Hurricane Milton, October 2024

Extreme Weather Impacts on PV System Reliability: Tropical Cyclones

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Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Technology Collaboration Programme

by iea

This material is based on work supported by the U.S. Dept of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office Award Number 38268.

SAND# 2024-xxxx

Outline

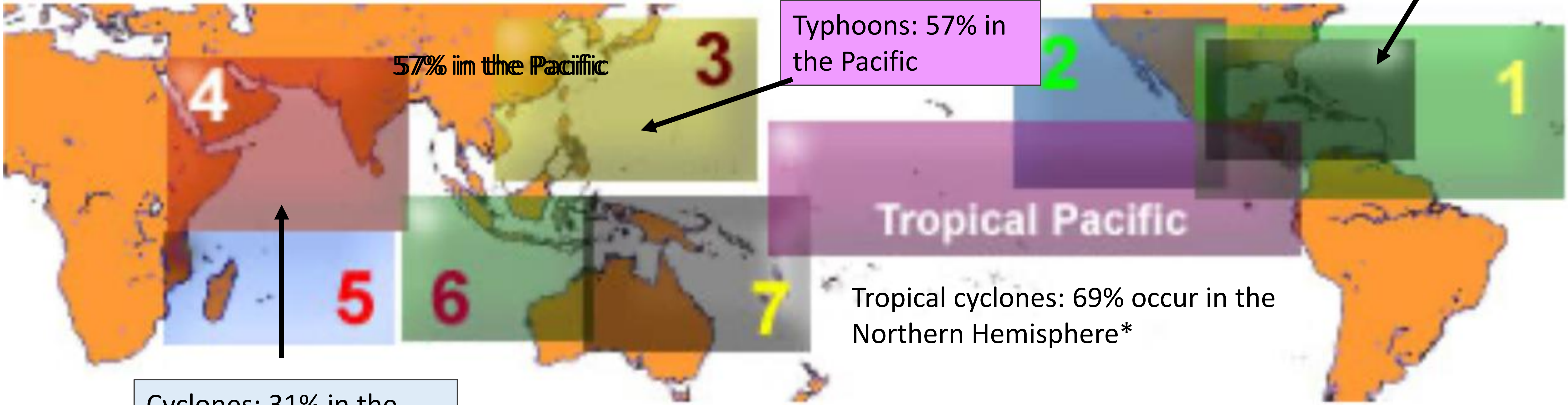
1. Overview of tropical cyclones
2. Impact of PV systems (case studies)
3. Pre-event and post-event strategies
4. Recommendations and take-home messages

Tropical Cyclones

- Rotating systems of clouds, with low-pressure centers that originate over tropical or subtropical waters that unleash a spiral pattern of thunderstorms accompanied by strong winds.
- Defined by minimum wind speed of >121km/h
- Majority (69%) occur in the Northern Hemisphere*

Hurricanes: 12% in the Atlantic

Typhoons: 57% in the Pacific



Tropical cyclones: 69% occur in the Northern Hemisphere*

Cyclones: 31% in the Indian Ocean

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* NOAA National Hurricane Center

High-Visibility, High-Impact Events

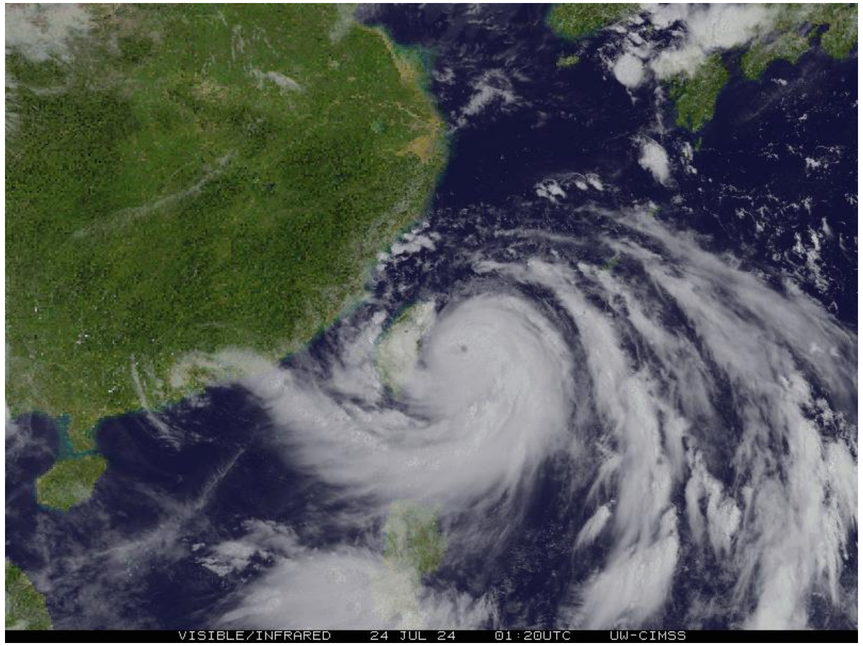
Hurricanes are High-Wind Events

CATEGORY	WIND SPEED MPH	KM/H	KNOTS	DAMAGE POTENTIAL MULTIPLIER
1	75	121	65	1x
	80	129	70	1.6x
	85	137	74	2.9x
	90	145	78	4.3x
	95	153	83	6.6x
2	100	161	87	10x
	105	169	91	15x
	110	177	96	21x
3	115	185	100	30x
	120	193	104	43x
	125	201	109	60x
4	130	209	113	82x
	135	217	117	110x
	140	225	122	147x
	145	233	126	195x
	150	241	130	256x
	155	249	135	333x
5	160	257	139	429x
	165	266	143	549x
	170	274	148	697x
	175	281	152	879x
	180	290	156	1101x
	185	298	161	1371x
	190	306	165	1696x

Saffir Simpson Hurricane wind scale

Hurricane Damage Potential

- Potential damage increases logarithmically from category 1 to Category 5, so small increases in wind strength can dramatically increase damage.
- IPCC assigns high confidence to increase in intensity and frequency of tropical cyclones
- WMO and IPCC projections project an increase in intensity, maybe not frequency
- Lawrence Berkeley National Lab in US proposes a Category 6



Typhoon Gaemi, July 2024

Source: SSEC/CIMSS, University of Wisconsin–Madison.

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Is PV at Risk?

“Information from multiple sources shows that during 2012 hurricane Sandy, virtually all PV systems received no damage by the storm and, if not disconnected, produced electricity following the storm.”

--V. Fthenakis, "The resilience of PV during natural disasters: The hurricane Sandy case" PVSC, *2013 IEEE 39th PVSC*, Tampa, FL.

Well, Maybe… Reasons for Concern

- Climatic stressors are increasing
- Rapid industry transition to thinner, larger PV modules, relatively untested under long-term dynamic and repetitive field conditions
- Diversification of supply chains and BOMs
- Predominance of single-axis tracker systems that are vulnerable to vibration and resonance
- Minimal standards for racking system, including assembly hardware and fasteners; wire management; stow capabilities for SATs
- Installation quality/availability of skilled workers
- Lack of publicly-available post-event data

Typical Exclusion for Module Warranty: “Damage caused by extreme natural phenomena (earthquakes, typhoons and tornados, volcanic eruptions, flood and storm tides, lightning, hailstorms and heavy snowstorms, tsunamis, etc.”

■ **Mechanical Specification**

Format	96.9 in × 44.6 in × 1.38 in (including frame) (2462 mm × 1134 mm × 35 mm)
Weight	76.9 lbs (34.9kg)
Front Cover	0.08 in (2.0 mm) thermally pre-stressed glass with anti-reflection technology
Back Cover	0.08 in (2.0 mm) semi-tempered glass
Frame	Anodised aluminium

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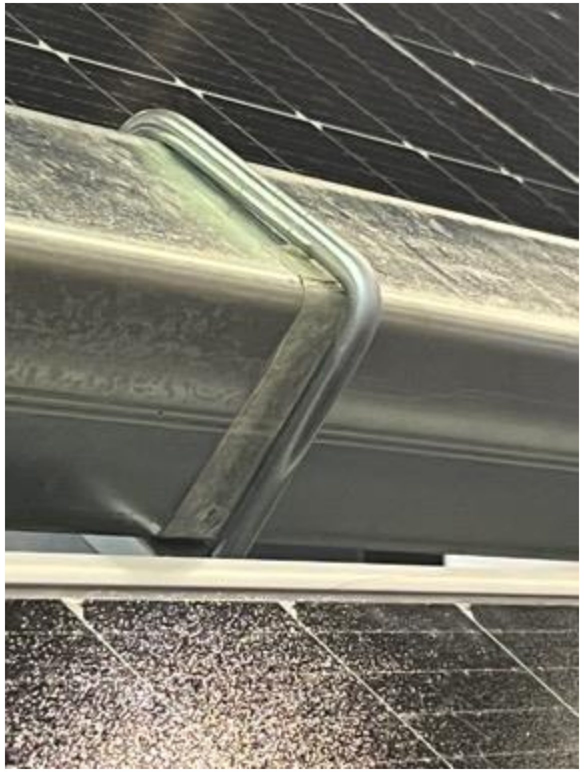
Proliferation of Poor SAT Designs

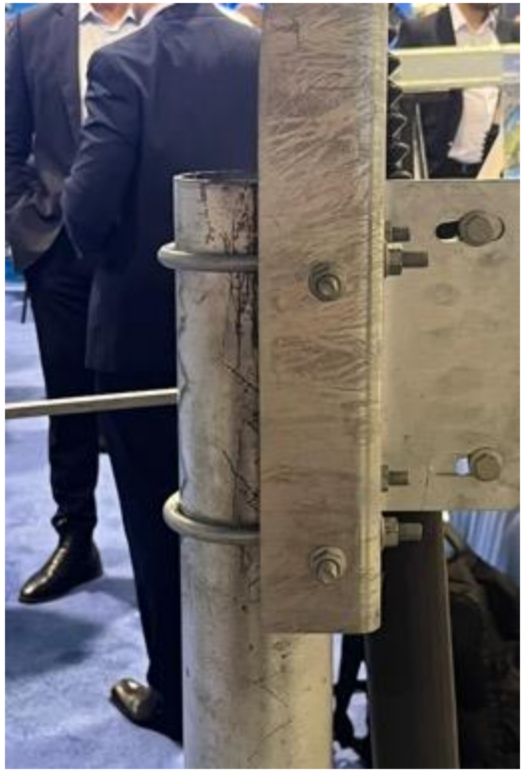
- Competitive industry
- Downward cost pressure
- Impact of Inflation Reduction Act in the US

Washer in slotted plate



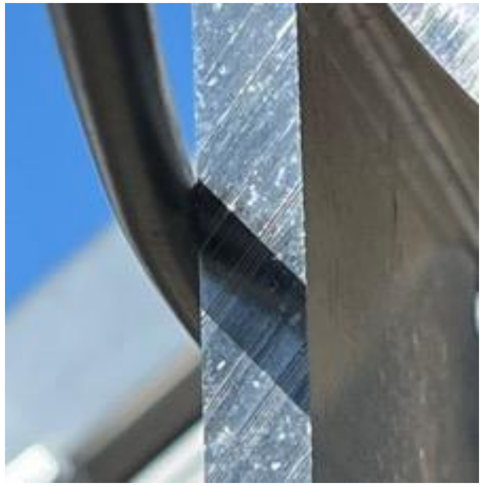
Bent wire under tension

Cotter pin??



At-risk joint

Bad Construction and Installation Practices



Sharp edges; abrasion of the cable is inevitable

Modules stored backside up; connectors fully exposed

Plastic cable ties are a disaster waiting to happen

Modules left in open circuit, connectors uncapped

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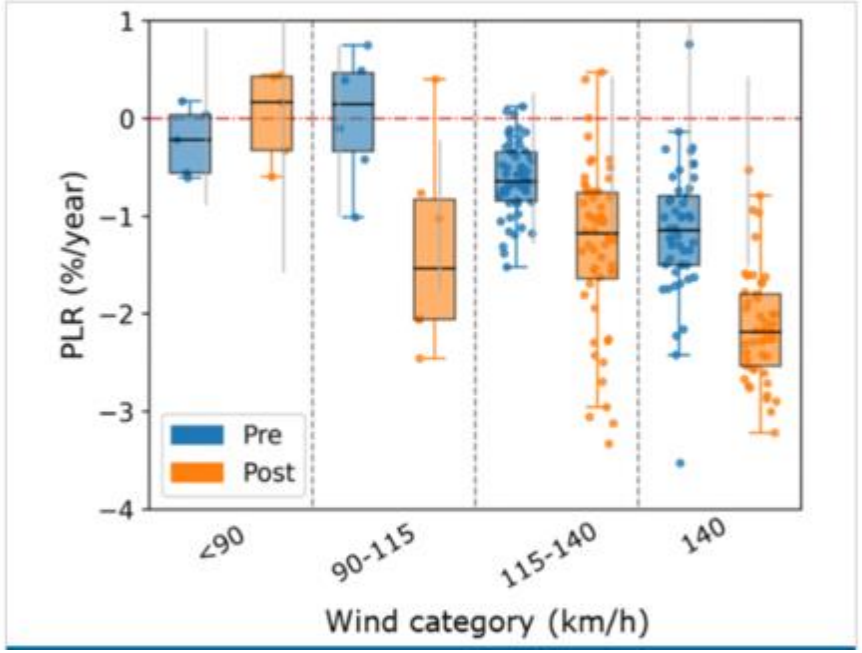
Impacts of Tropical Cyclones on PV Power Plants

Immediate:

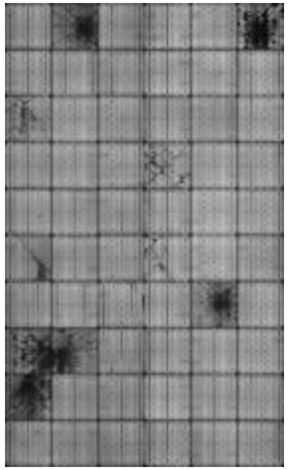
1. Reduced power generation = lack of irradiance
2. Total/partial loss of power = site/partial-site destruction

Delayed Manifestation:

1. Reliability of modules and balance-of-system components
2. Under-performance and accelerated degradation



Jordan, D., et al. *PV Tech,* 2023



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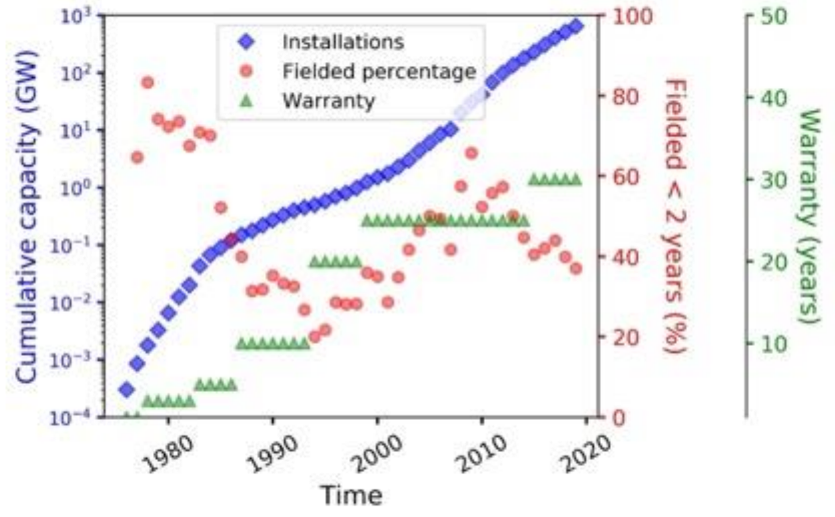
Why It is Hard to Know

- Little data available (most is confidential related to plant value and insurance/litigation):

"National databases significantly under-report damage losses because the complete picture is hard to obtain (federal agency data, private sector date, confidentiality, litigation, etc.)"

Source: Science for Disaster Reduction (US inter-Agency Working Group)

  - No centralized repository for reporting damages,
  - No standardized methodology for systematically recording loss and damage; no common vocabulary
  - No comprehensive studies on the long-term impacts on LCOE and performance



Gregory M Wilson *et al* 2020 *J. Phys. D: Appl. Phys.* **53** 493001

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What About Accelerated Testing?

- Accelerated testing does not capture the full picture, as evidenced by continued field failures and skyrocketing insurance claims.
  - EAST - Extended Accelerated Stress Testing (single-factor indoor testing, multiple repetitions) -- IEC
  - CAST - Combined Accelerated Stress Testing (E, T, RH, H_2O stressor sequences; dynamic measurements). -- NREL
  - FAST – Field Accelerated Stress Testing -- ASU
- Above allows for performance comparisons across modules; identifies electrical degradation and materials failures but under defined conditions.
- Do not fully represent the many variables and their interactions in the field: does not test for specific extreme weather events; doesn't capture system-level vulnerabilities, inter-dependencies and materials substitutions.
- Misses important degradation mechanisms, including backsheet cracking, moisture ingress, interconnect corrosion, LeTID and PID.

C-AST chamber, from the uncapped connector experiment; Source: David Miller, NREL..

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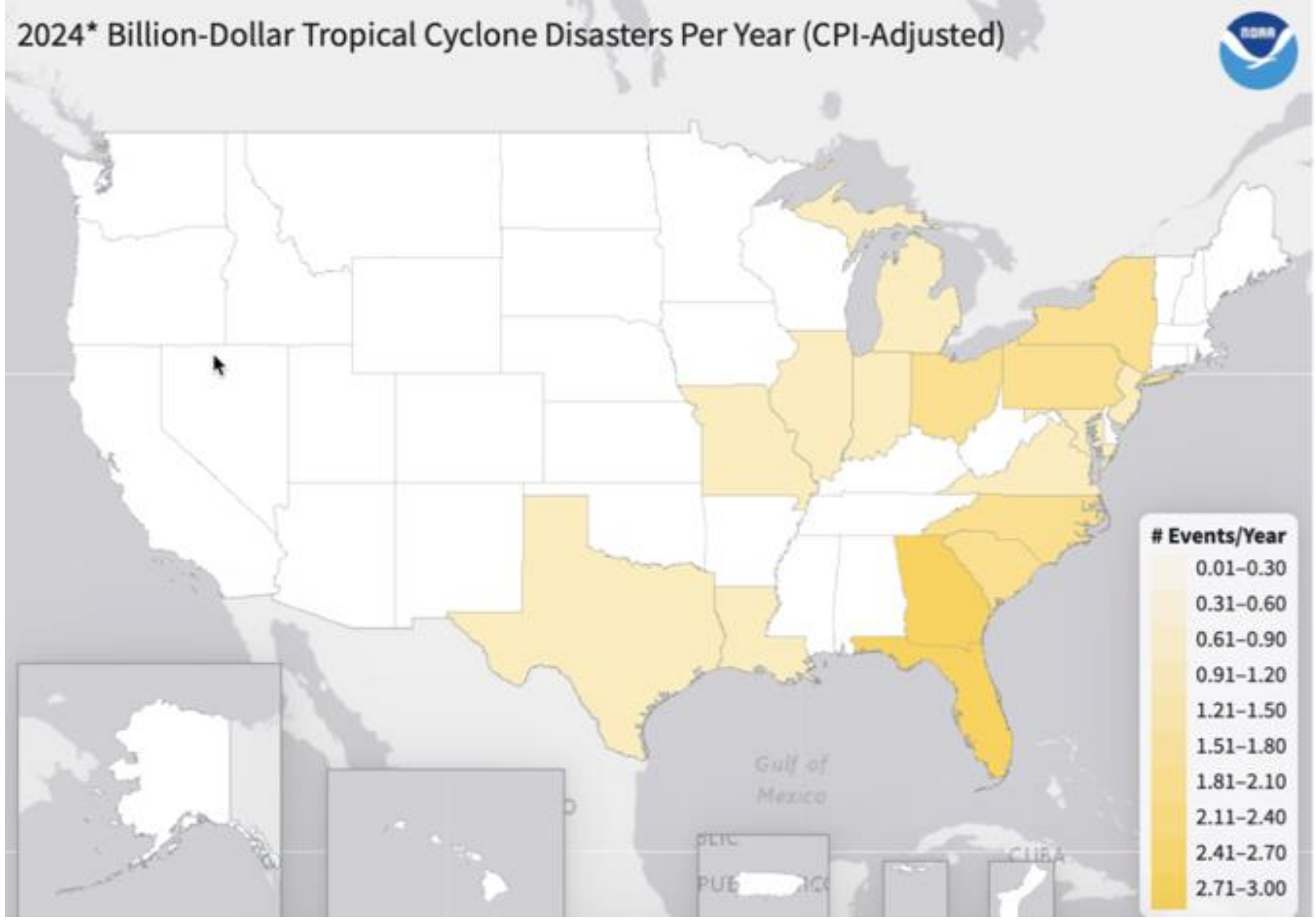
What About Standards?

- Module reliability (UL61730, IEC 61215, IEC 62938); structural and electrical reliability (IEC 61730, UL2703, DIN25201, ASCE 7-16
- Slow process relative to pace of technological change and new operating conditions and stresses
- Data confidentiality also an issue

Perspective from the US



State ranking by cumulative solar capacity

1. California - 49,421 MW
2. Texas - 34,907 MW
3. Florida - 16,865 MW
4. North Carolina - 9,698 MW
5. Arizona - 8,934 MW
6. Nevada - 7,644MW
7. Georgia - 6,147 MW
8. New York - 6,125 MW
9. Virginia - 5,799 MW
10. New Jersey - 5,434 MW

Of the 363 billion-dollar weather disasters since 1980 (as of August 2023), tropical cyclones (or hurricanes) have caused the most damage: over $1.3 trillion total, with an average cost of $22.8 billion per event. They are also responsible for the highest number of deaths: 6,890 since 1980.

Case Studies from the US in 2024

- Sandia-led, US DOE-funded investigation of extreme weather and PV
- We are partnering with 2 EPCs; 3 asset owners on hurricane damages

Hurricane Milton – Oct 7-10

- Localized tornado hit operating PV plant
- Damage to a plant under construction was non-uniform; ~ 100 modules broken
- More extensive damages to PV plants occurred; TBD

Hurricane Helene – Oct 26-29

- 30% of this one EPC’s sites in NC and SC impacted by Hurricane Helene: all damage was caused flooding and site erosion
- Only 50% of modules installed
- Onsite pallets appear undamaged
- Intense soiling on backside of the modules

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Check List for Possible Damages

Modules

- Frame and glass breakage from torsional stress (winds > 240 km/h)
- Glass breakage from flying debris
- Torsional galloping
- Excessive soiling (front and back)

Racking and Hardware

- Structural deformation: twisting
- Fasteners (break and loosen from vibrational forces); also susceptible to corrosion: torque verification; visible inspection for deformation and corrosion

Cables and Connectors

- Fretting and abrasion
- Moisture ingress
- Partial unseating
- Electrical resistance and thermal imaging of connectors

Site Damage

- Flooding and erosion (impact on electrical system, racking)
- Debris onsite and on panels

Other

- For plants under construction: partially assembled strings (modules in open circuit); exposed module pallets; open trenches and cable spools)
- Long-term O&M (increased electrical resistance; performance losses)
- Crew interviews

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Best Practices

Siting Analysis

- Estimate site risk based on climate projections and historic patterns
- Consider site topology

Design Considerations

- Ground-mounted SAT vs fixed-tilt; double-posts
- Modules; glass/bs, smaller form factor; reinforced
- Cable and connector management
- Lockbolt fasteners (not threaded bolts)

Pre-Storm Planning

- Response plan in place
- Onsite debris management
- Stow strategy in place
- O&M training

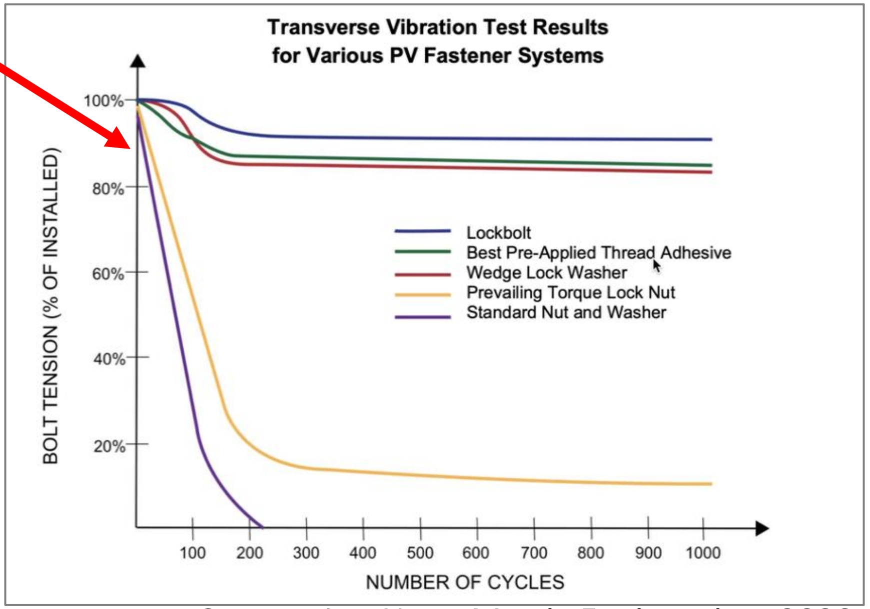
Post-Storm Response

- Safety issues paramount
- Execute inspection checklist
- Document

Long-term Monitoring

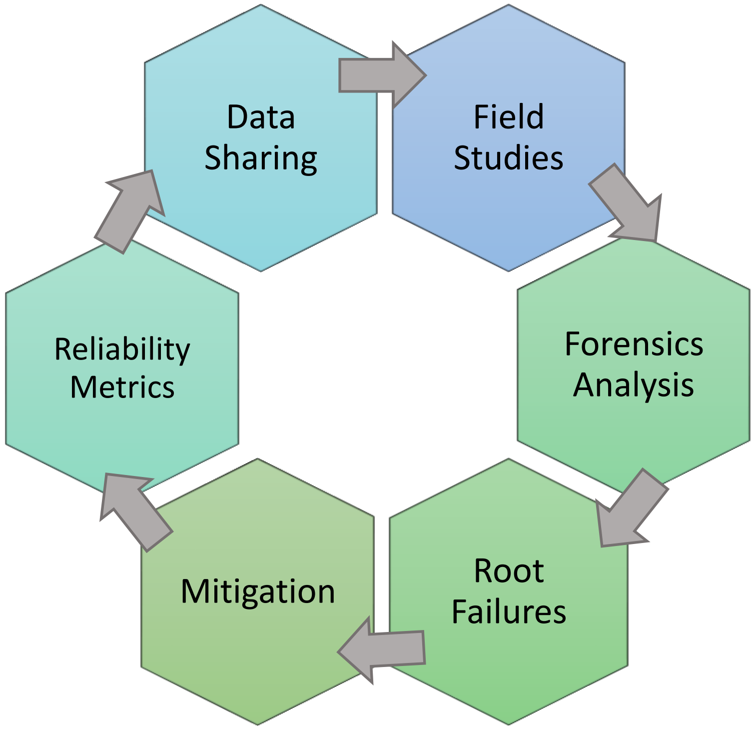
- Performance loss ration
- Thermal imaging

Connector caps



Source: Jon Ness. Matrix Engineering, 2020.

Summary



Multi-faceted ,, cooperative approach is needed

- Tropical cyclones are projected to increase in intensity across the northern hemisphere.
- Significant reduction in risk is possible: siting and design/procurement decisions; pre-and post-storm response plans (field forensics are essential); workforce training (installation and O&M); standards.
- More research is needed on intra-modular and component performance and reliability to inform the design of climate-specific modules
- Multi-partite approach is needed with significant cooperation between research community and industry
- Important to remember that weather knows no boundaries; must be a global collaborative effort

Thank You

Arigatō

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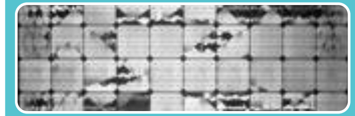
Weather-Induced Failures and Consequences

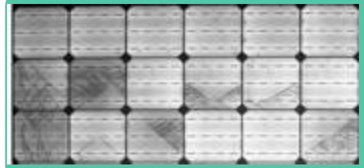
Catastrophic failure

- Obvious visible damage/destruction



Sub-catastrophic failure

- Invisible damage
- Cells, encapsulants, backsheets, soldering joints, cell inter-connects



Delayed failure modes

- Moisture ingress/oxidative stress
- Crack propagation from further mechanical stress

Accelerated degradation

Changing climate = increase in heat and humidity

Risks shifted to asset owner

- Module warranties
- Insurance coverage

Typical Exclusion for Module Warranty:
"Damage caused by extreme natural phenomena (earthquakes, typhoons and tornados, volcanic eruptions, flood and storm tides, lightning, hailstorms and heavy snowstorms, tsunamis, etc."

$$\mathrm{LCOE} = \frac{I - \sum_{t=1}^{T} d_t\, \gamma^t \times \alpha + \sum_{t=1}^{T} c_t\, \gamma^t \times (1-\alpha) - S\, \gamma^T}{\eta \sum_{t=1}^{T} \gamma^t \times x_t}$$

Higher LCOE

Not yet apparent; metrics for success are rates of deployment and costs per kWh instatlled

Power Losses ?