National Laboratory of the Rockies

Resilience Metrics Framework for Solar Photovoltaics

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IEEE PVSC 54; New Orleans, Louisiana

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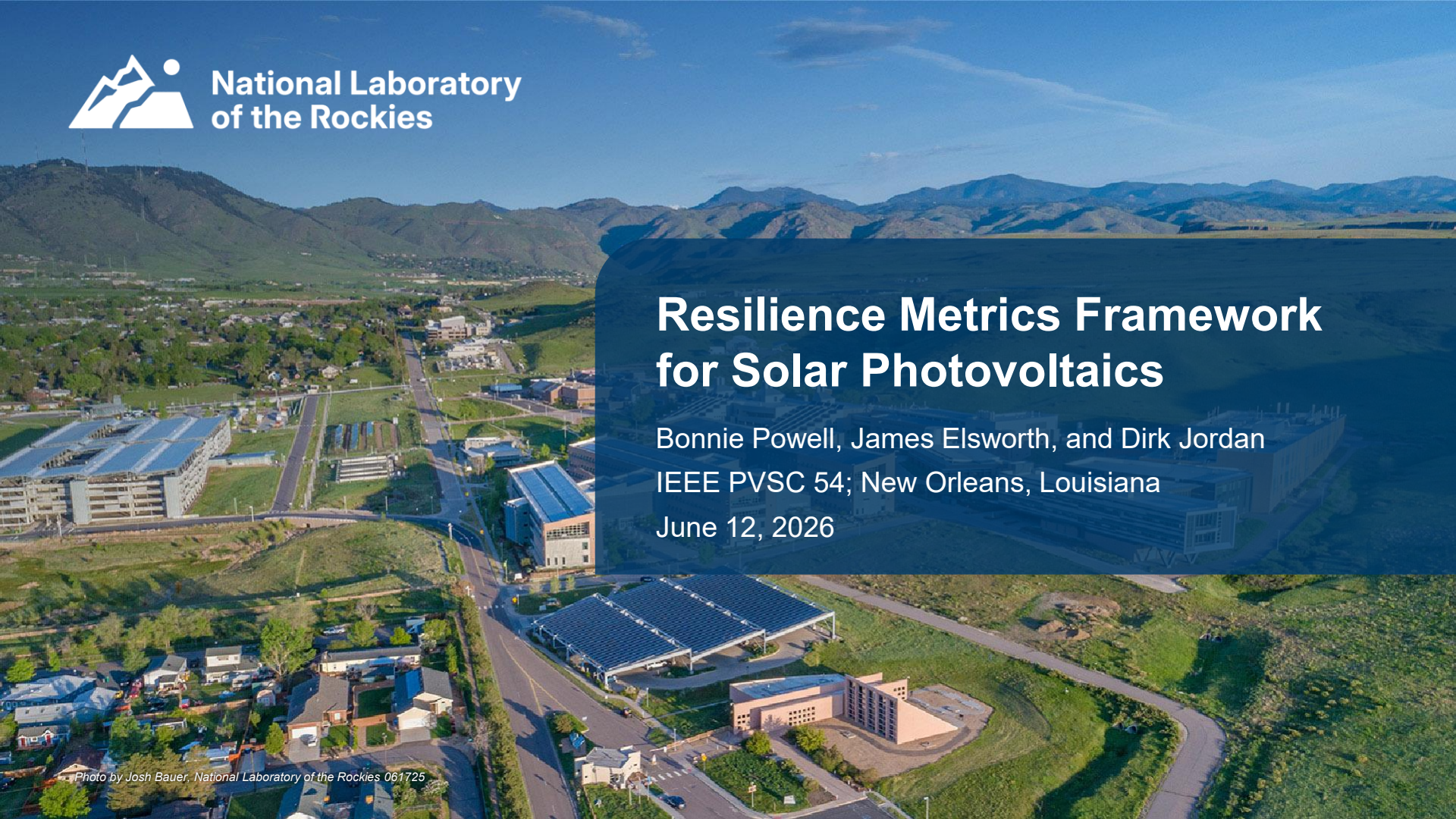


Photo by Josh Bauer, National Laboratory of the Rockies 061725

Solar Photovoltaics (PV) Resilience

- PV systems can survive storms, but are not inherently resilient
- Analysis of 170 weather-impacted systems found a median loss of 1% of annual production (Jordan et al. 2023)

No damage to a PV array in Guam after category 4 Typhoon Mawar hit in 2023. Photo from James Elsworth, NLR

Solar Energy Largely Unscathed by Hurricane Florence's Wind and Rain

In North Carolina, the #2 solar state, Florence was the first extreme weather test for much of its renewable energy.

By Dan Gearino
September 20, 2018

Source: https://insideclimatenews.org/news/20092018/hurricane-florence-solar-panel-energy-resilience-extreme-weather-damage-wind-flooding/

Solar survives storms: Sunnova, D3Energy systems prove resilient through Hurricanes Milton and Helene

October 17, 2024 By Paul Gerke 4 MIN READ SHARE TO:

Source: https://www.renewableenergyworld.com/solar/residential/solar-survives-storms-sunnova-d3energy-systems-prove-resilient-through-hurricanes-milton-and-helene/

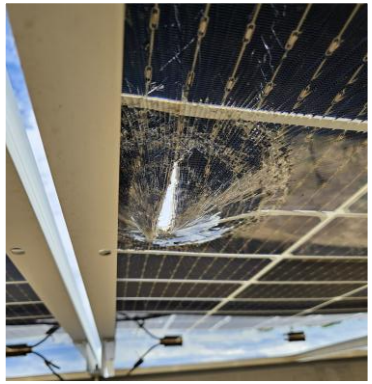
Local News

Massive Hail Storm Takes On Over 3,000 Solar Panels And Loses

May 10, 2017 / 10:46 AM MDT / CBS Colorado

Source: https://www.cbsnews.com/colorado/news/solar-panels-survive-hailstorm/

Solar PV Damage From Severe Weather



Photos by James Elsworth, NLR

Impacts of PV Damage

- Damaged PV leads to financial and operational impacts
  - Clean-up, re-design, repair, installation costs
  - Lost power production
- Resilient PV could:
  - Suffer less damage
  - Recover more quickly
  - Have lower insurance premiums
  - Meet performance/levelized-cost-of-energy targets
  - Deliver critical power (if designed to do so)

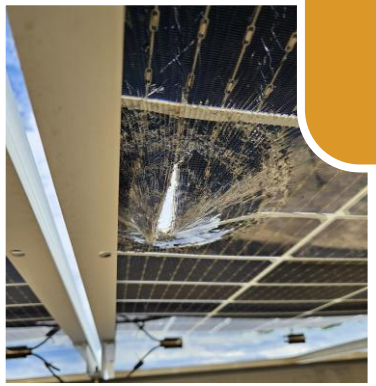
Hail damage to solar projects: 1% of filed claims, but over 50% of total losses

Hail damage has become a real headache for project developers in the United States, where growing deployment has increased exposure to weather-related risk. As project owners seek to limit the impact of hail on their bottom line, innovations in tracking systems and insurance can help.

By **Mark Hutchins** | 19 Sep 2025

Source: https://www.pv-magazine.com/2025/09/19/hail-damage-to-solar-projects-1-of-filed-claims-but-over-50-of-total-losses/

Solar PV Damage From Severe Weather



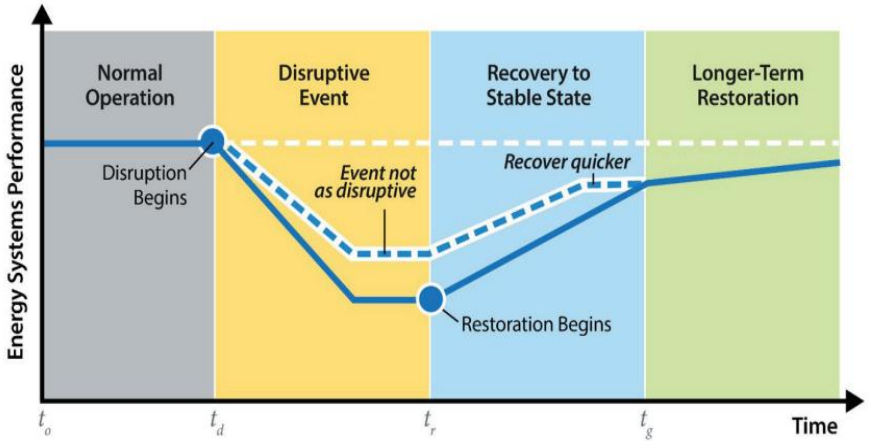
How resilient were these systems?

Photos by James Elsworth, NLR

Resilience vs. Reliability

Resilience: "A system's ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions." (Hotchkiss and Dane 2019)

- Resilience focuses on **low-probability, high-consequence events that are *external* to the system**
- Reliability focuses on the ability to meet electricity needs under **normal operating conditions and from disruptions *internal* to the system**



Source: NLR and Panteli et al. 2015

Measuring Resilience

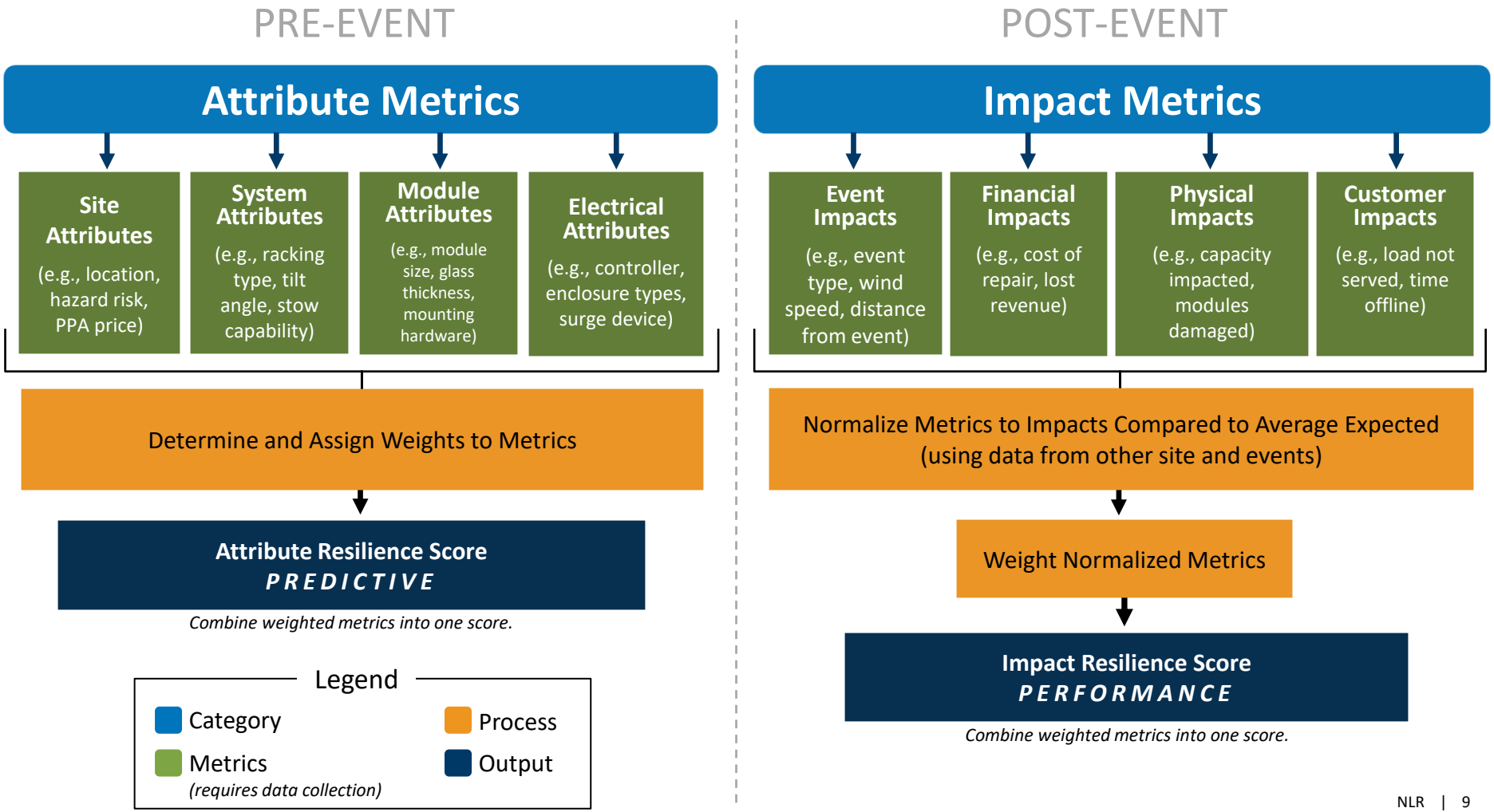
- Metrics are needed to **quantify, predict, and compare** the resilience of PV, considering different:
  - **Hazard intensities and risks** (locations)
  - **System attributes** (e.g., fixed/tracker, module size, type of bolts, stow capabilities, module glass thickness, installation quality)
    - Varying attributes can make systems more or less vulnerable to impacts from hazards
- Metrics can be used to correlate resilience to different system attributes and hazard intensities

PV Resilience Metrics Can:

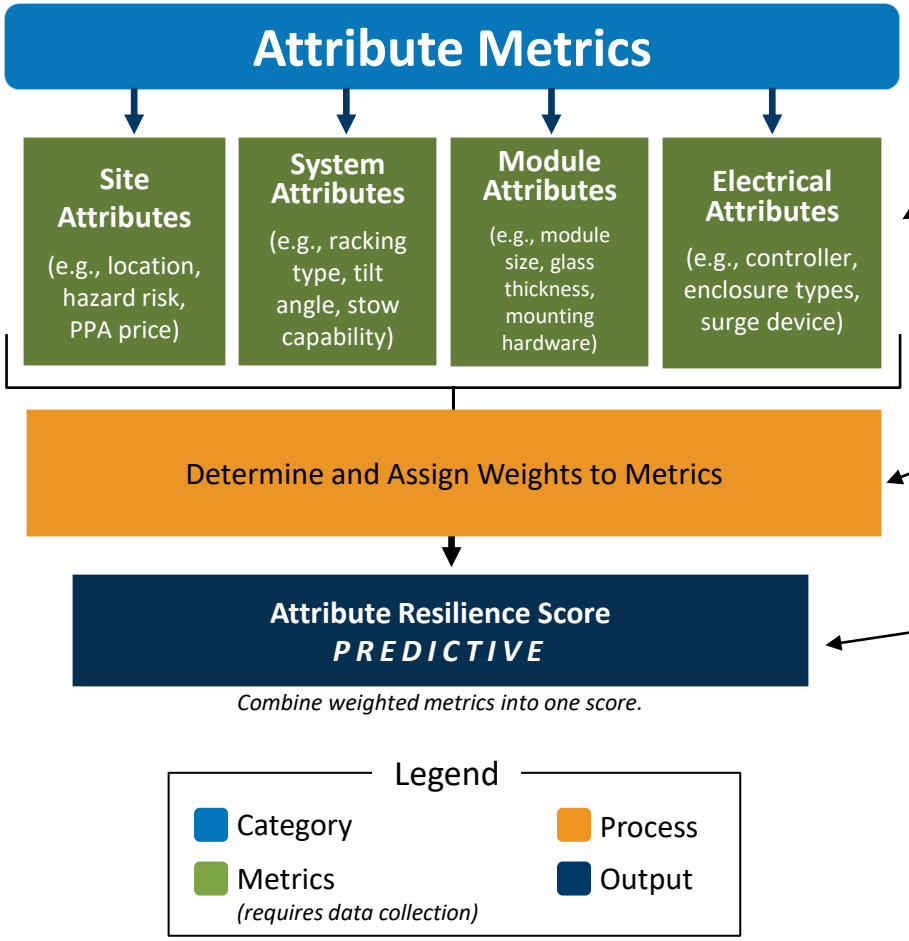
- Guide improved design and standards
- Enable more customized insurance rates
- Establish a consistent basis for data collection, reporting, and evaluation by industry
- **Evaluate the impacts of PV systems that have been subject to natural hazards (post-event)**
- **Predict resilience for any PV system (pre-event)**

The PV Resilience Metrics Framework

Note: this work is building off the metrics framework first presented in Elsworth and Powell 2025


PRE-EVENT
Attribute Metrics
Site Attributes
(e.g., location, hazard risk, PPA price)
System Attributes
(e.g., racking type, tilt angle, stow capability)
Module Attributes
(e.g., module size, glass thickness, mounting hardware)
Electrical Attributes
(e.g., controller, enclosure types, surge device)
Determine and Assign Weights to Metrics
Attribute Resilience Score
PREDICTIVE
Combine weighted metrics into one score.
Legend
Category
Process
Metrics
(requires data collection)
Output
POST-EVENT
Impact Metrics
Event Impacts
(e.g., event type, wind speed, distance from event)
Financial Impacts
(e.g., cost of repair, lost revenue)
Physical Impacts
(e.g., capacity impacted, modules damaged)
Customer Impacts
(e.g., load not served, time offline)
Normalize Metrics to Impacts Compared to Average Expected (using data from other site and events)
Weight Normalized Metrics
Impact Resilience Score
PERFORMANCE
Combine weighted metrics into one score.

PRE-EVENT



Collect attribute data points

Specific to the hazard type

Quantify the data points

Based on the hazard risk, quantify how good/bad that attribute is, based on performance of past systems

Future work

Assign weights

Impacts of storms on past systems, considering their different attributes, will determine the weights

Future work

Sum into one **attributes resilience score**

Predicts resilience to future hazards based on attributes of the site + system

Collect impact data points

Specific to the hazard type

Using damage functions!

Normalize data points

First to the system size, then by comparing to the performance of comparable systems that have been impacted by the same hazard. Results in impact ratios.

Future work

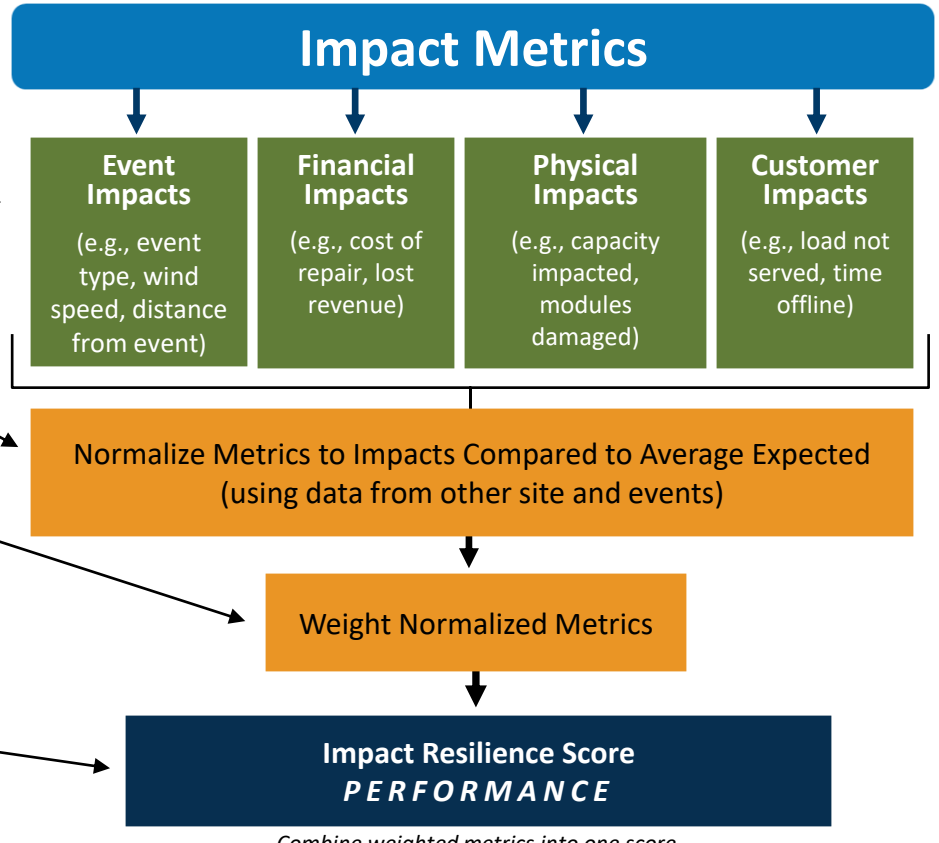
Assign weights to the impact ratios

Based on the hazard risk and past system data

Sum into one **impact resilience score**

Evaluates resilience compared to a baseline system.

POST-EVENT



Combine weighted metrics into one score.

Repeat for Each Hazard

Attribute Resilience Score (ARS)

$$Overall\ ARS = ARS_{hail} + ARS_{wind} + ARS_{snow} + ARS_{earthquake} + \ \ldots$$

Attribute Resilience Score
PREDICTIVE

Impact Resilience Score (IRS)

$$Overall\ IRS = IRS_{hail} + IRS_{wind} + IRS_{snow} + IRS_{earthquake} + \ \ldots$$

Impact Resilience Score
PERFORMANCE

Impact Metrics Example
"Modules Visibly Damaged"

Site 1

Category	Sub-category	Data Point	Collected Value	Data Point Normalized to System Size	Normalized Value	Baseline System (Avg. Expected Value)	Impact Ratio Metric	Impact Ratio Value	Weight	Impact Resilience Score
Impact (Post-Event)	Physical Impacts	Modules Visibly Damaged	1,700 modules	Percentage of Modules Visibly Damaged	14%	X	Module impact damage ratio	Y	TBD	TBD

How do we compare to a baseline system?

$$= \frac{14\%}{X\%}$$

Damage Functions

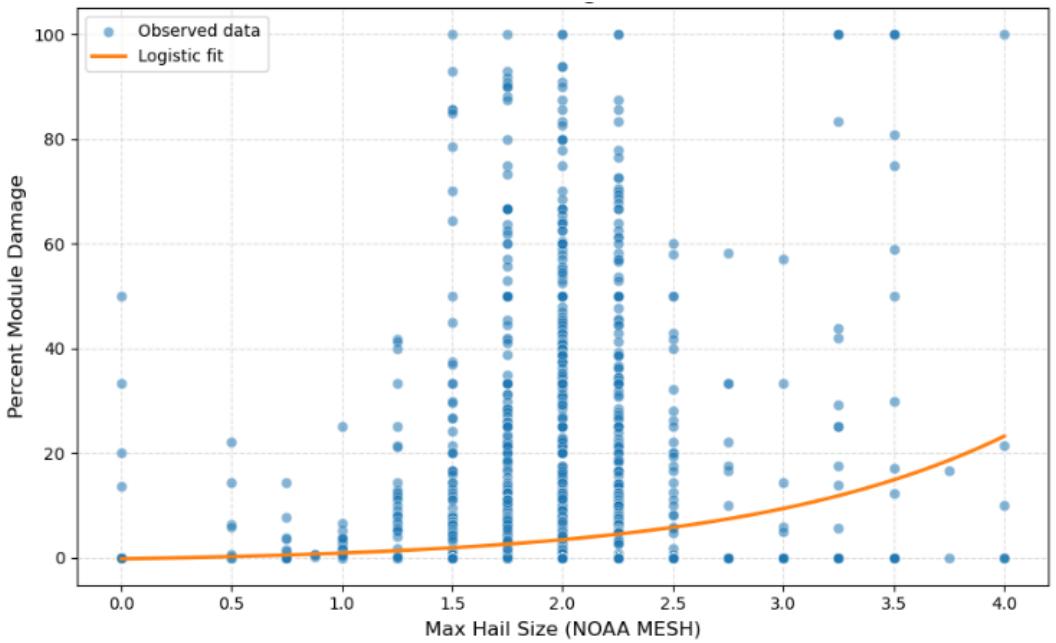
Damage Functions Establish A Baseline To Compare Against

Hail

- Dataset of **~11,500 systems** analyzed using satellite imagery
  - 99% in Austin, Texas impacted by a 2023 hailstorm – and **94% of these had no observed damage** (Perry et al. 2025)
  - 1% from utility-scale systems damaged by various hail events nationwide
- Variability of damage
  - The radar reports maximum expected hail size, which likely did not impact each module. Some modules may not have been hit by any hail.
  - System attributes could impact survivability more than the hazard
- Logistic function applied

$$y = L\left(\frac{1}{1 + e^{-k(x-x_o)}}\right) + b$$

$L = maximum\ damage, x_0 = midpoint,$
$k = shape\ factor\ accounting\ for\ steepness,$
$b = y\ intercept$

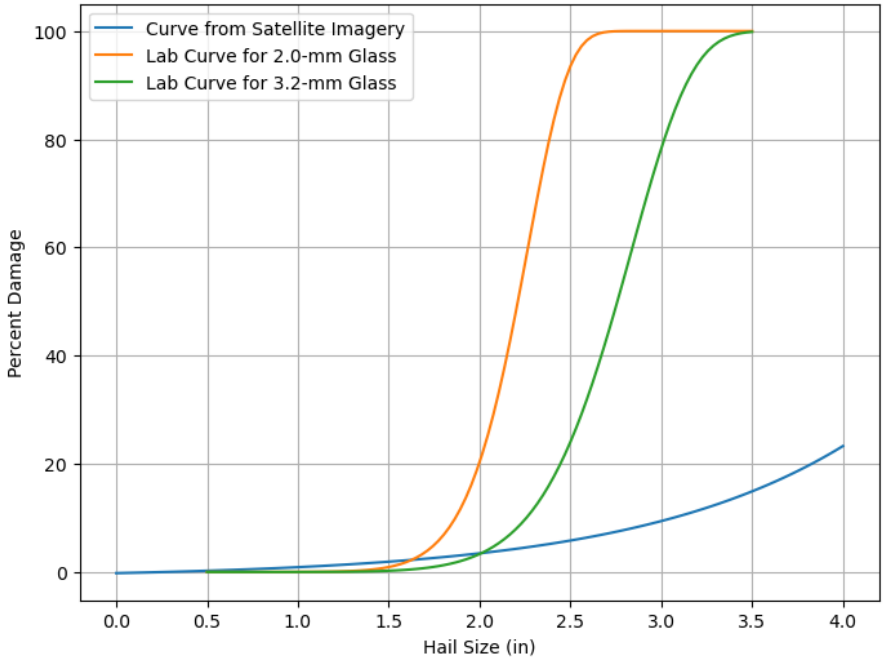


Solar PV module hail damage from 11,481 systems. Fitted parameters: L=30,615, x_0=12.45, k=0.84, b=-1.04. Data from Perry et al. 2025, supplemented with additional data from the authors.

Damage Functions From Laboratory Testing

Hail

- Laboratory testing from Renewable Energy Test Center (RETC; kWh Analytics 2023) show greater damage than field at high hail sizes
- Many differences between lab and field
  - Distribution of hail stone sizes
  - Unknown if all field sites were actually hit by hail
  - Wind that changes hail impact angle and speed
  - Varying module tilt angles and azimuths (incl. stow mode)
- **Field damage functions needed for different system attributes** (future work)
  - Glass thickness, size of module, frame thickness, module attachment method



Probability of glass breakage curves from laboratory hail damage testing for different PV module glass thicknesses (orange and green lines) compared to the curve derived from the field damage using satellite imagery (blue line). Source: laboratory curves recreated from RETC (kWh Analytics 2023).

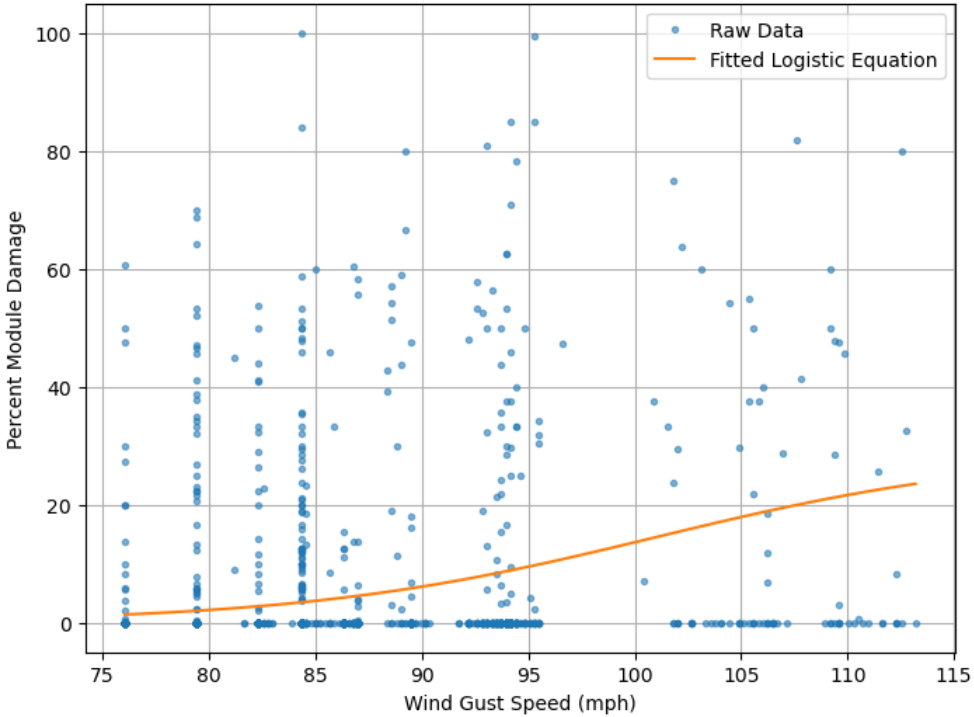
Damage Function for Wind

Wind

- Dataset of ~1,500 systems impacted by two 2017 tropical hurricanes (Perry et al. 2025)
  - **83% of the sites that experienced hurricanes had no observed damage**
- Variability of damage
  - Radar-reported wind speed may not have been what actually hit the system (or all of the system)
  - System attributes could impact survivability more than the hazard
- Same logistic function applied

$$y = L\left(\frac{1}{1 + e^{-k(x-x_o)}}\right) + b$$

$L = maximum\ damage, x_0 = midpoint,$
$k = shape\ factor\ accounting\ for\ steepness,$
$b = y\ intercept$



Solar PV module wind damage from two 2017 tropical hurricanes, representing 1,534 damaged systems. Fitted parameters: L=29, x_0=101, k=0.12, b=0. Data from Perry et al. 2025.

Case Studies

Colorado Hailstorm

- Baseball sized hail (2.75”) in Colorado in 2025
- Hail damaged front and rear windshields, trees, property
- Two PV sites on adjacent plots were in the storm’s path

		Site 1	Site 2
Attributes	System Size	6.4 MW_{DC}	7.6 MW_{DC}
	# Modules	11,934	14,059
	Module Front Glass Thickness	2.0 mm	3.2 mm
	Module Frame Height	30 mm	35 mm
	Tilt Angle at Time of Event	0°	55°
	Max Hail Size	2.75”	2.75”
Impacts	# of Modules w/ Fractured Glass	1,700	900
	% Modules w/ Fractured Glass	14%	6%
	Estimated Repair Cost (at $0.50/W replacement)*	$460,000	$240,000

**Repair cost considers materials and labor; does not consider business interruption from lost power production*

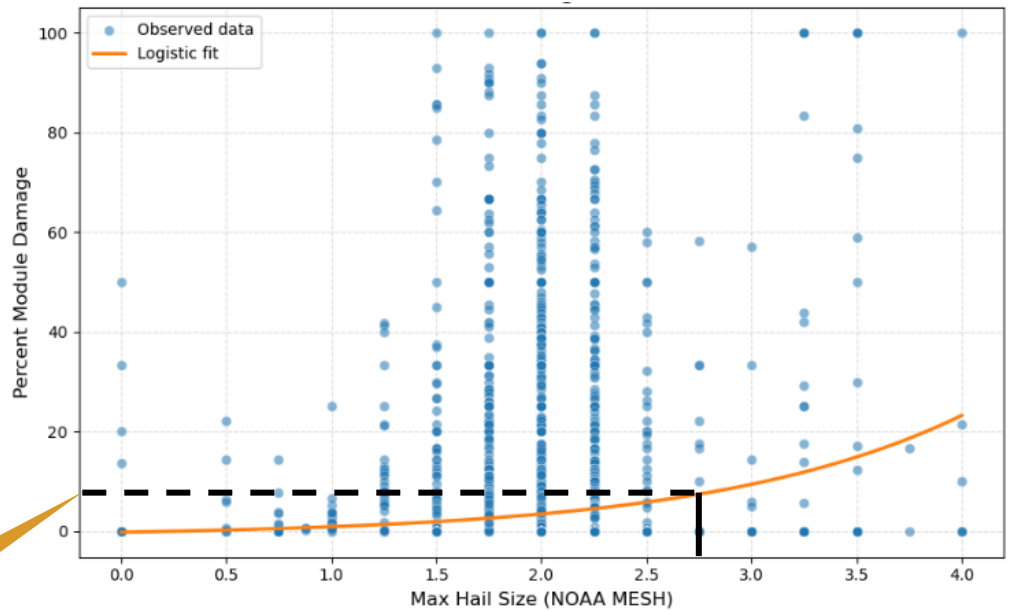
PV module damage from a Colorado hailstorm in 2025.

Photos by James Elsworth, NLR

Comparing Colorado Hail-Damaged Sites to the Hail Damage Function

Hail

- Colorado hailstorm
  - **Site 1:** 6.4 MW_{DC} system, 14% modules damaged
  - **Site 2:** 7.6 MW_{DC} system, 6% modules damaged
- Baseline system (avg. expected damage): 8%



Solar PV module hail damage from 11,481 systems. Fitted parameters: L=30,615, x0=12.45, k=0.84, b=-1.04. Data from Perry et al. 2025, supplemented with additional data from the authors.

This curve predicts 8% damage from 2.75” hail

Impact Metrics Example for Colorado Sites

"Modules Visibly Damaged"

Site 1
(2.0 mm glass)

$$= \frac{14\%}{8\%}$$

Damage was 75% higher than baseline

Category	Sub-category	Data Point	Collected Value	Data Point Normalized to System Size	Normalized Value	Baseline System (Avg. Expected Value)	Impact Ratio Metric	Impact Ratio Value	Weight	Impact Resilience Score
Impact (Post-Event)	Physical Impacts	Modules Visibly Damaged	1,700 modules	Percentage of Modules Not Visibly Damaged	14%	8%	Module impact damage ratio	1.75	TBD	TBD

Impact Metrics Example for Colorado Sites

"Modules Visibly Damaged"

Site 1
(2.0 mm glass)

$= \frac{14\%}{8\%}$ Damage was 75% higher than baseline

Category	Sub-category	Data Point	Collected Value	Data Point Normalized to System Size	Normalized Value	Baseline System (Avg. Expected Value)	Impact Ratio Metric	Impact Ratio Value	Weight	Impact Resilience Score
Impact (Post-Event)	Physical Impacts	Modules Visibly Damaged	1,700 modules	Percentage of Modules Not Visibly Damaged	14%	8%	Module impact damage ratio	1.75	TBD	TBD
Impact (Post-Event)	Physical Impacts	Modules Visibly Damaged	900 modules	Percentage of Modules Not Visibly Damaged	6%	8%	Module impact damage ratio	0.75	TBD	TBD

Site 2
(3.2 mm glass)

Damage was 75% of baseline

$= \frac{6\%}{8\%}$

Tropical Storm – High Wind Event

- Tropical storm hit a ~90 MW_{DC} PV system with estimated maximum wind speeds of 106 mph

Photo by James Elsworth, NLR

	Site 3
Size	88.8 MW_{DC}
# Modules	220,000
# Racks	15,700
Module Front Glass Thickness	3.2 mm
Module Frame Height	40 mm
Module Length	2.0 m
Module Width	1.0 m
Module Attachment Clamp Surface Area in Contact with Module	1.17 in^2 per clamp x 4 clamps
Tilt Angle at Time of Event	10°
Max Wind Speed	106 mph
# Modules Damaged	755
% Modules Damaged	0.34%
# Racking Sets Damaged	110
% Racking Sets Damaged	0.70%
Estimated Repair Cost (at $0.50/W replacement)*	$460,000

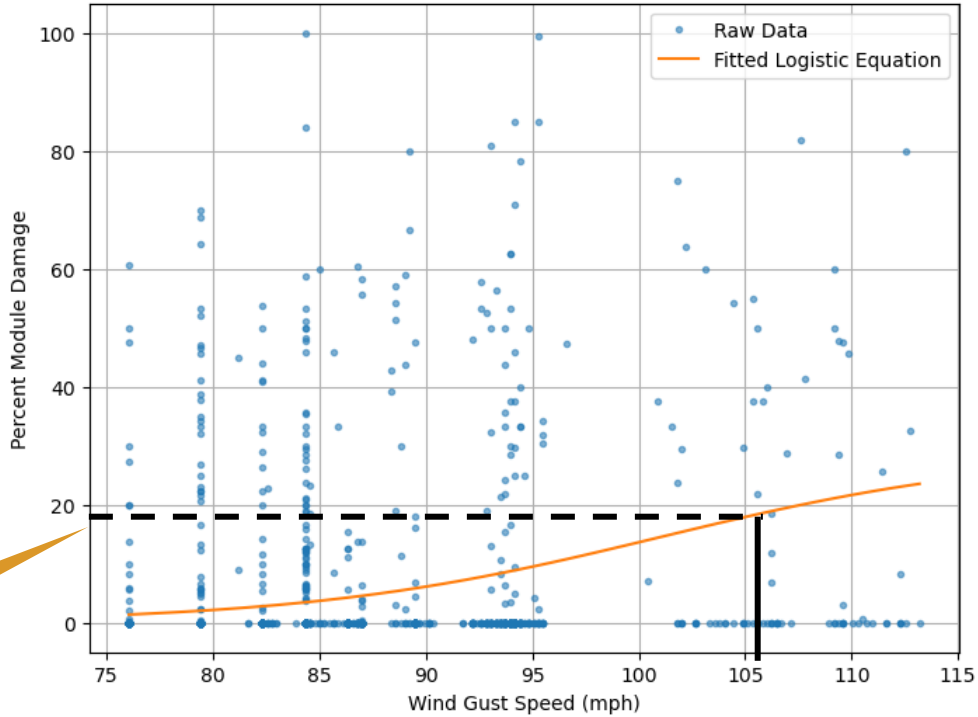
**Repair cost considers materials and labor; does not consider business interruption from lost power production*

Comparing Tropical Storm-Damaged Site to the Wind Damage Function

Wind

- Example: ~90 MW_{DC} system hit by a hurricane with 106 mph winds
  - Observed modules damaged: 0.34%
  - Baseline system (avg. expected damage): 19%

This curve predicts 19% damage from 106 mph winds



Solar PV module wind damage from two 2017 tropical hurricanes, representing 1,534 damaged systems. Two data points with a sample size of 1 at high wind speeds were omitted. Fitted parameters: L=29, x_0=101, k=0.12, b=0. Data from Perry et al. 2025.

Impact Metrics Example for Tropical Storm "Modules Visibly Damaged"

Site 3

$$= \frac{0.34\%}{19\%}$$

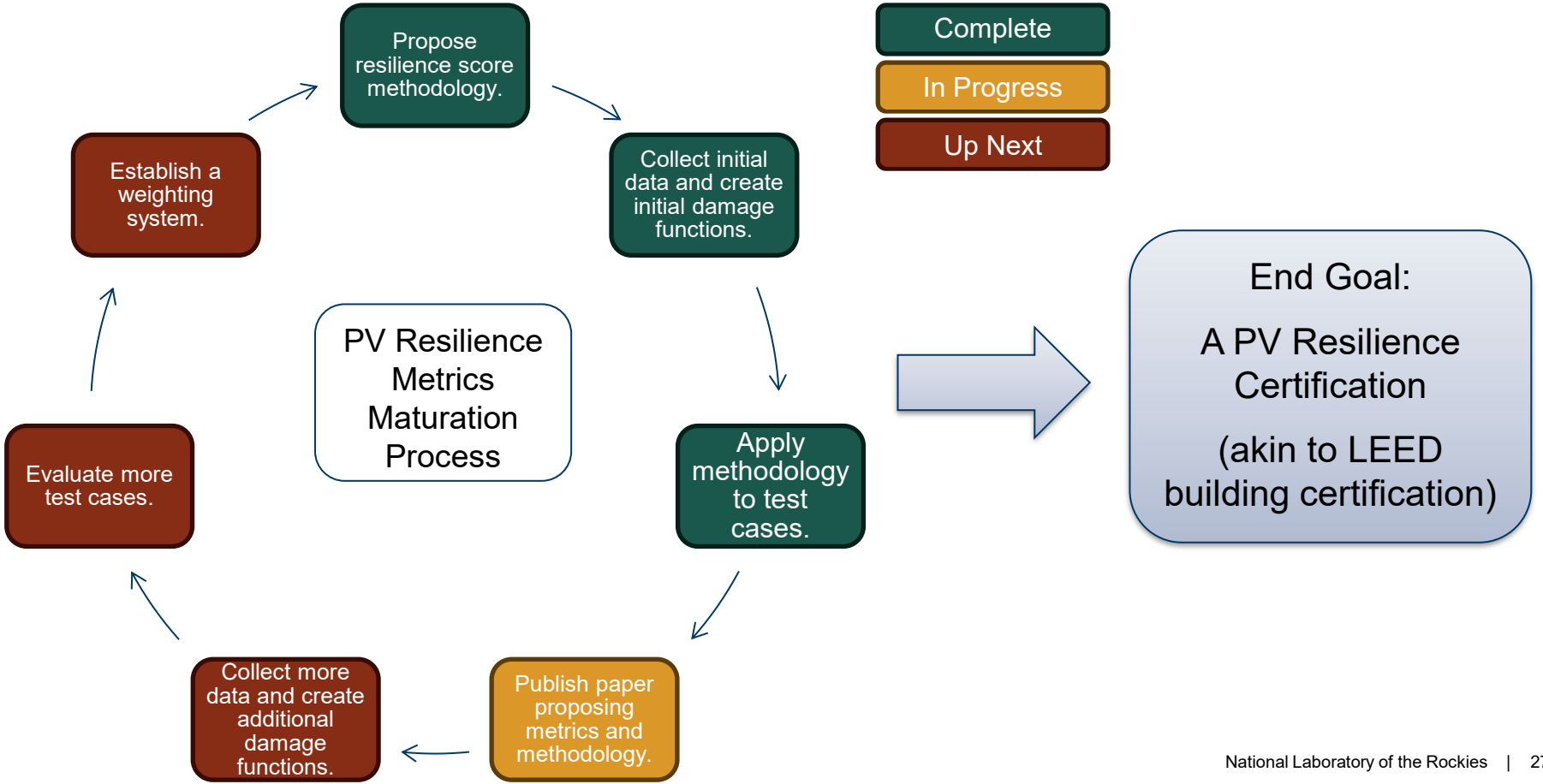
Category	Sub-category	Data Point	Collected Value	Data Point Normalized to System Size	Normalized Value	Baseline System (Avg. Expected Value)	Impact Ratio Metric	Impact Ratio Value	Weight	Impact Resilience Score
Impact (Post-Event)	Physical Impacts	Modules Visibly Damaged	755 modules	Percentage of Modules Not Visibly Damaged	0.34%	19%	Module impact damage ratio	0.02	TBD	TBD

Damage was 2% of baseline

Likely due to **robust system attributes** like low tilt angle, small modules, clamps with a large contact area, thick module frames, and robust racking support system

Next Steps

Refining the PV Resilience Metrics Framework



Resilient Solar PV Certification

- Based on resilience metrics framework
- Could follow LEED certification framework (checklists that earn points)
- Risk-based approach: analyzing hazards x vulnerabilities x consequences of failure
- Consider geographical hazards, criticality of load served

Photo by Werner Slocum/ NLR 065625

Call for Collaboration

- Join a working group to refine the framework and metrics, develop a PV resilience certification
- Beta test resilience metrics with site damage you have experienced
- Site assessments

Contact:

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Photo by Joe DelNero / NLR 103812

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Questions?

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