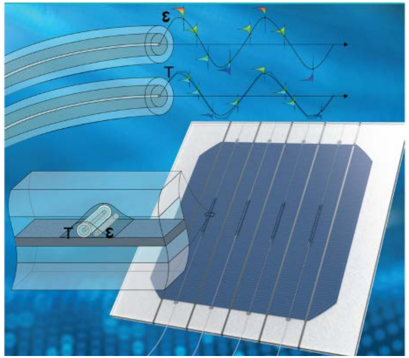
Sensors integrated on FZ-wafer



Beinert et al., Progress in PV, 2020.

1. Strain
2. Temperature
3. Moisture

Fiber-Bragg grating sensor



Nivelle et al., Progress in PV, 2022.

1. Strain
2. Temperature

Other sensors:

- Physical
- Chemical
- etc.

Conclusion

- Observed threshold behavior for high wind (90kmh/56mph) and hail (25mm/1”) above which we see higher performance loss.
- Choices in module design and installation quality can have substantial impact on inflicted damage even below these thresholds.
- Physics-based reliability and degradation science can help us make more resilient modules and systems and be more proactive.

“What we usually consider as impossible are simply engineering problems... there's no law of physics preventing them.” Michio Kaku

Acknowledgments

Thank you very much

شُكْراً جَزِيلاً

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Byron McDanold, Josh Parker,
Ingrid Repins, Katherine Jordan

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PV Fleet Performance Data Initiative

NREL/PR-5K00-89693

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