Energy Markets & Planning
BERKELEY LAB

Resilience Metrics: Current Practices, Challenges, and Emerging Approaches

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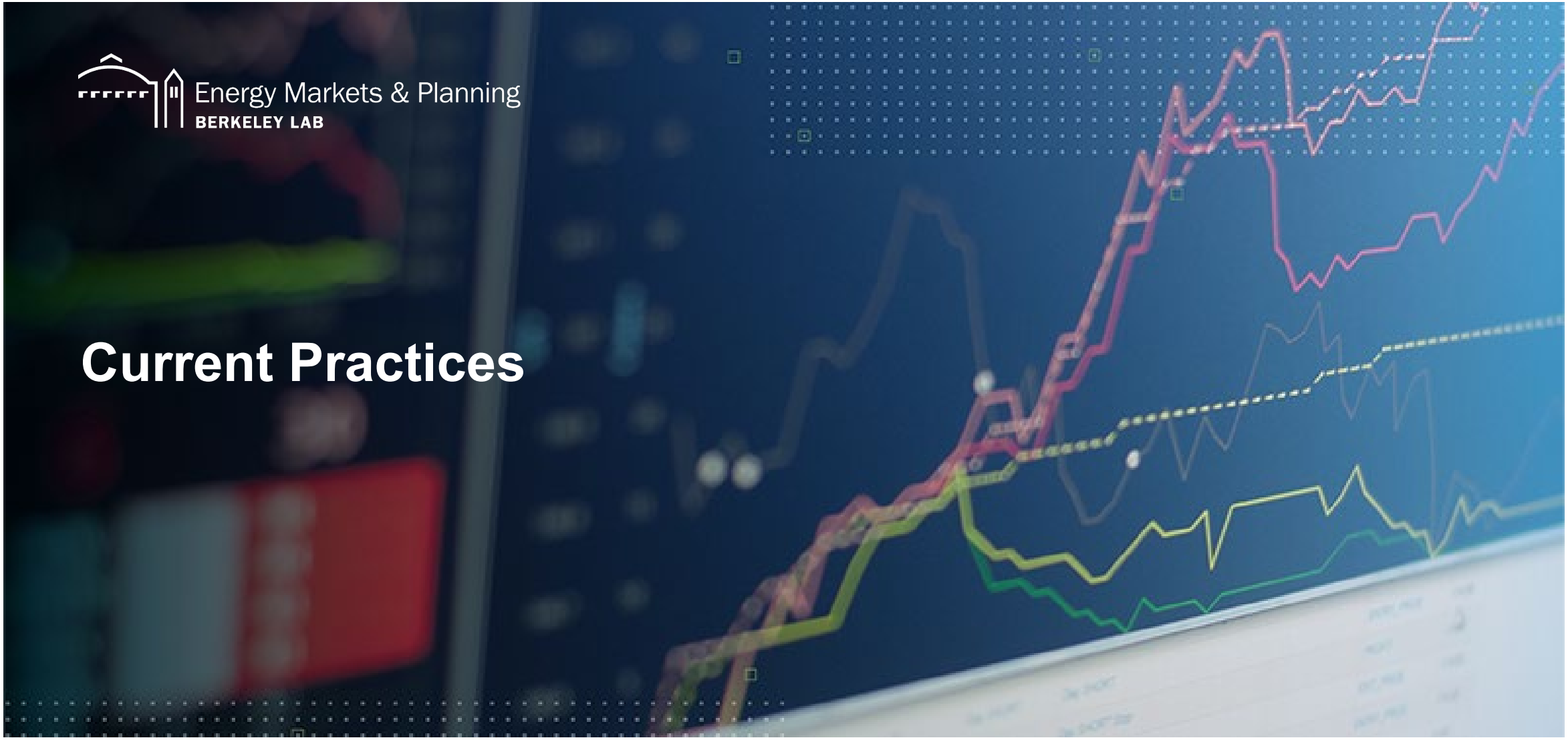
May 8, 2026

This work was funded by the U.S. Department of Energy's Office of Electricity under Contract No. DE-AC02-05CH11231.

Presentation Outline

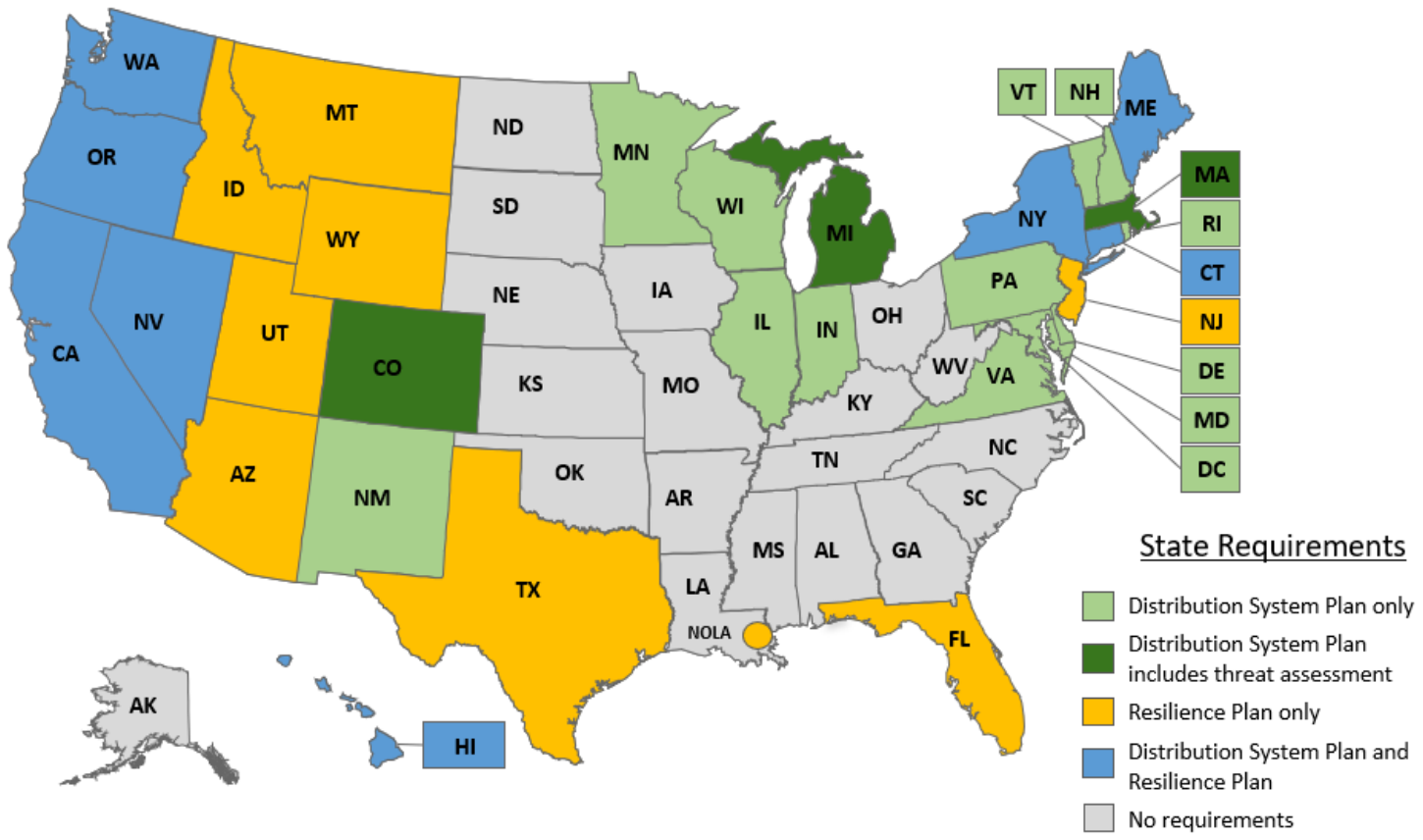
- Current practices
  - State requirements for resilience and distribution system planning
  - Types of metrics in filed utility plans
- Challenges in measuring and valuing resilience
- Emerging approaches
  - Utility plans
  - External research



Current Practices

State Requirements for Distribution System and Resilience Planning

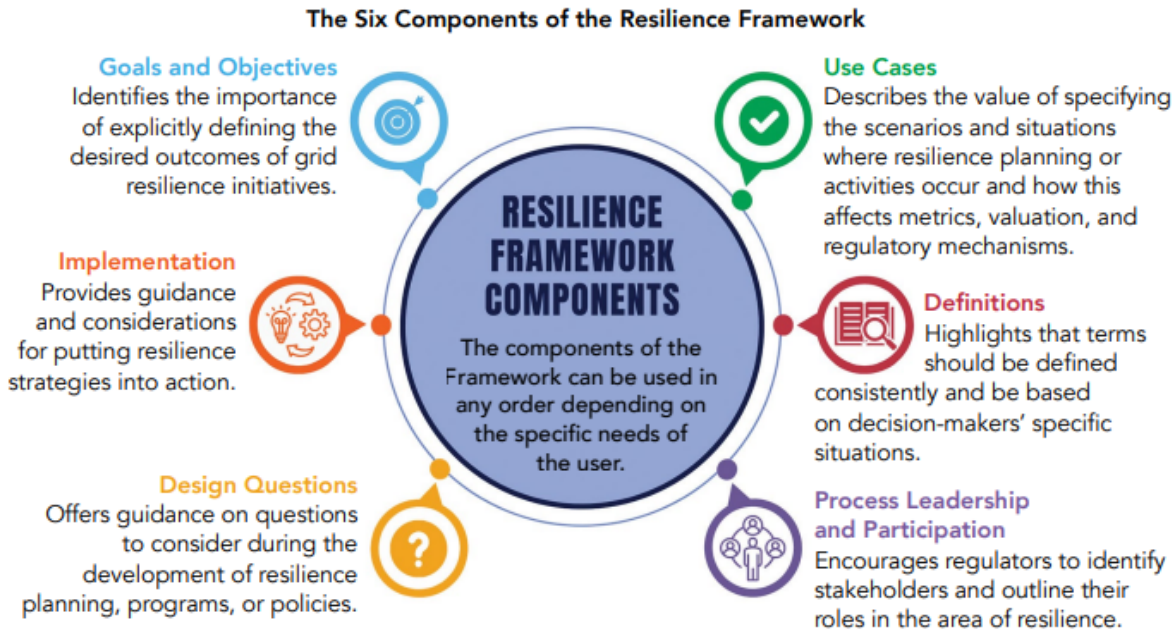
- A growing number of states are establishing requirements for electric utilities to file distribution system plans and grid resilience plans.
- Types of distribution system plans
  - Grid modernization plans, grid needs assessments, integrated resource plans, and integrated distribution system plans
- Types of resilience plans
  - Vulnerability assessments (multiple hazards), resilience plans, wildfire mitigation plans, and storm prevention plans



Planning Frameworks

- Utilities use metrics for defining objectives, evaluating improvements, and refining strategies

NARUC Resilience Framework



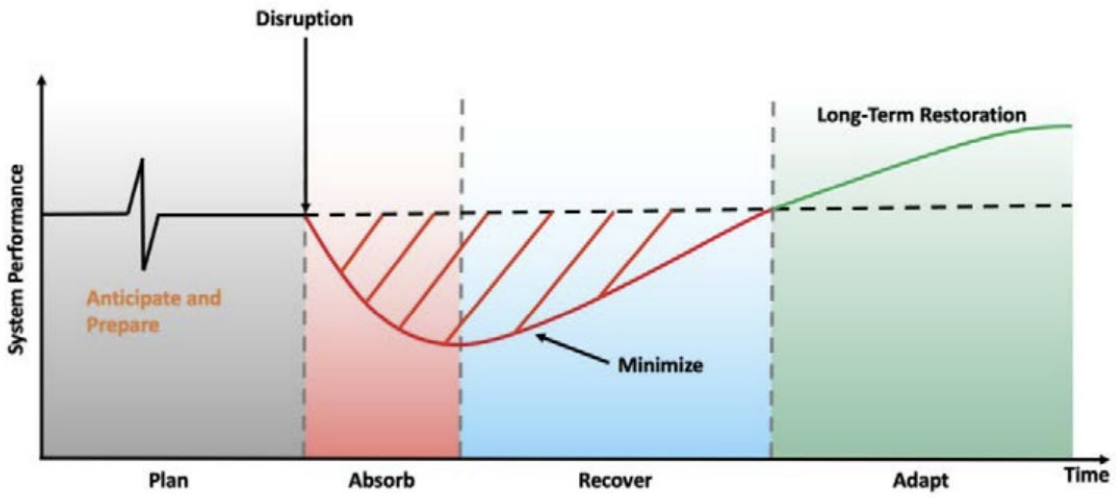
Source: NARUC (2025)

Resilience Analysis Process – Sandia National Lab

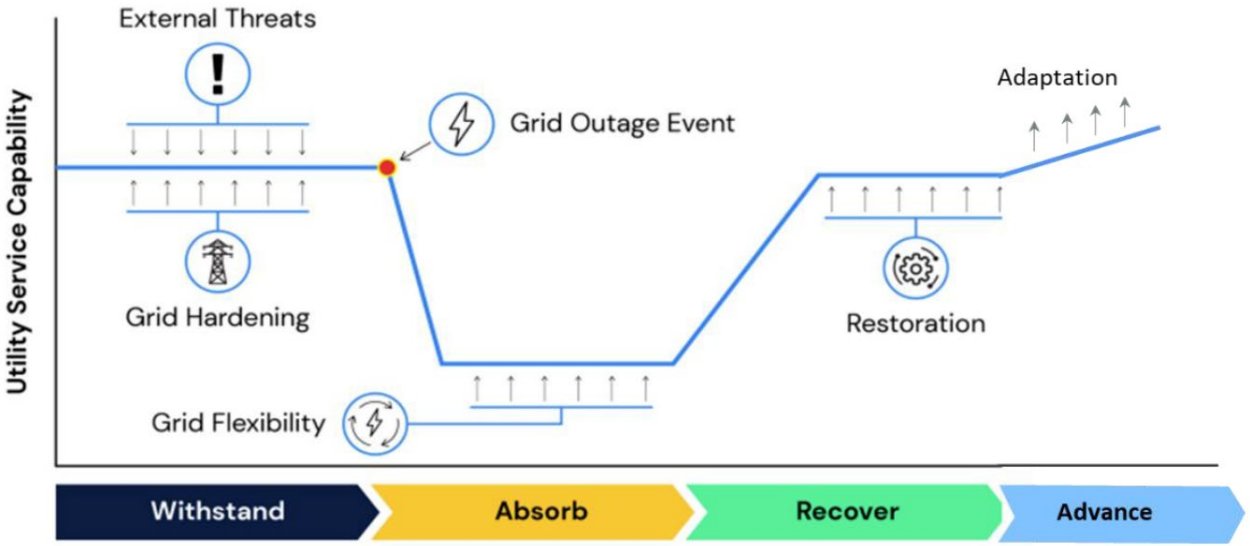
Source: Sandia National Laboratory (2014)

Phases of Resilience

Resilience: The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions, including the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents - Grid Modernization Lab Consortium (2020)



Source: Leddy et al. (2023)



Source: RG&E & NYSEG (2023)

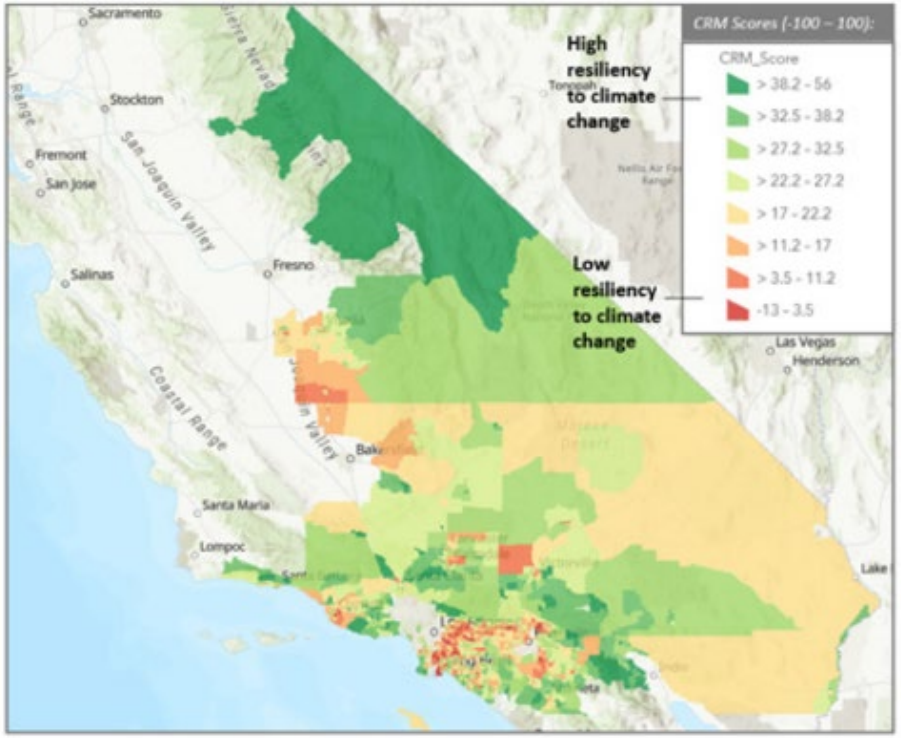
Attribute Metrics

- System characteristics that contribute to or describe aspects of the resilience of a system or community
- By tracking attribute metrics, utilities can connect infrastructure performance to tangible asset characteristics and hardening progress

Resilience Phase	Description	Metric Type - Examples
Anticipate	The ability of the system to anticipate threats and hazards and be ready to take mitigation actions.	Situational awareness - wind
		Situational awareness - ignition
		High fire threat
		Communications protocols
Withstand	The electrical system's capacity to avoid being affected by a hazard.	Asset condition
		Asset ratings
		Asset hardening status
Absorb / Adapt	The ability of the grid to respond to asset damage or the community to change behavior to minimize impacts to customers.	Automation and topology
		Emergency power
		Social indicators
		Community resilience
Recover	The ability to restore normal grid operation after a disruption.	Accessibility
		Power restoration
		Mutual aid agreements

Measuring Community Resilience

- Southern California Edison developed the Community Resilience Metric (CRM).
  - Measures the sensitivity and adaptive capacity of a particular community to an interruption
    - Uses 25 indicators of community sensitivity, including health risks, housing quality, and other socio-economic factors
    - Twelve indicators of adaptive capacity include cooling center access, available emergency services, and access to transportation.
  - SCE calculated a weighted CRM at the Census tract level, with final weighting of indicators incorporating input from community organizations.
- Pacific Gas & Electric uses the Baseline Resilience Indicators for Communities (BRIC) index to assess adaptive capacity.
  - Publicly available index based on six categories of community disaster resilience at the county level
  - Measures existing attributes of resilience to natural hazards



Community Resilience Metric Scores for Southern California Edison Territory

Source: Southern California Edison (2022)

Source: PG&E (2024)

Performance Metrics - Resilience

Category	Description
Electrical Service	Metrics describe power interruptions in terms of frequency, duration, location, cause, customers affected, and other variables.
Asset Damage or Failure	Metrics describe infrastructure impacts in non-monetary terms, such as counts of damaged utility structures.
Response and Restoration	Metrics describe response and recovery from a hazard event, such as the time to restore power to some or all of a utility service territory.
Monetary Impact	Metrics describe the cost of impacts and include capital costs of damaged assets, operations and maintenance (O&M) costs for restoration and recovery, costs incurred by customers as a result of power interruptions, and economy-wide impacts from power interruptions.
Customer Communications and Engagement	Metrics describe the effectiveness of utility outreach regarding a storm or interruption event.

Electrical Service – System Level Reliability

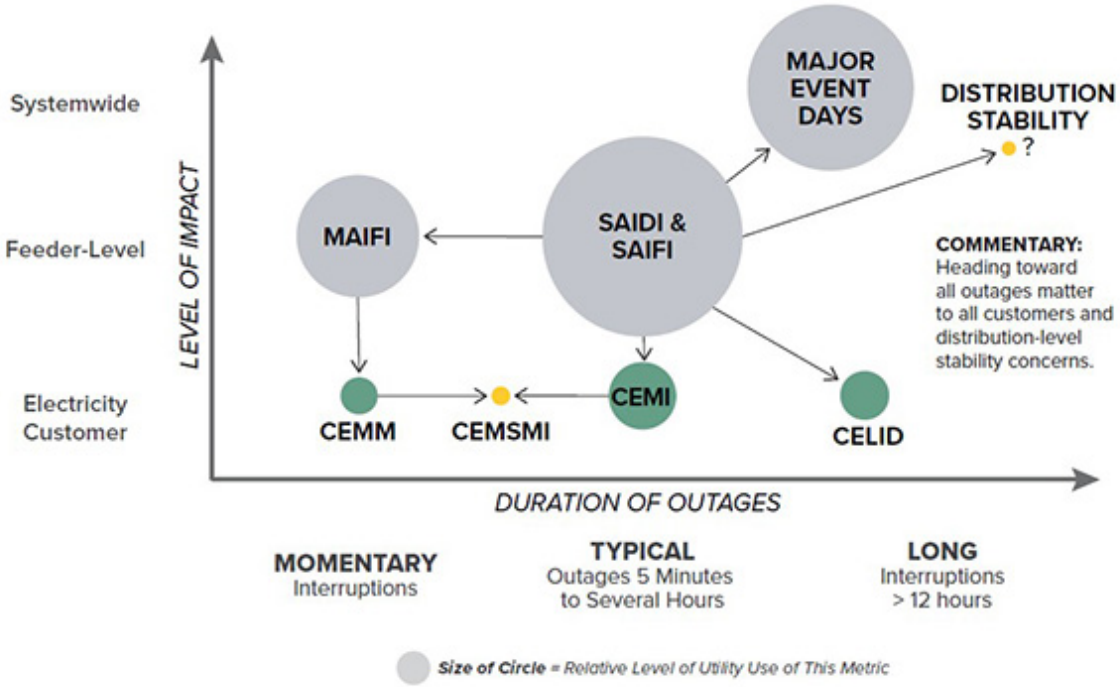
- Reliability indices are defined by IEEE 1366-2022.
- Standard reliability indices are normally calculated and reported on an annual basis, aggregating performance over an entire year.

Metric	Definition	Interpretation
SAIFI	System Average Interruption Frequency Index	Total number of interruptions that an average customer experiences over some time period
SAIDI	System Average Interruption Duration Index	Total number of minutes that an average customer is without power over some time period
CAIFI	Customer Average Interruption Frequency Index	Average number of interruptions per customer interrupted over some time period
CAIDI	Customer Average Interruption Duration Index	Time required to restore service for an average customer over some time period
MAIFI	Momentary Average Interruption Frequency Index	Total number of momentary interruptions (< 5 minutes) that an average customer experiences over some time period
MED	Major Event Day	Any day with a daily reliability metric that exceeds a statistically-defined threshold based on the previous five years of daily data

Electrical Service – Customer-Centric Reliability

- More recent iterations of the IEEE standard have added customer-centric metrics.

Metric	Definition	Interpretation
$CEMI_n$	Customers Experiencing Multiple Interruptions	Ratio of customers experiencing *n* sustained interruptions to the total number of customers served
$CEMM_n$	Customers Experiencing Multiple Momentaries	Ratio of customers experiencing *n* momentary interruptions to the total customers served
$CEMSMI_n$	Customers Experiencing Multiple Sustained Interruptions and Momentary Interruptions	Ratio of individual customers experiencing *n* or more of both sustained interruptions and momentary interruption events to the total customers served
CELID-s; CELID-t	Customers Experiencing Long Interruption Durations	Ratio of individual customers that experience interruptions with durations longer than or equal to a given time: • (*s*), where the time is a single interruption • (*t*), defined as the total time a customer has been interrupted



Source: S&C 2020, Moving Beyond Average Reliability Metrics

Performance Metrics - Resilience

	Metric	Description
Electric Service	Customer Interruptions	Sum of all customers interrupted over a given time period
	Customer Minutes Interrupted	Sum of all customer minutes interrupted over a given time period
	Targeted reliability indices	SAIDI, SAIFI, CEMI, etc. specific to time, circuit, weather conditions, outage cause, etc.
Asset Damage or Failure	Asset damage from major events	Extent and characteristics of asset damage from a resilience event
	Structure failures during a hurricane	Count of structure failures from hurricane
	Conductor performance during major events	Damage events from vegetation during major storms
Restoration	Time to Restore X% of Customers (CR-X)	Hours from onset time to restore X% of customers impacted (usually 50%, 90%, or 100%)
	Time to restore from peak customers interrupted to 95% restoration (National Grid)	For a major storm, the time it takes to restore from peak customers interrupted to 95% restoration
	Percent of Customers Restored within X hours of a Major Storm	Among customers impacted by a major storm (or other major event designation), the percent restored within X hours of interruption onset time

Key Dimensions of Granularity

- Start and end of event or interruption
- Interruption cause
  - IEEE Standard 1782-2022 provides a structured approach to identify and categorize causes of interruptions to enable consistent reporting and analysis.
- Interruption location
  - Circuit, substation, or other location
- Conditions
  - Major Storm
  - Red Flag Warning
  - High Wind Warning

Electrical Service – Example of Granular Data Reporting

Utility	X
Table No.	5
Date Modified	

Notes:
Transmission lines refer to all lines at or above 65kV, and distribution lines refer to all lines below 65kV.
Data from 2015 - 2021 should be actual numbers. 2022 and 2023 should be projected. In future submissions update projected numbers with actuals

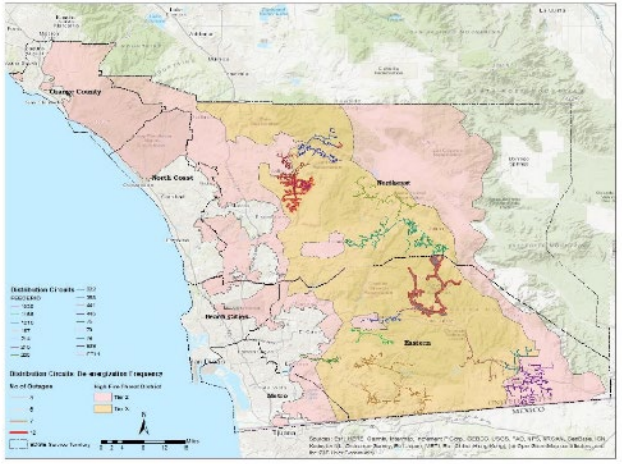
Table 5: Risk event drivers

							Actual number of risk events					
							Q1	Q2	Q3	Q4	Q1	Q2
Risk event category	**Metric type**	**#**	**Risk event driver**	**Line Type**	**HFTD Tier**	**Are risk events tracked for ignition driver? (yes / no)**	**2022**	**2022**	**2022**	**2022**	**2023**	**2023**
Unplanned Outage	13. Object contact	13.f.d.0	Other	Distribution	Non-HFTD							
Unplanned Outage	13. Object contact	13.f.d.2	Other	Distribution	HFTD Tier 2							
Unplanned Outage	13. Object contact	13.f.d.3	Other	Distribution	HFTD Tier 3							
Unplanned Outage	13. Object contact	13.f.t.0	Other	Transmission	Non-HFTD							
Unplanned Outage	13. Object contact	13.f.t.2	Other	Transmission	HFTD Tier 2							
Unplanned Outage	13. Object contact	13.f.t.3	Other	Transmission	HFTD Tier 3							
Unplanned Outage	13. Object contact	13.g.d.0	Unknown	Distribution	Non-HFTD							
Unplanned Outage	13. Object contact	13.g.d.2	Unknown	Distribution	HFTD Tier 2							
Unplanned Outage	13. Object contact	13.g.d.3	Unknown	Distribution	HFTD Tier 3							
Unplanned Outage	13. Object contact	13.g.t.0	Unknown	Transmission	Non-HFTD							
Unplanned Outage	13. Object contact	13.g.t.2	Unknown	Transmission	HFTD Tier 2							
Unplanned Outage	13. Object contact	13.g.t.3	Unknown	Transmission	HFTD Tier 3							
Unplanned Outage	14. Vegetation contact	14.a.d.0	Vegetation contact	Distribution	Non-HFTD							
Unplanned Outage	14. Vegetation contact	14.a.d.2	Vegetation contact	Distribution	HFTD Tier 2							
Unplanned Outage	14. Vegetation contact	14.a.d.3	Vegetation contact	Distribution	HFTD Tier 3							
Unplanned Outage	14. Vegetation contact	14.a.t.0	Vegetation contact	Transmission	Non-HFTD							
Unplanned Outage	14. Vegetation contact	14.a.t.2	Vegetation contact	Transmission	HFTD Tier 2							
Unplanned Outage	14. Vegetation contact	14.a.t.3	Vegetation contact	Transmission	HFTD Tier 3							
Unplanned Outage	15. Equipment / facility failure or damage	15.a.d.0	Anchor/guy	Distribution	Non-HFTD							
Unplanned Outage	15. Equipment / facility failure or damage	15.a.d.2	Anchor/guy	Distribution	HFTD Tier 2							
Unplanned Outage	15. Equipment / facility failure or damage	15.a.d.3	Anchor/guy	Distribution	HFTD Tier 3							
Unplanned Outage	15. Equipment / facility failure or damage	15.a.t.0	Anchor/guy	Transmission	Non-HFTD							
Unplanned Outage	15. Equipment / facility failure or damage	15.a.t.2	Anchor/guy	Transmission	HFTD Tier 2							
Unplanned Outage	15. Equipment / facility failure or damage	15.a.t.3	Anchor/guy	Transmission	HFTD Tier 3							
Unplanned Outage	15. Equipment / facility failure or damage	15.b.d.0	Capacitor bank	Distribution	Non-HFTD							
Unplanned Outage	15. Equipment / facility failure or damage	15.b.d.2	Capacitor bank	Distribution	HFTD Tier 2							
Unplanned Outage	15. Equipment / facility failure or damage	15.b.d.3	Capacitor bank	Distribution	HFTD Tier 3							
Unplanned Outage	15. Equipment / facility failure or damage	15.b.t.0	Capacitor bank	Transmission	Non-HFTD							
Unplanned Outage	15. Equipment / facility failure or damage	15.b.t.2	Capacitor bank	Transmission	HFTD Tier 2							
Unplanned Outage	15. Equipment / facility failure or damage	15.b.t.3	Capacitor bank	Transmission	HFTD Tier 3							
Unplanned Outage	15. Equipment / facility failure or damage	15.c.d.0	Conductor	Distribution	Non-HFTD							
Unplanned Outage	15. Equipment / facility failure or damage	15.c.d.2	Conductor	Distribution	HFTD Tier 2							
Unplanned Outage	15. Equipment / facility failure or damage	15.c.d.3	Conductor	Distribution	HFTD Tier 3							
Unplanned Outage	15. Equipment / facility failure or damage	15.c.t.0	Conductor	Transmission	Non-HFTD							

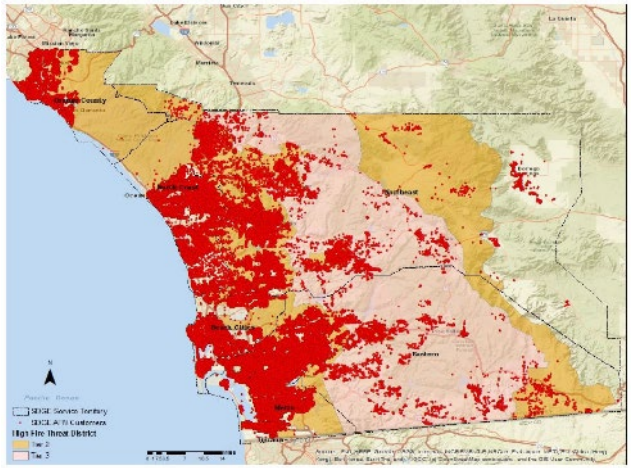
California Office of Energy Infrastructure Safety
Energy Safety Data Guidelines – Wildfire Mitigation Data Tables Template

Potential Targets for Specialized Performance Metrics

- **Critical facilities:** Infrastructure which is essential for the health, safety, and economic well-being of a population (e.g., hospitals, fire stations, emergency operation centers, public drinking water facilities, sewer and wastewater facilities)
- **Public Safety Power Shutoffs:** Intentional de-energization of portions of the grid to reduce the risk of a wildfire caused by a utility asset
- **Distributional impacts:** Customers or areas within service territory (e.g., census tracts designated by state governments) meeting a certain set of criteria



Frequently De-Energized Circuits



Access and Functional Needs (AFN) Customers in the Service Territory

Source: SDG&E Wildfire Mitigation Plan (2023)

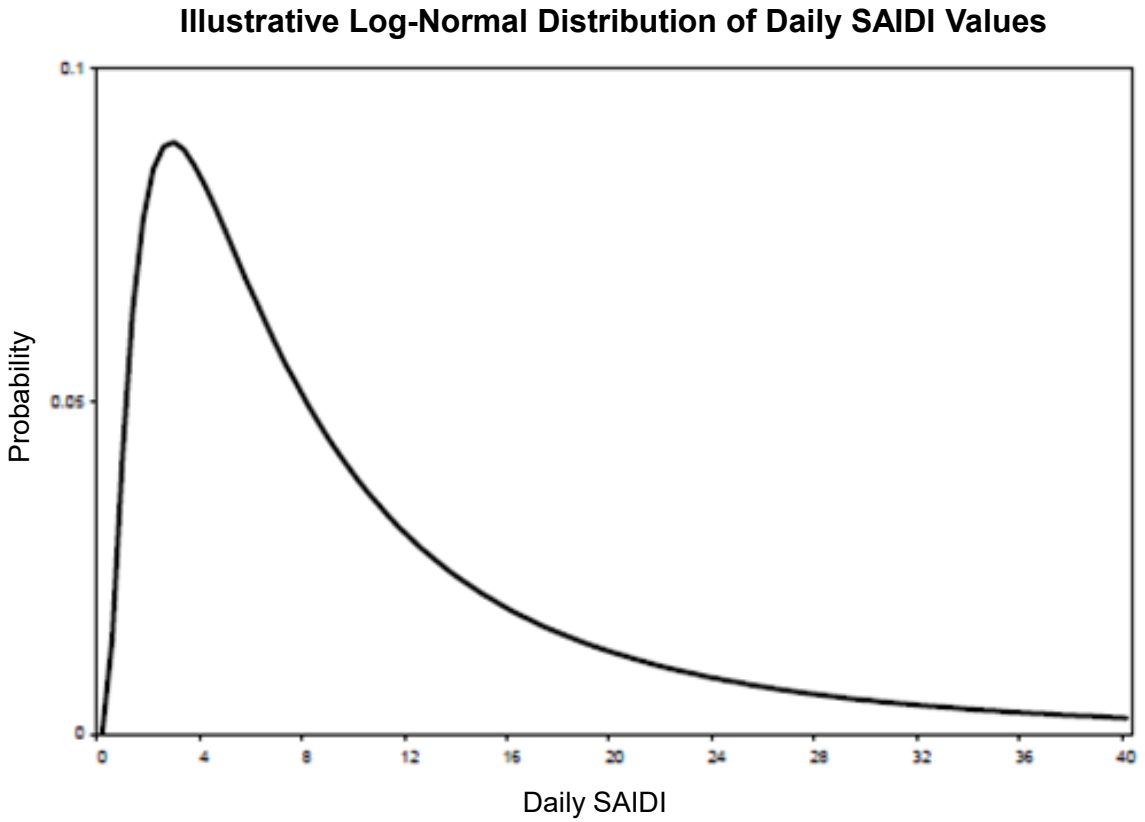
Challenges with Measuring and Valuing Resilience

Challenges with Measuring and Valuing Resilience

- Events are infrequent, highly impactful, and variable
- Existing system-level metrics are difficult to interpret
- Effectiveness of mitigation measures is difficult to estimate
- Widespread, long-duration interruptions cause “spillover” effects to regional economy

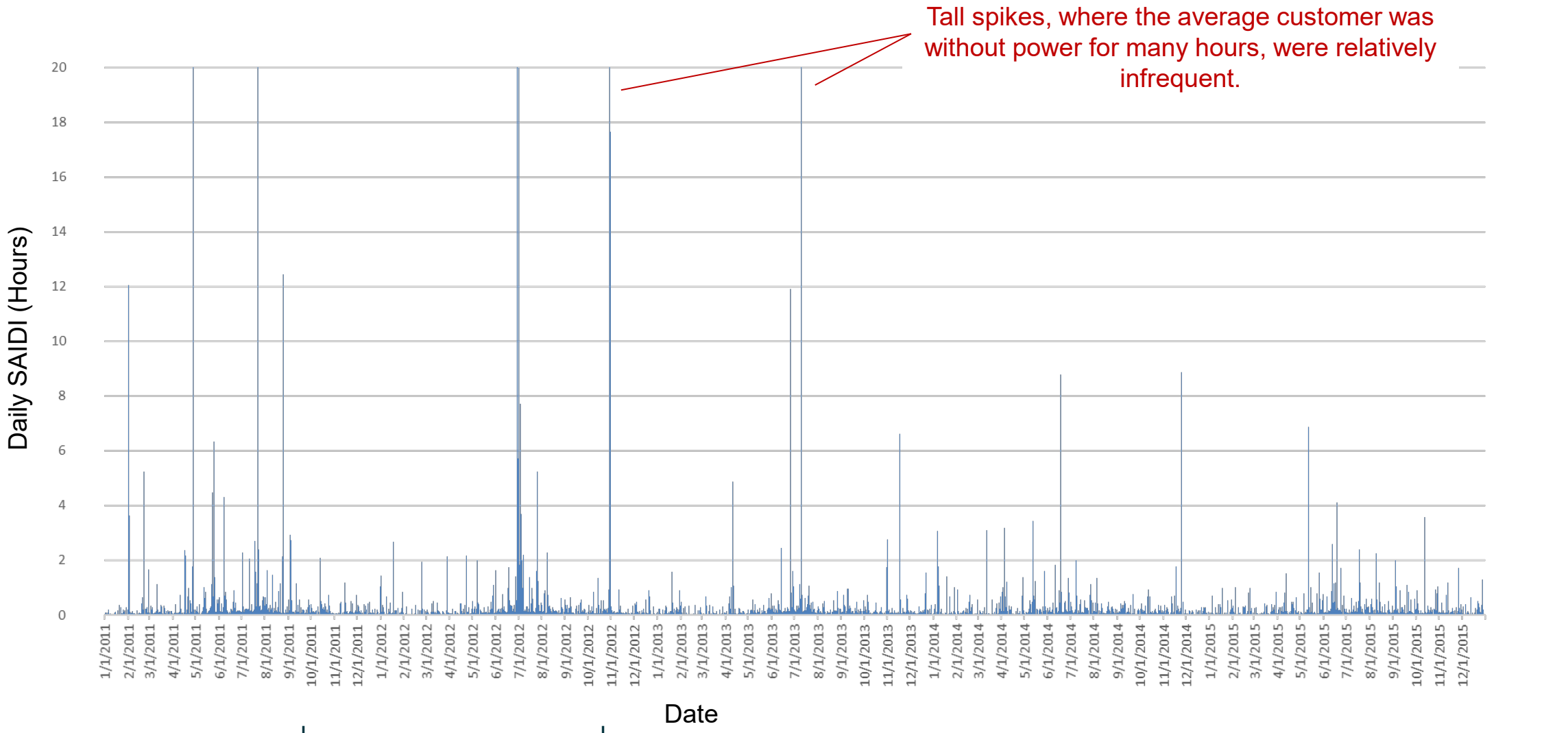
Major Event Day (MED)

- Day with a daily reliability metric that exceeds a statistically-defined threshold based on the previous five years of daily data
- Developed to enable year-by-year tracking of reliability performance (under normal operating conditions) that would otherwise be skewed by weather events that vary in number and severity from year to year
- To set the MED threshold (T_{med}):
  - Use log-distributed daily SAIDI
  - Set T_{med} at a value that is 2.5 standard deviations above the mean
- For a *normal* distribution, this covers 99.379% of the expected observations
  - Translates to an expectation of 2.3 MEDs per year



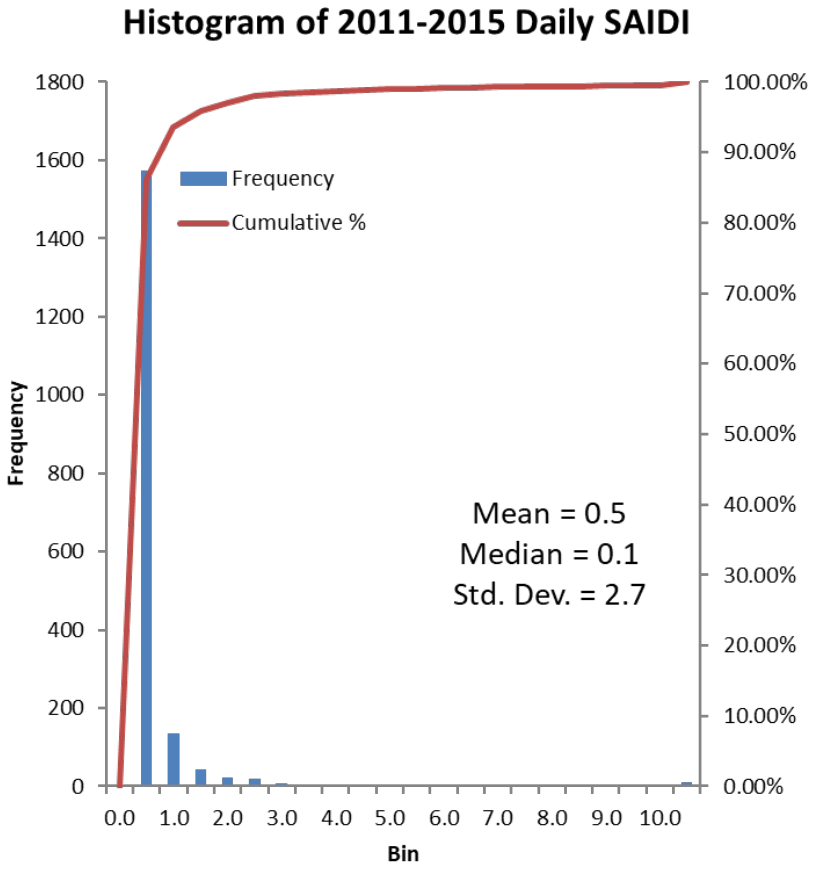
Source: IEEE Standard 1366-2012

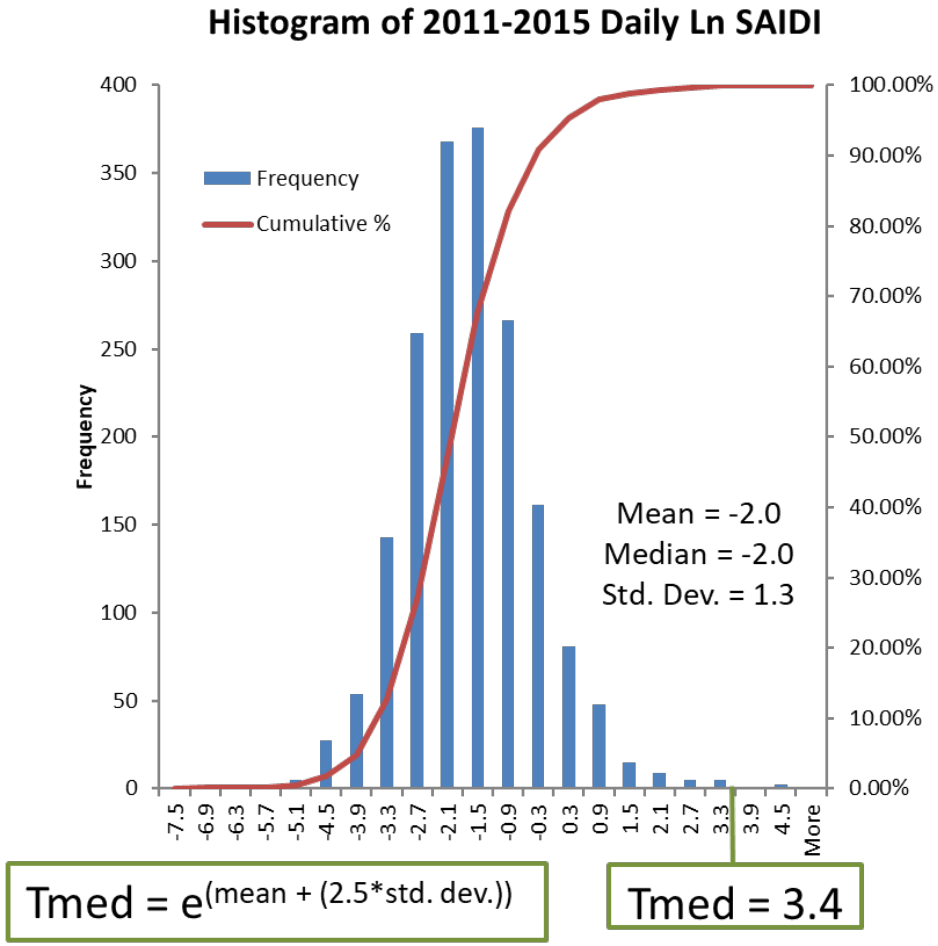
Daily SAIDI for 5 Years (2011-2015)



Source: Berkeley Lab

Daily SAIDI Log-Transformed



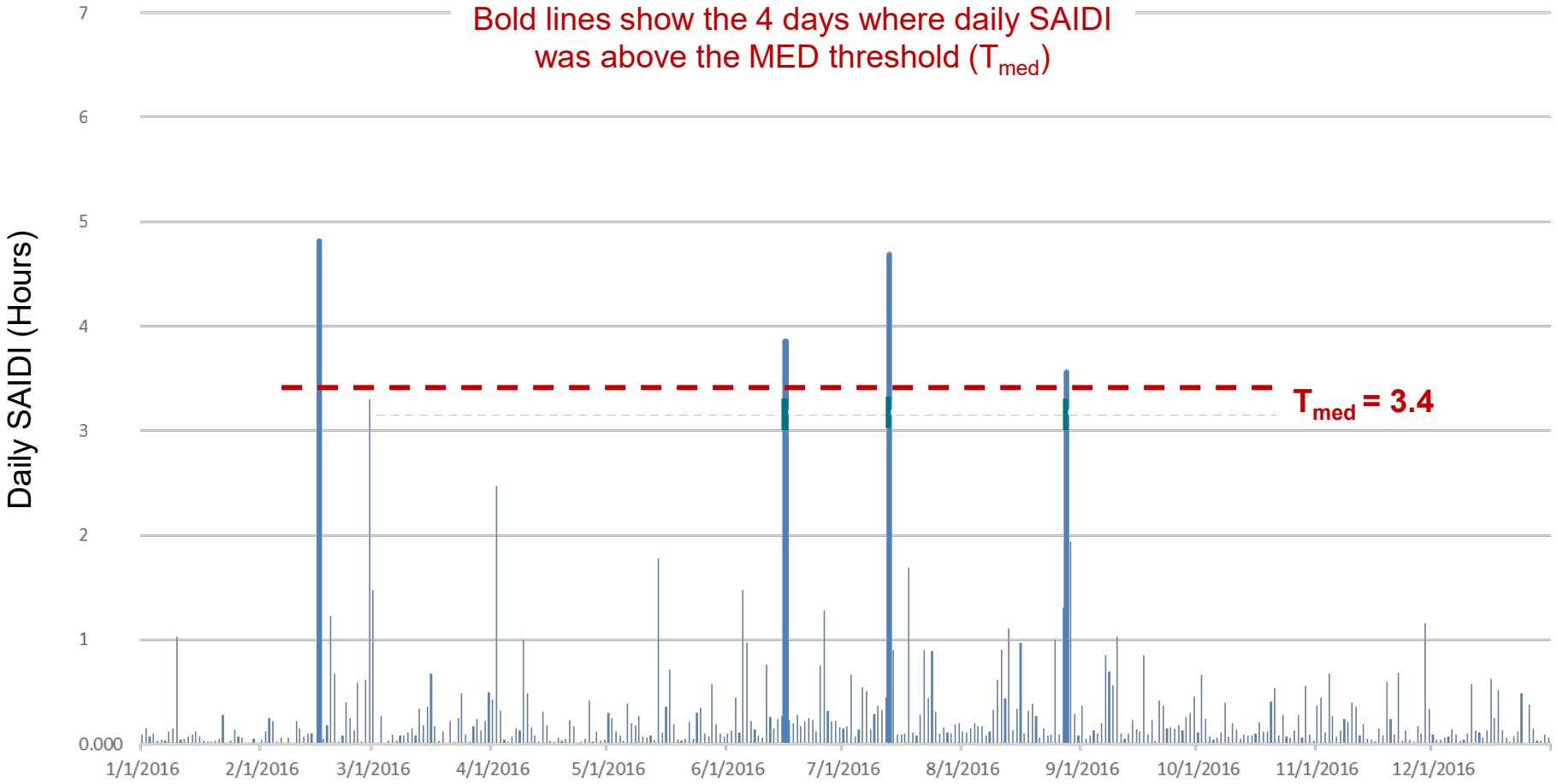


$Tmed = e^{(mean + (2.5*std.\ dev.))}$

Tmed = 3.4

Source: Berkeley Lab

Identifying MEDs Using Daily SAIDI for 2016



4 MEDs in year 2016:

1. Feb 16
2. Jun 16
3. Jul 13
4. Aug 28

Source: Berkeley Lab

Impact of Removing MEDs from SAIDI and SAIFI Data

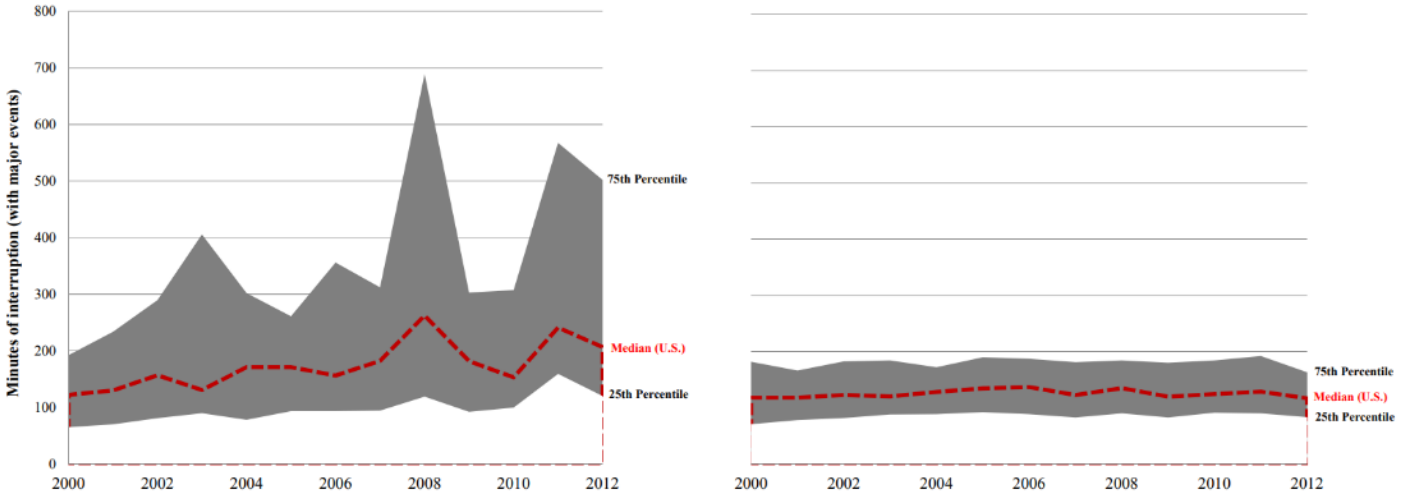
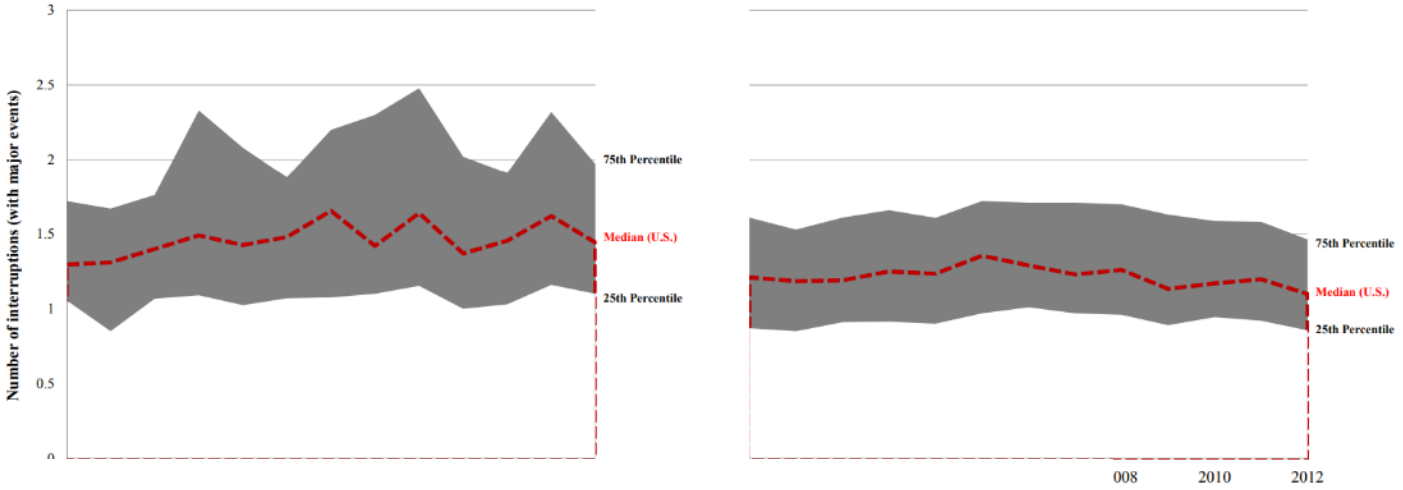


Fig. 2. Average minutes of interruption (SAIDI) with (left) and without (right) major events included.



Source: [Larsen et al. (2016)]

Emerging Approaches

Network Resiliency Index – Consolidated Edison (ConEd)

- Network Resiliency Index (NRI) - “models the relative strength of each network by calculating the probability of failure of multiple associated feeders within a network over time, as caused by individual component failures" (ConEd, 2023)
  - Network ***Reliability*** Index typically calculated annually using ***actual*** system data
- Developed NRI in 2022 to evaluate future scenario that assumed networks in 2030 were designed with the same strength as in 2021, but with higher temperatures
  - Analysis showed that 8 networks would not meet ConEd’s target NRI of 1.0 and that average NRI for the 25 worst performing circuits would increase to 0.87
  - Context: when NRI is low (e.g., < 0.2), the company may defer certain minor overloads, focusing instead on high-risk NRI zones

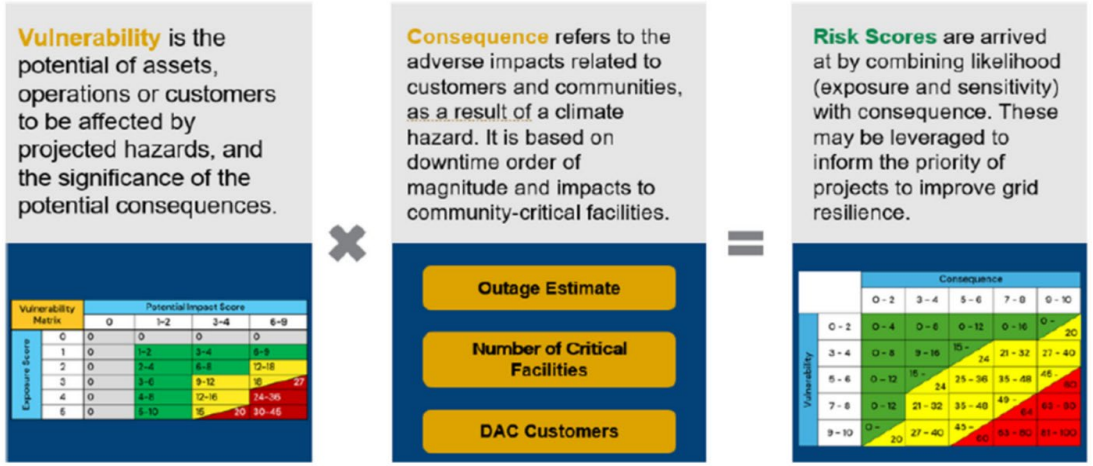
Ranking	NWK ID	Network	What if 2030 @TV=87? (No Reliability Improvements)
1	5B	Ridgewood	1.708
2	7X	Southeast Bronx	1.561
3	6B	Williamsburg	1.420
4	4X	Central Bronx	1.382
5	9Q	Jackson Heights	1.279
6	3X	Fordham	1.151
7	2X	West Bronx	1.055
8	5X	Northeast Bronx	1.043
9	7B	Ocean Parkway	0.953
10	3M	Yorkville	0.889
11	9B	Richmond Hill	0.870
12	1B	Borough Hall	0.857
13	5Q	Jamaica	0.768
14	10B	Sheepshead Bay	0.761
15	2B	Park Slope	0.710
16	1X	Riverdale	0.652
17	7Q	Flushing	0.646
18	4B	Flatbush	0.614
18	8B	Bay Ridge	0.556
20	3Q	Rego Park	0.556
21	20M	Sutton	0.486
22	3B	Crown Heights	0.486
23	10M	Sheridan Square	0.486
23	11B	Brighton Beach	0.480
25	6Q	Maspeth	0.473

Source: ConEd (2025)

Public Service Company of CO (PSCo) - Circuit-level Risk Scores

- PSCo calculated risk scores at the asset level as the product of vulnerability and consequence, where vulnerability was assessed across five natural hazards.
- Risk scores can technically be considered attribute metrics because they describe a characteristic or condition of the system.
- Functionally, they can serve as a bridge between attribute and performance metrics, as the scores quantify the potential for failure based on specific traits.

PSCo Risk Scoring Process



PSCo Heat and Flood Risk Scores for Substation Transformers

		Heat		Flood	
Substation	Consequence Score (out of 10)	Vulnerability Score (out of 10)	Risk Score (out of 100)	Vulnerability Score (out of 10)	Risk Score (out of 100)
G.J.	4.8	2.7	12.9	0	0
A.	4.1	2.1	8.8	0	0
S.	4.1	1.9	7.7	0	0
D.	4.1	1.6	6.6	0	0
R.	4.0	0.3	1.1	0	0
G.	1.5	2.1	3.2	0	0
A.	1.5	1.9	2.7	2.7	6.3
Av.	0.8	1.9	1.5	0	0
L.	0.8	1.9	1.5	0	0
S.	0.7	0.3	0.2	0	0

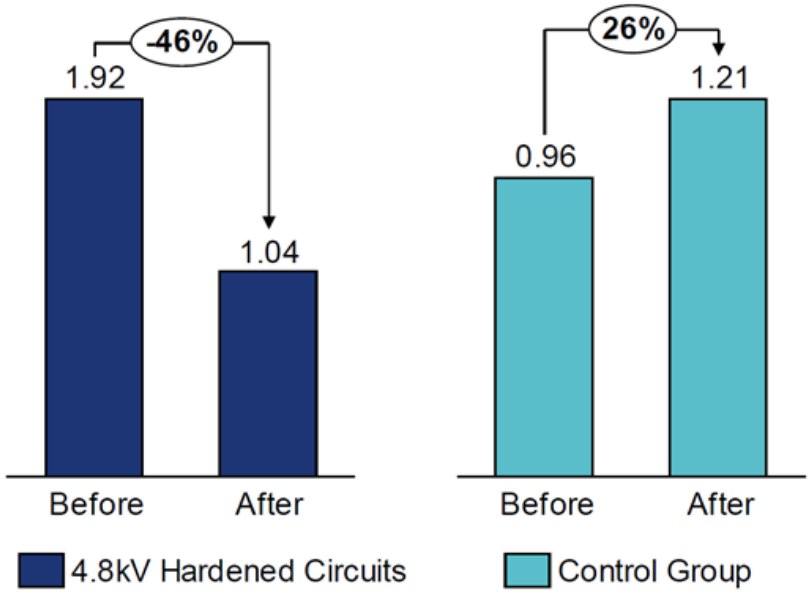
Source: PSCo (2024)

DTE Electric – Measuring Pole Hardening Effectiveness

- Using a control group is a means of controlling for weather, adding confidence that changes in metrics before and after project implementation are due to improved grid performance and not simply more favorable weather.

- DTE Electric measures results of hardening programs by comparing targeted circuits to a control group of similar unhardened circuits.

All-weather SAIFI before and after hardening



Source: DTE Electric (2023)

System Average Large Event Duration Index (SALEDI)

- Ahmad & Dobson (2025) use log transformations of interruption data to address variability of large events
- Resilience events defined as a group of outages that overlap in time.
  - "Event" starts when initial outage starts.
  - All subsequent outages that start before all the previous outages are restored are grouped into the same event (while assuming that each outage duration is limited to 3 hours)
- Use OMS data to systematically identify where outages bunch up and overlap

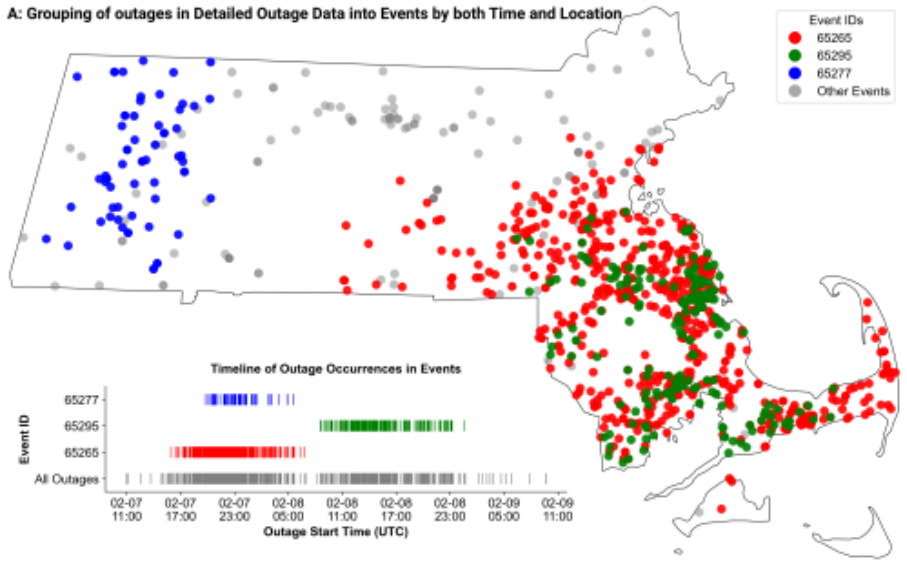


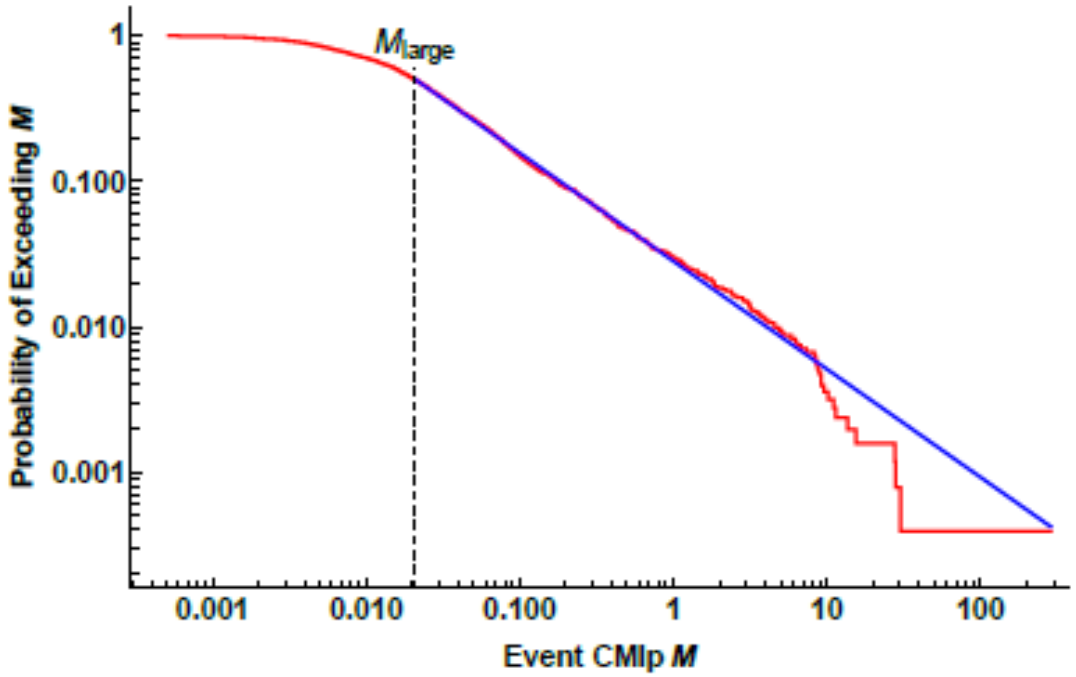
TABLE I
WEATHER ASSOCIATED WITH AUTOMATICALLY EXTRACTED EVENTS

# Outages	Start DateTime (LST)	Duration (hr)	Weather Event
7739	2021-10-26 14:44:41	179.9	Oct. '21 Nor'easter
7392	2018-03-02 04:25:50	178.0	March '18 Nor'easter
5301	2018-03-12 05:22:42	178.2	March '18 Nor'easter
4622	2018-03-07 06:25:25	192.9	March '18 Nor'easter
3287	2013-02-08 14:48:00	149.1	Winter Storm Nemo
3248	2017-10-29 19:18:00	114.6	Oct. '17 Nor'easter
3178	2019-10-16 20:03:00	102.9	Coastal Storm
2775	2020-10-07 11:06:29	124.3	Derecho
2773	2020-08-04 13:00:00	129.3	Hurricane Isaias
2065	2020-04-13 09:15:48	67.7	Easter Tornado

Source: Ahmad and Dobson (2025)

SALEDI: Large Event Threshold

- Process defines a large event threshold M_{large}
- SALEDI is defined over events whose CMI_p (M_i) exceeds the M_{large} threshold
- M_{large}
  - Small enough to give sufficient large events to keep the variability sufficiently small
  - Within the approximately linear region (on a log-log plot) of the tail of the distribution of M_i
  - Determined by a statistical method (minimum Kolmogorov-Smirnov distance)

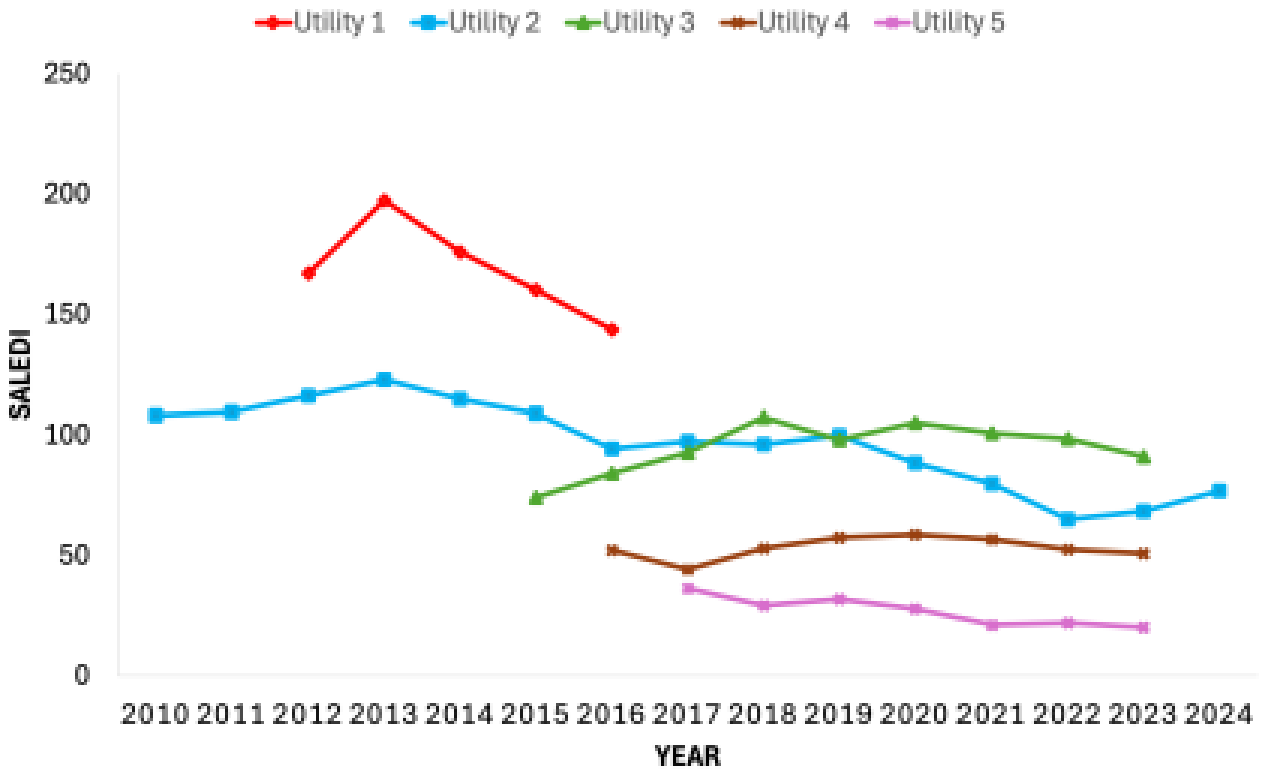


Source: Ahmad and Dobson (2025)

Calculate SALEDI

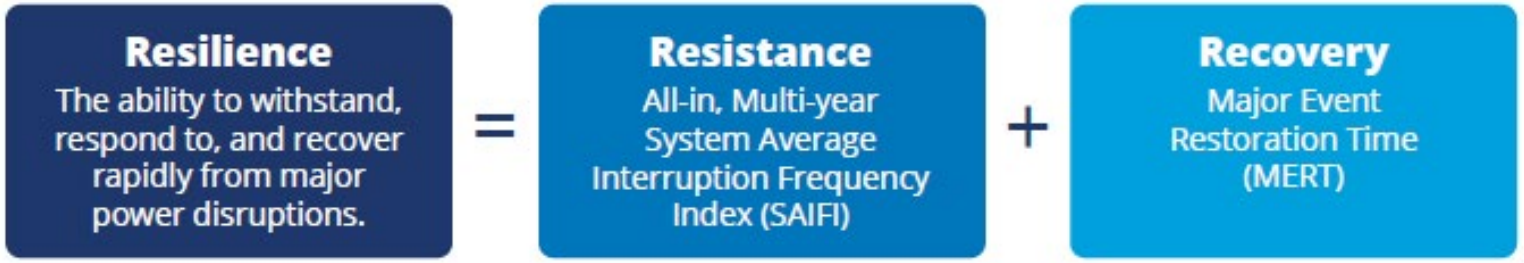
$$\text{SALEDI} = \frac{1}{n_{\text{year}}} \sum_{i=1}^{n_{\text{large}}} \ln \frac{M_i}{M_{\text{large}}}$$

- Sums the logarithms of large event CMI_p over a period of a few years
- SALEDI is responsive to resilience investments
- SAIDI without major event days and SALEDI quantify different aspects of CMI_p and are complementary



Source: Ahmad and Dobson (2025)

Dual Metric Framework – SEPA and Baringa



Source: Beyond the Baseline (2025)

- Resistance: Multi-year SAIFI ("MY SAIFI")
  - Average annual number of times a customer experiences an outage over a rolling average window of 4-7 years
  - MED-inclusive
  - Reduces year-to-year volatility
- Recovery: Major Event Restoration Time (MERT)
  - Time it takes the utility to restore power to most of its customers (typically 95%) after a major event
  - MED-only

Examples of information needed to value an investment in the grid

Cost	Benefits: Non-monetized	Benefits: Monetized	Other
• Capital/installation • Annual operations and maintenance	• Avoided pollution • Avoided health/safety risk • Avoided damage to utility infrastructure • Reduction in frequency and/or duration of power interruptions • Avoided impacts to national security	• Avoided morbidity and mortality costs • Avoided capital and O&M costs to utility • **Avoided interruption costs to customers** • **Avoided "spillover" effects to regional economy** • Avoided aesthetic costs (if applicable)	• Real discount rate (or weighted average cost of capital) • Lifespan of strategy • Local, state, and federal incentives and rebates • Frequency and duration of power interruptions before and after investment • Detailed information about customers impacted

- Costs of past or proposed investments are generally easy to estimate
- However, the benefits of these investments are often difficult to quantify and monetize

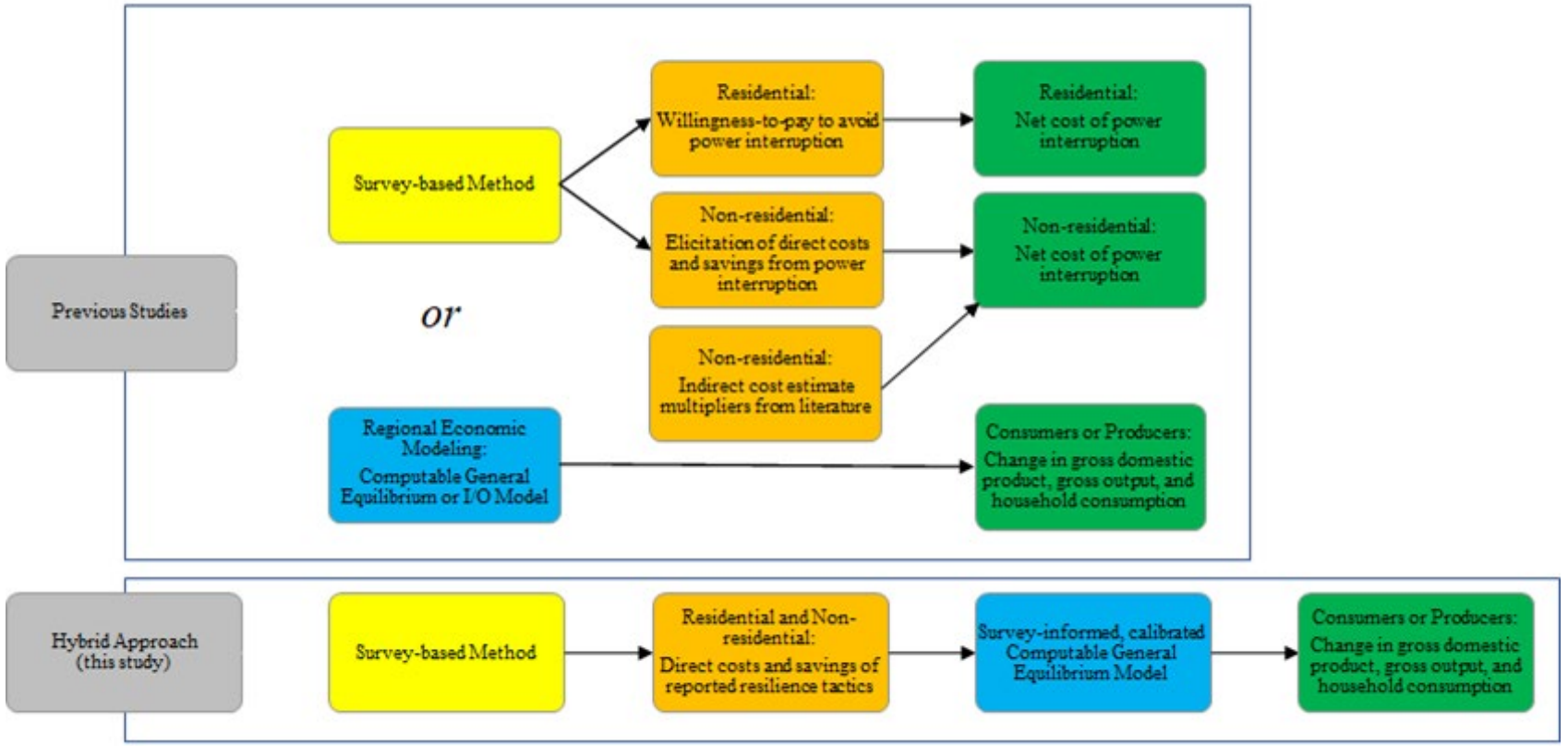
Complementary tools to estimate economic impacts of power interruptions

Used by stakeholders to estimate the costs of shorter duration (< 24 hours), localized power interruptions *or* the economic value of investments in “reliability”

Used by stakeholders to estimate the costs of longer duration (> 24 hours), widespread power interruptions *or* the economic value of investments in “resilience”

POET uses a hybrid valuation approach

- POET's hybrid valuation approach relies on CIC surveys to collect information on household and firm behaviors and then uses this information to calibrate a computable general equilibrium (CGE) model
- Resulting valuation estimates are both grounded empirically and based on a consistent, integrated representation of the regional economy



Modeled scenarios and impact metrics

Modeled scenarios

- Research team used POET to evaluate 3 WLD power interruptions (1-day, 3-day, 14-day) in ComEd service territory, including:
  - Extreme case where the entire ComEd service territory is without power
  - Less extreme cases where only portions of the service territory are without power
- Estimated economic impacts for 15 micro-regions and 38 industrial sectors in ComEd's service area as well as the greater region
- Estimated impacts of doubling the penetration of backup generation across ComEd's service territory

Impact metrics

- POET estimates 3 measures of economic activity for a business as usual (BAU) baseline and for each interruption scenarios
- Reports the difference between BAU and each power interruption scenario

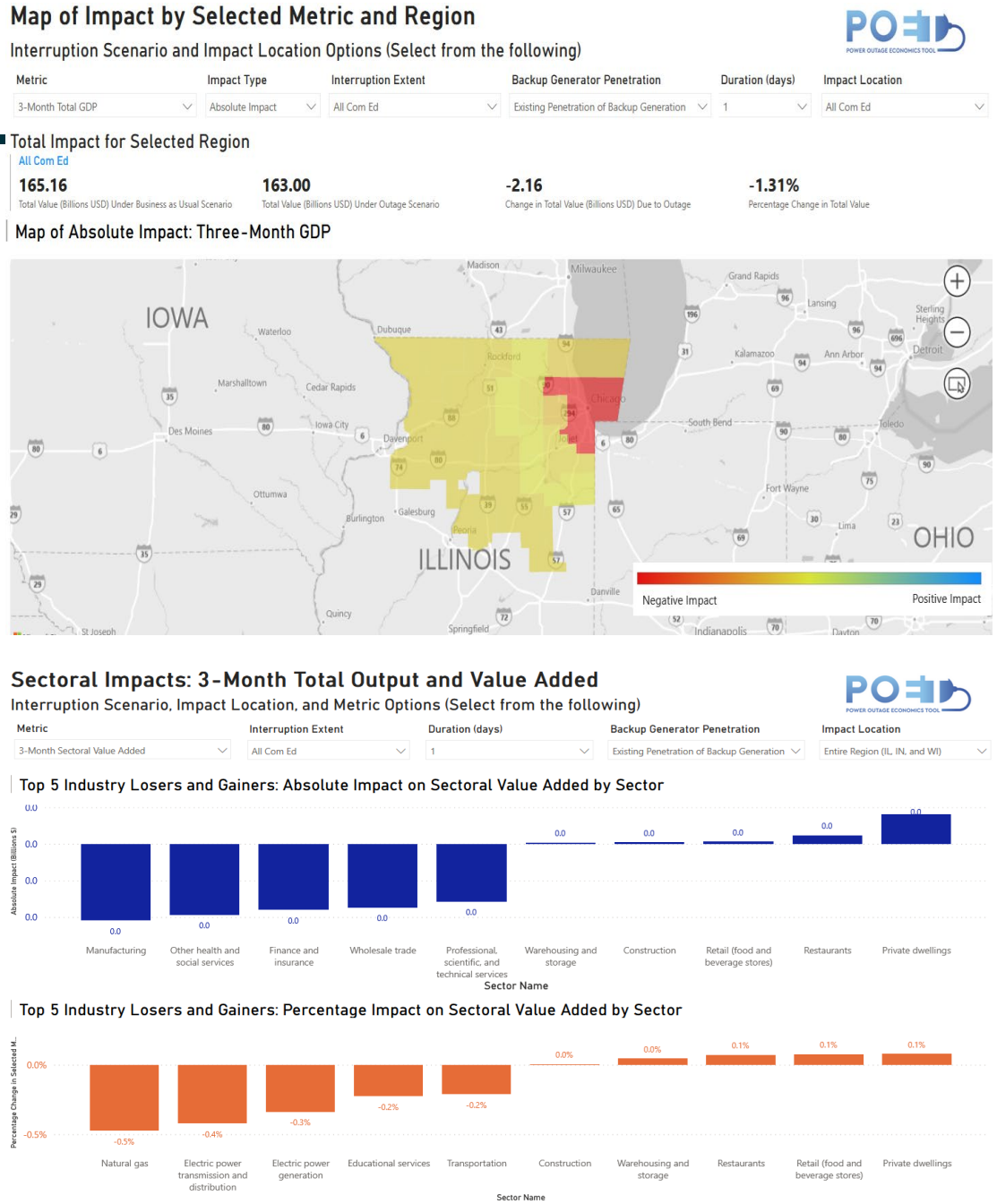
Economic impact metric	Definition
Gross output	% and dollar change industry revenue relative to BAU
GDP	% and dollar change of the total value of final goods and services generated by the economy relative to BAU
Change in household consumption	Average lost consumption attributed to power disruption (alternatively, this is the amount of a subsidy to households to make them indifferent to the power disruption) relative to BAU

POET Example: Change in Overall Gross Domestic Product

Source: Larsen et al. (2024)

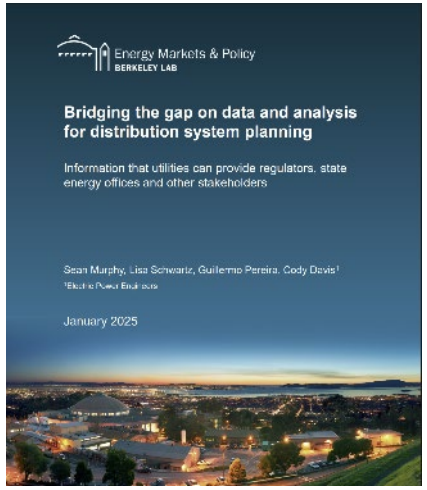
Update on POET

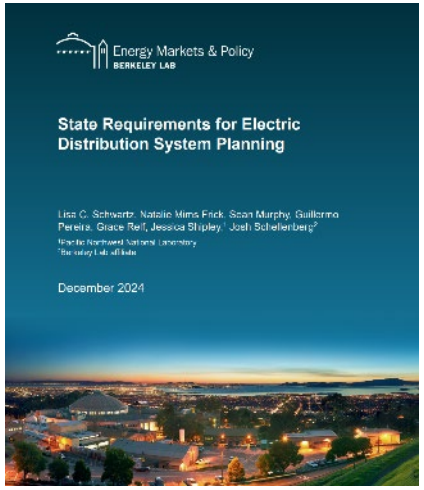
- U.S. DOE has committed resources to deploy POET nationally—this is a multi-year effort
- Project involves:
  1. surveying customers in a number of utilities to collect information on household and firm behaviors
  2. calibrating the POET model based on these responses
  3. assessing resilience gains from various investments
  4. generating county-level economic impacts of outages of various duration and extent—with and without investments
  5. making the results available—most likely as a module within the ICE Calculator website
- New training and technical assistance effort will support stakeholder adoption when tool is released

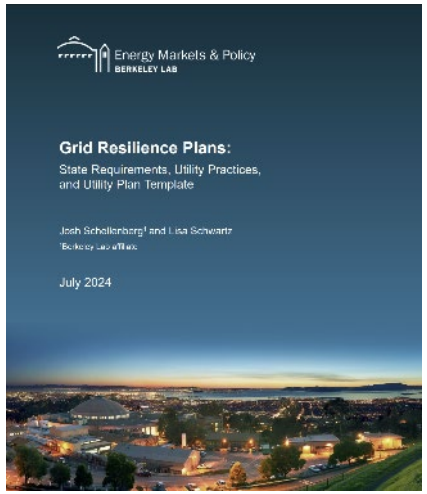


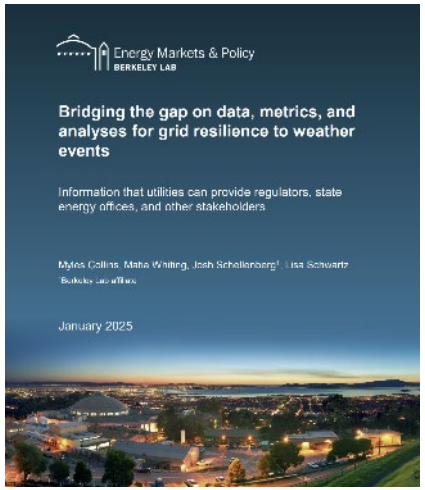
Additional Resources

- Bridging the Gap on Data and Analysis for Distribution System Planning
- State Requirements for Electric Distribution System Planning (includes a review of filed utility plans for leading practices)
- Grid Resilience Plans: State Requirements, Utility Practices, and Utility Plan Template
- Bridging the Gap on Data, Metrics, and Analyses for Grid Resilience to Weather Events
- Interruption Cost Estimate (ICE) Calculator – Online tool for estimating interruption costs and/or the benefits associated with reliability improvements
- Power Outage Economics Tool (POET) – Economic model to estimate economic impacts of widespread, multi-day outages across an entire region









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Acknowledgements

This work was funded by the U.S. Department of Energy, Office of Electricity, under Contract No. DE-AC02-05CH11231.

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Extra Slides

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