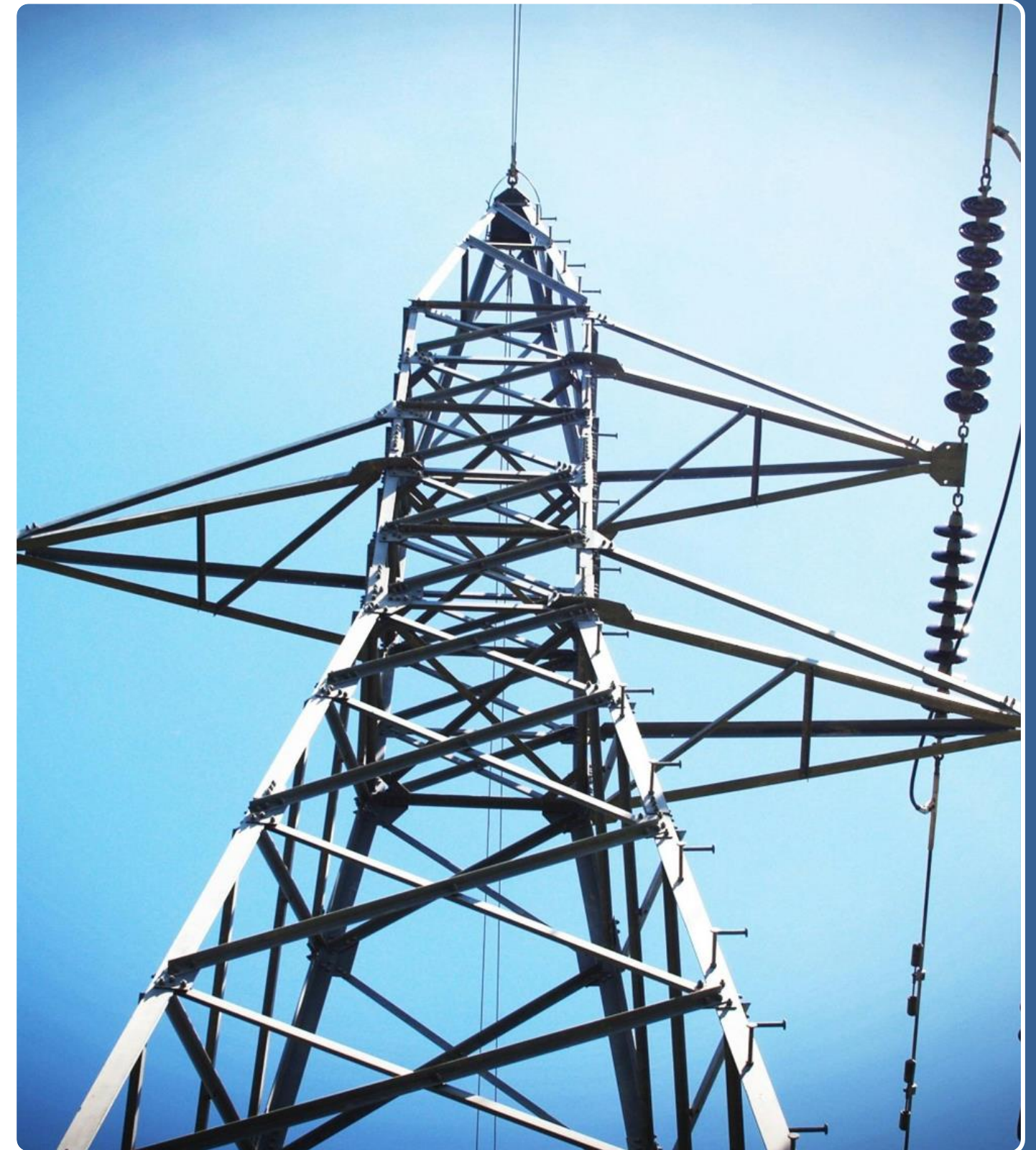


# Resiliency Metrics & Valuation for Electric Grid Decision-Making

 Presented by | Shikhar Pandey  
April 28, 2026



# Outline

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IEEE Resilience Metrics

System Resilience

Operational Resilience

Case Studies

Valuing Resiliency

Tool Demo





# 01 | IEEE Resiliency Metric



# What is Resiliency?

- FERC has proposed that resilience means the “**ability to withstand and reduce the magnitude and/or duration of disruptive events**, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event.”

*Credit: Utility Dive Feb 2, 2018, by Kate Konschnik and Brian Murray*

## ● Proposed IEEE Definition

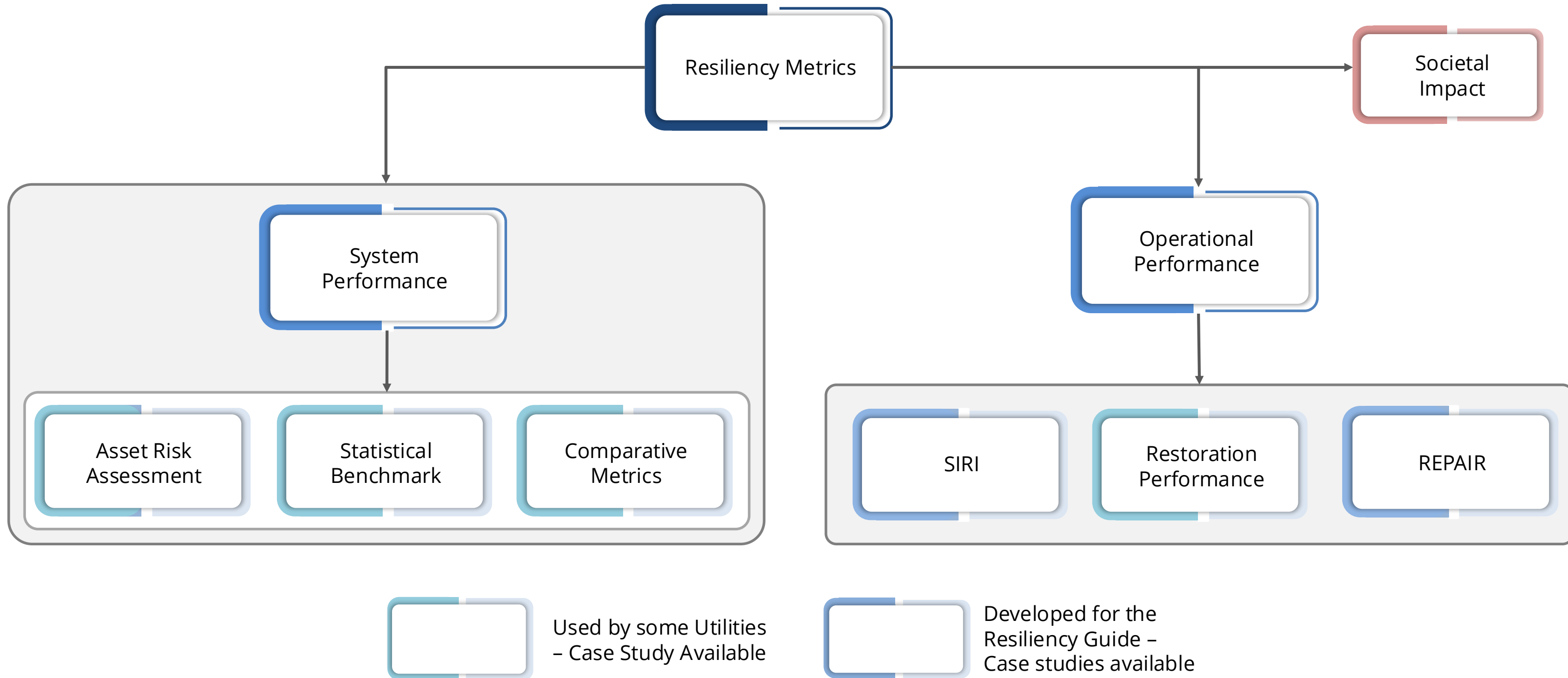
The capability of electric power **distribution** systems to **deliver** electric energy to end-use customers by **avoiding interruptions and/or recovering this capability** following exposure to **naturally occurring high impact low frequency events**.

### **IEEE Distribution Resiliency Focus**

Out of scope: BES, Cyber/Physical Security, Operational Events

Primary Focus: Extreme Weather Events, Natural Phenomenon

# A Comprehensive Suite of Metrics



These metrics are designed by the IEEE Distribution Resiliency Taskforce. They are currently in draft and will be refined.



**1. Climate Vulnerability Studies:** Utilities are assessing risks from climate hazards to understand the impact on their assets

Description	Temperature, Heat and Humidity	Flooding	Wind and Ice	Wildfire
<b>Exposed Assets-At-Risk Properties</b>	Thermal rating reduction, Accelerated asset degradation	Water-related equipment sensitivity, Corrosion, Soil Weakening	Wind and Ice Loading Tolerance, Vegetation Proximity	Fire-related equipment damage, Smoke on conductors, Soot accumulation over insulators, damaged insulators exhibiting high leakage currents, Vegetation Proximity

**2. Asset-Risk Assessment Metric:** Utilizes two matrices:

- **Exposure Properties to Risk Matrix:** Identifies asset properties affected by climate change
- **Assets-to-Exposure Matrix:** Prioritizes asset strengthening based on risk levels (medium, high, low) against climate change variables

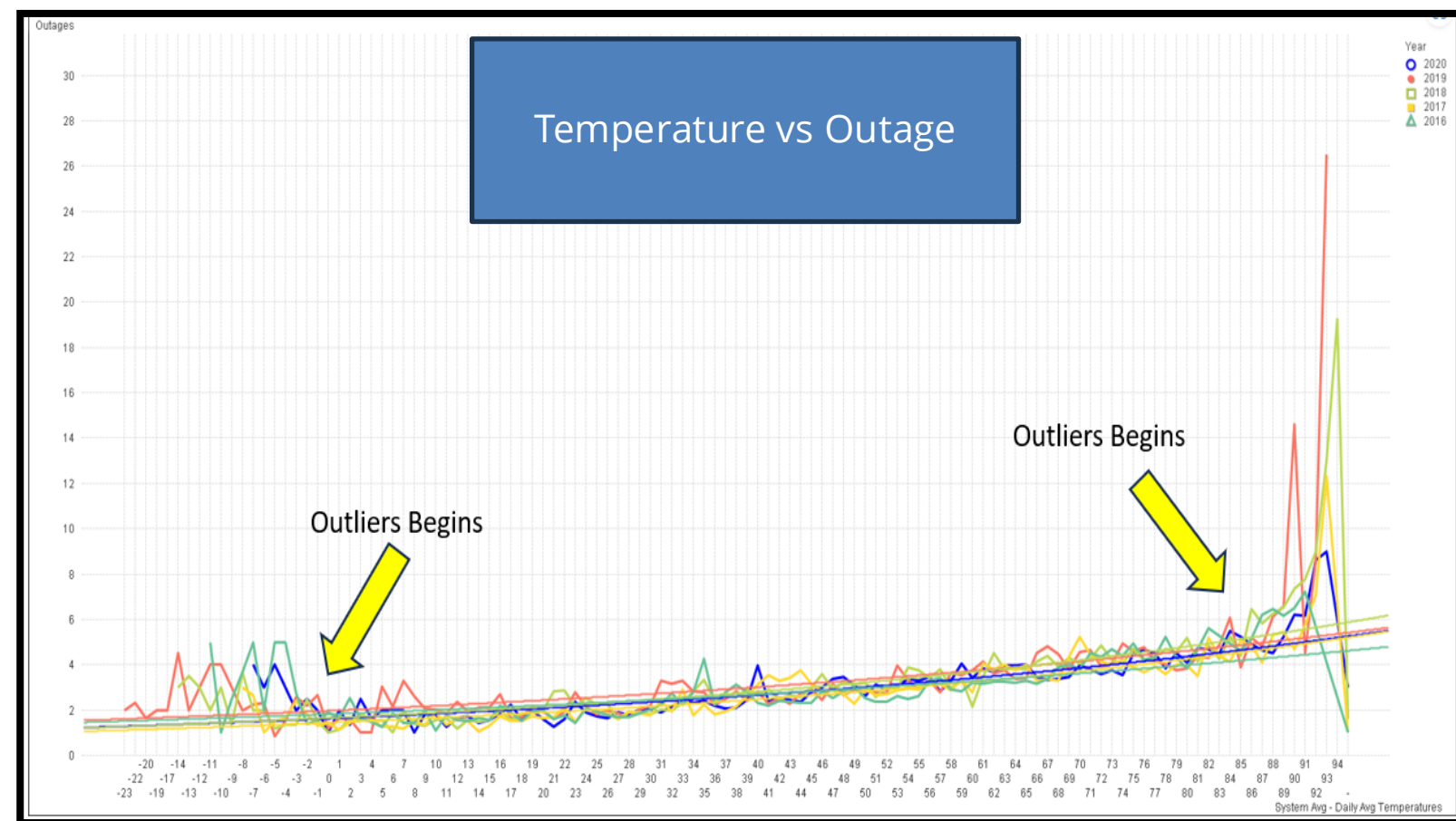
Equipment vs Threat	Temperature, Heat and Humidity	Flooding	Wind and Ice	Wildfire
Substation	High Risk	High Risk	Low Risk	Low Risk
Overhead Equipment	Medium Risk	Low Risk	High Risk	High Risk
Underground Equipment	High Risk	Medium Risk	Low Risk	Low Risk



# Statistical Benchmark: Outages on Gray Sky days

Gray Sky Day: Focuses on robustness and the ability to withstand most weather events

- We established a statistical benchmark based on weather parameters and historical outages
- This benchmark tracks the system performance (of outages) during gray sky days



**Yellow** !

- Average temperature between 80 and 85 degrees
- Average temperature between 0 and -5 degrees
- Average sustained wind speed between 25 and 30 MPH
- Average of one-hour wind gust between 25 MPH and 30 MPH
- Average rainfall between 0.75" and 1"
- Lightning stroke count between 3,000 and 6,000

**Orange** !

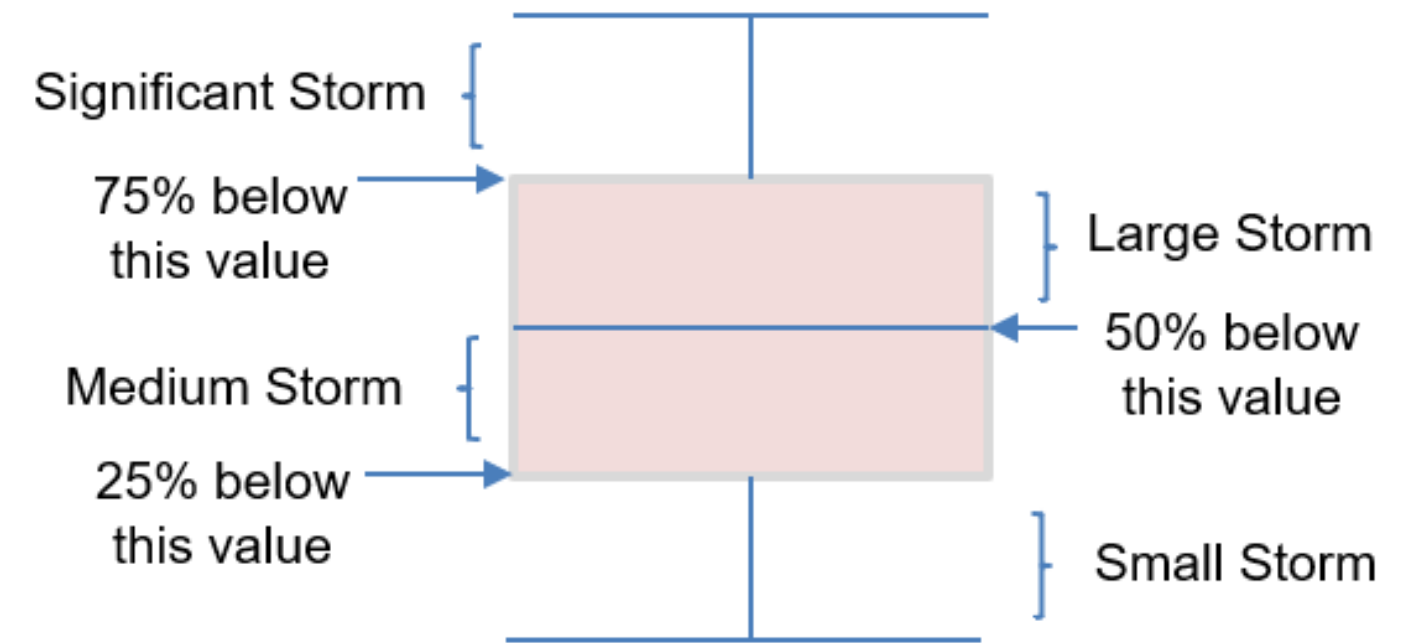
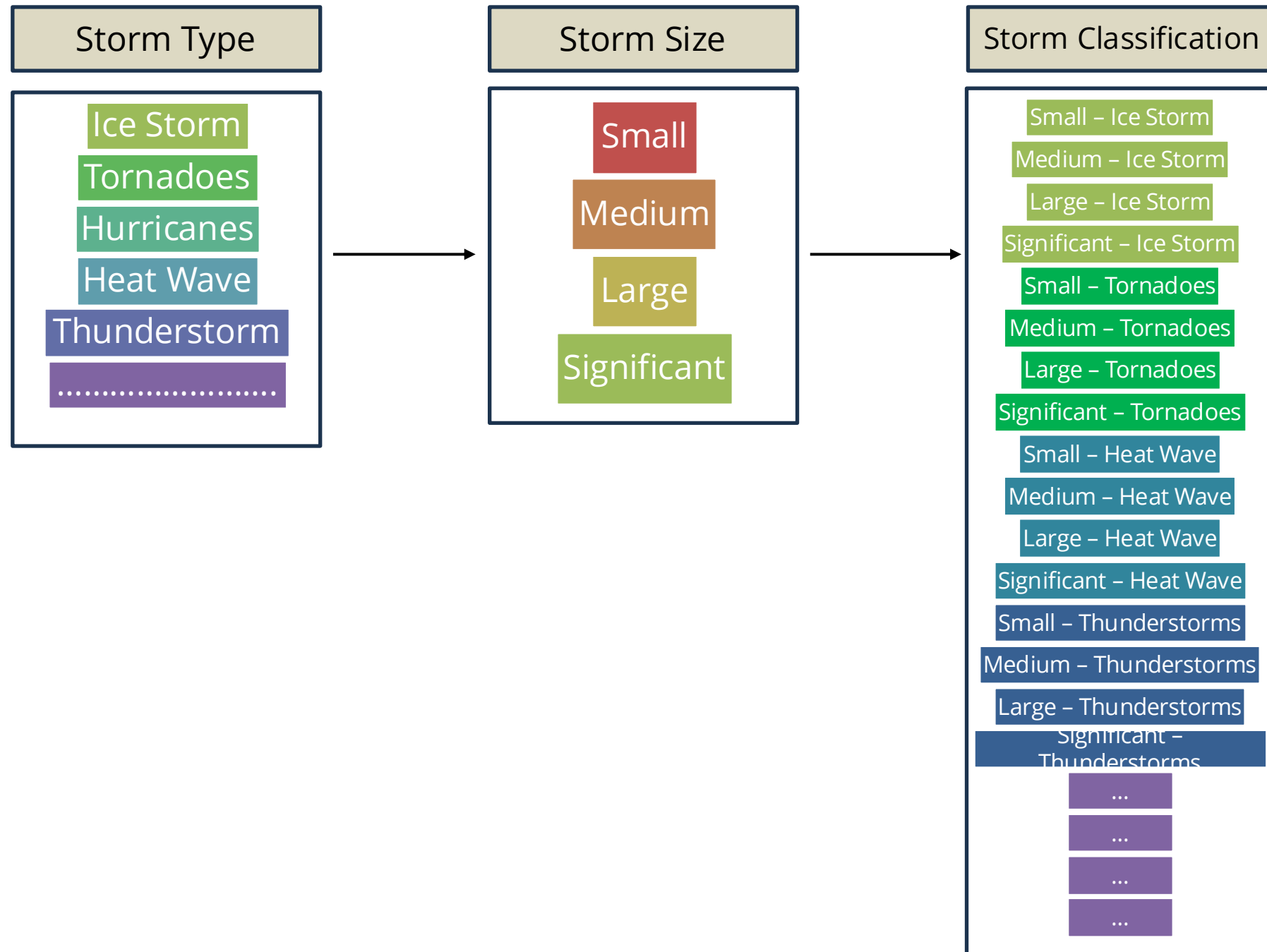
- Average temperature between 85 and 90 degrees
- Average temperature between -5 and -10 degrees
- Average sustained wind speed between 30 and 35 MPH
- Average of one-hour wind gust between 30 MPH and 35 MPH
- Average rainfall between 1" and 1.25"
- Lightning stroke count between 6,000 and 10,000

**Red** !

- Average temperature greater than 90 degrees
- Average temperature less than -10 degrees
- Average sustained wind speed  $\geq$  35 MPH
- Average of one-hour wind gust  $\geq$  30 MPH
- Average rainfall greater than 1.25"
- Lightning stroke count greater than 10,000



# Storm Classification



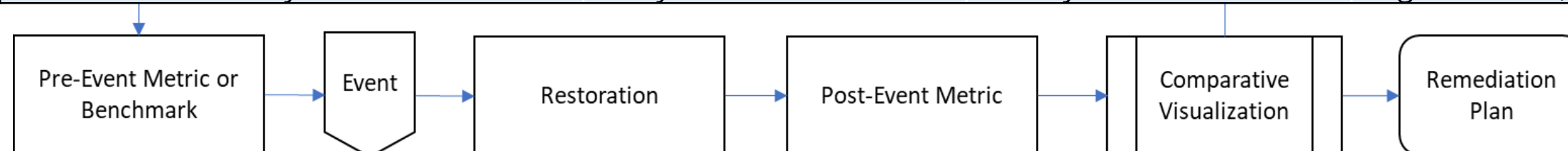
It is Important to classify different storm categories to apply the metrics on.



# Comparative Metrics



Metric	Attributes	Historical Benchmark	Current Event Records	Performance Assessment
Storm Strength Comparison	Wind Speed	70 mph	80 mph	Increased wind speed, correlates with longer outages
	Precipitation	2 inches	3 inches	Higher precipitation, potential cause for disruptions
Flood Comparison – Substations/Underground Equipment	Substation Outages due to Flood	5 incidents	3 incidents	Improved resilience, fewer outages
	Underground Equipment Outages due to Flood	10 incidents	12 incidents	Slight increase, review flood mitigation strategies
Square Miles Impacted/Customer Density	Square Miles Impacted	50 sq miles	60 sq miles	Larger area impacted, reassess preparedness
	Customer Density	1,000 customers/sq mile	1,200 customers/sq mile	Higher density, more significant impact
Pole Damage Comparison	Pole Damage Incidents	15 incidents	20 incidents	Increased incidents, consider reinforcement strategies
Equipment Damage Comparisons	Equipment Damage Incidents	30 incidents	52 incidents	Increased incidents, proactive maintenance strategy
Construction Person Hours to Restore Hardened vs. Non-Hardened	Construction Person Hours - Hardened	500 hours	450 hours	Improved efficiency, hardening measures effective
	Construction Person Hours - Non-Hardened	1,200 hours	1,400 hours	Increased time, need for further hardening measures
Smart Grid Performance	Smart Grid - Interruptions Avoided	300 incidents	350 incidents	Improvement, smart grid enhancing resilience
Equipment Comparison (Substation /Distribution)	Hardened Substation (Outages)	80,000	60,000	Improved performance, effective hardening measures
	Non-Hardened Substation (Outages)	86,667	125,333	Increased, monitor for further hardening
	Hardened Distribution (Outages)	106,667	155,333	Big increase, analysis needed
	Non-Hardened Distribution (Outages)	126,667	185,333	Increased vulnerability, consider reinforcement
Restoration Comparison to Prior Events	Restoration - 24 hrs	60% restored	55% restored	Slight delay, assess resource allocation
	Restoration - 48 hrs	85% restored	80% restored	Similar delay, possible need for more resources
	Restoration - 72 hrs	95% restored	92% restored	Minor delay, review efficiency
	Total Restoration Days	5 days	5.5 days	Slight increase, investigate specific challenges



# Example on Comparative Metrics Application

$$\text{X-Parameter Performance Ratio (X-PR)} = \frac{\text{Incidents Avoided}}{\text{Incidents Avoided} + \text{Sustained Incidents}}$$

- Take a circuit that has 200 poles and historically experiences 20% of them being damaged during significant storms.

$$\text{Historical Pole Damage metric} = \frac{(200 - 40)}{(200 - 40) + (40)} = \mathbf{0.8}$$

- Event 1 affects 25% of the poles Event 2 affects 5% of the poles.

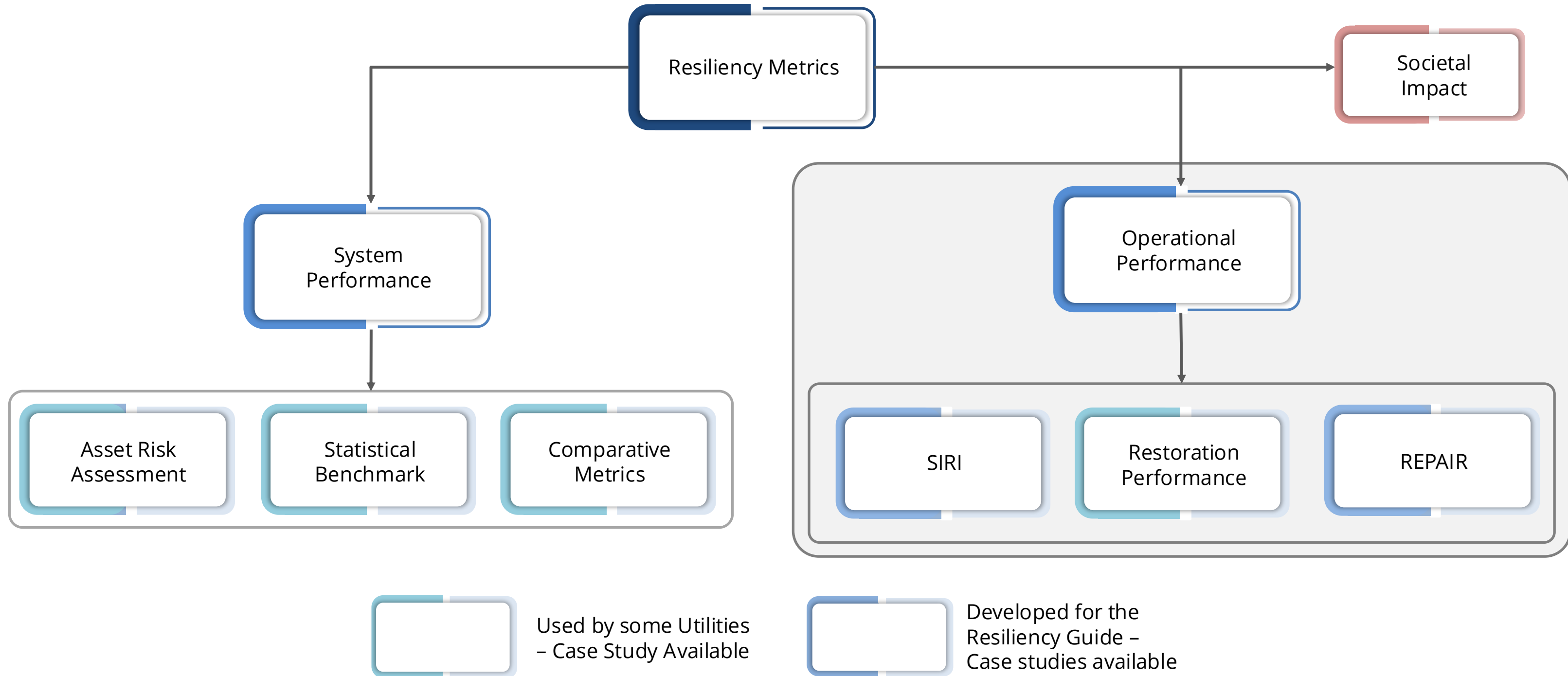
$$\text{Event 1 Pole Damage Metric} = \frac{(200 - 50)}{(200 - 50) + (50)} = \mathbf{0.75} \qquad \text{Event 1 Pole Damage Ratio} = \frac{(0.75)}{(0.8)} = \mathbf{0.94}$$

$$\text{Event 2 Pole Damage Metric} = \frac{(200 - 10)}{(200 - 10) + (10)} = \mathbf{0.95} \qquad \text{Event 2 Pole Damage Ratio} = \frac{(0.95)}{(0.8)} = \mathbf{1.19}$$

Ratio less than unity indicates system performance less favorable than historical; whereas the event ratio greater than unity indicates performance favorable than historical benchmark.



# A Comprehensive suite of Metrics



These metrics are designed by the IEEE Distribution Resiliency Taskforce. They are currently in draft and will be refined.



# Sustained Interruption Reduction Index (SIRI)



$$\text{SIRI} = \frac{\text{Avoided Sustained Customer Interruption (CI) by Automation/Hardening}}{\text{Avoided Sustained CI by Automation/Hardening} + \text{Sustained CI}}$$

Aspect	Key Points
Perfect Resilience Scenario	Automation Performance <b>Ratio of 1</b> signifies perfect resilience, ensuring uninterrupted service and high customer satisfaction.
Factors Influencing the Ratio	<b>Automation Mechanisms:</b> Impact on outage prevention. <b>Sustained Outages:</b> Causes like equipment failure or external disruptions.
Real-World Implications	<b>Case Studies:</b> Successful automation in outage prevention. <b>Challenges:</b> Areas where automation needs improvement.
Trends Over Time	<b>Historical Analysis:</b> Trends in Automation Performance Ratio and automation strategies. <b>Continuous Improvement:</b> Informing ongoing efforts.
Comparisons with Other Metrics	<b>Comprehensive Resilience:</b> Alignment with other metrics. <b>Interconnected Nature:</b> Holistic understanding of grid resilience.
Operational Considerations	<b>Response Times:</b> Speed of detection, decision-making, and execution. <b>Adaptability:</b> Handling different disturbances.
Scalability and Adaptability	<b>Scalability Challenges:</b> For larger grid systems. <b>Technological Advances:</b> Enhancing automation systems.
Practical Applications	<b>Decision-Making Support:</b> Helps in prioritizing investments. <b>Customer Impact:</b> Improved service reliability through outage prevention.



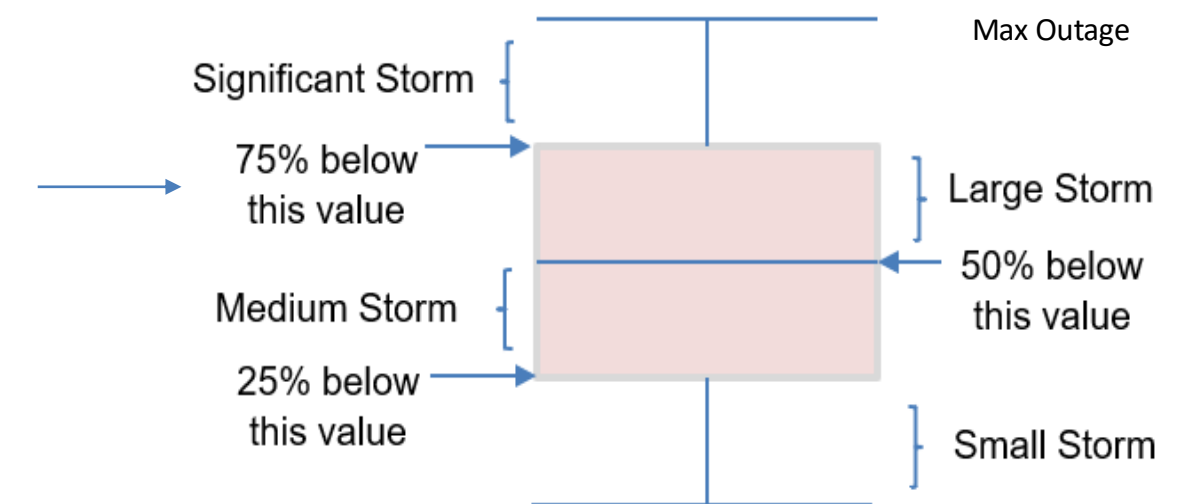
# Restoration Performance

## Calculation:

- 1) For each storm in a calendar year, calculate the ratio of customers without power for more than 12 hours and total customer interruptions (CI) including customers automatically restored (ACI) through smart switch operations (DA devices), community energy storage, and microgrids (does not include substation reclosing events – measured in %)

$$\text{Storm Event: } X = \frac{\sum \text{Customers Without Power for More than } Z \text{ hours}}{\text{Avoided Sustained CI by Automation /Hardening} + \text{Sustained CI}}$$

- 2) Based on number of interruptions (storm outages), categorize each storm event significant, large, medium, or small
- 3) Determine if X is greater than or equal to the threshold value (Y) for the category
- 4)  $X < Y$ , storm met expectations. If  $X \geq Y$ , storm did not meet expectations

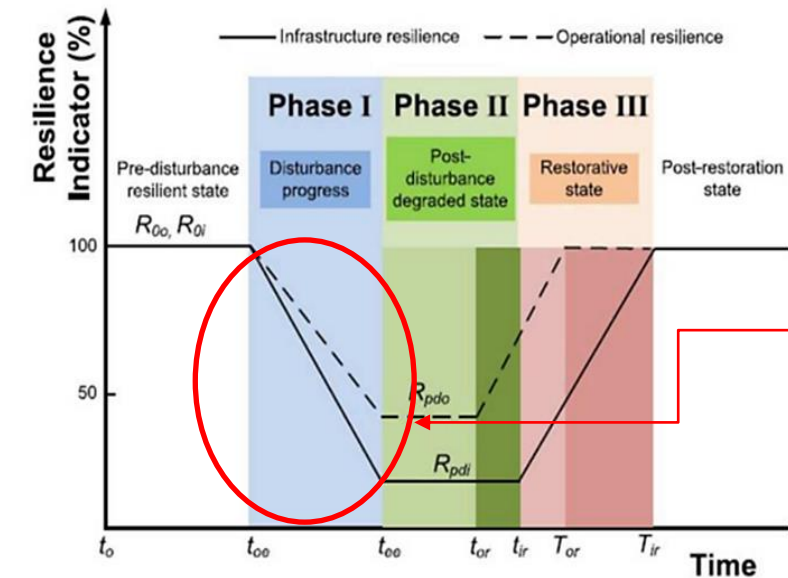


Threshold “Y” is calculated based on data analytics of small, medium, large, and significant size storm with 5 year moving average data. Details are explained in IEEE distribution resiliency guide.

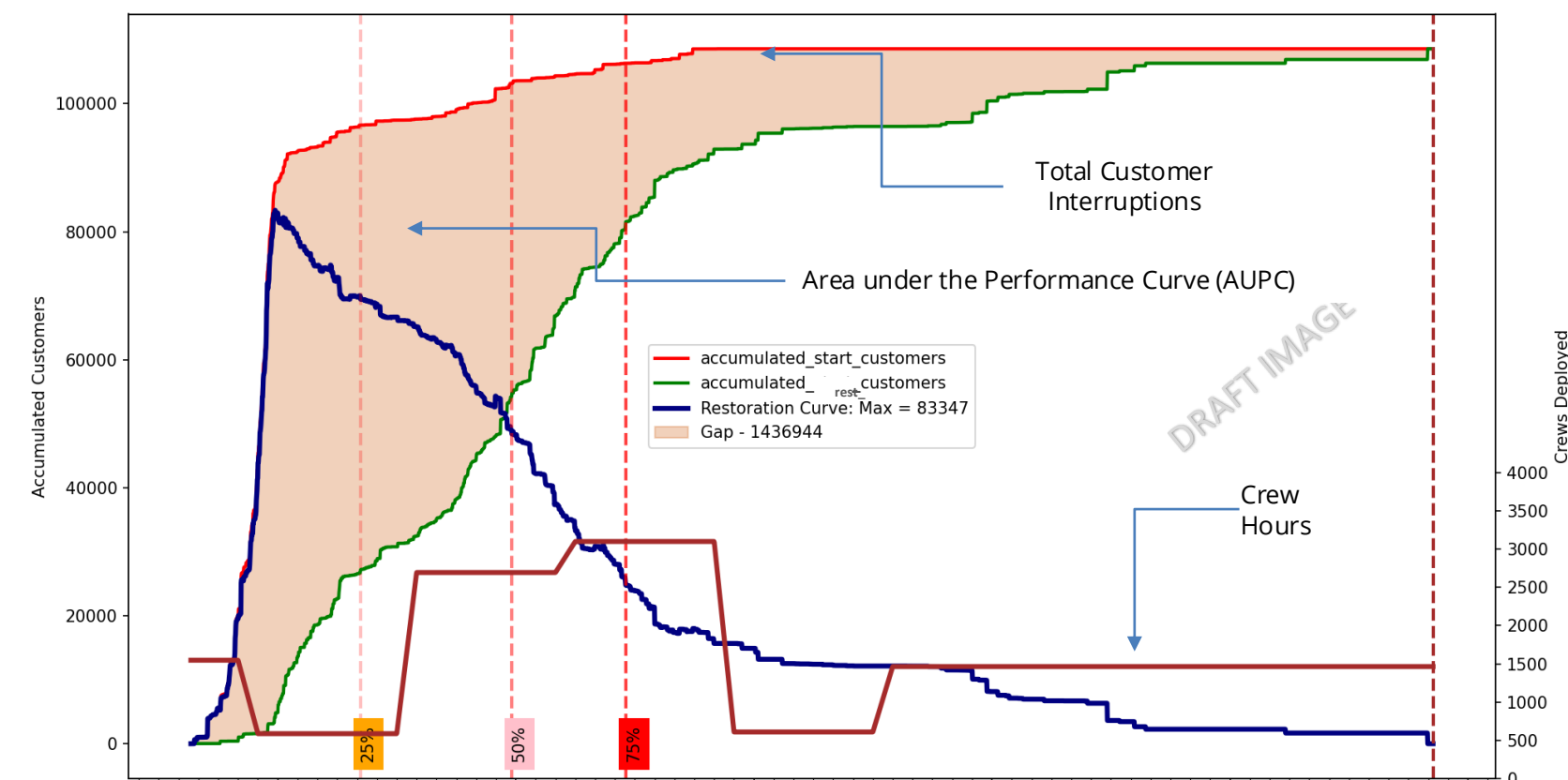
# REPAIR Metric

FACTORS

- 1 **Total Outages** – Intensity of the storm [Non-controllable]
- 2 **Max Customer Interruptions** – Indicator of crew efforts in curbing maximum degradation
  - Semi-Controllable – better human performance, lower CI.
  - But for severe events where all outages happen at the head end of the chart, there will be significant lag in start of restoration by crews
- 3 **Area under the Restoration Curve** – Indicator tracking restoration efforts vs emerging outages. Smaller the area under the curve better restoration performance [Controllable – Better human performance, lower AUPC]
- 4 **Crew Hours** – Total hours spent on the field by crew [Controllable – Better human performance, lower crews needed for 100% restoration]
- 5 **Storm duration**
- 6 **Full restore time** – Controllable but already captured by AUPC



If Customer Interruptions is the resilience indicator in this figure, then the operational resilience is enabled by restoration efforts, both automated and by crew work



# Sample Calculations for 9 storms

Wide range – compression required – Use Log scale

Outages(n)	Crew Hours	RE	CI	AUPC	AIR	REPAIR
1,536	142,172	1.97	1,135,907	176,929	0.81	2.77
1,126	49,549	1.64	370,417	107,578	0.54	2.18
1,267	42,399	1.53	282,653	128,132	0.34	1.87
216	31,866	2.17	31,786	28,724	0.04	2.21
2,588	118,405	1.66	2,221,044	208,613	1.03	2.69
850	75,411	1.95	753,380	88,923	0.93	2.88
457	30,250	1.82	91,268	49,497	0.27	2.09
347	30,816	1.95	80,027	38,053	0.32	2.27
1,129	49,443	1.64	576,270	111,156	0.72	2.36

$$\text{Repair} = \log \left( \frac{\text{CrewHours}}{\text{Outages}} \cdot \frac{\text{AUPC}}{\text{CI}} \right)$$

↑ Restoration Effectiveness (RE)
 ↑ Area Index Resiliency (AIR)

### Insights:



- Crew
- Max customer Interruptions
- AUPC

Average	2.37
Standard Deviation	0.32
Range	2.05 -2.69





# 02 | Case Studies



# Case Study 1: Illinois



Storm 1 and 2 are comparable in nature

Storm 1 was hit in a lower DA Penetration area

ACI is lower for Storm 2

Storm 2 hit at 8 PM vs Storm 1 was at 5 PM

$$X = \frac{\sum \text{Customers Without Power for More than Z hours}}{\text{Avoided Sustained CI by Automation /Hardening} + \text{Sustained CI}}$$

$$\text{SIRI} = \frac{\text{Avoided Sustained Customer Interruption (CI) by Automation/Hardening}}{\text{Avoided Sustained CI by Automation/Hardening} + \text{Sustained CI}}$$

Description	Storm 1	Storm 2	Storm 3
Start Storm Date Time	6/26/20 16:53	6/20/21 20:18	9/7/21 13:02
End Storm Date Time	6/27/20 18:51	6/21/21 17:34	9/8/21 6:13
Sustained Outage Count	575	527	420
Sustained Cust Inter	57,504	53,156	40,946
Max Outage (Hours)	75.7	93.1	39.4
DA ACI	30,537	26,511	30,372
X : Restored >12Hrs (w/ ACI)	4.18%	8.01%	3.67%
SIRI	35%	33%	43%
Restored ≤12Hrs	93.60%	88.00%	93.60%
Major Causes	HAIL, LIGHTNING, RAIN, WIND	RAIN, TORNADO, WIND	HAIL, LIGHTNING, RAIN, WIND



# Case Study 1: Illinois

## Sequential vs. Multiple Storm Waves

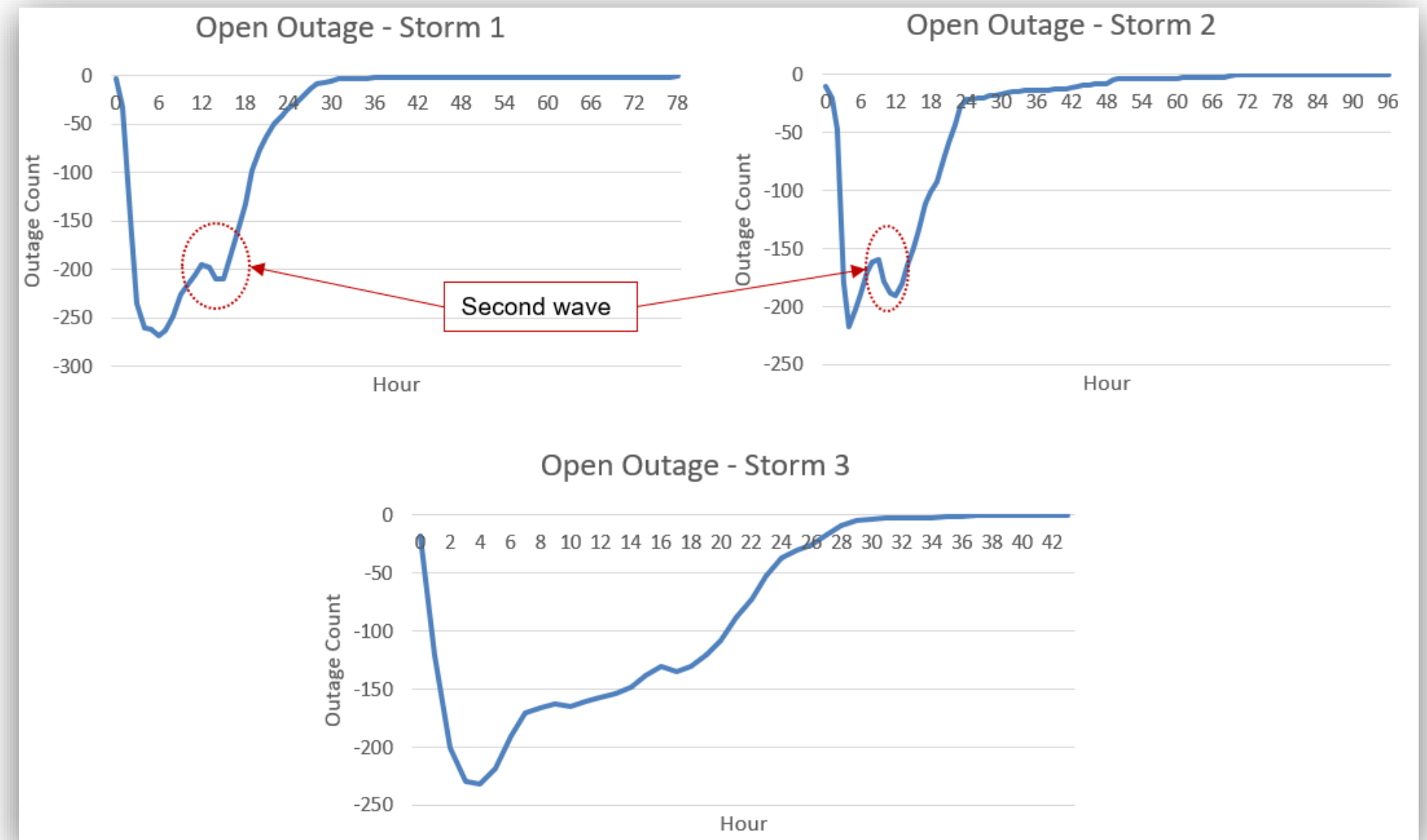
- Surge in outages after 10 hours, indicating a second wave of storm, not just initial tripping/fuse events

## Impact on Restoration Planning

- Multiple storm waves disrupt restoration, complicating crew deployment and resource management during recovery

## Timing and Automation Matter

- Faster deployment in the first 12 hours and higher automation (e.g., DA devices) significantly improve performance against ComEd's resiliency targets



# Case Study 2: Midwest & East Coast

## What Was Done

- Utility tested IEEE's Restoration Effectiveness, which measures % of customers out >12 hours during storms.
- Applied across 5 regions using real utility data from 2018–2023.

## Storms classified by severity using IEEE 1366 TMED multipliers

- *Small*: 1.0–1.5 | *Medium*: 1.5–2.5
- *Large*: 2.5–3.5 | *Significant*: 3.5+

## Key Results

- More than 70–90% of storms across most regions in 2023 performed better than the 5-year baseline.
- Backbone device analysis (reclosers, breakers, switches) showed even better resiliency scores, especially for small/medium storms.
- High variability in performance tied to storm type and location (e.g., rural vs. urban, weather-driven vs. equipment failure).

# Case Study 2: Midwest & East Coast



Date	Outages	Customers Out	>12hr Outages	% Saved via Self-Healing	X : Restored >12Hrs (w/ ACI)
Jan 7, 2023	88	10,082	4,638	0%	<b>46%</b> (very poor)
Apr 7, 2023	310	39,922	20	15%	<b>0.04%</b> (excellent)

Jan 7: Transformer failure in rural area with no backfeed capability led to high outage duration.

Apr 7: Widespread storm but automation saved 7,000+ customers, leading to excellent score.



# Case Study 3: Florida



Hurricane	Year	Grid Strategy	% Feeders Hardened	Smart Devices (Reclosers)	50% Restored	100% Restored	Avg. Outage
#1	Pre-Resiliency	None	0%	None	3 days	13 days	3.5 days
#2	Pre-Resiliency	None	0%	None	5 days	18 days	5.4 days
#3	12 yrs later	Storm hardening + Reclosers	27%	Moderate	<b>1 day</b>	10 days	2.1 days
#4	17 yrs later	Storm hardening + More Reclosers	58%	<b>Doubled</b>	<b>1 day</b>	<b>8 days</b>	<b>1.5 days</b>



# Case Study 3: Florida

## Post-Hurricane #2, launched aggressive storm hardening

- Upgraded poles and feeders to high wind-load standards
- Reduced pole damage significantly (from 12,400 to 3,200)

## Installed smart grid tech (self-healing reclosers)

- Avoided 546k interruptions (Hurricane #3)
- Avoided 405k interruptions (Hurricane #4)

## Improved resource deployment and grid design

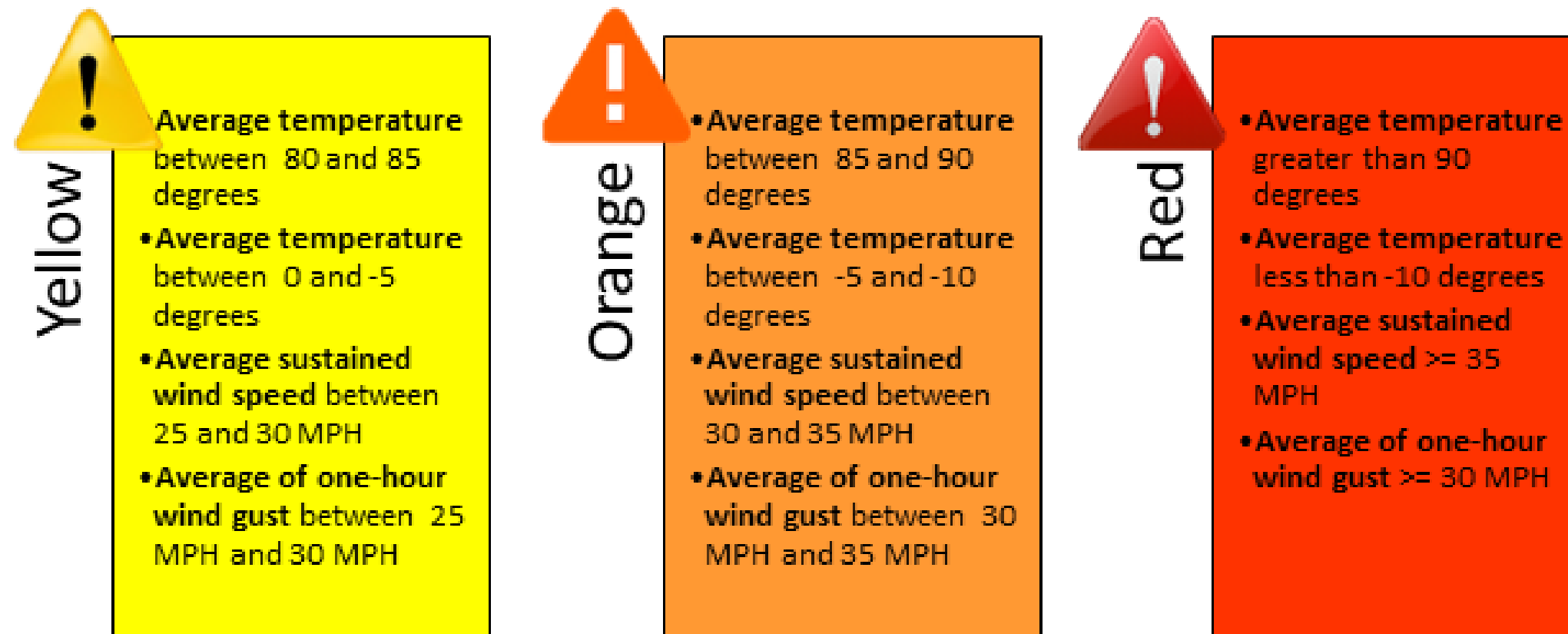
- Cut average outage duration by over 70%
- Achieved 50% restoration in 1 day, even for stronger storms



# Case Study 4: Northeast

Evaluated Gray Sky Day (GSD) metric using divisional-level analysis, not company-wide, due to varied geography and weather patterns.

Used airport weather stations



## Metric Definition

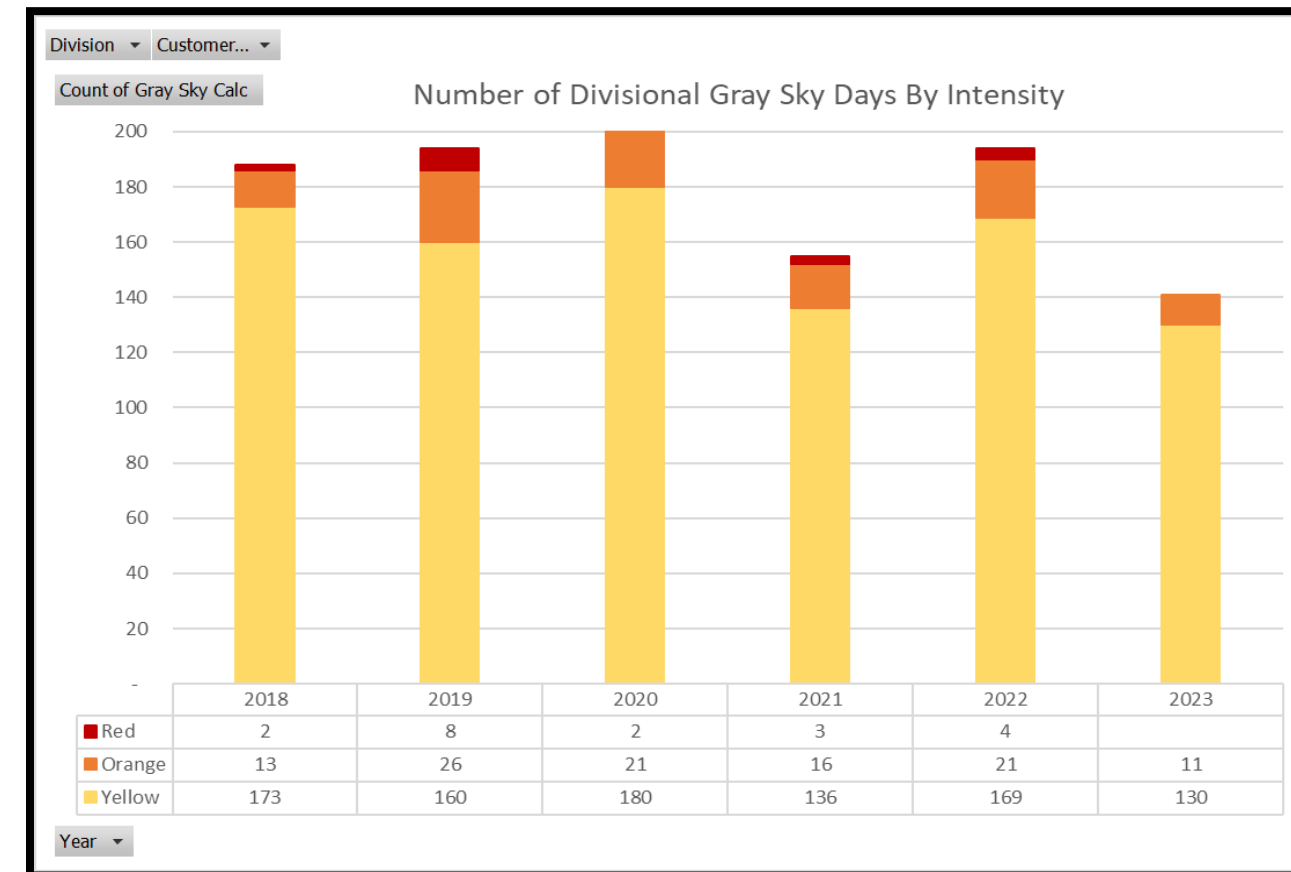
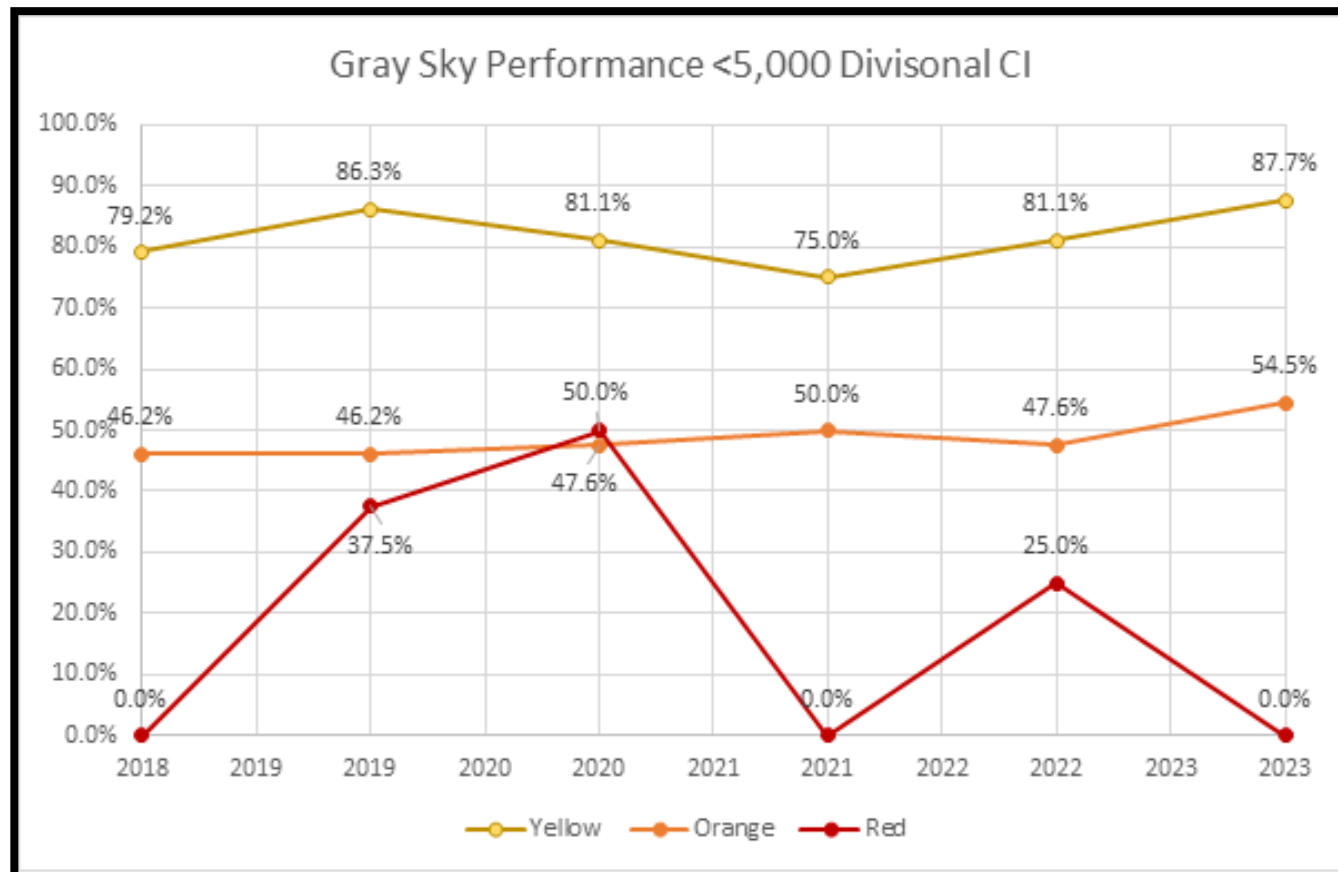
- Success = % of GSDs where  $< 5,000$  customers were interrupted
- Target value: 5,000 Customer Interruptions (CI) (based on 5-year average daily CI incl. major storms from 2018–2022)



# Case Study 4: Northeast



All Gray Sky Days	Yellow	Orange	Red	Grand Total	<5,000 CI Gray Sky Days	Yellow	Orange	Red	Grand Total	%	Yellow	Orange	Red	Grand Total
2018	173	13	2	188	2018	137	6		143	2018	79.2%	46.2%	0.0%	76.1%
2019	160	26	8	194	2019	138	12	3	153	2019	86.3%	46.2%	37.5%	78.9%
2020	180	21	2	203	2020	146	10	1	157	2020	81.1%	47.6%	50.0%	77.3%
2021	136	16	3	155	2021	102	8		110	2021	75.0%	50.0%	0.0%	71.0%
2022	169	21	4	194	2022	137	10	1	148	2022	81.1%	47.6%	25.0%	76.3%
2023	130	11		141	2023	114	6		120	2023	87.7%	54.5%	-	85.1%
<b>Total</b>	<b>948</b>	<b>108</b>	<b>19</b>	<b>1,075</b>	<b>Total</b>	<b>774</b>	<b>52</b>	<b>5</b>	<b>831</b>	<b>Total</b>	<b>81.6%</b>	<b>48.1%</b>	<b>26.3%</b>	<b>77.3%</b>



# Case Study 4: Northeast

## Key Results

- 2023 performance >70% success rate across all divisions
- Year-over-year improvement since 2018 in Yellow & Orange GSDs
- Red GSDs lacked sufficient data for conclusions

## Challenges & Observations

- Limited localized weather station data (mostly from airports) reduced ability to classify more days as GSDs
- Variability in data granularity across divisions
- Results show system resiliency investments are paying off

## Next Steps

- Incorporate longer weather and outage history for better trend detection
- Enhance weather station network granularity
- Continue using this metric to guide targeted infrastructure upgrades



# Takeaways and Next Steps

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ComEd has been utilizing two metrics, restoration performance and Gray Sky day, since 2020.

These metrics have allowed ComEd to concentrate on system enhancements and improvements in resiliency.

Through the IEEE Distribution Resiliency Working Group, three other utilities have adopted the restoration performance and Gray Sky day metrics for their systems.

The final draft of the guide will be submitted for review and ballot at IEEE in 2026.

GridCo & PNNL are developing Resiliency Valuation tool to evaluate investment scenarios in rate cases.





# 03 | PNNL – GridCo Resiliency Valuation



## DSO RISE

### At-scale Grid Response

Quantifying demand in extreme weather

Modeling and simulation platform to reflect realistic conditions during extreme weather conditions

### Resilience Enhancement Mechanisms

- Meter Data Historian
- Switching Schemes
- Comfort-Levels
- Analytics
- Customer Bids
- Emergency Retail Markets

Implementation of Advanced Outage Management approaches including (1) Controlled Outages, (2) Direct Load Control, & (3) DER Coordination Mechanisms for Resilience enhancement

### Valuation

- Energy Not Served
- Resource Utilization
- Thermal Stress-Level
- Response & Exposure Analysis
- VSL (mortality)
- Medical Costs
- Cost of Interruption
- Property Loss
- Damage Estimation
- Capital Expense
- O&M Expense
- Purchase Cost
- Lost Sale
- Cost of Deployment

Developed method for calculating cost of outages including mortality risks, productivity & property damage  
Determine the cost of deployment for resilience enhancement mechanisms



# Resiliency Investment Benefits Calculator

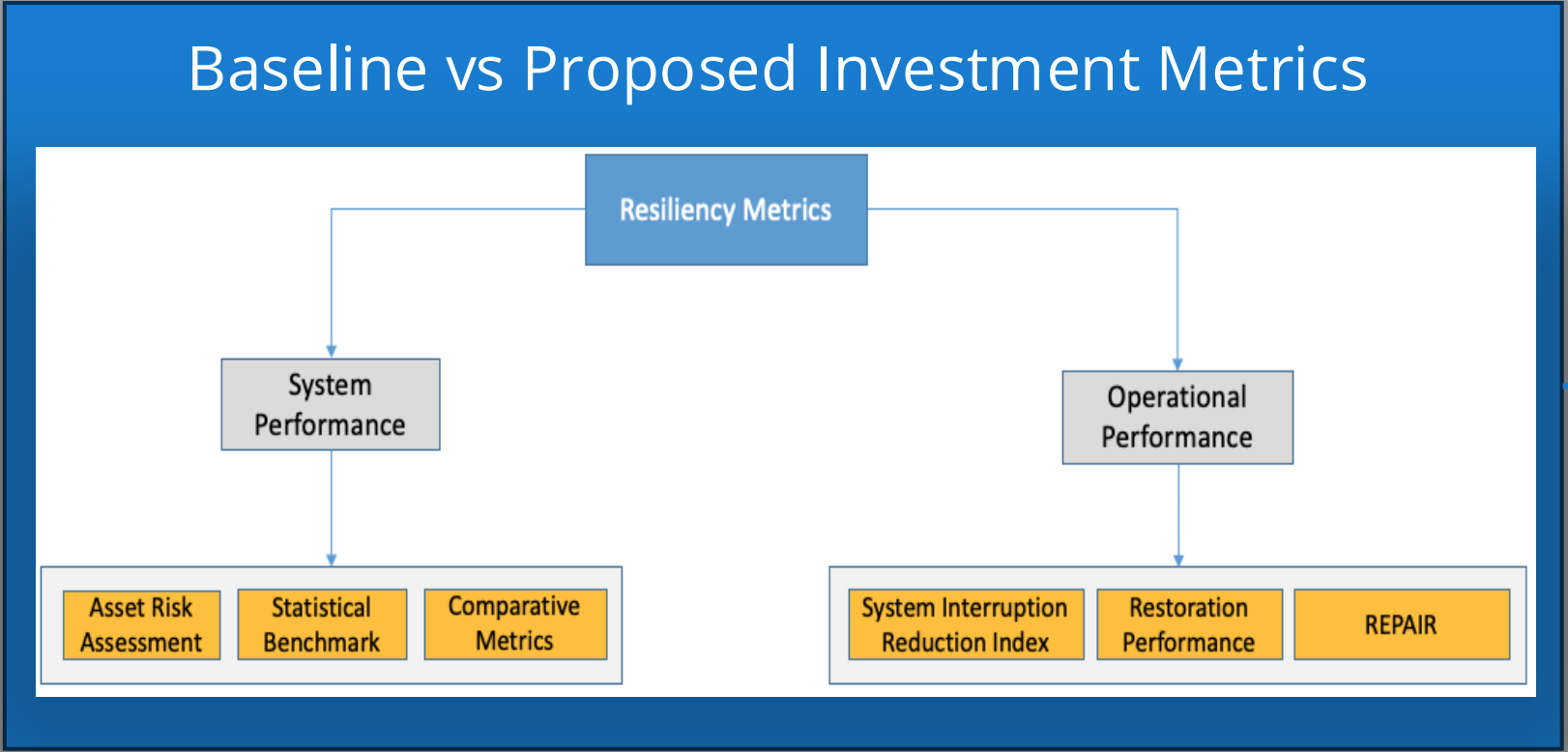
## Historical Outage Data

Circuit	Element ID	Status	Duration in Minutes	Affected Consumers	Is Permanent Placement
1	North Central Zone L15-79746	0	88	667	FALSE
2	North Central Zone L46-142477	0	137	6	FALSE
3	North Central Zone L15-74618	0	56	666	FALSE
4	North Central Zone L6-120634	0	32	935	FALSE
5	North Central Zone L25A-144621	0	20	412	FALSE
6	North Central Zone L10407	0	84	682	FALSE
7	North Central Zone L12-53673	0	156	5	FALSE
8	North Central Zone L16-79679	0	124	600	FALSE
9	North Central Zone L39-102321	0	101	415	FALSE
10	North Central Zone L36-142306	0	164	696	FALSE
11	North Central Zone L11-124888	0	84	696	FALSE
12	North Central Zone L30-122163	0	22	193	FALSE
13	North Central Zone L19-47407	0	153	324	FALSE
14	North Central Zone L31-92703	0	11	159	FALSE
15	North Central Zone L6-119948	0	139	768	FALSE
16	North Central Zone L34-68947	0	175	361	FALSE
17	North Central Zone L18-52070	0	156	705	FALSE
18	North Central Zone L13-125260	0	37	547	FALSE
19	North Central Zone 7676	0	5	206	FALSE
20	North Central Zone	0			

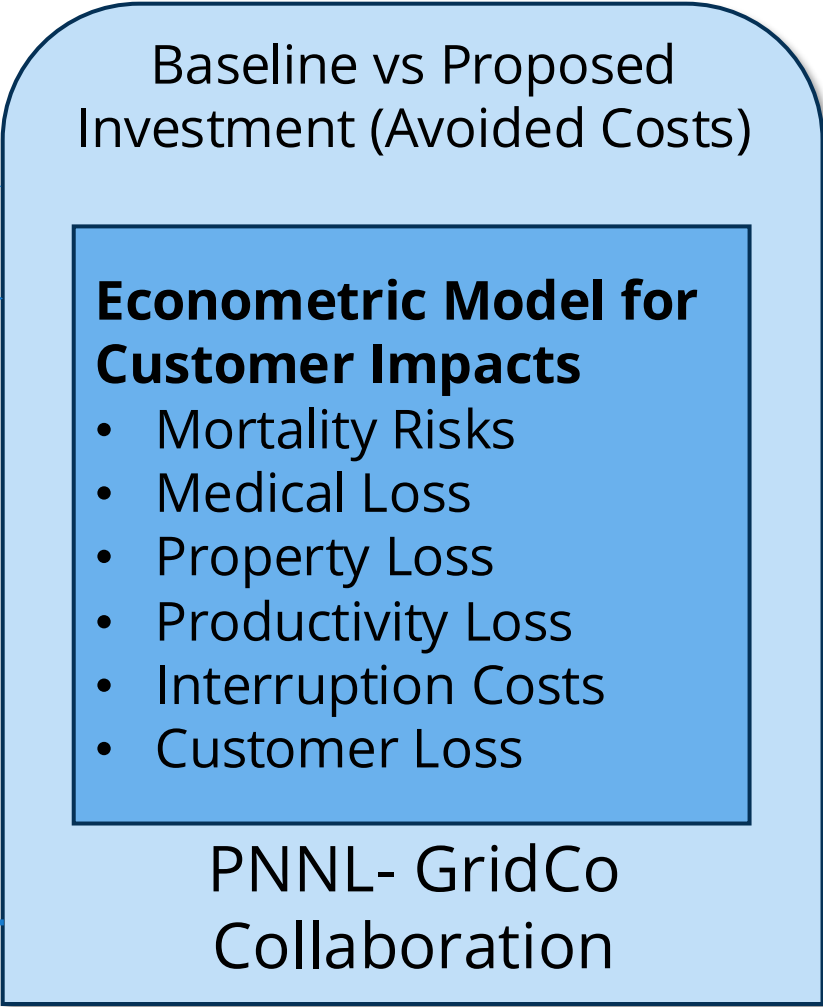
Customer Mix, Consumption, Critical Equip. (Utility CIS)

Customer Demographics, Characteristics (EIA, Utility)

Income Level, Type of Jobs, Avg. Wages, Insurance (BLS)



Proposed Resiliency Investment

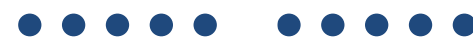
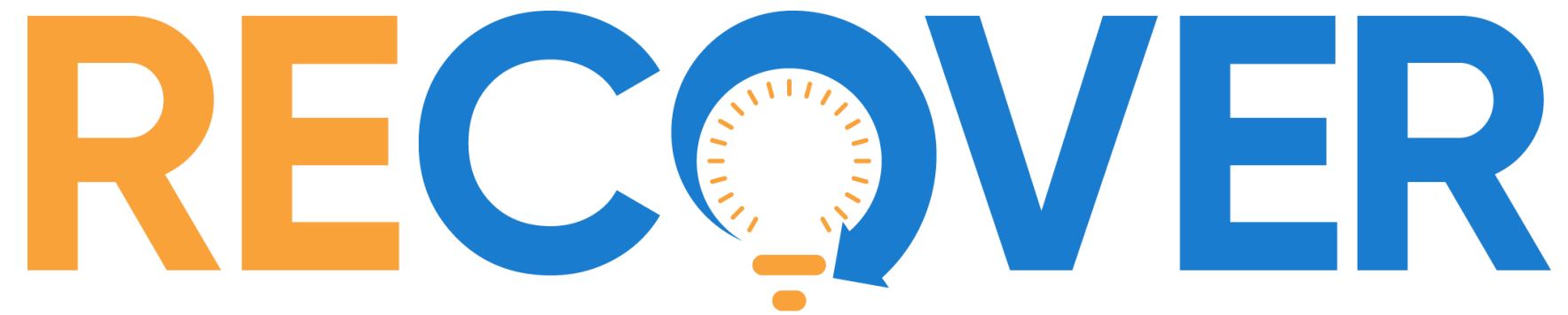


Resiliency Investment Cost Benefit Analysis



# Enhance Operational Resilience using

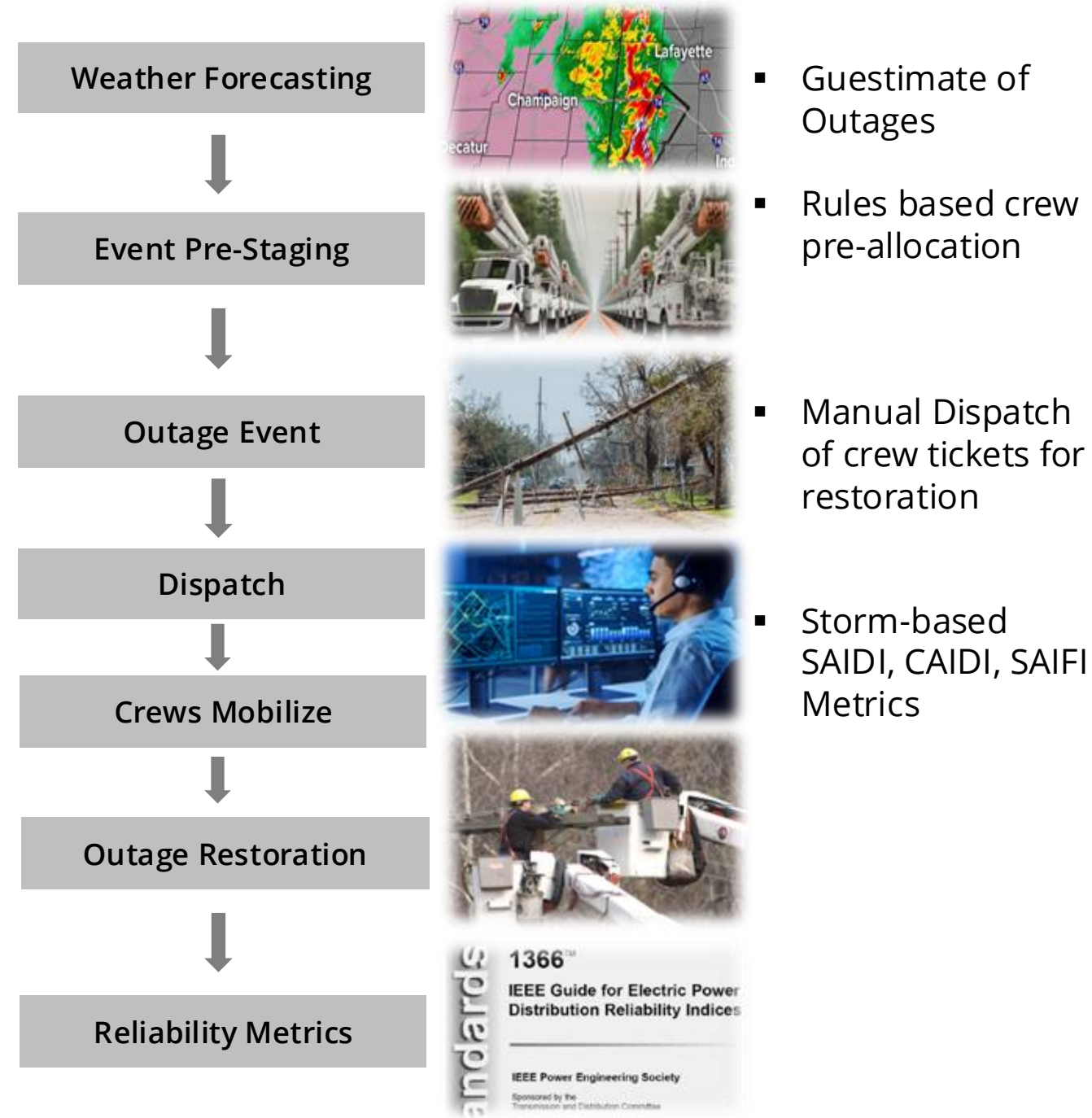
**RECOVER**



# Storm Process : Enhanced through RECOVER Intelligence

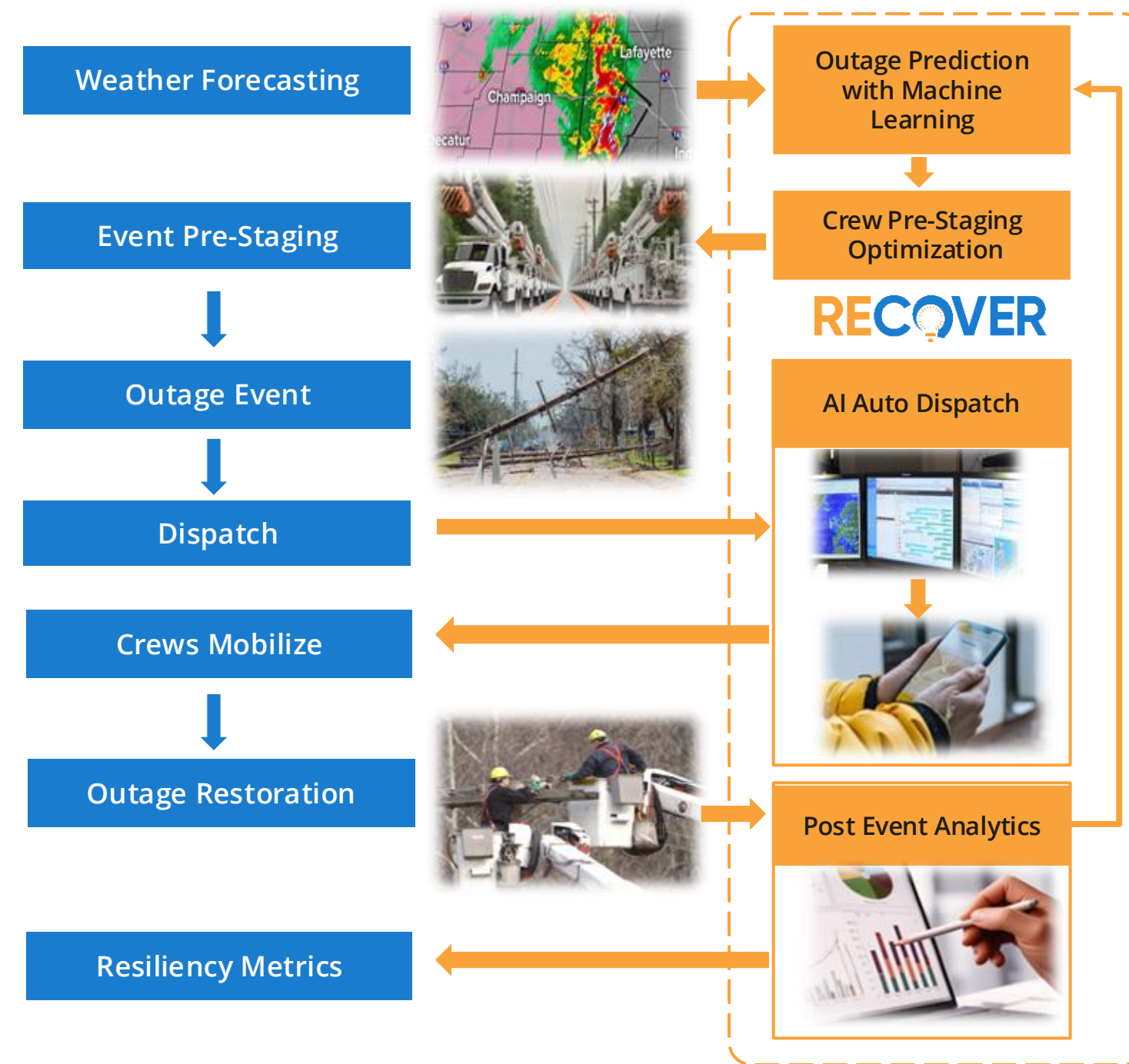
## Current Utility Response

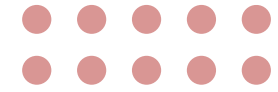
Limited Outage Prediction, Static Plans, and Manual Dispatch



## Response with RECOVER

Machine Learning Outage Prediction, Dynamic Plans, and AI Auto Dispatch





# DEMO

<https://www.recover.gridcooperator.com/>

