Steady and Strong: The Case for Reliability and Resilience

Myles Collins, Berkeley Lab
Paul De Martini, Newport Consulting

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Reliability and Resilience: Definitions, Metrics, and Data

Myles Collins
Berkeley Lab

Definitions

- Reliability – The ability to maintain the delivery of electric services to customers in the face of routine uncertainty in operating conditions.[1]
  - Bulk power system: adequate generation and transmission resources to meet demand under normal and expected peak conditions
  - Distribution system: delivering electricity in sufficient quantities and of sufficient quality to meet electricity users' needs
- 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.[1]
- What's the difference?
  - Reliability – normal conditions and foreseeable stress
  - Resilience
    - Extremes far beyond normal operating conditions
    - High-impact, low-frequency events

[1] GMLC (2020)

Reliability Indices

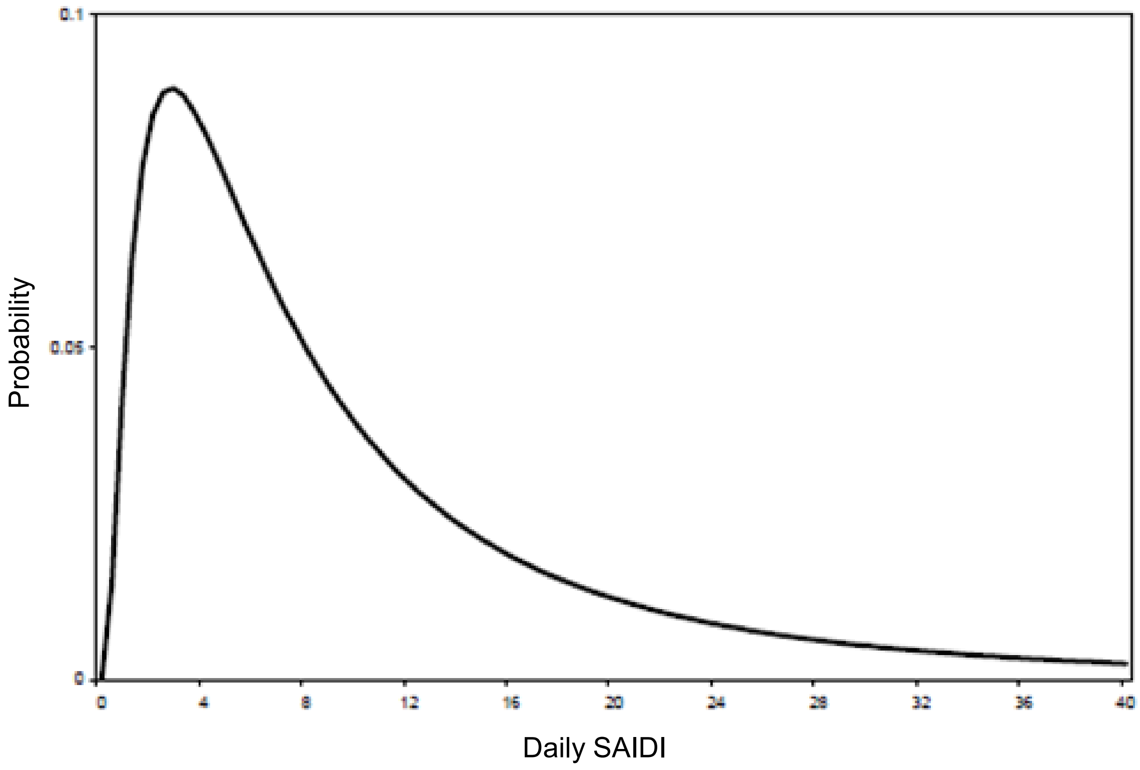
- Reliability indices are defined by IEEE 1366-2022.
- Standard reliability indices are normally calculated and reported on an annual basis, aggregating performance over an entire year.
  - In contrast, resilience metrics tend to focus on notable events that occur at specific times within a year (e.g., over a day or week).
- SAIDI, SAIFI, CAIDI, MAIFI are commonly reported.
  - Less-common metrics focus on impacts to individual customers.

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
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
$CEMI_n$	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

Major Event Day (MED)

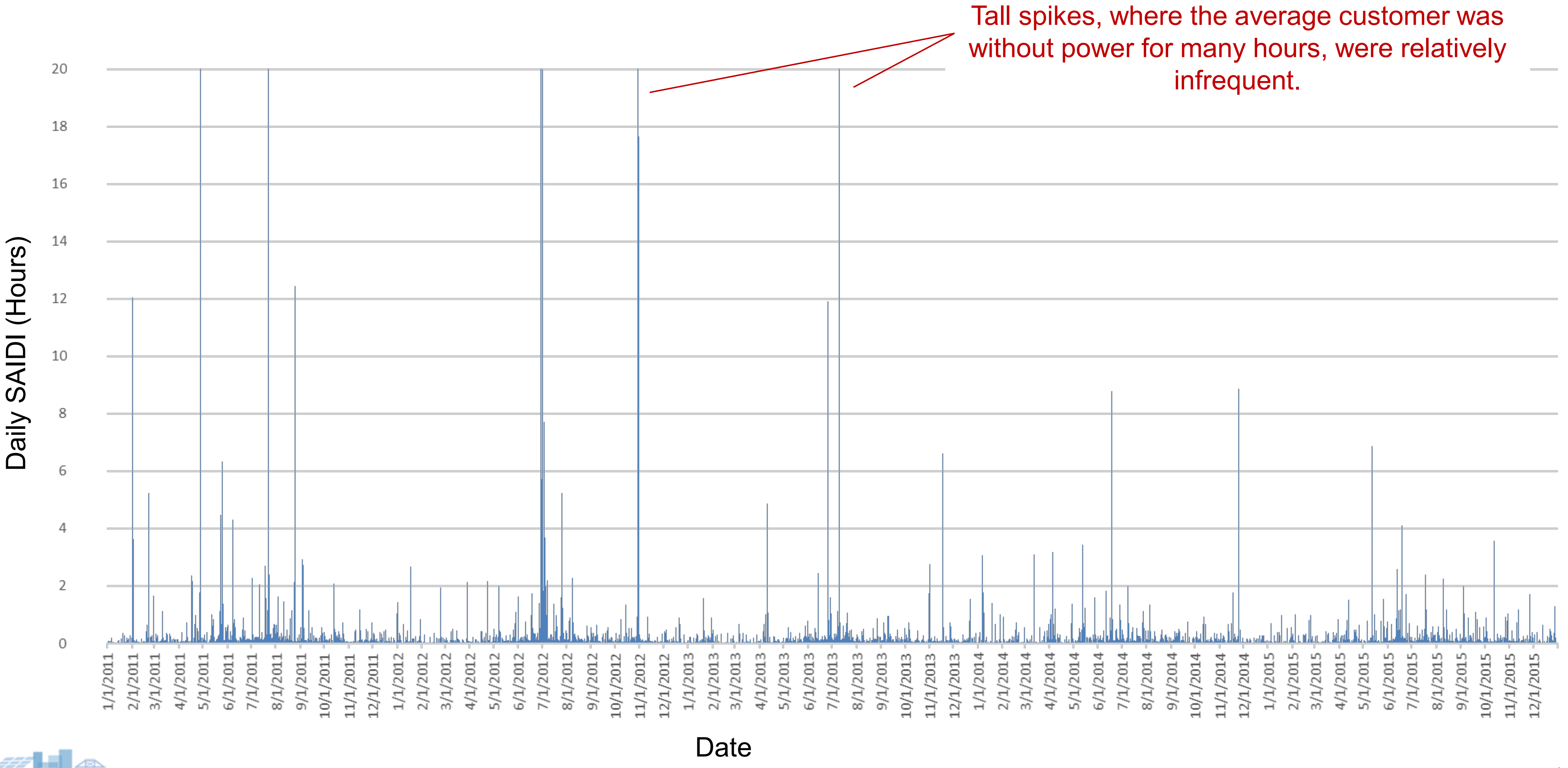
- Day with a daily reliability metric that exceeds a statistically-defined threshold based on the previous five years of daily data
- Developed to enable year-by-year tracking of reliability performance (under normal operating conditions) that would otherwise be skewed by weather events that vary in 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

Illustrative Log-Normal Distribution of Daily SAIDI Values



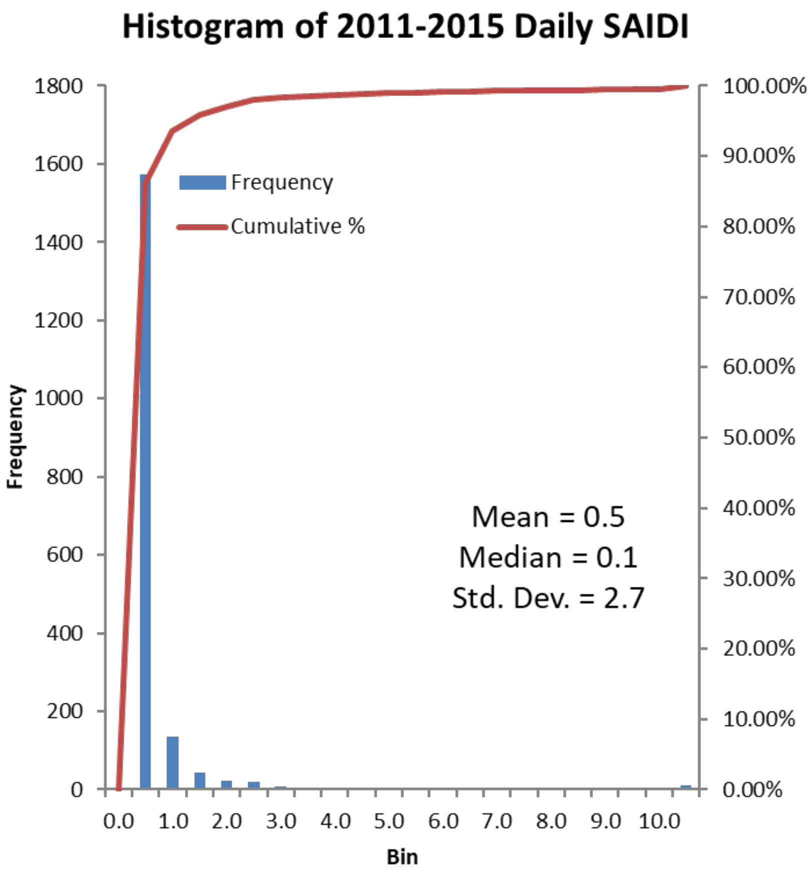
Source: IEEE Standard 1366-2012

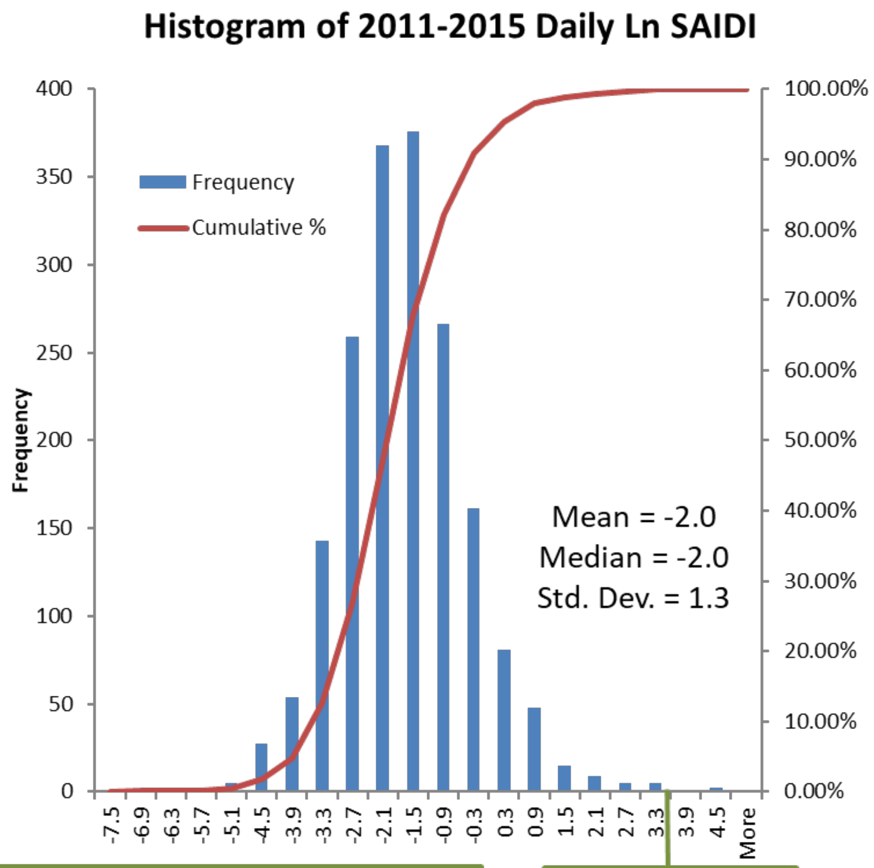
Daily SAIDI for 5 Years (2011-2015)



Source: Berkeley Lab

Daily SAIDI Log-Transformed



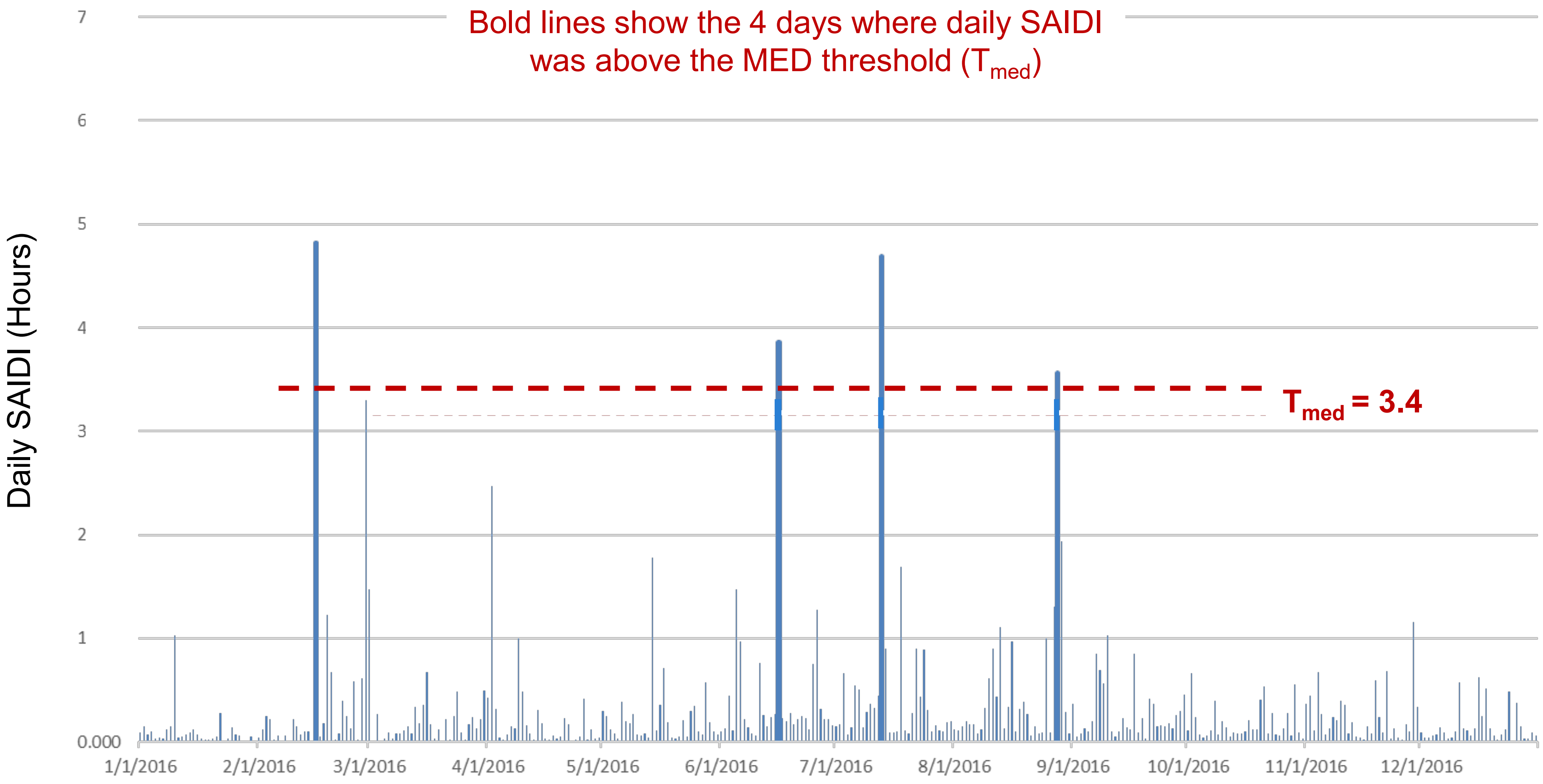


$$\text{Tmed} = e^{(\text{mean} + (2.5 * \text{std. dev.}))}$$

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

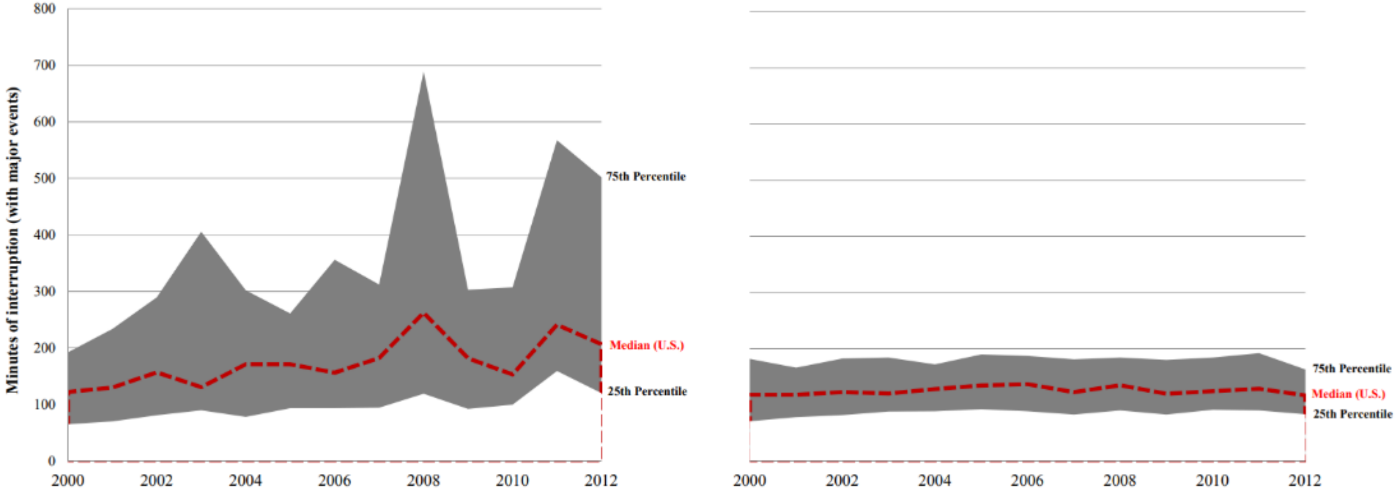
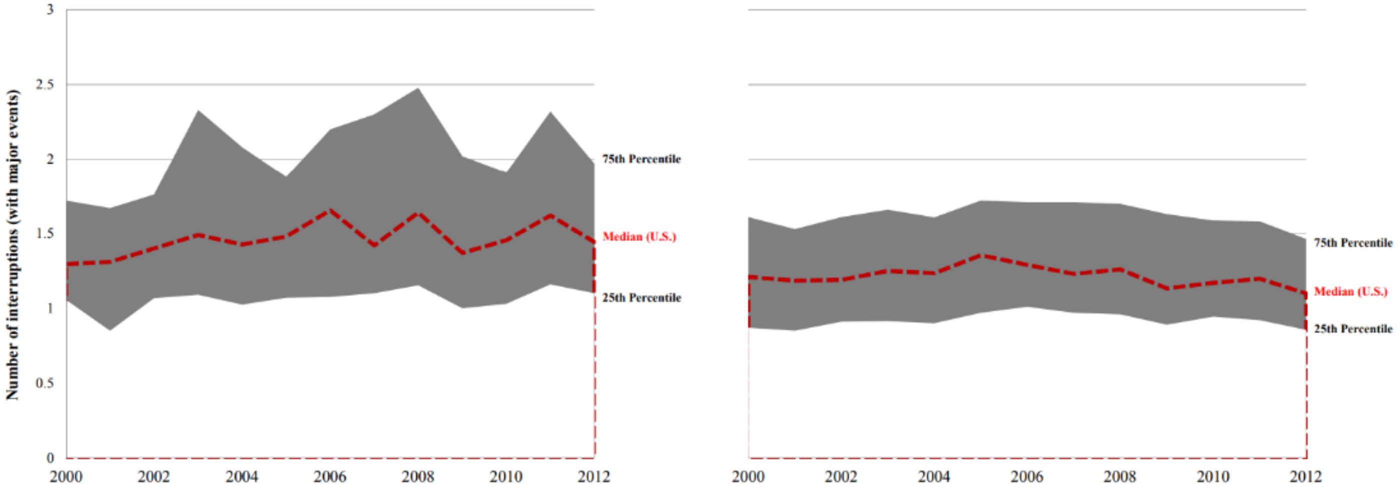
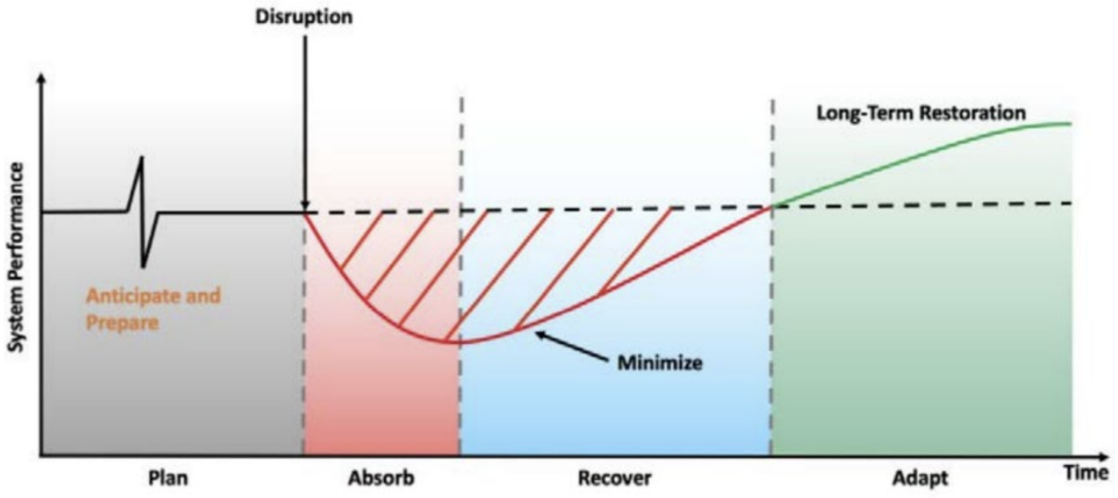


Fig. 2. Average minutes of interruption (SAIDI) with (left) and without (right) major events included.

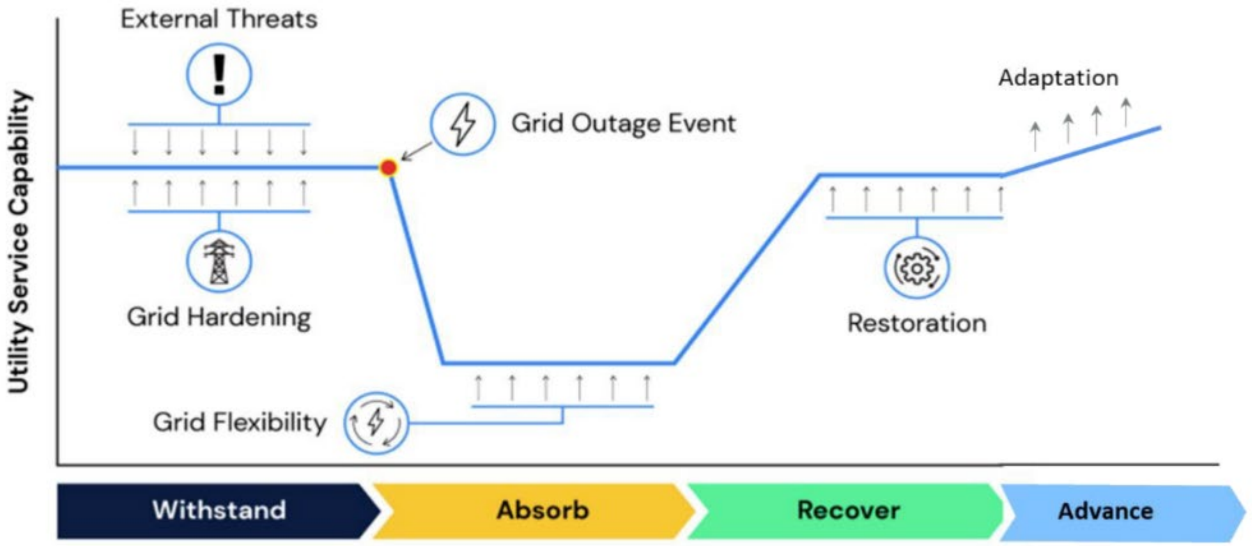


Source: Larsen et al. (2016)

Phases of Resilience



Source: Leddy et al. (2023)



Source: RG&E & NYSEG (2023)

Performance Metrics - Electrical Service

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.
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
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
Custom Indices	Circuit Performance Indicator (Rocky Mountain Power)	Weighted combination of SAIDI, SAIFI, MAIFI, lockouts
	IEEE Storm Resilience Metric (IEEE, 2020)	Quantifies speed of recovery during first 12 hours of a storm from customers losing power

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

Monetary Impact Metrics and Example

Examples of Metrics	
Utility Costs	Value of assets damaged and destroyed by major events
	Post-event O&M restoration costs
Customer Interruption Costs	Cost per event
	Cost per average kW
	Cost per unserved kWh
Economy-wide Impacts	Gross output
	Gross (regional) Domestic Product
	Change in household consumption

Change in Overall Gross Domestic Product for All of ComEd's Service Territory

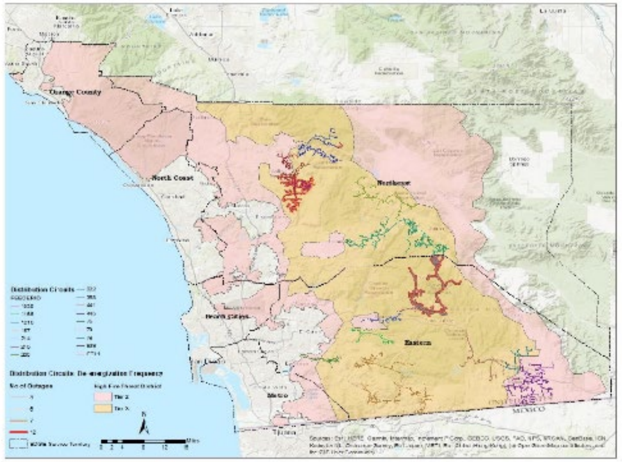
Source: Larsen et al. (2024)

Potential Targets for Specialized Performance Metrics

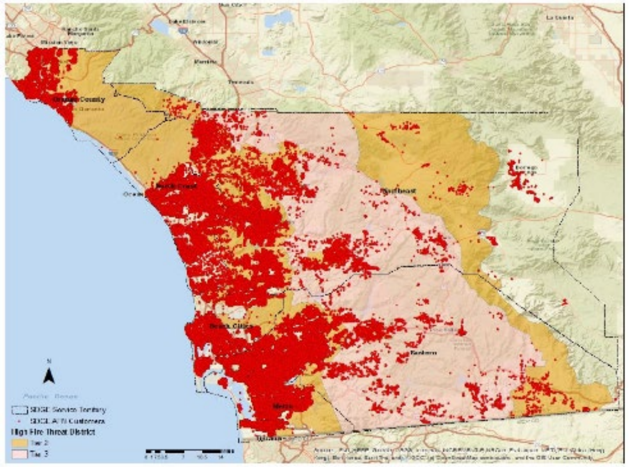
- **Critical facilities:** Infrastructure which is essential for the health, safety, and economic well-being of a population (e.g., hospitals, fire stations, emergency operation centers, public drinking water facilities, sewer and wastewater facilities)

- **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

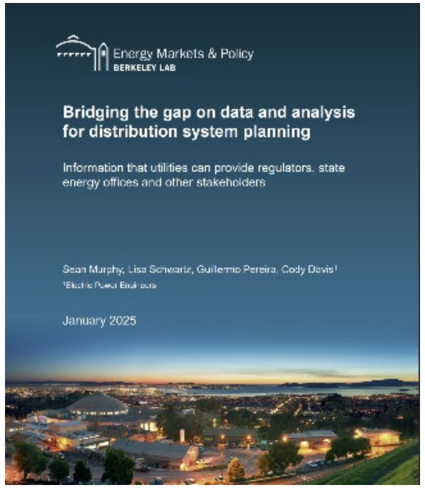
Source: SDG&E Wildfire Mitigation Plan (2023)

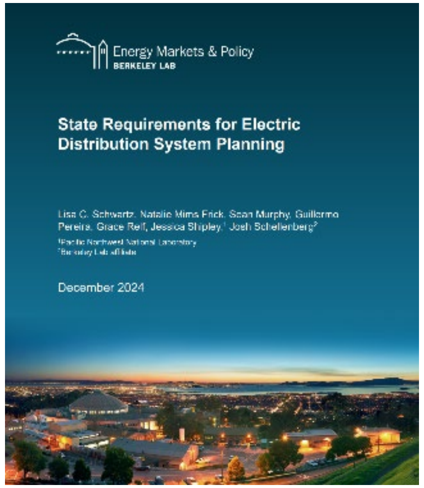
Factors to Consider When Developing and Applying Performance Metrics

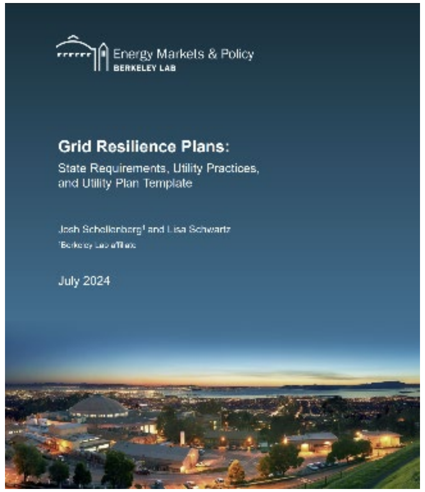
- Caution is warranted when interpreting all-weather SAIDI and SAIFI (including MEDs) as measures of resilience, as these metrics can be significantly impacted by the frequency and intensity of weather events.
- Indices that combine and weight multiple components can be useful for ranking or prioritizing mitigation measures.
  - They are less useful for understanding the specific impacts of resilience measures, as information from each component is lost in the aggregation process.
- Combinations of metrics are more informative than standalone metrics, as they provide a more comprehensive view of the impacts of resilience investments.
  - The process of averaging across systems or even circuits can mask how interruption frequencies and durations are distributed across populations.
- It is important to understand the interplay and tradeoffs between metrics in the context of resilience improvements—for example:
  - Reducing the frequency of short-duration interruptions can decrease SAIDI but increase CAIDI.
  - Implementing safety-adjusted protection settings for reducing fire ignition risk can present a tradeoff between reliability and resilience.

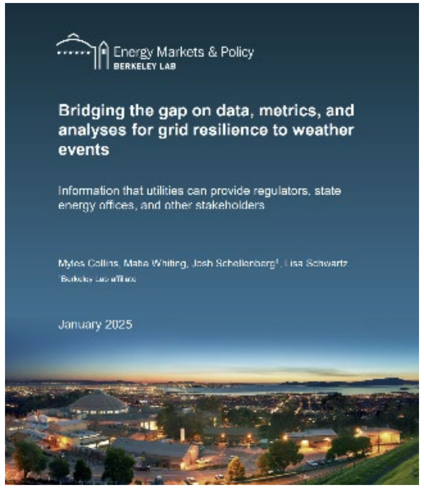
Additional Resources

- □ 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.







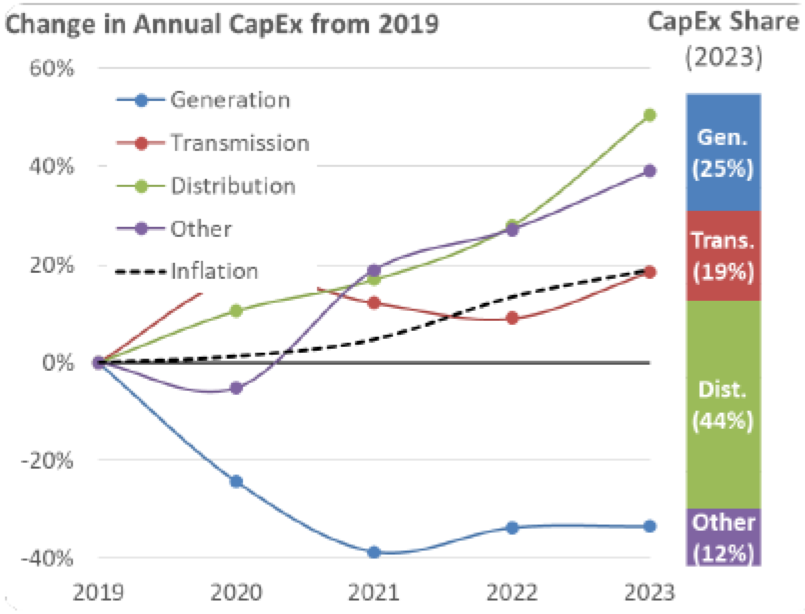


Incorporating Reliability & Resilience into Distribution System Planning

Paul De Martini
Newport Consulting

Distribution Capital Expenditure Growth

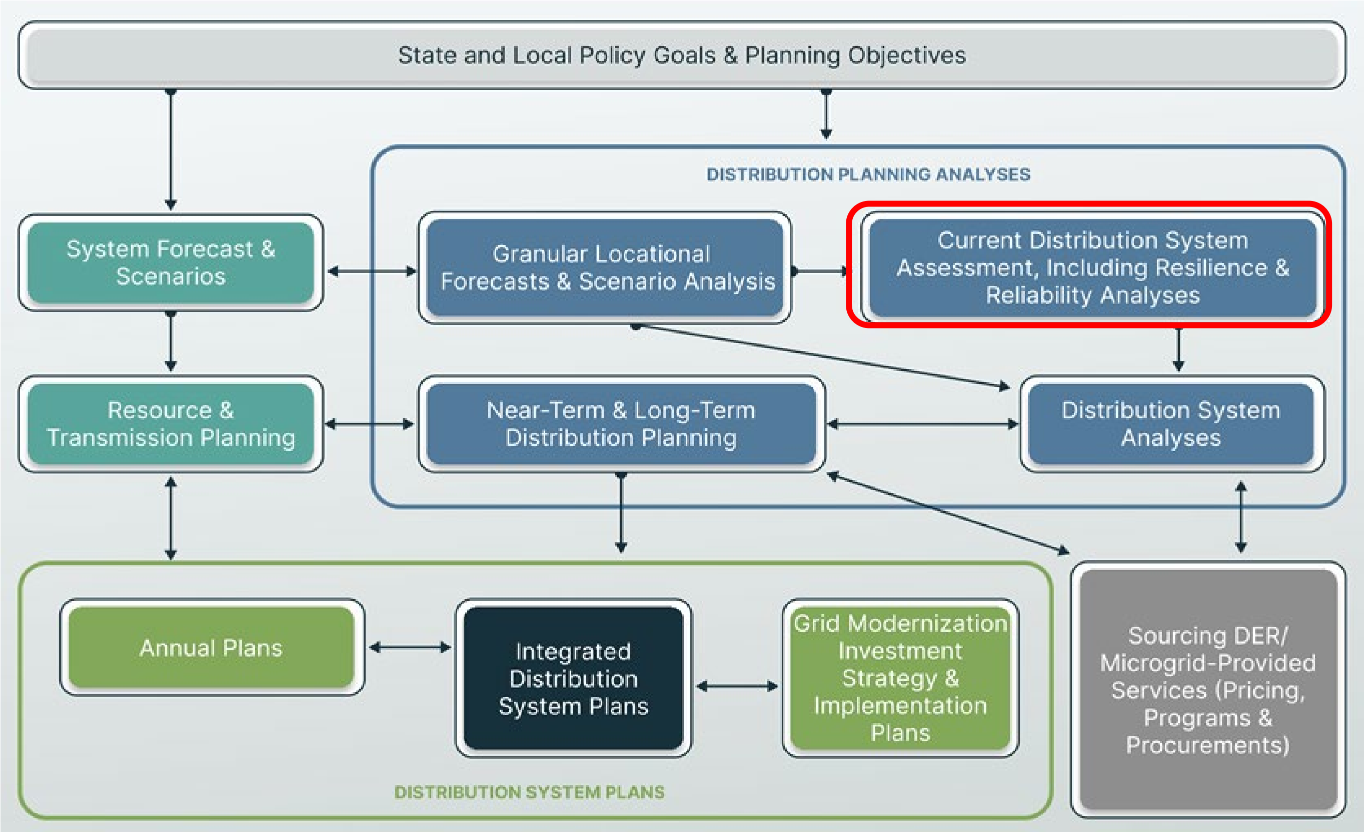
- Spending focus on Adaptation, Hardening, and Resilience (AHR), Replacement, and Capacity Expansion.
  - **AHR 37%, Replacement 28%, Capacity Expansion 28%, Other 7%** (EEI)
  - Capital spending on overhead lines, poles, and towers increased the most. Utilities spent **$17.4 billion on overhead infrastructure in 2023**, an 11% increase from 2022 and a 220% increase from 2003 (EIA).
  - Investment in **undergrounding** also increased considerably, **doubling over the past 20 years** to reach **$11.8 billion in 2023** (EIA).
- Integrated Distribution System Planning is a holistic approach to planning that enables *multi-objective value* decision making by identifying investments that address more than one planning need.



Source: Lawrence Berkeley National Laboratory

Reliability and Resilience Planning in IDSP

Integrated Distribution System Planning is more than assessing capacity expansion – reliability and resilience analysis are key elements to understand overall distribution needs and expenditures.

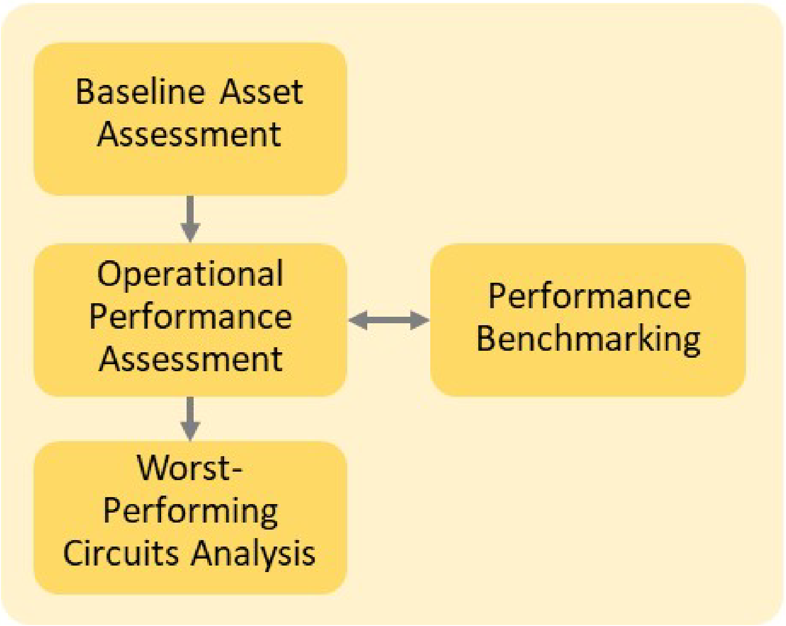


Source: Grid Resilience Plans: State Requirements, Utility Practices, and Utility Plan Template

Asset Management

- Asset management is the process of managing the physical infrastructure involved in delivering electric service.
- It includes a systematic analysis of the condition and performance of physical grid assets according to statutory, regulatory, and technical standards and priorities.
  - Establish a baseline assessment of the distribution system using a detailed asset inventory.
  - Examine operational performance since the prior plan and in the broader context of historical performance trends and reliability standards.
  - Conduct benchmarking to assess performance compared to other utilities and regional/national averages.
- Asset management includes the foundational analysis of the physical grid that serves as the basis for all other aspects of distribution planning analysis.

Current Distribution System Assessment



Reliability Planning: Worst-Performing Circuits Analysis

What is worst-performing circuits analysis?

- Utility engineers analyze outage data to develop a list of circuits (or feeders) with the worst reliability performance and assess the potential root cause(s).
- The utility uses this information to develop a remediation plan to reduce the duration and/or frequency of power interruptions.

Why is the analysis of the worst-performing circuits important?

- To determine priority reliability improvements for customers who have experienced the highest frequency and/or duration of power interruptions.
- Many states require that regulated utilities submit a list of worst-performing circuits on an annual basis, along with a remediation plan.

Worst-performing Circuits Analysis Example

San Diego Gas & Electric calculates and ranks annualized SAIDI for each circuit based on two years of data, excluding planned outages, major event days, and CAISO-mandated load curtailment. The 10 circuits with the highest SAIDI comprise the 1% worst-performing circuits list. The utility develops a similar worst-performing list based on SAIFI, with several circuits that are on both lists. If a circuit is on one of the lists for consecutive years, SDG&E develops a remediation plan for its annual report.

Table 5.1: 2022 Worst SAIDI Circuits List based upon 2021-2022 data (Excludes Planned, MED and Load Curtailment)

Circuit	District	Circuit Customers	Substation Name	Circuit Miles	% OH	% UG	Annualized Feeder Outage Count	Annualized Total Circuit SAIDI **
*445	Eastern	970	BOULEVARD EAST	110.7	93%	7%	7	1645
CCB1	Beach Cities	171	COUNTRY CLUB	3.3	3%	97%	2	1311
CTL1	Northeast	200	CRESTLINE	5.8	69%	31%	5	828
RA3	Northeast	368	RAMONA	3.6	82%	18%	5	785
*220	Northeast	328	SANTA YSABEL	54.0	95%	5%	2	739
CHA1	Eastern	190	CHALLENGE	2.4	100%	0%	2	737
1233	Northeast	293	PALA	28.2	95%	5%	2	734
212	Northeast	630	WARNERS	113.2	96%	4%	6	726
*217	Northeast	1,170	RINCON	84.7	83%	17%	2	639
442	Eastern	1,127	GLENCLIFF	58.7	66%	34%	6	634

* Circuit appeared on the previous worst performance list

** Circuit SAIDI represents the two-year average (2021-2022) of all outages: Mainline, Feeder, Backbone, and Branch

Source: SDG&E 2023 Electric Reliability Performance Report (Section 5)

Reliability Planning: Root Cause Analysis

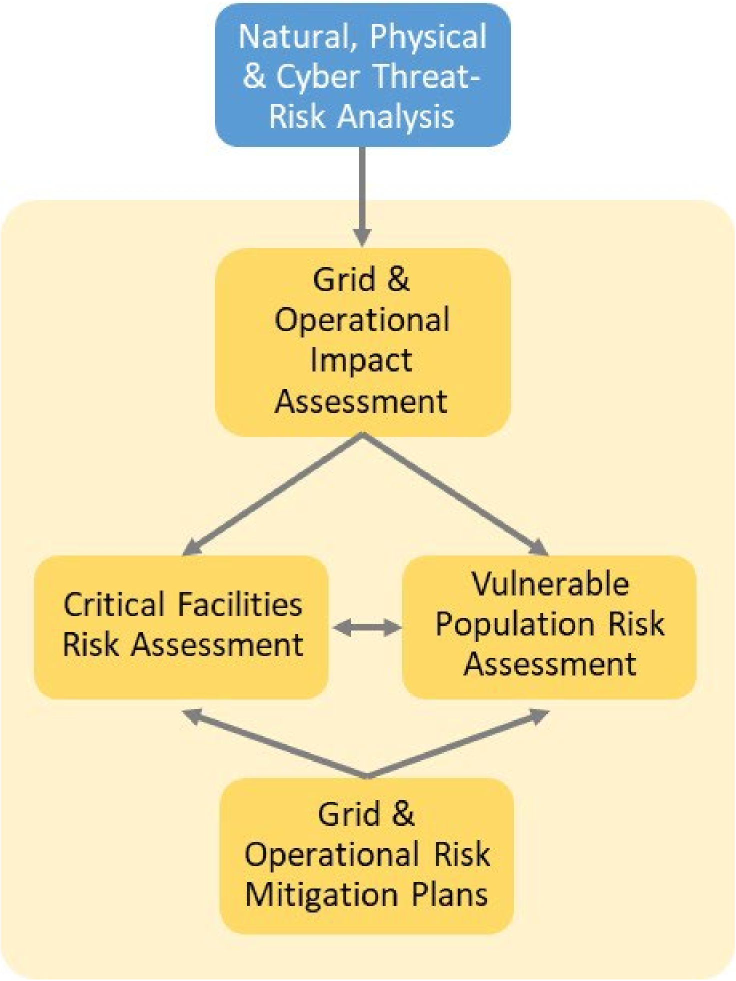
- Utilities delve deeper to understand the underlying “root cause” issues causing poor reliability performance.
- Root cause analysis identifies the underlying reasons for failures or problems in the distribution system:
  - Identifying a specific reliability issue, such as a specific equipment or operational failure
  - Gathering detailed information about the incident, including when, where, and how it occurred
  - Examining the collected data to trace back the sequence of events leading to the issue
  - Determining the fundamental factors that caused the problem, which could be technical, human, organizational, or external
- Root causes may involve inadequate vegetation management, systemic equipment defects, or outdated equipment failure.
- Root cause analysis is vital for improving the reliability of the electric distribution system by addressing the underlying core issues rather than just the symptoms or initiating causes.

Reliability Best Practices

- Follow well-established industry standards – notably IEEE Std 1366 and IEEE Std 1782 – for collecting, segmenting, and reporting outage data for assessing reliability performance.
- Specify criteria for a subset of circuits to include in the worst-performers list.
  - For example, identified state requirements typically direct that the list include the worst-performing 1% to 8% among all distribution circuits.
- File annual utility reports on distribution reliability performance, including worst-performing circuits.
  - Highest circuit-level SAIFI and SAIDI
  - Most recent 3 years
  - A cost-effective remediation plan based on a root-cause assessment if a circuit is on the worst-performing list more than once in the past two to three years
- Continually assess opportunities to improve outage data collection and validation to more accurately measure the frequency and duration of power interruptions for specific customers.

Resilience Planning: Threat-based Risk Assessment

- Threat-based risk assessment identifies specific threats to a utility's assets and operations based on consequences from related grid damage and customer interruptions.
  - **Threats in Scope**: All potential natural, physical, and cyber hazards that have the potential to cause physical grid damage and related power interruptions
  - **Planning Horizon**: Typically, a risk-threat horizon of 10 years
  - **Vulnerability Assessment**: Analyze all hazards to grid assets and operations, with vulnerabilities identified, and impacts on customers and communities assessed
- A stakeholder-informed and objectives-based process identifies critical facilities and vulnerable populations to determine the impact of potential physical grid failures.
- Mitigation plans address identified grid vulnerabilities, such as vegetation management, infrastructure hardening, and undergrounding.



Resilience Planning: Electric System Impact Assessment

- Grid & Operational Impact Assessment involves:
  - Determining potential risks to assets, such as mechanical failure, and operational considerations,
  - Evaluating the probability and propensity by location, and the potential impact of identified risks on the reliability and performance of the assets, and
  - Identifying and assessing non-grid risks (e.g., wildfire ignition) associated with asset failure or degradation and prioritizing actions based on these risks.
- The frequency and intensity of extreme weather events can create significant issues for aging distribution systems that were originally designed to withstand lower-intensity events — for example:
  - Engineering designs that previously specified poles that withstand 60 mph winds may now face 80 mph winds that can cause failures, particularly with older poles.
  - Sea-level rise and increased flooding can pose physical risks to substations and other low-lying and underground grid equipment, particularly in coastal areas.

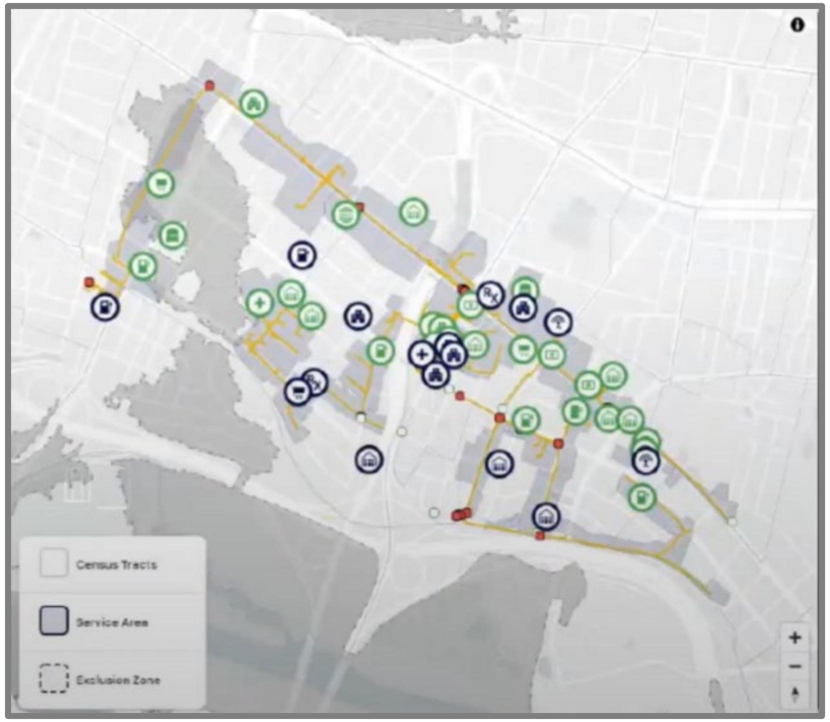
Summary Grid Vulnerability Assessment

	Temperature and Temperature Variable (TV)	Flooding	Wind and Ice
Area and Unit Substations	Primary	Primary	Low
Transmission Substations	Primary	Primary	Low
Overhead Transmission	Primary	Low	Secondary
Overhead Distribution	Secondary	Low	Primary
Underground Transmission	Secondary	Secondary	Low
Underground Distribution	Primary	Secondary	Low
Key Company Facilities	Secondary	Secondary	Low

Source: ConEdison's 2023 grid vulnerabilities assessment

Critical Facilities & Vulnerable Populations

- Critical Facilities
  - Facilities and infrastructure that are critical to the health and welfare of the population and that are especially important following hazard events (FEMA)
  - Critical facilities include, but are not limited to, hospitals, water and waste treatment facilities, telecommunications, shelters, police and fire stations
- Essential Facilities
  - A secondary category of buildings and other structures intended to remain operational in the event of a multi-day outage, such as gas stations, grocery stores, and pharmacies
- Vulnerable Populations
  - The elderly, people with life support systems, disabilities, or other medical needs, and low-income and rural populations that require specific attention in electric resilience planning due to their unique challenges during and after power outages



Source: Sandia National Laboratory ReNCAT Model

Reliability & Resilience IDSP: DTE Electric Company's 2023 Distribution Grid Plan (1/2)

DTE's [2023 Distribution System Plan] incorporates a comprehensive analysis of both reliability and resilience for their distribution system, in addition to the grid needs associated with their planning objectives.

DTE Electric's Planning Objectives

SAFE
Build, operate and maintain the distribution grid and generation fleet in a manner that ensures public and workforce safety, operational risk management and appropriate fail-safe modes and is compliant with state and federal requirements

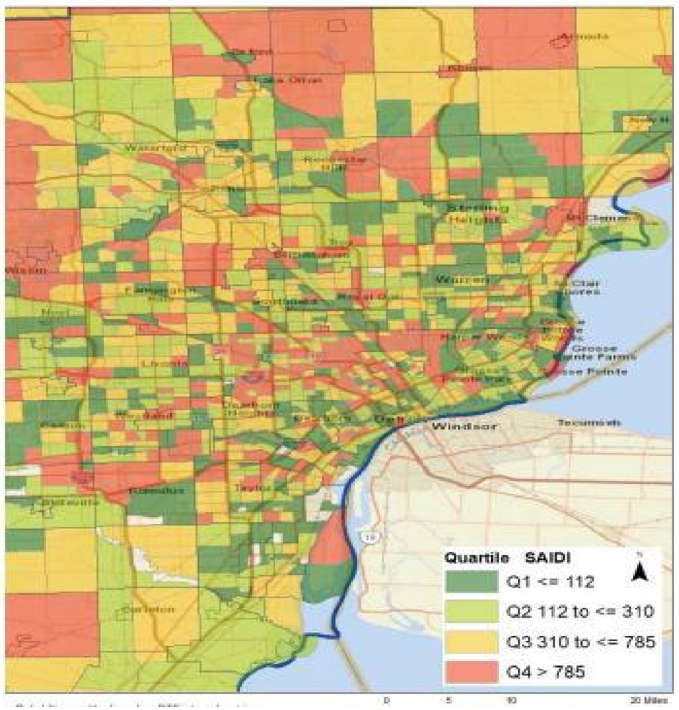
RELIABLE AND RESILIENT
Build, operate and maintain the power system within acceptable standards to withstand sudden disturbance or unanticipated failure of elements. Ensure the grid and diverse generation resources are integrated, with secure supply resources, and can quickly recover from high impact, low frequency events

AFFORDABLE
Provide efficient and cost-effective service along with diverse and flexible generation resources by optimizing the system and benefiting all customers

CUSTOMER ACCESSIBILITY AND COMMUNITY FOCUS
Provide flexible and accessible technology and grid options, and information that empowers and engages customers. Provide effective and timely communication with customers and stakeholders. Favor plans that support the diversity of Michigan communities, suppliers and workforce

CLEAN
Build, operate and maintain the resource fleet and grid platforms in an environmentally sustainable manner by achieving low carbon aspirations and clean -energy goals. Provide a grid that facilitates a transition to a decarbonized economy

Exhibit 12.2.1.3 2022 All Weather SAIDI by Census Tract for DTE Electric (Metro Detroit Area)



Reliability & Resilience IDSP: DTE Electric Company's 2023 Distribution Grid Plan (2/2)

DTE's plan provides an example of detailed analysis of both reliability and resilience risks and explanation of proposed mitigation measures that illustrate the level of analysis that can enable an effective evaluation of a distribution plan.

DTE Reliability Improvement Map (Detroit Metro Area) & Legend

	Tree Trimming	Tree limbs and branches are responsible for nearly 70% of the time our customers spend without power. That's why we're surging our efforts to trim overgrown trees in your neighborhood to keep you safe and the energy grid reliable.
	Strengthen Power Lines	We're upgrading and strengthening power lines to ensure the electric system in your neighborhood is more resilient and reliable.
	Utility Poles Maintenance	We're inspecting and repairing utility poles and replacing cross arms and other pole top equipment to ensure our system delivers the power you need when you need it.
	Rapid Response	Tree trimming and pole top equipment repairs/replacements to quickly improve reliability in communities experiencing emergent issues in between planned maintenance schedules.
	Modernizing & Rebuilding the Grid	Modernizing electrical substation equipment, as well as the underground and overhead infrastructure that delivers power to you, including replacing poles and wiring. Tree trimming will be completed, as necessary, in advance of pole replacements.

Reliability & Resilience Planning Regulatory Practices References

Regulatory Reliability Analysis Practices

Many states have established requirements related to worst-performing circuits for regulated electric utilities, including annual reports that provide remediation plans.

State	Requirement	Percentage of Circuits on Worst-Performing List	Time Period Analyzed	Threshold for Remediation Plan	Reliability Indices Used for Identifying Worst-Performing Circuits
California	Decision Updating the Annual Electric Reliability Reporting Requirements	1%	2 to 3 years	On list for 2 consecutive years	SAIDI and SAIFI
Florida	Annual Distribution Service Reliability Report	3%	1 year	All circuits on list	Number of feeder breaker interruptions
Illinois	Annual Reporting Requirements (Section 411.120 b.3.I and b.3.J)	1%	1 year	All circuits on list, with option to take no action	SAIDI, SAIFI, and CAIFI
Missouri	Electric Utility System Reliability Monitoring and Reporting Submission	5%	1 year	On list more than once in past 3 years	SAIFI
New Jersey	Individual Circuit Reliability Performance and Annual Performance Report	8%	TBD by utility	All circuits on list	TBD by utility
New York	Order Adopting Changes to Standards on Reliability Of Electric Service (Section 3b)	5%	1 year	Lowest-performing operating areas	TBD by utility (including momentary interruption data where practical and feasible)
Ohio	Distribution Circuit Performance	8%	1 year	All circuits on list	SAIFI, CAIDI, and SAIDI
Oklahoma	Individual Circuit Reliability and Annual Reliability Report	5%	1 year	All circuits on list	SAIDI and SAIFI (and to the maximum extent practicable, MAIFI)
Pennsylvania	Reliability Reporting Requirements	5%	1 year	All circuits on list	SAIFI, CAIDI, SAIDI, and if available, MAIFI

Regulatory Resilience Planning Practices

Many states have established threat-based risk assessment requirements for regulated utilities, including resilience planning related to storm protection and other natural events, and wildfire mitigation.

State	Requirement	State	Requirement
California	• Climate Change Vulnerability Assessment • Risk-based Decision-making Framework • Wildfire Mitigation Plan	**Nevada**	Natural Disaster Protection Plan
Colorado	Distribution System Plan	**New Jersey**	Infrastructure Investment Program
Connecticut	Resilience Plan	**New York**	Climate Change Vulnerability Study and Resilience Plan
Florida	Storm Protection Plan	**Oregon**	Wildfire Mitigation Plan
Louisiana	Grid Resilience Plan (rule does not apply to the City of New Orleans)	**Texas**	T&D System Resiliency Plan
Michigan	Distribution System Plan	**Utah**	Wildland Fire Protection Plan

Contacts

Myles Collins: mtcollins@lbl.gov
Lisa Schwartz: lcschwartz@lbl.gov

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QUESTIONS

Extra Slides

U.S. Distribution System Metrics with and Without MEDs

	All Events (With Major Event Days)			Without Major Event Days		
Year	SAIDI (minutes per year)	SAIFI (times per year)	CAIDI (minutes per interruption)	SAIDI (minutes per year)	SAIFI (times per year)	CAIDI (minutes per interruption)
2013	227.2	1.187	191.5	111.9	0.994	112.6
2014	236.2	1.257	188	114.2	1.038	110
2015	209	1.275	163.9	117	1.073	109.1
2016	268.4	1.327	202.2	119.8	1.082	110.7
2017	505.9	1.42	356.2	117	1.023	114.3
2018	349.2	1.34	260.5	121.4	1.051	115.5
2019	295.5	1.332	221.8	122.2	1.04	117.5
2020	456.1	1.385	329.3	116	1.013	114.5
2021	475.8	1.436	331.2	125.7	1.039	120.9
2022	333	1.426	233.5	131.1	1.09	120.2

Source: EIA

NARUC

National Association of Regulatory Utility Commissioners

Thank You

Please feel to reach out if have any additional questions:

hoquinn@naruc.org