Title

Bridging the Gap on Data, Metrics, and Analyses for Grid Resilience to Weather Events: Information that utilities can provide regulators, state energy offices, and other stakeholders

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Bridging the gap on data, metrics, and analyses for grid resilience to weather events

Information that utilities can provide regulators, state energy offices, and other stakeholders

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January 2025

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Prepared for the
Grid Deployment Office
U.S. Department of Energy

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Acronyms

AI	Artificial Intelligence
ASCE	American Society of Civil Engineers
BCA	Benefit-Cost Analysis
BCJ	Business Case Justification
BCR	Benefit-Cost Ratio
BRIC	Baseline Resilience Indicators for Communities
CAIDI	Customer Average Interruption Duration Index
CAPEX	Capital Expenditures
CAVA	Climate Adaptation and Vulnerability Assessment
CELID	Customers Experiencing Long Interruption Duration
CEMI	Customers Experiencing Multiple Interruptions
CEMM	Customers Experiencing Multiple Momentaries
CEMSMI	Customers Experiencing Multiple Sustained Interruption and Momentary Interruption Events
CI	Customers Interrupted
CIC	Customer Interruption Cost
CMI	Customer Minutes Interrupted
CPUC	California Public Utilities Commission
CRM	Community Resilience Metric
CVA	Climate Vulnerability Assessment
DOE	Department of Energy
EPRI	Electric Power Research Institute
FEMA	Federal Emergency Management Agency
GCM	Global Climate Model
GDP	Gross Domestic Product
GIS	Geographic Information System
HFRZ	High Fire Risk Zones
ICE	Interruption Cost Estimate
IEEE	Institute of Electrical and Electronics Engineers
IGSD	Intelligent Grid Switching Device
IOU	Investor-owned utility
IPCC	Intergovernmental Panel on Climate Change
LOCA	Localized Constructed Analogs
MAIFI	Momentary Average Interruption Frequency Index
MCA	Multi-Criteria Analysis
MED	Major Event Day
NOAA	National Oceanic and Atmospheric Administration
OPEX	Operational Expenditures
POET	Power Outage Economics Tool
PSPS	Public Safety Power Shutoff
PUC	Public Utilities Commission
PURA	Public Utilities Regulatory Authority

RAMP	Risk Assessment and Mitigation Phase
RAP	Resilience Analysis Process
RBA	Risk-Based Analysis
RCP	Representative Concentration Pathway
RSE	Risk-Spend Efficiency
SAIDI	System Average Interruption Frequency Index
SAIFI	System Average Interruption Duration Index
SB	Senate Bill
SME	Subject Matter Expert
SPP	Storm Protection Plan
T&D	Transmission and distribution
USGCRP	United States Global Change Research Program
VSE	Value-Spend Efficiency
WLD	Widespread and Long Duration
WMP	Wildfire Mitigation Plan

Executive Summary

States and utilities are increasingly taking action to improve grid resilience to mitigate threats to electricity systems from more frequent and severe weather events. Yet many utility regulators and stakeholders are not fully aware of the wide range of information that utilities can provide related to grid resilience planning and how the information can be used to improve regulatory decision-making and stakeholder engagement. In particular, utility regulators may not be familiar with effective metrics for measuring grid resilience performance. One reason is that these metrics are relatively nascent. Another reason is that measuring resilience is inherently complex, with a focus on grid performance during low-probability, high-consequence events. Also, severe weather hazards vary widely—for example, wildfires versus winter storms—and resilience approaches are often hazard-specific.[1]

This report aims to bridge the gap between electric utilities and the regulators, state energy offices, and other stakeholders that engage in grid resilience planning—specifically, with respect to resilience-related data, metrics, and analyses.[2] To develop the report, Berkeley Lab reviewed 43 utility resilience plans. The plans primarily addressed the distribution system, but some also addressed transmission. Figure ES - 1 shows the categories researchers used to organize and present the information found in the plans. Researchers also reviewed state resilience planning requirements, academic literature, and materials from industry resilience initiatives and working groups and conducted interviews with staff at public utility commissions, state energy offices, and utilities.

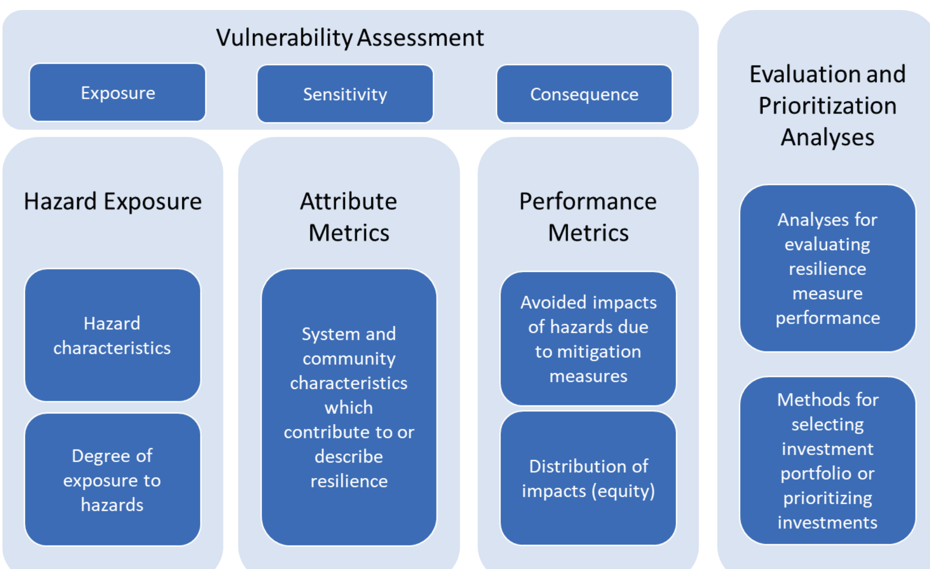


Figure ES - 1. Categories of Data, Metrics, and Analyses in Resilience Plans

[1] While this report focuses on regulated utilities, primarily investor-owned utilities (IOUs), rural electric cooperatives and municipal utilities also conduct grid resilience planning. State energy offices and stakeholders may engage in these processes. In addition, state programs funded under section 40101(d) of the Bipartisan Infrastructure Law (Infrastructure Investment and Jobs Act, 2021) are developing metrics that may be useful for all types of utilities.

[2] See a related Berkeley Lab study by Murphy et al. (2025), *Bridging the Gap on Data and Analysis for Distribution System Planning: Information That Utilities Can Provide Regulators, State Energy Offices and Other Stakeholders*.

At the top of the figure is the Vulnerability Assessment category (covered in Chapter 4). This assessment is a stakeholder-informed process that: (1) identifies communities, infrastructure, facilities, and processes that are vulnerable to specific hazards and (2) prioritizes vulnerabilities that are most important to mitigate, based on likelihood and potential impacts. The Vulnerability Assessment spans three areas: Hazard Exposure (Chapter 5), Attribute Metrics (Chapter 6), and Performance Metrics (Chapter 7). Information included in these three areas aligns with the subcategories of vulnerability assessments: Exposure, Sensitivity, and Consequence. The outputs can serve as inputs into other areas. For instance, hazard exposure data inform "exposure," attribute metrics inform "sensitivity," and performance metrics inform "consequence."

State resilience planning requirements direct utilities to provide information in one or more — or all — of the categories in Figure ES - 1. Requirements also vary in terms of flexibility, prescriptiveness, and the extent that analysis frameworks, data, and performance metrics are defined.

Table ES - 1 specifies the types of data, metrics, and analyses in the utility resilience plans reviewed for this study. The five rows of the table correspond to the five categories in Figure ES - 1. The resilience plans and academic literature included a variety of frameworks for categorizing data, metrics, and analyses for grid resilience planning. Frameworks differed somewhat in structure and nomenclature but generally aligned with one another. Table ES - 1 summarizes information that utilities can provide regulators, state energy offices, and other stakeholders during the resilience planning process to improve regulatory decision-making and public engagement. This report provides examples across the country.

Key findings of the study include the following:

1. Resilience planning presents unique challenges for utilities, regulators, and stakeholders. These include the severity of resilience events, variation in how different customers experience resilience events, potential for underutilized resilience investments, planning requirements that surpass those that have applied to traditional reliability planning, and coordination with other agencies.
2. Methods for approaching risk and vulnerability assessments have a similar framework across utilities, even though the terms vary.
3. An increasing number of indices are in use for characterizing resilience attributes or performance.
4. Utilities and regulators acknowledge the need to augment standard reliability metrics with more tailored metrics for measuring resilience.
5. Regulators and stakeholders face a tradeoff between interest in more granular utility data and limited resources to analyze and interpret the data.
6. Utilities and regulators are increasingly considering vulnerable populations in planning efforts.
7. Utilities and regulators are increasingly taking steps to systematically measure and track performance of resilience investments, such as measuring ex post impacts.

Table ES - 1. Data, Metrics, and Analyses in Utility Resilience Plans

Category	Description
Vulnerability Assessments (Chapter 4)	Evaluations of the susceptibility of systems, communities, or assets to potential harm from identified hazards. These assessments often focus on understanding key factors such as exposure, sensitivity, adaptive capacity, and potential consequences.

Hazard Exposure (Chapter 5)	Data on hazards and the exposure of a utility's assets or its operations, and ultimately its customers to these hazards.
	• Utility resilience plans with forward-looking hazard projections that describe projections across four dimensions:
	   ○ Hazard data variables
	   ○ Future climate scenarios
	   ○ Analysis timeframe
	   ○ Data sources
	• Exposure data that describe the degree to which assets may experience specific climate hazards.

Attribute Metrics (Chapter 6)	System characteristics that contribute to or describe aspects of the resilience of a system or community. Metric categories align with the four phases of resilience: • Anticipate: The likelihood or characteristics of potential impacts caused by a hazard. • Withstand: The electrical system's capacity to avoid being affected by a hazard. • Adapt: The ability of the grid to respond to asset damage or the community to change behavior to minimize impacts to customers. • Recover: The ability to restore normal grid operation after a disruption.
Performance Metrics (Chapter 7)	Impacts of resilience investments on system performance—generally, measures of expected or actual reduction of negative impacts from hazard events. • Electric 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.
Evaluation and Prioritization (Chapter 8)	Evaluations cover analyses that utilities undertake to estimate impacts from resilience measures. These include: • Ex post studies to estimate the performance of measures that have already been implemented. • Ex ante studies to estimate the future performance of proposed measures. Prioritization analyses prioritize resilience measures based on costs and estimated impacts. These include benefit-cost analysis, risk-based analysis, and multi-criteria assessment.

A number of methods, processes, and approaches have significant potential for improving and advancing the use of data, metrics, and analyses in grid resilience planning, including the following practices:

1. Select or establish a clear analysis framework based on capabilities, regional preferences, and resilience objectives.
2. Establish and maintain consistent definitions and accurate location data for critical facilities.
3. Understand the key socioeconomic factors that define populations that are more vulnerable to adverse impacts of power interruptions and severe weather.
4. Measure resilience impacts at a granular level and be consistent in tracking interruption causes.
5. Advance efforts to address uncertainty associated with the likelihood and magnitude of resilience events.
6. Use a combination of metrics to understand system performance.
7. Conduct regular, systematic ex post (backward-looking) analyses following resilience events and apply learnings in future planning cycles.

1. Introduction

A growing number of states are establishing requirements for regulated electric utilities to file grid resilience plans. Many requirements focus on planning for increasing frequency and severity of extreme weather events ([Schellenberg and Schwartz, 2024](#)). State objectives for resilience preparedness detailed in the plans drive the need for data, analyses, and metrics to assess weather-related hazards, determine appropriate investments, and measure the expected and actual performance of investments in improving resilience.

From 1980 to 2024, the United States experienced roughly 400 weather-related disaster events with damages greater than $1 billion (NOAA, 2024). The average number of events per year was 8.5 events, whereas the average for the 5-year period from 2019-2023 was 20.4 events (adjusted for inflation). Figure 1.1 shows the number of billion-dollar disaster events each year by type of event. The bars show the trend of increasing costs of extreme weather events and the black line shows the rolling 5-year average cost, which has climbed from $20 billion in the 1980's to over $120 billion today. State regulators and utilities are increasingly aiming to improve grid resilience to address the threats posed to the electric system from increasing severe weather events.

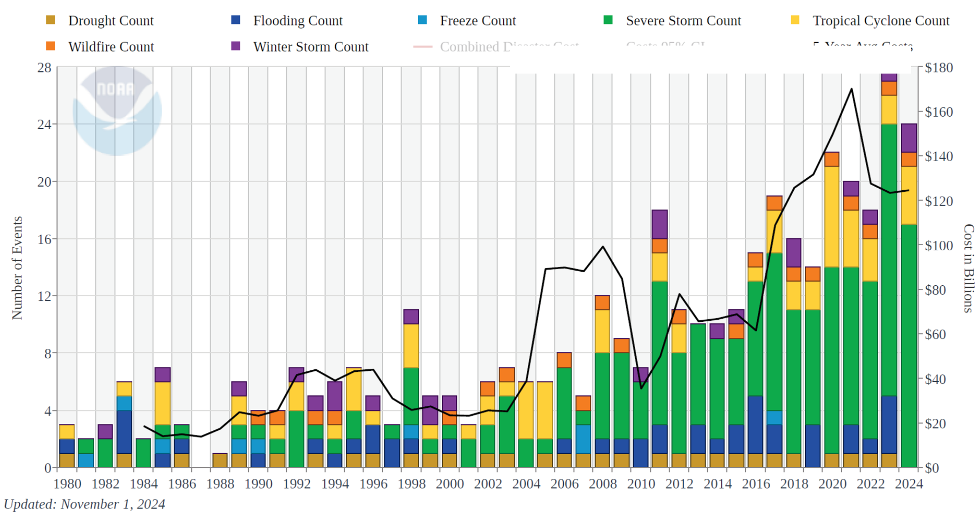


Figure 1.1. Billion-Dollar Disaster Events in the U.S. from 1980-2024 (Adjusted for Inflation)

1.1 Reliability and Resilience Planning

Reliability refers to maintaining the delivery of power (Eto et al., 2020). Utilities have factored resilience events into reliability planning processes for decades, particularly for the bulk power system.[3] For the distribution system, [IEEE Standard 1366](#) established metrics to guide reliability planning. These metrics distinguish between normal operating conditions and less frequent, abnormal operating conditions

[3] See North American Electric Reliability Corporation (2024) for a complete set of reliability standards for the bulk electric systems of North America.

using statistical analysis to identify and report separately on Major Event Days (MEDs) when calculating reliability indices.[4]

Resilience focuses on grid performance during extremes far beyond normal operating conditions. The term "resilience" is defined as "preparing for, adapting to, withstanding, and recovering rapidly from major disruptions,"[5] such as those resulting from extreme weather. While there is overlap in metrics between reliability and resilience, reliability metrics focus on all operating conditions, whereas resilience metrics focus on large disruptions and their outsized impacts and are relatively nascent. With increasing frequency and severity of extreme weather events, new resilience planning tools and approaches are needed to complement established reliability planning processes, including resilience-specific plans and metrics that focus on extreme weather conditions (Schellenberg and Schwartz 2024).

Urgent threats have prompted a recent wave of resilience-oriented planning activities. For example, the increasing frequency and severity of wildfires in the Western United States have led several states to establish requirements for utilities to file Wildfire Mitigation Plans (WMPs) every one to three years. Ideally, the utility considers grid resilience solutions in the context of other electricity system plans, as illustrated in Figure 1.2 for Integrated Distribution System Planning.[5] At a minimum, priorities, data, and methodologies in the grid resilience plan can be aligned with other types of utility planning processes to prioritize capital investments and other expenditures across multiple objectives, reveal how investments fit together over time, and avoid redundancy. Utilities, regulators, state energy offices, and stakeholders can consider how grid resilience planning fits into a broader planning framework across all levels of the electricity system.

Key Resilience Terms

Hazard – Anything that can expose a vulnerability, either intentionally or accidentally, or that can damage, destroy or disrupt the power sector. Hazards can be natural, technological, or human caused. They are typically not within the operator's control and can include wildfires, hurricanes, storm surge, cyber-attacks and so on. Often used interchangeably with *threat*.

Threat – Something that is likely to cause damage or danger to the power sector. Often used interchangeably with *hazard*.

Vulnerability – A weakness in a system or process which, when exposed, can lead to a negative impact or consequence. Typically, vulnerabilities are within control and can be mitigated to avoid exposure.

Impact or Consequence – To have a direct effect or significant effect on something such as the power sector or components of the system.

Source: Gayathri Krishnamoorthy, National Renewable Energy Laboratory, "Introduction to Resilience for Electricity Systems," March 11, 2024.

[4] See Section 3.5.1 for a discussion of "major event" criteria.

[5] Presidential Policy Directive. (2013). *Critical Infrastructure Security and Resilience*. Retrieved from https://obamawhitehouse.archives.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil

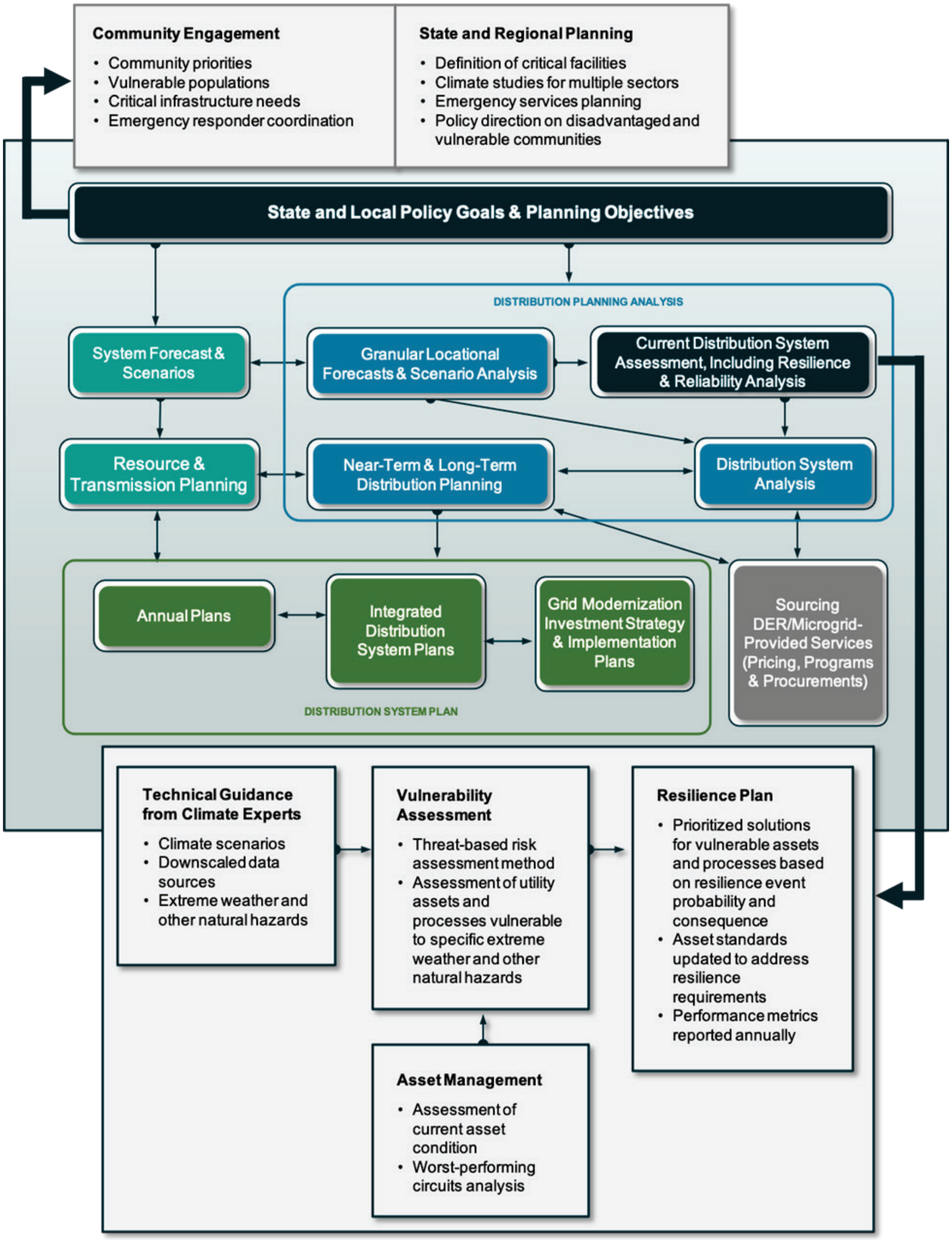


Figure 1.2. Resilience Planning in the Context of an Integrated Distribution Planning Framework

Source: Schellenberg and Schwartz (2024)

1.2 Study Objective and Scope

Focused planning activities to improve the resilience of the power system is at a relatively nascent stage. There is not yet an industry-wide consensus on the metrics, data, and analyses that are most effective to improve decision-making related to resilience investments. This report aims to help bridge the gap between the grid resilience data, metrics, and analyses that utilities use, and the information provided to utility regulators, state energy offices, and other stakeholders that engage in grid resilience planning. The report includes example state requirements and utility filings and regulatory proceedings across the country. The objective is to help state regulators identify, describe, request, and use utility data and analyses to inform their decisions on utility resilience plans and investments and help stakeholders understand why certain information is needed and what information the utility can provide.

To develop this report, Berkeley Lab reviewed state resilience planning requirements in 14 states and one city (New Orleans), 43 utility resilience plans, academic literature, and materials from industry resilience initiatives and working groups. [6] Researchers also conducted interviews with staff at state energy offices, public utility commissions, and utilities. The data, metrics, and analyses detailed in this report focus on resilience to events resulting from severe weather and climate conditions. While grids face other hazards, such as earthquakes and threats to physical security and cybersecurity, these threats are not within the scope of this report.

1.3 Report Organization

The remainder of this report covers the following information:

- Chapter 2 explains the study methodology, including the approach, data sources, and analysis framework.
- Chapter 3 summarizes state requirements for providing resilience data, metrics, and analyses.
- Chapters 4 through 8 detail the resilience data, metrics, analyses, and other relevant information in regulatory filings reviewed for this analysis, organized by category.
    - Chapter 4 – vulnerability assessments
    - Chapter 5 – hazard exposure
    - Chapter 6 – attribute metrics
    - Chapter 7 – performance metrics
    - Chapter 8 – evaluation and prioritization analyses
- Chapter 9 discusses key findings and presents emerging best practices for utilities to provide data, metrics, and analyses, as well as considerations to advance these practices.
- Appendix A lists hazard data variables used by utilities.
- Appendix B lists external hazard data sources leveraged by utilities.
- Appendix C lists attribute and performance metrics from the utility resilience plans.
- Appendix D lists of socioeconomic adaptive capacity indicators that states can consider in

[6] EPRI Climate-READI and IEEE Task Force on Power System Resilience Metrics and Evaluation Methods.

planning guidance to utilities.

- Appendix E lists organizations interviewed for this report.

2. Methodology

2.1 Approach and Data Sources

A recent Berkeley Lab report (Schellenberg and Schwartz, 2024) summarizes state requirements for grid resilience plans, identifies emerging best practices, and provides a template for utility filings that utilities and states can adapt to meet their own needs (and that utilities can consider absent state requirements). Building on that work, this report digs deeper into these state requirements and details the data, metrics, and analyses contained in 43 plans filed by 30 utilities.

As of September 2024, 14 states and one city (New Orleans) required electric utilities to file resilience plans. Figure 2.1 shows the status of resilience planning requirements and utility filings. Regulated utilities in the states shaded green had filed at least one resilience plan by September 2024. Utilities in states shaded blue (Connecticut and Hawaii) had not filed resilience plans, as these states recently finalized requirements. In Louisiana, state regulators had not yet adopted a final proposed rule.

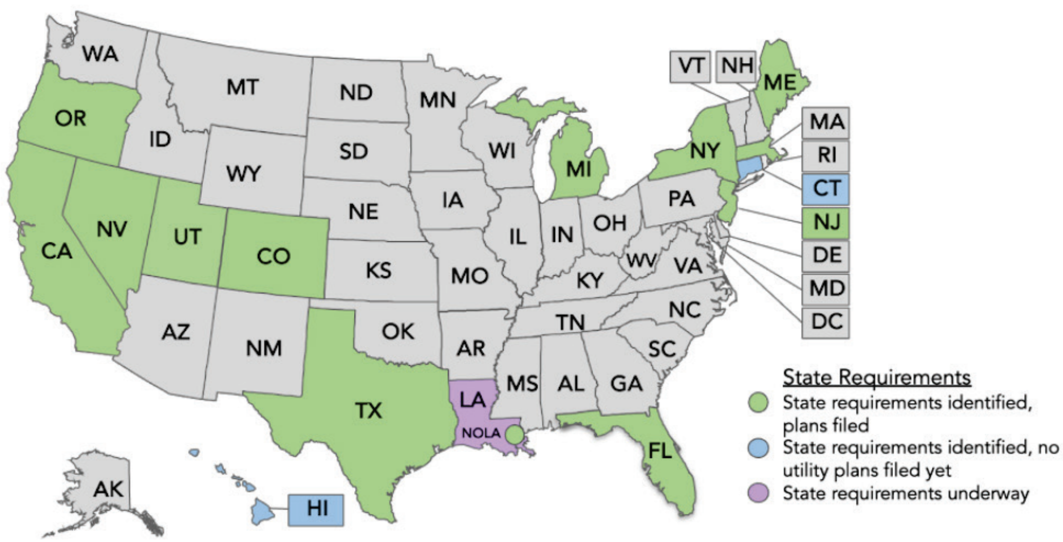


Figure 2.1. Status of Resilience Planning Requirements and Utility Filings

Table 2.1 contains links to resilience planning requirements for each state (first column). In addition to mandating specific plans to address certain hazards, some state requirements included language on the data, metrics, and analyses to be included. Berkeley Lab reviewed state requirements to determine what data, metrics, and analyses must be filed, either as part of the plan or in supplemental reports.

Table 2.1 also lists the resilience plans reviewed for this report by state, plan name, and utility, with hyperlinks to the utility filings. Berkeley Lab reviewed the resilience plans utilities submitted to comply with state requirements—and one utility submitted voluntarily—to assess the resilience data, metrics, and analyses that utilities provided to regulators and stakeholders.

Table 2.1. Utility Resilience Plans Reviewed for Data, Metrics, and Analyses

State	Plan Name	Utility Plans Reviewed
California	Wildfire Mitigation Plan	· Pacific Gas & Electric (PG&E) (2024a) · Southern California Edison (SCE) (2023) · San Diego Gas & Electric (SDG&E) (2023)
California	Climate Change Vulnerability Assessment	· PG&E (2024b) · SCE (2022)
Colorado	Distribution System Plan	· Xcel Energy (2022) Phase I · Xcel Energy (2023) Phase II
Connecticut	Resilience Plan	Plans in progress
Florida	Storm Protection Plan	· Florida Power & Light (FPL) (2022) · Duke Energy (2022) · Tampa Electric (TECO) (2022) · Florida Public Utilities (FPU) (2022)
Hawaii	Natural Hazard Mitigation Plan	Plans in progress
Maine	Climate Protection Plan	· Central Maine Power (CMP) (2023) · Versant (2023)
Massachusetts (Section 92B)	Electric-sector Modernization Plan	· Eversource (2024) · National Grid (2024) · Unitil (2024)
Michigan	Distribution System Plan	· DTE Electric (2023) · Consumers Energy (2023) · Indiana Michigan Power (2023)
Michigan	Climate Risk, Vulnerability, and Resilience Report	· Consumers Energy (2022)
Nevada	Natural Disaster Protection Plan	· NV Energy (2023a) Part 1 · NV Energy (2023b) Part 2
New Jersey	Infrastructure Investment Program	· PSE&G (2018)
New Orleans	System Resiliency and Storm Hardening Plan	· Entergy New Orleans (2023)
New York	Climate Change Vulnerability Study	· Con Edison (2023a) · Orange & Rockland (O&R) (2023a) · RG&E and NYSEG (2023) · National Grid (2023a) · Central Hudson (2023a) · PSEG Long Island (2024a)
	Climate Change Resilience Plan	· Con Edison (2023b) · Orange & Rockland (2023b) · RG&E (2023) · NYSEG (2023) · National Grid (2023b) · Central Hudson (2023b) · PSEG Long Island (2024b)
Oregon	Wildfire Mitigation Plan	· Pacific Power (2023) · Portland General Electric (2023) · Idaho Power (2023)
Texas	T&D System Resiliency Plan	· Oncor (2024) · CenterPoint (2024)
Utah	Wildland Fire Protection Plan	· Rocky Mountain Power (RMP) (2023)

Resilience plans may be called a variety of names, in some cases reflecting the specific types of hazards they address. Some resilience plans focus on specific extreme weather threats, such as storms in Florida and wildfires in Western states. Others, such as climate change vulnerability assessments and resilience plans, cover multiple extreme weather threats. While some resilience plans are incorporated into broader planning filings such as distribution system plans, most are standalone reports.

To supplement review of utility filings, Berkeley Lab conducted nine interviews with subject matter experts at utilities, public utility commission staff, and state energy office staff throughout the country. The objective of the interviews was to identify common practices and emerging best practices related to grid resilience data, metrics, and analyses—both in terms of the types of information shared and how it is shared between utilities and state agencies.

2.2 Framework for Analyzing and Measuring Resilience

This section summarizes the academic literature Berkeley Lab reviewed to develop a taxonomy for classifying and describing the data, metrics, and analyses required by states and included in the grid resilience plans examined.

Presidential Policy Directive-21 (2013) defines resilience as “the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions.” A number of organizations have adopted similar definitions of resilience (IEEE, 2020). While precise wording may vary across sources, the definitions consistently align across academic literature and utility planning documents, reflecting a shared conceptual framework with similar components.

A number of organizations have developed resilience planning frameworks that utilities can leverage in their planning processes (EPRI, 2023; Leddy et al., 2023; Watson et al., 2014). These frameworks generally include an assessment of climate hazard risk or vulnerability and follow the key steps of evaluating electric system exposure to the hazard, sensitivity to the hazard, and expected consequences (Reisinger et al., 2020). They also typically include a prioritization process or selection method for potential mitigation measures based on the results of the vulnerability assessment and the expected cost and effectiveness of mitigation measures. For example, Homer et al. (2023) examines best practices for electric utility planning with climate variability and includes a systematic approach to asset planning with four steps: 1) exposure of critical assets or operations to an adverse climate event, 2) probability of damage to assets or disruption to operations, 3) likely consequences if the event were to occur, and 4) mitigation measures. Watson et al. (2014) presents a similar Resilience Analysis Process with seven steps: 1) define resilience goals, 2) define system and resilience metrics, 3) characterize threats, 4) determine level of disruption, 5) define and apply system models, 6) calculate consequences, and 7) evaluate resilience improvements. Utility resilience plans reviewed for this study generally aligned with the frameworks outlined in the literature, though they differ in certain process steps and nomenclature.

Figure 2.2 shows the overarching categories used in this study. The Vulnerability Assessment category (covered in Chapter 4) is at the top of the figure. This assessment is a stakeholder-informed process that: (1) identifies communities, infrastructure, facilities, and processes that are vulnerable to specific hazards and (2) prioritizes vulnerabilities that are most important to mitigate, based on potential impacts. The Vulnerability Assessment spans three areas: Hazard Exposure (Chapter 5), Attribute Metrics (Chapter 6), and Performance Metrics (Chapter 7). Information in these three areas aligns with the subcategories of vulnerability assessments: Exposure, Sensitivity, and Consequence. The outputs can serve as inputs into other areas. For instance, hazard and exposure data inform "exposure," attribute metrics inform "sensitivity," and performance metrics inform "consequence."

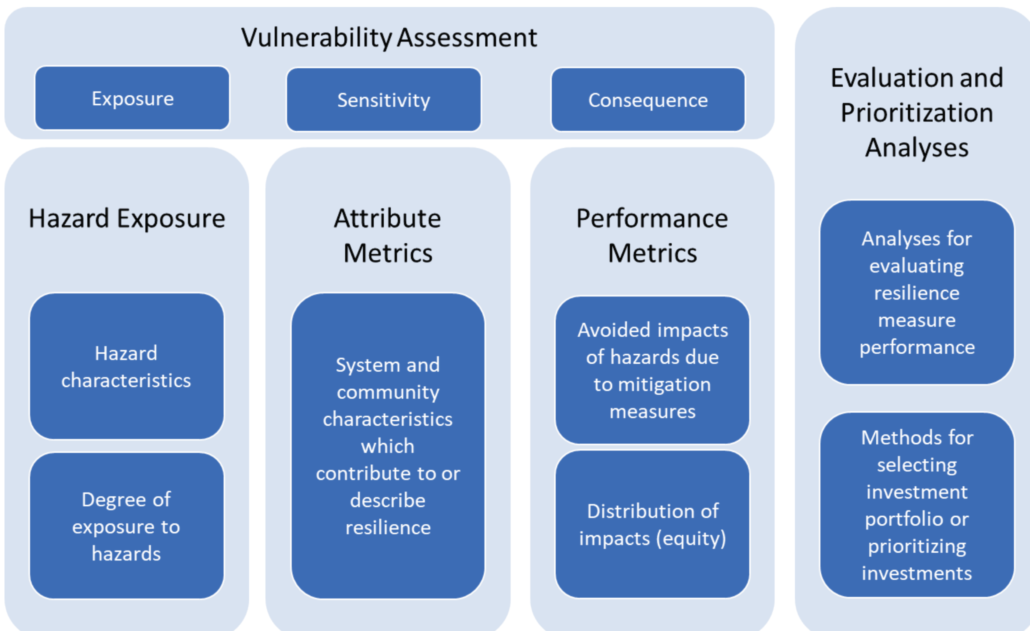


Figure 2.2. Organization of Data, Metrics, and Analyses

Hazard Exposure (Section 5) comprises data on hazards and the exposure of a utility's assets or operations, and ultimately its customers, to these hazards. Hazard characteristics may cover a range of potential threats, depending on which are relevant for the service territory, and the data may be at different levels of granularity. Data can cover both historical climate and weather information, as well as future projections. The degree of utility exposure is characterized by data on which assets, locations, and customers may experience a climate hazard and the extent to which they may experience that hazard.

Attribute Metrics (Chapter 6) measure system characteristics that contribute to or describe the resilience of the system and community (Leddy et al., 2023, Keen et al., 2024a, Anderson et al., 2021). These metrics characterize the ability of the system and community to anticipate, withstand, adapt to, and recover from hazard events. For example, they can describe the extent to which assets have been hardened or mitigation measures have been implemented and thus whether the electric system and its customers are sensitive to damage from a particular hazard. Certain metrics within this category reflect the capacity of the system or customer population to adjust to potential impacts or respond to consequences.

Performance Metrics (Section 3.5) measure the impacts of resilience investments on system performance, often through a reduction in the negative consequences of hazard events (Leddy et al., 2023). Performance metric subcategories generally align with those proposed by the Grid Modernization Laboratory Consortium (Petit et al., 2020). Performance metrics are presented in the following subcategories:

- Electric 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, 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.

In addition to the performance metrics themselves, Section 3.5 includes metrics and information regarding critical facilities, public safety power shutoffs, and equity.

Evaluation and Prioritization Analyses (Chapter 8) consider two main subcategories of methodologies that utilities employ to assess and prioritize resilience measures for implementation. The first includes efforts that utilities are undertaking to estimate impacts from resilience measures. These efforts leverage ex post studies (backward-looking analyses) to estimate the performance of measures that have already been implemented, and ex ante studies (forward-looking analyses) to estimate the future performance of proposed measures. Ex ante studies include analyses for prioritizing measures based on estimated costs and impacts. These include benefit-cost analysis (BCA), risk-based analysis (RBA), and multi-criteria assessment (MCA).

This report presents data, metrics, and analyses that state regulators can request from utilities in categories that align with the frameworks found in the literature and in filed resilience plan filings. Each of these items is defined as follows:

- **Data** are descriptions about the state of the world — including the current state or conditions of the utility's infrastructure and operations — that are used to describe the issues addressed by resilience planning, such as expected sea level rise over the next 30 years and the current location and elevation of a utility's substations.
- **Metrics** can be either attribute-based or performance-based, with distinctions between the two

types.

- **Attribute metrics** describe characteristics of the electrical system and communities it serves that make the system and communities more resilient.
- **Performance metrics** describe the results expected from utility activities that seek to address resilience. They must describe factors over which a utility has a certain level of control or whose actions are expected to influence (that is, these are the factors that the plans when implemented are expected to affect or cause to take place). Consequently, these are the factors that the utility and stakeholders can use to measure progress (or lack thereof) toward a resilience objective.

- **Analyses** are manipulations of data and other information that are used to support decision-making or assist in the resilience planning process. Analyses often result in expected performance metrics.

Each of the five categories in Figure 2.2 may predominantly comprise either data, metrics, or analyses, but not exclusively. For example, vulnerability assessments are types of analyses, but utilize data and metrics. The Hazard Exposure category contains a wealth of data on hazards and utility asset exposure, but hazard data are developed through modeling and analysis. Attribute metrics describe characteristics that make the electrical system and customers more resilient, but also can serve as data to inform a vulnerability analysis by characterizing sensitivity. Performance metrics include combinations of indices that require some level of analysis to compute. Finally, evaluation and prioritization analyses generate results—such as benefit-cost ratios—that can be considered metrics.

For each type of data, metric, or analysis, this report provides the following information:

- A definition of the data, metric, or analysis
- An explanation of what it measures and how it can support the resilience planning process
- Examples of utilities submitting the information—either in resilience plans or in separate reporting processes
- For performance metrics, considerations for implementing the metric (where applicable), including potential shortcomings of using it as a standalone metric.

3. State Requirements

This section reviews state requirements for regulated utilities to submit grid resilience data, metrics, and analyses. State resilience planning requirements may be legislative or regulatory — typically, public utility commission (PUC) decisions. In cases where the state legislature mandated resilience analyses and reporting, PUCs subsequently provided specific guidance on required analyses and performance metrics.

Severe weather events are common catalysts for legislative or regulatory action on resilience planning requirements. For example, after California's catastrophic 2018 wildfire season, the state legislature passed SB 901, which mandated that utilities submit Wildfire Mitigation Plans. In subsequent years, the California PUC and Office of Energy Safety built out more specific requirements for the plans and associated reporting requirements. Similarly, Florida passed SB 796 in 2019, requiring public utilities to file storm protection plans in response to increasingly intense hurricane seasons and recent destructive storms such as Hurricane Irma in 2017 and Hurricane Michael in 2018.

States may require that resilience plans address a range of hazards, or they may focus on specific extreme weather events such as storms and wildfires. Resilience requirements reviewed for this report focus on:

- General system resilience (Hawaii, Louisiana, Texas)
- Climate change resilience and vulnerability (California, Maine, New York)
- Infrastructure modernization (Massachusetts, New Jersey)
- Storm protection (Connecticut, Florida, Michigan, New Orleans)
- Wildfire mitigation (California, Nevada, Oregon, Utah)

In addition to mandating specific plans to address certain hazards, some state requirements provided guidance on the data, metrics, and analyses to be included, either within the plans themselves or in separate filings.

Table 3.1 summarizes state requirements for each of the five categories: vulnerability assessment, hazard exposure, attribute metrics, performance metrics, and evaluation and prioritization analysis. The first three columns contain information on the state, the name of the plan, the plan frequency, and the hazards addressed by the plan. The table is divided into three groups of states and associated resilience plans, based on the types of hazards the plans address. The first eight rows address an ensemble of climate hazards and cover plans focused on general system resilience, climate change vulnerability, and infrastructure modernization. The next four plans explicitly address severe storms, and the last four plans predominantly address wildfire.

Table 3.1. State Requirements for Resilience Data, Metrics, and Analyses

Legend
- Required and specific
- Required and high-level
- Recommended and high-level

State	Plan	Plan Frequency	Hazards Covered	Vulnerability Assessment	Hazard Exposure	Attribute Metrics	Performance Metrics	Evaluation & Prioritization Analyses
Ensemble of Climate Hazards								
California	Climate Vulnerability Assessment, Risk-based Decision-making Framework	4 Years (Part of GRC)	Temperature, Preciptiation (includes Drought and Subsidence), Sea Level Rise, Wildfire	Required and specific	Required and specific	Required and specific	Required and specific	Required and specific
Colorado	Distribution System Plan	2 Years	Natural disasters and cyber/physical security threats (wildfire, flood, severe storms)	Required and high-level	Required and high-level		Required and specific	
Hawaii	Natural Hazard Mitigation Plan	TBD	Wildfires, tsunamis, hurricanes, floods, landslides, extreme heat, drought, seismic/volcanic activity	Recommended and high-level	Required and specific	Recommended and high-level	Recommended and high-level	Recommended and high-level
Maine	Climate Change Protection Plan	3 Years	Expected effects of climate change on utility assets		Required and high-level			
Massachusetts	Electric-sector Modernization Plan	5 Years	Weather and disaster-related risks		Required and high-level		Required and high-level	
New Jersey	Infrastructure Investment Program	Voluntary	Any hazard that impacts safety, reliability, and/or resiliency, including cybersecurity				Required and high-level	Required and specific
New York	Climate Change Vulnerability Study and Resilience Plan	5 Years	Increase in severe weather expected from climate change, including stronger storms and more flooding	Required and high-level	Required and specific		Required and high-level	Required and specific
Texas	T&D System Resiliency Plan	3 Years (Voluntary)	Extreme weather conditions, wildfires, or cyber/physical security threats		Required and high-level	Recommended and high-level	Required and high-level	Required and high-level
Severe Storms								
Connecticut	Resilience Plan	4 Years (Part of GRC)	Tropical storms, hurricanes, ice storms	Required and specific	Required and specific	Required and specific	Required and specific	Required and specific
Florida	Storm Protection Plan	3 Years	Storms			Required and specific	Required and high-level	Required and specific
Lousiana (only New Orleans)	System Resiliency and Storm Hardening Plan	TBD	Storms	Required and high-level	Required and high-level			Required and specific
Michigan	Distribution System Plan	2 Years	Storms		Required and specific		Required and specific	
Wildfire								
California	Wildfire Mitigation Plan	Annual	Wildfires	Required and specific	Required and specific	Required and specific	Required and specific	
Nevada	Natural Disaster Protection Plan	3 Years	Wildfires are primary focus, other natural disasters also covered	Required and specific	Required and specific	Required and specific	Required and specific	
Oregon	Wildfire Mitigation Plan	Annual	Wildfires	Required and specific	Required and high-level	Required and high-level	Required and specific	Required and high-level
Utah	Wildland Fire Protection Plan	3 Years	Wildfires		Required and high-level	Required and high-level	Required and high-level	Required and high-level

The rightmost five columns in Table 3.1 characterize state requirements for vulnerability analysis, hazard and exposure data, attribute metrics, performance metrics, and evaluation and prioritization analysis along two dimensions — flexibility and prescriptiveness. Flexibility refers to whether the specific data or analysis is required or simply recommended. Prescriptiveness refers to the extent to which state guidance explicitly defines requirements for analysis frameworks and performance metrics. For example, California Public Utilities Commission (CPUC) guidance is considered prescriptive, as it provides utilities with a framework by which to calculate risk and details each component of this framework.

Non-prescriptive guidance includes implied analyses, data, and metrics. For example, Maine mandates that utilities outline specific actions for addressing the expected effects of climate change. It does not prescribe specific analyses to achieve these goals, but implies performing intermediary steps of identifying and assessing relevant hazards and analyzing their impacts on utility assets.

As Table 3.1 shows, all 14 states required information in at least one category. Requirements vary between whether requirements are specific or high-level. Two states—Hawaii and Texas—*recommend* providing certain types of information, in addition to information requirements. The following subsections address state guidance for data, metrics, and analyses for each of the five categories.

3.1 Vulnerability Analysis

States are increasingly requiring or recommending that utilities conduct system vulnerability or risk assessments. While specific methodologies differ between states and utilities, they typically include an analysis of asset exposure to potential hazards, sensitivity to those hazards, and potential consequences.[7] The following examples provide more detail on the requirements for vulnerability analysis summarized in Table 3.1.

- **More prescriptive (California, Oregon, Connecticut, Nevada)**
  - The CPUC directs regulated California utilities to file Climate Adaptation and Vulnerability Assessments (CAVAs) and calculate risk using a combination of specific components (exposure, sensitivity, and adaptive capacity). The CPUC provides additional detail for each of these risk components, including identification of relevant variables and datasets.
  - In Oregon, the PUC requires that utilities include a risk analysis as part of their WMPs and provides minimum requirements for timing, subjects, and details.
  - In Connecticut, the Public Utilities Regulatory Authority (PURA) outlines an approach for identifying vulnerable segments of utilities' electric distribution systems and provides a matrix of criteria to identify and prioritize these vulnerable segments. Criteria are organized by category (interruption-based, system characteristics, community priorities) and by rank (primary, secondary).
  - The Public Utilities Commission of Nevada (PUCN) requires that utilities filing Natural Disaster Protection Plans provide a description of the risk-based approach used to identify disaster-prone areas in their service territory, as well as potential future threats, including those related to fire and other natural disasters.

- **Less prescriptive (Colorado, Hawaii, New Orleans, New York)**
  - In Colorado, the PUC requires that utilities provide an analysis of hazard-driven risks by substation as part of the security assessment component of Distribution System Plans, but does not outline any specific requirements for the analysis.

[7] See Section 3.2 for a more thorough discussion of vulnerability assessments.

- The [Hawaii] PUC affords utilities flexibility to design risk assessments by recommending that utility plans describe the methodology and process.
- In New Orleans, the Council Utilities Regulatory Office (CURO) directs Entergy New Orleans to consider in its System Resiliency and Storm Hardening Plan the current level of electricity system vulnerability, as well as vulnerability over the next five years,.
- State law in New York requires utilities to file both Climate Vulnerability Studies and Climate Change Resilience Plans. The law does not outline a required analytical framework, though it directs utilities to evaluate vulnerability to climate-driven risks as an integral part of Climate Vulnerability Studies.

3.2 Hazard Exposure

Some states direct utilities to acquire and analyze relevant hazard data as a foundation of their resilience plans. States may require hazard and exposure information as a component of vulnerability analysis or as context for other analyses. The following examples provide more detail on requirements for hazard exposure summarized in Table 3.1.

- **More prescriptive (California, Connecticut, Hawaii, Michigan, Nevada, New York)**
  - The CPUC requires that California utilities analyze temperature, precipitation, sea level rise, wildfire, and compounding events in CAVAs, using data from the California 4th Climate Change Assessment. In August 2024, the CPUC filed a Decision that updated climate change modeling specifications to reflect recent climate data updates. The Decision provides detailed guidance that specifies the required emissions scenario and reference case by time period and outlines an updated climate modeling approach.
  - In Connecticut, PURA requires utilities filing resilience plans to analyze tropical storms, hurricanes, and ice storms using event-level classifications ranging from Level 5 to Level 1, with Level 1 the most destructive. Utilities classify storms into Event Levels using an established set of parameters (e.g., number of damage locations and number of customer interruptions).
  - The Hawaii PUC identifies a set of hazards that utilities must address in their plans, if applicable. These hazards are tsunamis, wildfires/red flag events, hurricanes, volcanic hazards, earthquakes, floods and landslides, and extreme heat and drought.
  - The Michigan PSC indicates that utilities should consider wind speeds, storm frequency, and storm intensity in metrics and anticipate the occurrence of storms to determine necessary measures to improve system performance during a weather event.
  - Nevada state law requires utilities to identify areas in their service territories that are subject to heightened risk of wildfires and other natural disasters. PUCN defines fire-specific terms such as “critical fire weather conditions” and “ignition events.”
  - Under New York PSL § 66(29), utilities must prepare and submit climate change vulnerability studies, including a focus on storm hardening and resiliency measures. The New York PSC initiated Case 22-E-0222 to implement the requirements. Among other specifications, the PSC directed utilities to address, at a minimum, expected changes in

temperature, wind, and sea levels. The PSC is seeking comments on the precise elements of these climate hazards—and others, such as precipitation—to be included in utility vulnerability studies.

- **Less prescriptive (Colorado, Maine, Massachusetts, New Orleans, Oregon, Texas, Utah)**
  - Regulators in Colorado and Maine[8] require that utilities address the potential impacts of climate change on utility assets and systems as part of resilience planning processes. The requirements direct utilities to identify and analyze relevant hazards and understand risk levels, but do not prescribe specific methodologies.
  - Guidance on Electric-Sector Modernization Plans in Massachusetts requires utilities to include information on planned distribution system improvements to address potential weather-related risks and other hazards. This requirement implies some level of hazard exposure analysis to determine relevant risks in each utility's service territory.
  - In New Orleans, CURO directed Entergy New Orleans to identify distribution and transmission projects that are expected to result in the highest level of system resiliency and storm hardening, implying some level of analysis to understand the nature of present-day and future storm events in the service territory.
  - Utilities filing Wildfire Plans in Oregon and Utah must identify and describe areas of heightened wildfire risk in their service territories. State guidance does not detail data parameters or specific variables.
  - Given their diverse nature, the Public Utility Commission of Texas (PUCT) grants utilities flexibility to characterize and analyze hazards and impacts in a way that makes sense for their specific service area.

3.3 Attribute Metrics

Several states have requirements for resilience plans to include information that can be classified as an attribute metric. While none of the state requirements use the term "attribute metrics," the required information includes characteristics of the electrical system or community that describe their level of resilience. The following examples provide more detail on the requirements summarized in Table 3.1.

- **More prescriptive (California, Connecticut, Florida)**
  - The California Office of Infrastructure Safety requires utilities to report on a number of established attribute metrics on a quarterly basis as part of their WMP filing, such as metrics related to distribution pole replacements, installation of system automation equipment, and equipment settings to reduce wildfire risk. In its CAVA guidance, the CPUC requires California utilities to calculate asset risk using a combination of exposure and sensitivity information. Sensitivity information may be rooted in attribute metrics

[8] In addition to the resilience planning requirements cited for this report, in July 2024, the Maine PUC issued a Notice of Inquiry Regarding Improving Resiliency and Addressing Escalating Storm Costs. The objective of the inquiry is to identify additional, shorter-term solutions for reducing storm impacts and examine ways that utilities can address increasing storm costs.

that describe the degree to which equipment could be impacted by a hazard (e.g., attribute metrics like "distance from ground of elevated equipment" or "height of flood barrier" may be useful in understanding whether a substation component is sensitive to flooding). The CPUC also mandates that utilities analyze the adaptive capacity of their systems and customers and provides clear criteria for determining Disadvantaged and Vulnerable Communities.
    - PURA requires that Connecticut utilities evaluate and report on their infrastructure, facilities, and equipment to ensure that they're capable of meeting operational standards. PURA specifies required analyses and details related to reporting, such as age, condition, operation, and maintenance.
    - Florida requires descriptions of areas prioritized for enhancement and areas where enhancing transmission and distribution (T&D) facilities "would not be feasible, reasonable, or practical." Descriptions must include the reasons for the utility's area designations and information such as the number of customers served within each area.

- **Less prescriptive (Hawaii, Nevada, Oregon, Texas, Utah)**
    - Hawaii requirements state that utility plans may include information on the service territory, utility infrastructure, environmental conditions, relevant natural features, and communities and regions at risk.
    - The PUCN requires that Nevada utilities filing Natural Disaster Protection Plans indicate standards for infrastructure and vegetation inspections. The commission also requires that utilities provide information on asset hardening and modernization (e.g., underground, wire insulation, pole replacement).
    - Utilities filing Wildfire Plans in Oregon and Utah must identify and describe areas of heightened wildfire risk within their service territories. In this context, heightened risk may be related to increased hazard exposure and/or high sensitivity, which is rooted in system attributes.
    - Texas guidance states that when quantitative, performance-based evidence of resilience improvements is not available, "other evidence such as qualitative evidence, predictive models, or attribute-based evidence may be provided."

3.4 Performance Metrics

Some jurisdictions with resilience planning requirements mandate that utilities track and report metrics to measure the performance of the resilience initiatives outlined in their plans. These metrics fall under the categories of Electrical Service, Asset Damage and Failure, Response and Restoration, Monetary Impacts, and Customer Communications and Engagement.[9] The following examples provide more detail on the requirements summarized in Table 3.1.

- **More prescriptive (California, Colorado, Connecticut, Michigan, Nevada, Oregon)**

[9] See Chapter 7 for more details on performance metrics included in utility resilience plans.

- The California Office of Energy Infrastructure Safety requires utilities to report quarterly on a number of established metrics as part of their wildfire mitigation efforts. These metrics are both attribute- and performance-related. For example, performance metrics include equipment failures, Public Safety Power Shutoff (PSPS) hours, and interruption events. In addition, the CPUC requires that utilities track metrics related to customer outreach, engagement, and comprehension related to CAVAs. Metrics are both quantitative (e.g., web site visits, in-person meetings, and customers reached) and qualitative (e.g., takeaways from surveys and conversations).
- The Colorado PUC requires that utilities include, at a minimum, substation-specific SAIDI and SAIFI in filed Distribution System Plans, as well as a list of major interruptions and characteristics (cause and duration).
- In Connecticut, PURA requires utilities to report standard reliability indices (SAIDI, SAIFI, CAIDI, and MAIFI[10]), including and excluding major storms. The agency mandates that utilities report on specific metrics[11] for tranches of customers experiencing three or more, five or more, seven or more, and nine or more sustained interruptions. PURA also requires utilities to report on asset failures in resilience zones and non-hardened zones.
- Michigan required that utilities report on the "total cost" of interruption events during the August 2021 storms. Eligible items included materials, overtime pay, mutual assistance, community support, and advertisements. Michigan also requires utilities to report annually on the total dollar amount of customer credits provided after a failure to restore service to customers within a series of defined windows, under both catastrophic and normal conditions.
- The PUCN requires that Nevada utilities report annually on an established set of metrics. These metrics measure, for example, ignition-related customer costs and customer feedback on event awareness.
- The Oregon PUC directs utilities to track and report on the efficacy of community outreach and public awareness efforts as part of their WMPs. The commission specifies that utilities must consider different platforms and communication tools, outreach frequency, equity, and accessibility in these communication efforts and subsequent metrics.

- **Less prescriptive (Florida, Hawaii, Massachusetts, New Jersey, New York, Texas, Utah)**
  - In Florida, utilities must include a description of how their proposed Storm Protection Plans will reduce restoration costs and outage times associated with extreme weather. State law does not specify outage- and cost-related metrics related to these descriptions.
  - The Hawaii PUC recommends that utilities filing mitigation and adaptation plans for natural hazards conduct analyses on critical facilities and customers, as well as

[10] See 7.1 for an explanation of these metrics.
[11] Customers Experiencing Multiple Interruptions (CEMI), Customers Experiencing Long Interruption Duration (CELID), Customers Experiencing Multiple Sustained Interruption and Momentary Interruption Events (CEMSMI), Customers Experiencing Multiple Momentaries (CEMM).

vulnerable or special needs customers, and encourages utilities to provide key performance indicators.

- Guidance in Massachusetts requires utilities to submit two reports annually on deployment of approved investments included in Electric Sector Modernization Plans in accordance with performance metrics included in the plans. The guidance does not provide additional detail on required metric content.
- Utilities conducting Infrastructure Investment Programs in New Jersey must provide semi-annual status reports that contain information on program cost and progress, as well as any other relevant performance metrics.
- New York Public Service Law § 66(29) states that utility plans should lower restoration costs and interruption times and provide major performance benchmarks to measure plan effectiveness.
- The PUCT requires utilities to provide metrics or criteria for evaluating the effectiveness of each resiliency measure that they propose in their resilience plans. Commission guidance indicates that utilities may include SAIDI, SAIFI, and CAIDI information for evaluating measure performance, when relevant.
- State guidance in Utah broadly requires utilities to describe power restoration procedures and community outreach efforts during a fire season, without mandating specific metrics.

3.5 Evaluation and Prioritization Analyses

State guidance for resilience planning frequently requires utilities to prioritize their proposed resilience investments. Prioritization frameworks can include BCA, RBA, and MCA. Utilities may be required to undertake one or more of these analyses as part of their planning process. The following examples provide more detail on requirements for prioritization analysis summarized in Table 3.1.

- **More prescriptive (California, Connecticut, Florida, New Jersey, New Orleans, New York)**
  - The CPUC requires California utilities to design prioritization frameworks based on BCA as well as rigorous risk-based analyses. California IOUs must apply a risk-based decision-making framework as part of the Risk Assessment and Mitigation Phase (RAMP) of each general rate case. RAMP rules regulate the way utilities evaluate and report on safety, reliability, and financial risks.
  - Connecticut explicitly requires utilities to report on BCA associated with program costs, SAIDI reductions, and 5- and 10-year resilience benefits to determine prioritization of resilience solution sets for segments of the distribution system. Table 3.2, from PURA’s requirement, provides more detail.

Table 3.2. Connecticut PURA BCA Minimum Reporting Requirements

Resilience Plan	
Program Costs	Capital Expenditures
Assumed SAIDI Reduction	Customer minutes Interrupted
5-Year Resilience Benefit*	Avoided Interruption Costs
	Avoided Storm Restoration Costs
	Avoided VM and Pole Costs
10-Year Resilience Benefit*	Avoided Interruption Costs
	Avoided Storm Restoration Costs
	Avoided VM and Pole Costs
5-Year BCA	
10-Year BCA	

*Benefits should be provided such that they demonstrate a reasonable representation of the uncertainty of storm impact and resulting benefits.

Source: (PURA, 2022b)

- State guidance in Florida requires utilities to provide specific information on areas prioritized for resilience upgrades, including program costs and prioritization criteria.
- State guidance in New Jersey mandates that utilities present an engineering evaluation and report in association with the projects outlined in their Infrastructure Investment Programs. The reports must include expected resilience benefits, detailed cost estimates, and any applicable BCA conducted for each project.
- In New Orleans, CURO directs Entergy New Orleans to present information on the prioritization of proposed resilience projects based on BCA and other criteria.
- State guidance in New York mandates that utilities analyze and report on estimated costs and benefits to both utilities and their customers as a result of plan implementation. The requirement emphasizes the importance of incorporating equity considerations in the analyses and costs and benefits of undergrounding T&D lines.

- **Less prescriptive (Hawaii, Oregon, Texas, Utah)**
    - State guidance in Hawaii recommends that utilities include in their mitigation and adaptation plans how they identify, describe, and prioritize mitigation of disaster risks and the drivers for those risks.
    - State guidance in Oregon and Utah directs utilities to identify areas of heightened fire potential and preventative actions to minimize fire risk, balancing or contextualizing these actions with overall implementation costs, but does not identify a specific framework by which to prioritize fire mitigation options.
    - Texas grants utilities greater flexibility in shaping the details of their prioritization frameworks. Utilities must explain how they chose specific investments for inclusion in their plans, but the state does not mandate a standardized ranking or analytical framework.

4. Vulnerability Assessments

Assessing vulnerability to increasingly severe and frequent weather events is a critical part of developing a resilience plan. Regulators may dictate the specific set of steps utilities follow to assess vulnerabilities and risks, or leave the details to utilities. The definition of vulnerability and the interactions between the components of vulnerability and risk vary somewhat within the academic literature and among state guidance and utility assessments.[12]

The Intergovernmental Panel on Climate Change (IPCC) has reconceptualized vulnerability over the course of releasing its assessment reports (Estoque et al., 2023). The IPCC's Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaption defined vulnerability as the "propensity of exposed elements such as human beings, their livelihoods, and assets to suffer adverse effects when impacted by hazard events" and indicated that vulnerability, in combination with hazard exposure, determines risk. The CPUC identifies risk as a component of vulnerability, noting that exposure and sensitivity comprise risk and that the combination of risk and adaptive capacity determines vulnerability. This definition aligns more closely with a prior IPCC approach (Parry, 2007).

Regardless of how the definitions and components fit together, vulnerability assessments typically aim to evaluate the susceptibility of systems, communities, assets, and processes to potential harm from identified hazards. These assessments often focus on understanding key factors such as exposure, sensitivity, adaptive capacity, and potential consequences.

This chapter reviews the general steps of vulnerability assessments. The next three chapters—Hazard Exposure (Chapter 5), Attribute Metrics (Chapter 6), and Performance Metrics (Chapter 7)—discuss data and metrics that can support the analyses, regardless of the precise framework utilized.

Climate vulnerability assessments include the following elements:

- *Hazard characterization* – The assessment typically includes a matrix that summarizes all hazards analyzed relative to infrastructure and process areas, assessed with a clearly defined vulnerability rating.
- *Exposure* – The assessment determines the degree to which utility assets could face a given extreme weather hazard, based on asset location and downscaled climate projections.
- *Sensitivity* – The assessment evaluates the degree to which availability or performance of an asset could be affected by exposure to climate hazards.
- *Consequence* – The utility estimates the magnitude of negative outcomes on the availability or performance of assets.

Vulnerability assessments also may take into account community sensitivity and adaptive capacity (see Section 4.1 for details).

[12] See Keen (2024a), Appendix D, for a review of frameworks.

Table 4.1 summarizes the vulnerability rating components across eight utility assessments from Maine, New York, California, and the Carolinas. The table shows how the individual components of vulnerability differed between utilities. Con Edison (2023a) and O&R (2023a) did not include the Consequence category, while the vulnerability ratings for Duke Energy Carolinas (2023) broke the category into two components, with Potential Impact the potential for negative outcomes and Consequence the estimated magnitude of outcomes in the event of climate hazard exposure.

Table 4.1. Vulnerability Rating Components by Utility

Exposure	Sensitivity	Consequence	Potential Impact	Examples
X	X	X		• CMP (2023) • RG&E and NYSEG (2023) • National Grid (2023a) • SCE (2022)
X	X			• Con Edison (2023a) • O&R (2023a)
X	X	X	X	• Duke Energy Carolinas (2023)

Vulnerability assessments in the utility resilience plans combined quantitative and qualitative assessments to identify high, medium, and low vulnerabilities to extreme weather hazards for specific utility assets or processes. The exposure assessment was typically quantitative, involving granular geographic information system (GIS) analysis of utility asset locations combined with large datasets of downscaled climate projections (see Chapter 5). After identifying the asset-hazard combinations that were exposed, the sensitivity and consequence assessments involved qualitative assessments with significant subject matter expert (SME) input to supplement the quantitative exposure assessment.

Table 4.2 summarizes how RG&E and NYSEG (2023) determined the vulnerability ratings using a rating rubric. Based on combining the sensitivity and consequence assessments, planners determined the vulnerability rating for an asset–hazard combination for infrastructure exposed to climate hazards. Using SME input, the sensitivity rating was high for "assets that may be subject to major or sudden failure in the event of exposure to a climate hazard." The consequence rating was high if "damage could result in widespread or interruptions lasting more than 24 hours, safety risks or potential injuries to the public or utility personnel, and/or asset damage beyond repair." If the sensitivity and consequences ratings were both high, an asset was considered highly vulnerable to the specific climate hazard to which it was exposed. The resulting resilience plan could then prioritize mitigation measures for these climate vulnerabilities.

Table 4.2. RG&E and NYSEG Vulnerability Rating Rubric

Consequence \ Sensitivity	(Low)	(Medium)	(High)	(N/A)
(Low)	Low	Low	Medium	N/A
(Medium)	Low	Medium	High	N/A
(High)	Medium	High	High	N/A

Source: RG&E and NYSEG (2023)

Table 4.3 summarizes the vulnerability ratings for four transmission asset areas. This type of matrix that identifies high priority vulnerabilities, based on a clearly defined vulnerability rating, is an important part of a climate vulnerability assessment and the resulting resilience plan. In this case, RG&E and NYSEG prioritized wind and ice as high vulnerabilities, particularly for line structures and overhead conductors. The initial high vulnerability rating for line structures for flooding was de-prioritized based on SME feedback, as indicated by the asterisk (*), given that periodic inspections could identify and address vulnerabilities of specific poles and towers prior to failure. RG&E and NYSEG conducted a similar vulnerability assessment for nine distribution asset areas and eight substation asset areas. This high level of granularity in assessing and prioritizing vulnerabilities is useful as an input for targeting specific assets for mitigation measures, which can result in a more cost-effective resilience plan.

Table 4.3. RG&E and NYSEG Transmission Asset Vulnerability Ratings

Asset \ Hazard	Temperature	Precipitation	Flooding	Wind	Wind & Ice
Line Structures (Poles/towers)	N/A	N/A	High*	High	High
Conductors (Overhead)	Medium	Low	N/A	Medium	High
Conductors (Underground)	Medium	N/A	Medium	N/A	N/A
Open-Air Current-Carrying components	Medium	Low	N/A	Low	Medium
Priority Vulnerability	No	No	No	Yes	Yes

Source: RG&E and NYSEG (2023)

Resilience plans can include the same type of matrix and vulnerability assessment for planning and operational processes. For example, National Grid (2023a) provided a summary of climate change vulnerabilities by process area (Table 4.4). National Grid determined that hardening of physical infrastructure alone would not achieve resilience objectives. The utility assessed the impact of four climate hazards on six planning and operational functions to identify priority process vulnerabilities, most notably emergency response. Utilities can identify process-related resilience improvements to mitigate vulnerabilities, complementing capital investment solutions. Section 8.2.4 provides more detail on how utilities are incorporating climate change into existing analytical processes to increase resilience.

Table 4.4. National Grid Planning and Operational Process Vulnerabilities

OPERATIONS AND PLANNING FUNCTIONS	High Temperature	High Winds	Inland Flooding	Ice
Emergency Response	✓	✓	✓	✓
Vegetation Management		✓	✓	✓
Workforce Safety and Methods	✓	✓	✓	✓
Reliability Planning	✓	✓	✓	✓
Load Forecasting	✓			
Capacity Planning	✓			

Source: National Grid (2023a)

4.1 Adaptive Capacity

Some climate vulnerability assessments include the concept of adaptive capacity. The IPCC defines adaptive capacity as "The ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities or to respond to consequences."[13] When combining adaptive capacity with exposure and sensitivity to a specific hazard for a given asset, process, community or critical infrastructure facility, the vulnerability assessment follows a common framework that many utilities (electric, water and gas) and government agencies have used in resilience plans and for other infrastructure, processes, and services (Figure 4.1) (Schellenberg and Schwartz 2024). In the context of grid resilience planning, sensitivity involves the *inherent characteristics* that affect the extent to which an asset, process, or community are impacted by extreme weather and any resulting interruptions, whereas adaptive capacity involves how well the system or community can *change, adapt, or respond* to reduce those impacts .

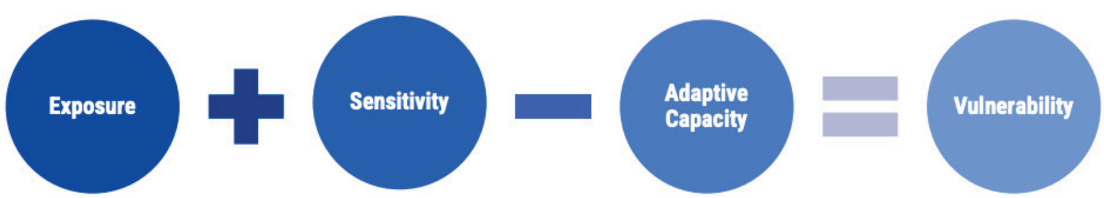


Figure 4.1. Vulnerability Assessment Framework
Source: City of Seattle (2023)

[13] IPCC (2018) Annex I: Glossary [Matthews, J.B.R. (ed.)]. In: Global Warming of 1.5°C.

As an example, consider two retirement communities that have high sensitivity to power interruptions during a heat wave due to the elderly populations — an inherent characteristic. With convenient access to transportation and cooling centers, one community has high adaptive capacity. The other community does not have access to those options in response to a power interruption, and thus has low adaptive capacity. As a result, the two substations that serve these communities could have the same level of exposure and sensitivity to extreme weather, but distinct vulnerability ratings due to differences in community adaptive capacity.

When assessing the adaptive capacity of a utility service territory with hundreds of communities, it may not be practical (or necessary) to estimate separate metrics for community sensitivity and adaptive capacity. Community data that are currently available throughout the service territory, at a sufficiently granular level, may combine indicators of adaptive capacity with inherent characteristics related to political, economic, and social conditions. These characteristics are closely tied to adaptive capacity, which is often driven by access to resources. Therefore, a single metric that combines indicators of community sensitivity and adaptive capacity may be sufficient. Section 6.3 reviews adaptive capacity metrics, which include indices that combine multiple factors related to adaptive capacity into a single value.

5. Hazard Exposure

Utilities collect and analyze data on hazards and exposure of utility assets and customers to these hazards. Regulators and stakeholders can request this information as part of the resilience planning process. Hazard exposure information is typically geospatial, developed by overlaying locational utility asset data with hazard information. These types of data allow utilities to identify which components of their systems are most exposed to potentially disruptive hazards, supporting targeted resilience efforts. The following subsections describe data from resilience plans on hazard characteristics and exposure of assets and customers to those hazards.

5.1 Hazard Characteristics

Utility resilience plans reviewed for this study addressed either a specific hazard or an ensemble of hazards. Which specific hazards are addressed is region- and jurisdiction-specific. The determination reflects relevant climate phenomena in a utility's service territory as well as constraints and sensitivities of utility infrastructure (Duke Energy Carolinas, 2022). In some jurisdictions, state requirements specify hazards to address. The CPUC, for example, prescribes a minimum list of hazards for utilities to analyze. In other jurisdictions, utilities may determine which types of severe weather pose threats to the electrical system that the resilience planning process should address.

Utilities may leverage historical climate information, forward-looking climate projections, or a combination of the two to characterize the geographical scope, severity, and likelihood of hazards. Emerging practices indicate that climate projections are generally preferable to historical data when developing a resilience plan (Schellenberg and Schwartz 2024), especially for extreme weather hazards with well-established global climate models (GCMs) and downscaling methods, as is the case for temperature and precipitation related hazards. Studies suggest that forward-looking projections are more appropriate than historical data for representing future conditions, given the trend toward increasing extreme temperatures, longer and more severe wildfire seasons, and more intense storms driven by climate change (USGCRP, 2023). For certain hazards, most notably maximum wind speeds, local projections are not as well-established and may not be available in many climate models (Komurcu and Paltsev, 2022).

Utility resilience plans reviewed for this report that included forward-looking hazard projections generally contained information to describe and support projections across four dimensions:

- Hazard data variables
- Future climate scenarios
- Analysis timeframe
- Data sources

This section addresses each of these components.

5.1.1 Hazard Data Variables

Utility resilience plans characterized relevant hazards using hazard data variables, which utilities typically selected based on a number of factors, including known asset sensitivities, input from utility SMEs, and data availability. For example, NYSEG and RG&E selected *days per year with average temperatures over 86°F* as a hazard data variable, which aligned with their transformer ambient temperature ratings (RG&E and NYSEG, 2023). Similarly, National Grid used *number of days with maximum temperatures over 104°F*, as this threshold represented a relevant design specification for its distribution lines (National Grid, 2023a). The National Grid CAVA noted that selection of the key climate hazards and hazard data variables involved extensive consultations with internal SMEs.

Table 5.1 contains hazard data variables found in the resilience plans reviewed for this study. The table provides two examples of hazard data variables for each hazard type and reflects the types of data that utilities are providing and that regulators and stakeholders in other jurisdictions can request. Appendix A contains the full list of hazard data variables found in the resilience plans, arranged by hazard type.

Table 5.1. Examples of Hazard Data Variables in Utility Resilience Plans

Inland Flooding Data Variables	Examples
100- and 500-year Floodplains: Extent	PG&E (2024), National Grid (2023a), SCE (2023), TECO (2022), NV Energy (2023)
100- and 500-year Floodplains: Extent and Depth	O&R (2023); Con Edison (2023a); RG&E and NYSEG (2023)
Coastal Flooding	
Sea Level Rise + 100-year Storm Condition	SCE (2022); PG&E (2024)
Coastal Flood and Storm Surge Potential	FPU (2022)
High Wind Speed	
High Wind Gust Hours	Consumers Energy (2022); Consumers Energy (2023)
1-in-x-year Wind Speeds	O&R (2023); National Grid (2023a); RG&E and NYSEG (2023)
Wildfire	
Wildfire Area Burned	SCE (2022); PG&E (2024); PGE (2023)
Days of Extreme Fire Danger / High Fire Weather Index	SCE (2023); SDG&E (2023)
Extreme Storms	
Major Storms Event Database	Entergy New Orleans (2022); TECO (2022); Oncor (2024)
Frequency and Intensity of Severe Storms	Consumers Energy (2022); Con Edison (2019)
Precipitation and Drought	
Extreme Precipitation Events (Multi-day)	SCE (2022); PG&E (2024); O&R (2023); Consumers Energy (2023); RG&E and NYSEG (2023); Con Edison (2019 Appendices)
Drought Risk	NV Energy (2023)
High Heat	
Average Maximum Temperatures	SCE (2022); National Grid (2023); RG&E and NYSEG (2023); Con Edison (2019 Appendices); SCE (2023); SDG&E (2023)
Days Over Temperature Thresholds	O&R (2023); National Grid (2023); Consumers Energy (2023); RG&E and NYSEG (2023)

5.1.2 Future Hazard Scenarios

Resilience plans may include multiple forward-looking hazard scenarios to support decision-making under uncertain future conditions. In a climate vulnerability assessment, this may involve choosing a climate scenario and identifying a source for downscaled climate data based on expert input. Representative Concentration Pathways (RCPs) are scenarios that represent varying levels of greenhouse gas concentration trajectories adopted by the IPCC. Recently, the IPCC adopted Shared Socioeconomic Pathways (SSPs), which forecast global economic, demographic and technological changes to the year 2100, informing greenhouse gas concentrations under various policy interventions. SSPs are now the reference scenarios for IPCC's work. RCPs and SSPs are labeled with a number that represents the net radiative forcing (i.e., net energy into the earth system from the sun) under that scenario in the year 2100, measured in watts per meter squared.

Based on expert input and projections from the Fourth Statewide Climate Change Assessment, California initially required that Climate Change Vulnerability Assessments filed by IOUs use RCP 8.5 — considered a high emissions scenario because it assumes that global growth through 2100 would be driven by fossil fuels. Utilities also commonly analyze RCP 4.5 — considered an intermediate scenario because it assumes that global emissions reach a peak during the 2040s and then gradually decline. More recently, the CPUC directed utilities to use SSP3-7.0 as a reference scenario for use in proceedings and for long-term infrastructure planning. This will align future CAVA analyses with California's Fifth Climate Assessment, which will use SSPs instead of RCPs.

The range of GCMs produces a set of potential climate futures for each RCP or SSP scenario. This allows researchers to generate projections based on different model percentiles, accounting for future uncertainty and reflecting a state or utility's accepted risk tolerance. Utility climate vulnerability assessments have typically applied the 50th to 90th percentile projections of a given RCP scenario (Con Edison, 2023a; PG&E, 2024b; SCE, 2022).

Utilities also may develop and apply their own planning scenarios based on a variety of applicable factors. For example, Consumers Energy (2023) developed three scenarios through 2050, assuming varying external trends related to both the rate of climate change and the rate of customer adoption of distributed solar generation, electric heat pumps, and electric vehicles. The three scenarios are referred to as Decelerated Transition, Continued Momentum, and Accelerated Transition. This process sought to answer the holistic set of challenges that the future grid must address and the most impactful potential grid impacts, including circuit-level impacts of load growth. Regulators and stakeholders can engage with utilities to define scenarios in advance of the utility's analysis and receive information on the utility's hazard scenarios, including the rationale for including each scenario in the analysis.

5.1.3 Analysis Timeframe

The analysis timeframe is the time period for which the analysis is conducted. It dictates the number of years into the future for projecting hazard data. Utilities may consider a number of factors when determining analysis timeframe, including state guidance, asset lifespans, and data limitations. Some states provide specific planning horizons for utilities. For example, the CPUC requires California utilities to analyze potential climate impacts 20–30 years into the future, while also assessing early-century (10–20 year) and late-century (30–50 year) timeframes.

5.1.4 Data Sources

Utility resilience plans leverage both historical and projected climate and weather data produced by government agencies, research institutions, and third parties. Historical climate records can be in the format of event databases and gridded historical re-analysis data, which are datasets that combine past observational data with advanced weather and climate models to project a complete and consistent record of historical atmospheric conditions. Utilities may use both historical and projected data to generate or calibrate future hazard projection data. For example, TECO, Entergy New Orleans, and Oncor all leveraged the Major Storms Event Database, which draws on NOAA records of major storms since 1852 to reflect present-day and potential future storm scenarios. Gridded hazard projections, such as those used by PG&E and Duke Energy to understand future temperature and precipitation conditions, also utilize historical reanalysis climate data to understand present-day risk and to calibrate future modeled data.

In California and New York, state energy offices worked with climate experts at universities in their state to develop and downscale climate projections and create tools for a variety of hazards, including temperature, precipitation, wildfire, and wind. For example, the California Energy Commission sponsored Cal-Adapt, a tool that provides granular climate projections and the underlying data through the end of the 21st century to California utilities for a variety of climate hazards and scenarios. Absent state-specific tools and datasets, utilities can use nationwide datasets such as the Climate Toolbox Climate Mapper by the University of California, Merced, the Climate Risk and Resilience Portal by Argonne National Laboratory, or they can generate their own tailored projections by manipulating raw downscaled data. While generating projections is more time- and computationally-intensive, it allows for greater flexibility in time period and variable selection.

Resilience planning requirements may specify sources for statistically downscaled data based on expert input. Raw GCM data are fairly coarse in resolution, with grid cells ranging from around 250 to 600 kilometers in area. For this reason, resilience planners typically use downscaled GCM data, with smaller grid cells that have been processed to provide higher-resolution information at regional or local scales. Examples of downscaled climate datasets used in resilience planning include global NEX-GDDP data and US LOCA data. Utilities generating their own tailored projections using these downscaled data can derive the specific variables of their choosing for time periods and future scenarios that align with their resilience planning needs.

Appendix B contains examples of external data sources leveraged by utilities in their resilience plans.

5.2 Exposure Data

Exposure data describe the degree to which assets may experience specific climate hazards. In the resilience plans reviewed for this study, utilities typically generated exposure data using geospatial asset and hazard data and analyzed it on an asset-hazard combination-specific basis (PG&E, 2024b; RG&E & NYSEG, 2023; National Grid, 2023a). This method allows utilities to identify which components of their system are most exposed to potentially disruptive climate hazards, enabling more targeted resilience efforts. Most resilience plans that addressed exposure presented findings as maps. For example, Figure 5.1 represents National Grid's distribution line exposure to high summer maximum temperatures through late-century.

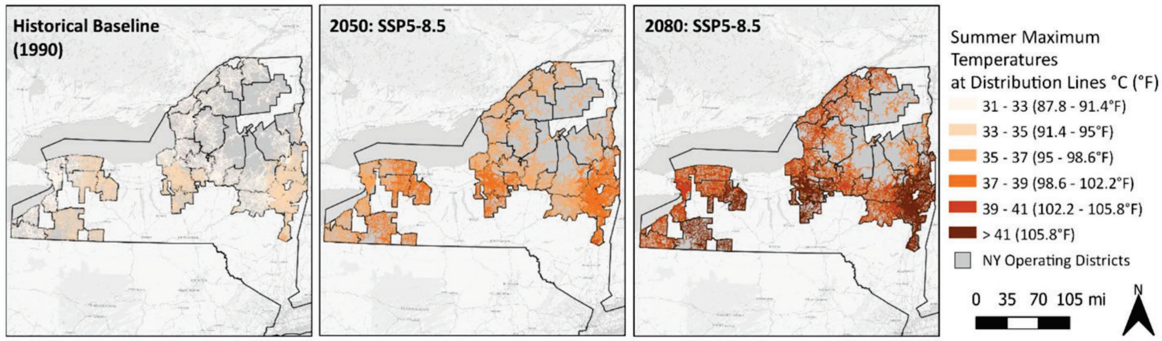
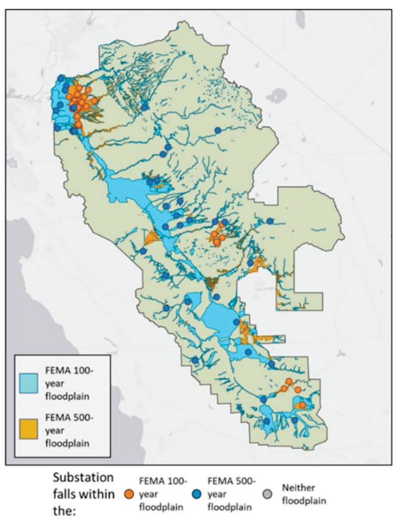


Figure 5.1. Exposure of National Grid's Distribution System to High Summer Temperatures

PG&E and O&R used FEMA floodplain data to represent inland flood risk, with O&R also showing flood depth values across the floodplains. Figure 5.2 shows PG&E's and O&R's FEMA inland flood datasets, overlaid with company substation data.



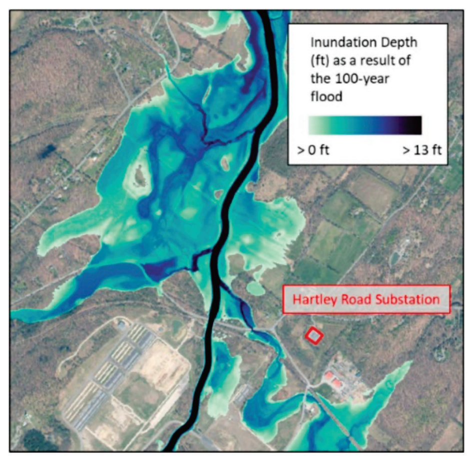


Figure 11. **100-year inland flood depths in an example floodplain adjacent to Hartley Road Substation, located in Orange County**

Figure 5.2. FEMA 100-year Floodplain Extent (Left) and Depth (Right) as shown in PG&E and O&R's Vulnerability Studies

Utilities also presented exposure findings in tabular form. For example, the PG&E CAVA included asset-hazard specific tables throughout all asset types indicating territory-wide exposures to all relevant climate hazards. Table 5.2 shows PG&E pad-mounted distribution transformer counts exposed to coastal flooding.

Table 5.2. PG&E Pad-Mount Distribution Transformer Counts Exposed to Coastal Flooding

Region	Baseline	2030	2050	2080
Bay Area	107 (0.08%)	1,501 (1.12%)	1,942 (1.45%)	3,598 (2.69%)
Central Valley	25 (0.02%)	754 (0.56%)	786 (0.59%)	1,420 (1.06%)
Sierra	6 (0.004%)	26 (0.02%)	29 (0.02%)	58 (0.04%)
North Coast	161 (0.12%)	306 (0.23%)	424 (0.32%)	743 (0.55%)
Central Coast	22 (0.02%)	62 (0.05%)	115 (0.09%)	490 (0.37%)
Total	**321 (0.24%)**	**2,649 (1.98%)**	**3,296 (2.46%)**	**6,309 (4.71%)**

NYSEG and RG&E overlayed substation data with temperature threshold data, multi-day precipitation event data and flood depth data, generating asset-specific information describing substation exposure to these hazards. PG&E overlayed substation data with 1-in-2 and 1-in-10-year maximum temperatures, 100- and 500-year FEMA floodplains, multi-day precipitation events and landslides, sea level rise and coastal storms, and High Fire Risk Areas (PG&E, 2024a).

In cases where exposure levels are determined categorically (e.g., high, medium, low) by SMEs using expert judgment, the maps and tables can provide a basis for making the scoring assessments.

6. Attribute Metrics

Attribute metrics are system characteristics that contribute to or describe aspects of the resilience of a system or community (Leddy et al., 2023; Keen et al., 2024a; Anderson et al., 2021). Using the definition of resilience used for this report,[14] attribute metrics reflect the ability of the electrical system and its customers to anticipate a hazard, withstand the hazard, adapt to hazard impacts, and recover from the hazard to a normal operating state. By tracking attribute metrics, utilities can connect infrastructure performance to tangible asset characteristics and hardening progress, and in doing so, assess both the components of their system that are more resilient and those that need improvement.

The academic literature includes some variation in the definition of resilience and its phases, which corresponds to differences in attribute metric subcategories. Regardless, a common visual representation of resilience shows system performance or resilience level on the y-axis and time on the x-axis. Figure 6.1 illustrates several versions of such graphics from the literature and one from RG&E and NYSEG (2023). The overarching concept remains largely the same between representations, and the phases labeled in the diagrams correspond to the respective resilience frameworks.

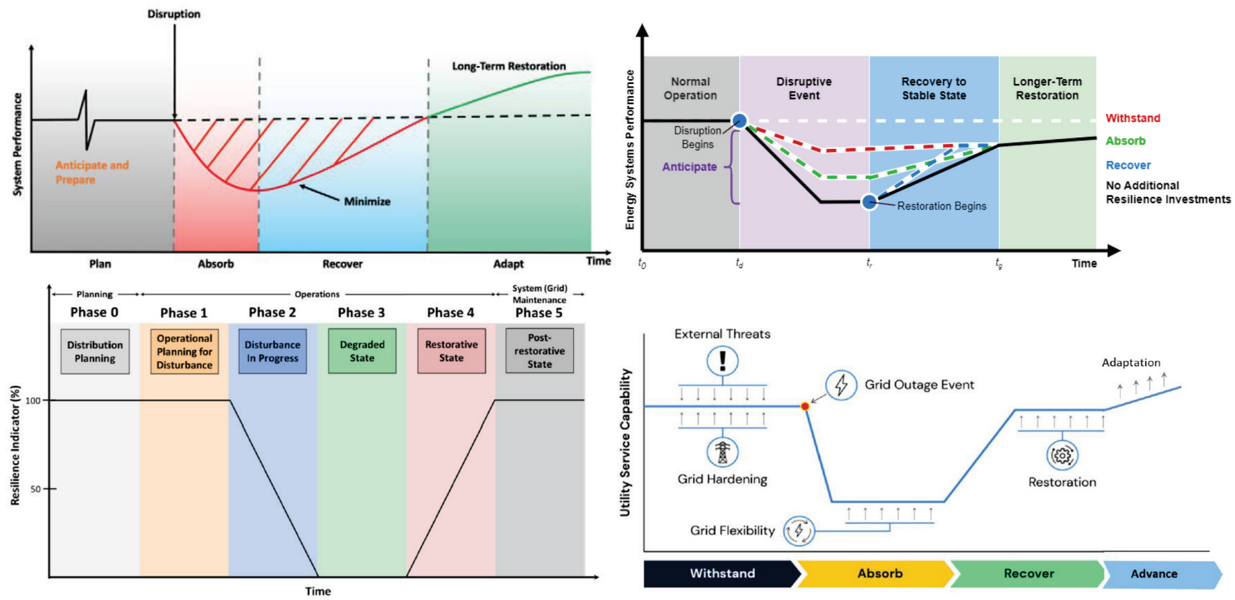


Figure 6.1. Phases of Resilience as Depicted across the Literature

Sources: From Leddy et al., (2023), Keen et al. (2024), EPRI (2023), RG&E & NYSEG (2023)

This report characterizes attribute metrics according to the following four phases, which align with the components of the resilience definition used in this report:

[14] Presidential Policy Directive (2013).

- **Anticipate** – The likelihood or characteristics of potential impacts caused by a hazard.
- **Withstand** – The electrical system's capacity to avoid being affected by a hazard.
- **Adapt** – The ability of the grid to respond to asset damage or of the community to change behavior to minimize impacts to customers.
- **Recover** – The ability to restore normal grid operation after a disruption.

Table 6.1 presents the types of metrics described in utility resilience plans for each of the four resilience phases.[15] This chapter uses these distinctions for the purposes of organizing metrics in a useful way for resilience planning. The four phases of resilience also can serve as a foundation for regulators and stakeholders to request information from utilities on the resilience of their electric systems and communities. The remainder of this section provides more details on each resilience phase.

Table 6.1. Attribute Metric Types by Resilience Phase

Resilience Phase	Metric Type
Anticipate	Potential for hazards to damage assets
	Potential for assets to damage surroundings
Withstand	Asset condition
	Asset ratings
	Asset hardening status
Adapt	Automation and topology
	Emergency power
	Social indicators
	Community resilience indicators
Recover	Preparedness
	Accessibility
	Power restoration

6.1 Anticipate

This phase of resilience refers to the likelihood or characteristics of potential impacts caused by a hazard. Attribute metrics in this phase typically describe either the potential for hazards to cause damage to assets or the potential for assets to cause damage to surroundings (e.g., by igniting a

[15] The table does not represent an exhaustive list of possible types of metrics.

wildfire). Table 6.2 shows examples of metrics for the *Anticipate* phase. Appendix C is a more comprehensive list of Attribute metrics.

In the resilience plans reviewed for this report, metrics describing the potential for hazards to cause damage to assets included both those that indicated asset locations in relation to a hazard and those that depicted the likelihood of damage. For example, PG&E mapped and calculated county-wide mileage totals for transmission lines in High Fire Risk Areas, allowing the Company to anticipate areas of the service territory with relatively higher wildfire potential. Similarly, many companies, including PG&E, National Grid, and O&R, identified substations within FEMA 100-and 500-year floodplains in their vulnerability assessments, which reflect a higher likelihood of being impacted by an inland flooding event. More robust monitoring systems which improve hazard anticipation can improve a utility's ability to withstand, adapt to, and recover from events (Keen et al, 2024a[16]).

Table 6.2. Attribute Metrics for the *Anticipate* Phase

Metric Type	Metric Description	Utility Example
Potential for hazards to damage assets	Substations located within a FEMA 100- or 500-year floodplain	National Grid (2023)
	Transmission line mileage located within High Fire Risk Areas	PG&E (2024)
	Environmental monitoring systems	California Office of Energy Infrastructure Safety WMP Reporting Requirements
	Weather forecasting	California Office of Energy Infrastructure Safety WMP Reporting Requirements
Potential for assets to damage surroundings	Annual probability of asset-caused ignition	PGE (2023)
	Number of asset management ignition risk-related work orders that are past due	SCE (2023)
	Number of vegetation contacts with lines in Wildfire Risk Tiers	NV Energy (2023)
	Ignition Potential Index – potential for ignition of a large wildfire given fuel and weather conditions	PGE (2023)

Metrics describing the potential for assets to cause damage to surroundings typically referred to utility equipment-caused wildfire ignition potential. For example, in its WMP, PGE calculated ignition probability, or the annual likelihood that a given piece of equipment could cause a wildfire ignition given its type, age, condition, and location. Other factors that may influence the potential for assets to cause a wildfire ignition include asset exposure to fire-prone land cover (e.g., dry brush, grasslands), topography (e.g., steeper, south-facing slopes), climatological trends (e.g., decreasing snowpack, heightened drought severity), and weather (e.g., low humidity, high winds) (Zhai et al., 2023; Gergel et al., 2017; National Weather Service, 2024).

[16] What this report refers to as the Adapt phase, Keen et al. (2024a) refer to as the Absorb phase.

In the context of a conducting a vulnerability assessment (see Chapter 4), attribute metrics for the *Anticipate* phase can be useful for characterizing the level of asset exposure to hazards. For example, the number of substations located within the FEMA 100-year floodplain is a metric that characterizes the potential for a flood to damage assets. This metric can inform the exposure ranking process (e.g., high, medium, or low), if applicable.

6.2 Withstand

The *Withstand* phase of resilience refers to a system's capacity to avoid being affected by a hazard. In this context, it would characterize the ability to avoid damage from the hazard. Attribute metrics for the *Withstand* phase describe asset condition, asset ratings, and the degree to which assets have been hardened against potential hazards.
In the context of a vulnerability assessment, *Withstand* phase metrics can help characterize asset or system sensitivity, providing an indication of whether an asset is sensitive to the negative impacts of a hazard. Table 6.3 provides examples of metrics for the *Withstand* phase.

Attribute metrics that describe the ability of an asset to withstand a hazard event may include asset age, location, and condition. These data are frequently stored and aggregated in utility asset condition databases, which include inspection data characterizing the condition of assets (e.g., wooden poles). Regulators may require that utilities report regularly on these types of attribute metrics. For example, the California Office of Energy Infrastructure Safety requires that utilities filing Wildfire Mitigation Plans report quarterly on a host of attribute metrics, including grid condition findings from inspections and grid condition fixes in response to inspection findings.

Asset Inspection Products

A number of utilities use custom inspection products to generate a central, standardized asset condition database. These products support information sharing across inspections, which improves data quality and accessibility to allow for more rapid and informed asset hardening. Examples of such products are SCE's InspectForce, Consumer Energy's Imagery Analytics, and NYSEG and RG&E's HealthAI.

InspectForce is SCE's equipment inspection management product that aggregates asset inspection data to promote better information sharing and availability between inspection teams and decision-makers. InspectForce notifies users of asset condition issues that require attention and provides high quality system data to support wildfire mitigation initiatives (SCE WMP 2022).

Through its **Imagery Analytics** initiative, Consumers Energy proposes an inspection process that would leverage detailed drone-derived information and automated imagery collection, as well as machine learning capabilities, to obtain comprehensive views of assets and detect defects.

NYSEG and RG&E are proposing a new project called **HealthAI**, which will analyze millions of street-level photographs of company poles, wires, and grid equipment to systematically assess asset health at the distribution level. HealthAI will represent a centralized catalog of asset condition data and will help the companies identify areas and assets of concern. NYSEG and RG&E anticipate that HealthAI could reduce interruption risk and improve worker safety by providing them with relevant information regarding the equipment they are maintaining.

Several utilities proposed measures for improving asset condition testing and tracking in their resilience plans. DTE Electric's Storm Protection Plan outlined its Pole Top Maintenance and Modernization Program, which involves pole and pole-top equipment testing to determine asset conditions. Assets that do not pass testing are replaced with stronger equipment, increasing their ability to withstand hazard events. In its Climate Vulnerability Assessment, Duke Energy recommended better tracking of data related to joint-use poles, including through available inspection data and deployment of additional inspection fleets. The plan stated that these data improvements would indicate areas of concern, or locations necessitating pole replacements, allowing the assets to better withstand hazard impacts such as pole damage.

Table 6.3. Attribute Metrics for the *Withstand* Phase

Metric Type	Metric Description	Utility Example
Asset condition	Asset age	PGE (2023)
	Asset condition (inspection data – source)	California Office of Energy Infrastructure Safety WMP Reporting Requirements
	Improvements to tracking of asset condition related to joint-use poles	Duke (2023)
Asset ratings or hardening status	Total number of transformers that meet the latest temperature specification	NYSEG (2023)
	Total number of upgraded transformers	National Grid (2023)
	Total number of upgraded transmission assets	TECO (2022)
	Distribution feeders upgraded	TECO (2022)
	Conductor temperature ratings by location in the service territory	PG&E (2024)
	Line miles undergrounded for wind and ice	O&R (2023)
	Critical substation assets elevated in floodplains	PSEG Long Island (2024)

Metrics describing asset ratings or hardening status reflect a system's ability to withstand hazards, especially when placed in the context of local climate conditions. For example, PG&E's CAVA indicated that its assets were rated using interior-coastal designations, where conductors in the interior district assumed maximum ambient summer temperatures of 109°F and those in the coastal district assumed temperatures of 99°F. PG&E placed these rating thresholds in the context of climate change-driven increases in temperatures across both the coastal and interior regions of its service area, effectively indicating where, and to what degree, its assets would be prepared to withstand future severe heat. Other utilities provided information on upgraded assets, the total number of upgrades to substation transformers, distribution lines, and transmission lines.

Utility resilience plans provided a number of asset hardening metrics, including those describing the status of flood protection projects at substation locations, the total number of distribution line miles converted to underground for storm protection, and tracking the completion of covered conductor. Information on the status of asset hardening projects is useful for project management tracking, but the purpose of attribute metrics is to characterize the resilience of the system. Regulators and utilities should distinguish between metrics that characterize the system (attribute metrics) and those that track project completion.

6.3 Adapt

Attribute metrics in the *Adapt* phase can refer to both the electrical system and the community.[17] These metrics reflect the ability of the electrical system to adapt to impacts from a hazard in order to deliver power from alternative sources or through alternative means. Thus, the metrics can reflect system redundancy, where backup systems or resources are in place to ensure that critical functions continue during a disruption. They also reflect the diversity and complexity of the system, such that it would be less likely to be impacted by a single point of failure. *Adapt* phase attribute metrics also describe the ability of communities to minimize negative impacts of power interruptions, such as implementation of consequence reduction measures, social indicators, and other community resilience indicators or indices (combinations of indicators).

Table 6.4. Attribute Metrics for the *Adapt* Phase

Metric Type	Metric Description	Utility Example
Emergency Power	Number of customers with solar + storage	PSE Customer Benefit Indicators
Automation and Topology	Network Reliability Index	Con Edison (2023b)
	Number of automatic transfer switch installations completed	Con Edison (2023b)
	Number of sectionalizing switches installed	Con Edison (2023b)
Social Indicators	Household disability composition	PGE (2023)
	Housing and transportation vulnerability	PGE (2023)
	Households below 200% Federal Poverty Line	PGE (2023)
	Social vulnerability index	PGE (2023)
	Age 65+	PGE (2023)
Community Resilience	Community implementation of resilience projects and initiatives	DTE Electric (2023)
	Community Resilience Metric	SCE (2022)
	Baseline Resilience Indicators for Communities	PG&E (2024)

Utilities and regulators may track the degree to which customers have access to emergency backup power. Power sources could include, for example, battery energy storage systems, solar plus storage, microgrids, or diesel generators. While not a resilience plan reviewed for this analysis, Puget Sound Energy's (PSE) Customer Benefit Indicator metrics included a component that tracks the number of customers with solar plus storage to measure "improved access to reliable clean energy" (PSE, 2023).

[17] Some resilience frameworks refer to this phase as *Absorb* (Keen et al., 2024).

Distribution engineers can use metrics to describe characteristics of grid topology, including its diversity and complexity. Con Edison's Network Reliability Index is the utility's "main tool for projecting network-specific failure risk across a number of hazard drivers…." It measures the relative strength of a network based on the probably of failure of multiple associated feeders caused by component failure rates, grid stress, and load shifts during contingencies (Consolidated Edison, 2023b). Other attribute metrics in the utility resilience plans reviewed for this report focused on grid automation and topology enhancements, such as the number of installations of automatic transfer switches and sectionalizing devices.

Social indicators reflect a community's capacity to minimize or avoid negative impacts from interruptions or utility equipment-caused hazards like wildfire ignitions. In its Wildfire Mitigation Plan, PGE outlined key social indicators that influence community ability to adapt to hazard impacts, including household disability composition, housing and transportation vulnerability, households below 200% of the Federal Poverty Line, and the prevalence of people age 65 or older.

Community resilience metrics also reflect the ability to minimize negative impacts during a hazard event. For example, DTE Electric tracked community implementation of resilience projects and initiatives, including construction of resilience hubs or community centers that support residents when extreme weather events occur (DTE Electric, 2023). If customers lose power from the grid, resilience hubs provide an alternative location from which to receive electrical service and reduce the negative impacts of the interruption.

Social indicators and community resilience metrics can describe a community's adaptive capacity (see Chapter 4). SCE (2022) developed a Community Resilience Metric (CRM) for its CAVA. The CRM measures the sensitivity and adaptive capacity of a particular community to an interruption. It uses 25 indicators of community sensitivity, including health risks, housing quality, pollution burden, and 11 socio-economic factors. The 12 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. Figure 6.2 summarizes CRM results for the utility service territory, ranging from low community resilience (-13) to high community resilience (56). SCE plans to continue refining the CRM score, including as it develops its next CAVA (due in 2026), and potentially use the CRM along with other utility planning and operational considerations to inform prioritization of investments that mitigate climate vulnerabilities.

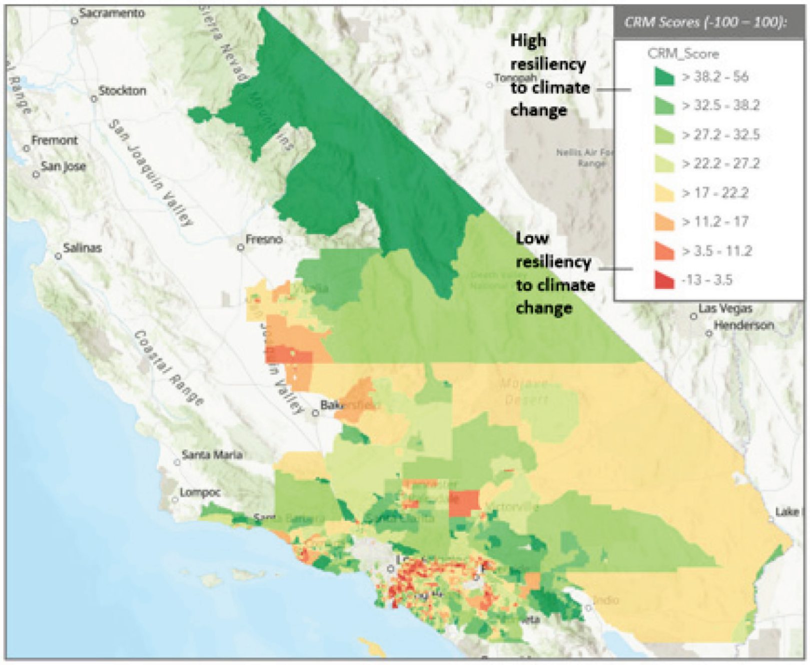


Figure 6.2. Community Resilience Metric (CRM) Scores for Southern California Edison Territory

Source: Southern California Edison (2022)

In its CAVA, PG&E used the Baseline Resilience Indicators for Communities (BRIC) index at a county level to assess adaptive capacity. The BRIC index is a publicly available index based on six categories of community disaster resilience at the county level: social, economic, community capital, institutional, infrastructural, and environmental. The index measures existing attributes of resilience to natural hazards. Table 6.5 summarizes the normalized BRIC scores from low community resilience (0) to high community resilience (1) across PG&E regions. The utility calculated a composite BRIC score for each region based on the county-level data. With this assessment of adaptive capacity using BRIC category scores by region, in addition to community feedback, PG&E plans to improve community resilience through existing or new programs and investments. The utility may improve and update these metrics as part of developing its next CAVA (due in 2028).

Table 6.5. BRIC Category and Composite Scores for PG&E Regions

Region	Bay Area Region	San Joaquin Valley Region	North Valley, Sacramento & Sierra Region	North Coast Region	Central Coast Region
Social	0.683	0.611	0.641	0.618	0.654
Economic	0.515	0.460	0.459	0.427	0.477
Community Capital	0.289	0.315	0.331	0.344	0.302
Institutional	0.379	0.377	0.389	0.371	0.402
Infrastructural	0.325	0.268	0.255	0.238	0.288
Environmental	0.555	0.498	0.535	0.563	0.528
BRIC Composite Score	**0.458**	**0.422**	**0.435**	**0.427**	**0.442**

Source: PG&E (2024)

Appendix D is a table of social indicators related to adaptive capacity, and data sources, for utilities and states to consider for resilience planning.

6.4 Recover

The *Recover* phase of resilience refers to the phase directly after a disruptive event, focused on restoring normalcy and minimizing negative consequences. *Recover* phase metrics describe the ability of the utility to return to normal operation after hazard events through preparedness, accessibility, and power restoration. Investments in a utility's ability to recover from a disruption can increase the speed with which utilities can respond to hazard events, repair the system, and restore power. Table 6.6 shows examples of the types of attribute metrics that regulators and stakeholders can request from utilities.

Table 6.6. Examples of Attribute Metrics for the *Recover* Phase

Metric Type	Metric Description	Utility Example
Preparedness	Collaboration on local wildfire mitigation planning	California Office of Energy Infrastructure Safety WMP Reporting Requirements
	Minimum staffing required in preparation for event response	PGE (2023)
Accessibility	Average drive time from a fire station	PGE (2023)
	Access/egress road density by HFRZ	PGE (2023)
	Asset accessibility and terrain	Entergy New Orleans (2023)
Power Restoration	Reclosers automated or remotely-controlled	Pacific Power (2023)
	Fire response time	PGE (2023)

A utility's degree of preparedness can impact its ability to recover quickly after a disruption. Metrics that reflect preparedness, or operational readiness, describe various facets of emergency preparation initiatives, such as:

- Internal emergency preparedness plans
- External collaboration and coordination, including mutual assistance
- Public emergency communication strategies
- Preparedness and planning for service restoration
- Work procedures and training in elevated risk zones

Preparation initiatives also may include event-driven impact forecasting, which allows for proactive mobilization of workers and resources to ensure more efficient event response. For example, Con Edison employs a team of meteorologists to monitor weather and provide impact forecasts such as the expected number of outage restoration jobs. Meteorologists participate in storm preparation meetings at Con Edison to help translate forecast metrics into storm response strategy (Con Edison, 2023).

Accessibility to roads and emergency services allows utilities to re-establish public safety, mitigate ignition events, and restore power after a hazard event. Accessibility also enhances a community's ability to safety evacuate from areas impacted by hazards. Examples of metrics included access/egress road density by fire risk zone and nearby fire stations by fire zone (PGE, 2023). *Recover* metrics reflecting the ability to restore power quickly to return to a normal state could include the number of automated or remotely-controlled reclosers. Utilities can reduce restoration times when they are able to activate reclosers remotely—instead of manually—once conditions are safe.

Attribute metrics allow the utility to systematically describe the resilience of its electrical system and the communities it serves. These metrics can provide insights for determining specific options for increasing resilience and improving performance metrics, which are covered in the next chapter.

7. Performance Metrics

Performance metrics measure the effectiveness of resilience investments by quantifying the extent to which they have (or have not) reduced the negative impacts of hazard events. Utility resilience measures seek to avoid some or all of the negative impacts that would have occurred without the measures. Performance metrics measure the progress toward achieving these resilience objectives (Keen et al., 2024; Broderick et al., 2021).

Some states require utilities to report specific resilience performance metrics. Other states give utilities leeway to determine the most appropriate metrics to report. Utilities can estimate the expected future values of performance metrics for proposed investments ("ex ante"), or track the actual performance of measures that they have implemented ("ex post"). (See Section 8.1 for a discussion of ex ante and ex post analyses.) Regulators can require that utilities evaluate metrics against a defined target or benchmark and monitor and report performance metrics. Regulators also can link metrics to financial incentives or penalties, or both (NC DEQ 2020).[18]

This section divides performance metrics into the following categories:

- Electrical Service (Section 7.1)
- Critical Infrastructure Electrical Service (Section 7.2)
- Asset Damage and Failure (Section 7.3)
- Response and Restoration (Section 7.4)
- Monetary Impact (Section 7.5)
- Customer Communications and Engagement (Section 7.6)

Which category to assign a metric depends on its usefulness for measuring relevant performance. For example, metrics that measure the cost of asset damage could fall under Asset Damage and Failure or Monetary Impact. Similarly, metrics that measure the cost of restoration activities could fall in either the Response and Restoration or Monetary Impact categories. In this report, both types of metrics are addressed in the Monetary Impact category.

Section 7.7 addresses performance metrics in utility plans associated with public safety power shutoffs—the intentional de-energization of portions of the grid to reduce the risk of a wildfire caused by a utility asset. Section 7.8 reviews how utilities and regulators can address equity in resilience plans. Appendix C contains a more extensive list of performance metrics and the utility resilience plans (or other sources) in which they were reported.

[18] Some utility plans report metrics that track implementation of resilience initiatives (e.g., O&R, 2023). While plan execution metrics are important for project implementation, this report refers to performance of investments to improve resilience, rather than utility implementation schedules. Thus, the report does not include implementation metrics.

7.1 Electrical Service

The most common performance metrics in utility resilience plans reviewed for this study measure electrical service by quantifying the frequency and duration of power interruptions using various methods. This section reviews three types of Electrical Service metrics that utilities can provide regulators and other stakeholders:

- Interruption Events, Frequency, and Duration
- Customer Interruption
- Other Interruption

First, the section discusses dimensions of granularity for examining interruption data and reporting performance metrics that support resilience planning. Then it provides more detail on each type of Electrical Service metric, including specific metrics and utility examples.

Dimensions of Granularity

Examining interruption data at a more granular level than the entire electrical system can help utilities to isolate the negative impacts of hazards and mitigating impacts of resilience measures. A typical utility outage management system (OMS) contains a number of data elements describing each interruption that occurs on the system. OMS data generally include the interruption cause, number of customers interrupted, start and end times, and circuit where the interruption occurred, among other elements. Utilities can use interruption data along several dimensions of granularity to measure performance of resilience programs by reducing the universe of interruptions studied to those impacted by the resilience measure.

IEEE Standard 1782-2022 provides guidance for collecting, categorizing, and using interruption information. The standard details a variety of data elements and practices to maintain consistency and compare data both within a utility and across utilities following the standard. Adhering to a set of standards allows utilities to draw resilience comparisons internally (between customer groups, asset groups, or regions of the service territory) and externally (against other utility companies).

Time

Interruption start and end times are essential for calculating interruption duration. The two data points also enable utilities to determine when the interruption occurred in relation to an extreme weather event. Utilities also can use start and end times to calculate Electrical Service performance metrics for specific time periods, such as days with extreme weather events.

Interruption Cause

Metrics describing interruption events caused by extreme weather illuminate the impacts of specific climate hazards on company equipment (National Grid, 2023b) and identify and address the primary drivers of service interruptions (DTE Electric, 2023; Indiana Michigan Power, 2023; Oncor, 2024).

IEEE Standard 1782-2022 provides a structured approach to identify and categorize causes of interruptions to enable consistent reporting and analysis. It presents four data elements which together can describe the cause of an interruption in detail (IEEE, 2022):

- *Cause category* – The standard suggests 10 cause categories: equipment, lightning, planned, power supply, public (e.g., car accident involving collision with a utility pole), vegetation, weather (other than lightning), wildlife, unknown, and other.
- *Cause subcategory* – Each cause category has up to six subcategories. For example, weather subcategories are precipitation, ice, wind, extreme temperature, and other.
- *Affected equipment* – The standard recommends 13 categories of equipment to classify what failed or was impacted: structure/support, insulator, conductor/cable, connector/splice, elbow/terminator, arrester, transformer, simple switching device, simple interrupting device, advanced interrupting/switching, controls, circuit breaker, and other.
- *Contributory factors* – Contributory factors help account for an interruption with multiple contributing causes. For example, high wind may cause a tree limb to contact a power line. The cause category and subcategory would be "vegetation," affected equipment would be "Conductor/Cable," and the "initiating" contributory factor would be "Weather – wind."

A utility's ability to collect complete reliability information depends on the sophistication of its information systems, especially training and reporting protocols for line crews. The interruption reporting system can use information from the utility's customer information system, GIS, SCADA system, OMS, and others (IEEE, 2022). Utilities with IT systems lacking the capability to report interruptions to the level of the standard may not be able to provide detailed interruption cause information.

Circuit

Identifying the circuits, substations, or other locations impacted by interruptions allows utilities to measure performance for specific portions of the system. Combining interruption cause data with circuit data enables utilities to evaluate which circuits are impacted by which types of interruptions and determine the most effective and targeted strategies for addressing interruption drivers. For example, data on circuits with the most interruption time from vegetation contacting conductors provide useful information for prioritizing where vegetation management measures would be most effective and evaluating post-implementation performance.

Interruption data at the circuit level allows utilities, regulators, and other stakeholders to understand impacts to different types of customers. The data can show impacts to critical facilities (e.g., hospitals and water treatment facilities)[19] if utilities know which circuits serve the facilities. The data also can show impacts to different customer classes if utilities know the customer composition for each circuit. This type of information is important for estimating the costs incurred by customers during interruptions, as commercial customers incur higher costs from interruptions on average than residential customers (see Section 7.5).

[19] See Section 7.2 for a discussion of critical facilities and associated performance metrics.

7.1.1 Interruption Events, Frequency, and Duration

Table 7.1 shows the metrics included in the Interruption Events, Frequency, and Duration category. The first metric, Interruptions, is the raw count of interruption events—unweighted by the number of customers experiencing the interruption. The next two metrics, Customers Interrupted (CI) and Customer Minutes Interrupted (CMI), express the count of customer interruptions and customer minutes interrupted, respectively. They reflect the magnitude of an interruption. For example, if 200 customers experienced an interruption for 10 minutes, CI would equal 200 customers interrupted and CMI would equal 200 customers x 10 minutes = 2,000 customer minutes interrupted. CI and CMI are common metrics in utility resilience plans.[20]

It is common to distinguish between grid performance under normal operating conditions and performance under abnormal operating conditions. To examine performance under normal conditions, utilities exclude MEDs, which are days when utility system performance is significantly impacted by events outside of normal operating conditions, such as extreme weather. MEDs were developed to enable year-on-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. Standard reliability metrics are normally calculated and reported on an annual basis, aggregating performance over an entire year. In contrast resilience metrics focus on identified, large, or otherwise notable events that occur at specific times within a year (e.g., over a day or week). Resilience events generally (but not always) occur during MEDs—often, the largest MEDs recorded in the year.

The utility industry has a set of well-established indices for measuring and benchmarking reliability. IEEE Standard 1366-2022 defines these indices. Table 7.1 shows four of these indices for measuring interruption frequency and duration: SAIFI, SAIDI, CAIDI, and MAIFI. SAIFI and MAIFI are measures of interruption frequency, representing the total number of interruptions that an average customer experiences over some time period. SAIFI measures the frequency of "sustained" interruptions, or interruptions lasting 5 minutes or more, while MAIFI measures "momentary" interruptions, which last less than 5 minutes.[21] SAIDI and CAIDI are measures of average interruption duration. SAIDI represents the total number of minutes that an average customer is without power over some time period, while CAIDI represents the time required to restore service for an average customer over some time period.

[20] TECO (2022), Entergy New Orleans (2023), Duke Energy (2022), PGE (2022), National Grid (2023b), CenterPoint (2024), SCE (2022), Indiana Michigan Power (2023), Con Edison (2023b)

[21] IEEE 1366-2022 defines momentary outages as outages less than 5 minutes. In Europe, the definition of a momentary outage ranges from 1 minute to 3 minutes, and in Canada, the Canadian Electricity Association defines momentary outages as those lasting 1 minute or less.

Table 7.1. Performance Metrics for Interruption Events, Frequency, and Duration

Metrics	Units	Description
Interruptions	Count	Count of unweighted interruption events
CI	Count	Customer Interruptions: sum of all customers interrupted over a given time period
CMI	Minutes	Customer Minutes Interrupted: sum of all customer minutes interrupted over a given time period
SAIFI (including and excluding MEDs)	Interruptions per Customer	System Average Interruption Frequency Index: total number of interruptions that an average customer experiences over some time period
SAIDI (including and excluding MEDs)	Minutes	System Average Interruption Duration Index: total number of minutes that an average customer is without power over some time period
CAIDI (including and excluding MEDs)	Minutes	Customer Average Interruption Duration Index: time required to restore service for an average customer over some time period
MAIFI (including and excluding MEDs)[22]	Interruptions per Customer	Momentary Average Interruption Frequency Index: total number of momentary interruptions (< 5 minutes) that an average customer experiences over some time period
Storm-only SAIFI	Interruptions per Customer	SAIFI specific to days with a storm designation
Storm-only SAIDI	Minutes	SAIDI specific to days with a storm designation
Storm-only CAIDI	Minutes	CAIDI specific to days with a storm designation

IEEE Standard 1366-2012 defines a MED as a day in which daily system SAIDI exceeds a statistically-determined MED threshold value (T_{MED}).[23] Daily SAIDI data are log-normally distributed, meaning that a histogram of historical daily SAIDI values would have a long tail to the right, reflecting infrequency of days when significant hazards impacted the grid and led to greater or more long lasting interruptions. Figure 7.1 shows an illustrative log-normal distribution. The formula for setting the T_{MED} threshold uses 5 years of daily SAIDI values, takes the natural log of the values to transform the skewed distribution

[22] Utilities can calculate MAIFI with and without MEDs, or for storm-only conditions, but did not report it in the resilience plans.
[23] The standard states, "Even though SAIDI is used to determine the MEDs, all indices should be calculated based on removal of the identified days."

into one that more closely follows a normal distribution (i.e., a bell curve), and sets T_{MED} at 2.5 standard deviations above the mean. This represents a threshold where, on average, the expected numbers of MEDs per year would be 2.3 days (0.4%).[24]

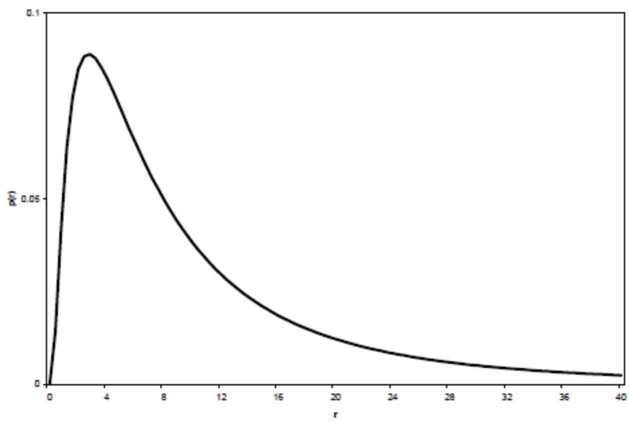


Figure 7.1. Illustrative Log-Normal Distribution of Daily SAIDI Values

Source: IEEE Standard 1366-2012

Notes: X axis is daily SAIDI; y axis is probability

Additional Designations for Major Events

Some jurisdictions have adopted additional designations of major events to distinguish between normal and abnormal operating conditions. Regulators may base the definitions on factors such as weather and customer impact, as opposed to historical data. The following are examples of additional designations.[25]

- New York defines a "major storm" as "a period of adverse weather during which service interruptions affect at least 10 percent of the customers in an operating area and/or result in customers being without electric service for durations of at least 24 hours" (16 NYCRR Part 97).
- Michigan designates "catastrophic conditions" as either severe weather conditions that result in interruptions for 10% or more of customers, or events which result in a local, state, or federal state of emergency declaration (Mich. Admin. Code R.460.702). This designation plays a factor in determining customer compensation for extended interruptions.[26]
- Massachusetts defines Excludable Major Events as interruption events caused by earthquakes, fires, or storms that give rise to a state of emergency proclamation, events which cause an

[24] A daily SAIDI aggregates in space over an entire service territory. One nuance associated with equating a high daily SAIDI with a resilience event is that a high daily SAIDI could include interruptions from "remote" or distant portions of the system that were not caused by the resilience event.

[25] In addition, the National Weather Service issues a Red Flag Warning "when the combination of dry fuels and weather conditions support extreme fire danger" (National Weather Service, 2024).

[26] DTE Electric has additional definitions for storm intensity based on the percentage of customers experiencing interruptions and uses them for customer compensation (DTE Electric, 2024) and analyzing SAIFI, SAIDI, and CAIDI (DTE Electric, 2023).

unplanned interruption of service to 15% or more of the utility's customers, or events that were the failure of another company's transmission or power supply system (D.P.U. 12-120-D, Att. A at 4).

Many utilities report SAIDI, SAIFI, and CAIDI both with and without MEDs in their resilience plans. Some utilities also report storm-only SAIDI, SAIFI, and CAIDI. For example, DTE Electric (2023) reported yearly SAIDI, SAIFI, and CAIDI values for three types of conditions: catastrophic storms only, non-catastrophic storms only, and no storms. In the resilience plans reviewed for this study, it was less common for utilities to track CAIDI with MEDs included, as long-duration interruptions for relatively few customers can skew the average. However, PG&E and SCE WMPs used CAIDI to monitor outage duration on circuits with preventive devices that quickly and automatically shut off power when faults were detected (PG&E, 2024; SCE, 2022).

Resilience plans that mentioned MAIFI typically did so in the context of measuring reliability (Xcel Energy, 2019; Indiana Michigan Power, 2023; DTE Electric, 2023). However, in its Climate Change Resilience Plan, PSEG-LI indicated that storm hardening measures led to a 65% decrease in interruptions lasting less than 5 minutes (PSEG Long Island, 2024). Additionally, PGE used MAIFI as one of several metrics to quantify impacts of ignition safety measures undertaken to mitigate wildfire risk (PGE, 2023).

Utilities can track and report the performance metrics in Table 7.1 at different levels of granularity, from the system level to the circuit level and for different interruption causes. For example, utilities reported interruptions from high wind events (Consumers Energy, 2023), five-year average interruption events by cause (DTE Electric, 2023), and circuit-level customer interruptions (RG&E and NYSEG, 2023). Illustrating the levels of granularity that are possible, the California Office of Energy Infrastructure Safety Wildfire Data reporting template contained metrics such as "outage events caused by contact with vegetation in Tier 3 High Fire Threat District during high wind warning" (COEIS, 2024).

7.1.2 Customer Interruption Metrics

As defined in this report, Customer Interruption metrics account for impacts to individual customers. These metrics help paint a more complete picture of interruption experiences between customers across the utility service territory. This section provides detail on the following metrics: CELID, CEMI, CEMM, CEMSMI, and CELID, which are also defined by IEEE Standard 1366-2022.

Table 7.2 summarizes Customer Interruption performance metrics. Several utilities reported these metrics in their resilience plans. Such metrics can help identify customer issues that are not apparent when only examining averages, such as the portion of customers experiencing multiple interruptions or longer-duration interruptions.

- *Customers Experiencing Multiple Interruptions* ($CEMI_n$) tracks the percentage of customers who experience *n* multiple sustained interruptions within a given timeframe. Utilities that included CEMI in their resilience plans noted that this metric provided a way to benchmark against peer companies (DTE Electric, 2023), identify priority areas for system hardening (DTE Electric, 2023;

PGE, 2022; PG&E, 2024), measure performance of resilience or reliability measures (Xcel Energy, 2019), and improve overall customer satisfaction (Indiana Michigan Power, 2023).

- *Customers Experiencing Multiple Momentaries* ($CEMM_n$) uses the same formula as CEMI, but for interruptions lasting less than 5 minutes. This metric also is indexed to a particular number of interruptions (*n*).
- *Customers Experiencing Multiple Sustained Interruption and Momentary Interruption Events* ($CEMSMI_n$) is calculated in a manner similar to CEMI and CEMM, but includes momentary interruptions as well. Regulators and stakeholders can request this information to develop a more comprehensive understanding of system performance from a customer standpoint (S&C, 2020).
- *Customers Experiencing Long Interruption Durations* (CELID) reflects the ratio of customers who experience interruptions longer than a given time to the total number of customers. Resilience plans that included CELID indicated that the utility is gauging service reliability and resiliency from a customer standpoint (Indiana Michigan Power, 2023; PGE, 2022) and measuring the performance of reliability and resilience programs (Xcel Energy, 2019). O&R proposed using CELID to prioritize stakeholder needs in the Resilience Analysis Process for performance-based metrics (O&R, 2023), allowing the utility to measure customer interruptions ranging from less extreme (e.g., CELID-8) to more extreme (e.g., CELID-60). The Michigan Public Service Commission requires utilities to report CELID-8, CELID-24, and CELID-48 using its reliability data template.

Table 7.2. Customer Interruption Performance Metrics

Metrics	Units	Description
$CEMI_n$	Percent (%)	Customers Experiencing Multiple Interruptions: ratio of customers experiencing *n* sustained interruptions to the total number of customers served
$CEMM_n$	Percent (%)	Customers Experiencing Multiple Momentaries: ratio of customers experiencing *n* momentary interruptions to the total customers served
$CEMSMI_n$	Percent (%)	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	Unitless	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
CELID-t	Unitless	Customers Experiencing Long Interruption Durations: ratio of individual customers that experience interruptions with durations longer than or equal to a given time (*t*), defined as the total time a customer has been interrupted

Utilities may report on Customer Interruption metrics at a more granular level. For example, a utility may report on event-based CELID or CEMI for a specific geographic area.

7.1.3 Other Metrics

Several additional Electrical Service performance metrics are reported in utility resilience plans and the academic literature. These metrics measure different dimensions of performance and in certain cases reflect the efforts of SMEs to think about new ways to measure resilience. Table 7.3 summarizes several examples of additional metrics and their sources.

For example, Rocky Mountain Power (2019) developed a Circuit Performance Indicator, using reliability metrics of the circuit (inclusive of MEDs) to identify underperformance. The metric is a combination of

SAIDI, SAIFI, MAIFI, and lockouts,[27] each multiplied by a weighting factor and normalizing factor. IEEE (2020) presents two draft metrics developed by the IEEE Power and Energy Society Distribution Resilience Working Group. The "storm resilience metric" focuses on the speed of recovery during the first 12 hours of a storm. The "non-storm resilience metric" "focuses on robustness and the ability to withstand events." It measures performance on gray sky days, which are defined based on specific weather thresholds. These two metrics would be combined into one overall resilience metric.

Expected Unserved Energy (EUE) is the estimated quantity of electricity that would have been consumed if an interruption had not occurred. This metric can account for the amount of electricity that different types of customers use. For example, an interruption to 10 large commercial customers would have a much higher EUE than an interruption to 10 residential customers, even though the CMI value would be the same.

Table 7.3. Additional Electrical Service Metrics

Metric	Source	Units	Description
Circuit Performance Indicator	RMP (2019)	Unitless	CPI = Index*[(SAIDI*WF*NF)+(SAIFI*WF*NF)+(MAIFI*WF*NF)+(Lockouts*WF*NF)]
IEEE Storm Resilience Metric	IEEE (2020)	Unitless	Quantifies the speed of recovery during the first 12 hours of a storm from customers losing power (IEEE 2020)[28]
IEEE Non-Storm Resilience Metric	IEEE (2020)	Number of days	Total number of gray sky days in a calendar year with no more than the threshold value of customer interruptions (IEEE 2020)
Expected Unserved Energy	Sullivan et al. (2018)	Kilowatt-hours	Estimated quantity of electricity that would have been consumed if an interruption had not occurred

Considerations for Electrical Service Performance Metrics

Utilities, regulators, and stakeholders can consider the following issues with Electrical Service performance metrics identified in the utility resilience plans and academic literature reviewed and interviews conducted for this report.

- Indices that combine and weight multiple components (or events) can be useful for ranking

[27] Lockout is a safety procedure that ensures electrical equipment is properly shut off and not able to be restarted prior to completion of maintenance or repair work.

[28] Section 3.5.4 covers other performance metrics that measure restoration time.

circuits or prioritizing investments with an aggregate scoring mechanism. However, 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 (EPRI, 2023)—for example:
    - The process of averaging across systems or even circuits can mask how interruption frequencies and durations are distributed across populations. SAIDI or CAIDI may be mathematically equivalent for significantly different situations—for example, a small number of customers experiencing long-duration interruptions and a large number of customers experiencing shorter interruptions. However, these two situations would have different implications for how to invest in the grid. Customer Interruption metrics (e.g., CELID and CEMI) would help reveal a clearer picture of the impact of the interruptions.
    - A situation in which a small number of customers experience long-duration interruptions and all other customers experience no interruptions could yield a low CAIDI value, obscuring the fact that part of the system is significantly less resilient (IEEE, 2020). An emerging best practice is to supplement traditional averaging metrics, such as CAIDI, with additional, more granular metrics to capture a nuanced view of electrical service quality and reliability (such as CEMI and CELID).[29]
- It is important to understand the interplay between metrics in the context of resilience improvements—for example:
    - An increase in MAIFI could actually indicate that a resilience investment was successful. Automation and topology improvements, such as increasing the level of networking and adding automatic switches, can reduce the duration of power interruptions (see NYSEG, 2023; RG&E, 2023; CMP, 2023). In some cases, what would have otherwise been a sustained interruption (>5 minutes) could instead become a momentary interruption (<5 minutes) after the improvements. Thus, a circuit-level view of metrics would show a reduction in SAIFI and SAIDI, but an increase in MAIFI.
    - CAIDI values, representing a ratio of interruption duration over interruption frequency, may be misleading. For example, if resilience investments decrease the frequency of interruptions, CAIDI values may increase if the duration of the avoided interruptions are less than the average duration of all other interruptions—even though the system may be more resilient (Watts et al., 2020). Conversely, an increase in short duration interruptions when there is no change in the number of longer duration interruptions may decrease CAIDI, even though the system is not becoming more resilient.
- Caution is warranted when interpreting all-weather SAIDI and SAIFI as measures of resilience, as these metrics can be significantly impacted by the frequency and intensity of weather events. For example, all-weather SAIDI and SAIFI values may be low in a year with no extreme weather events, but much higher in a year with one or two major extreme weather events, even if there is no difference in actual system resilience between the two years (or resilience

[29] Interview with utility SME (2024).

actually improved). This observation led IEEE to develop a methodology for identifying MEDs.[30]

7.2 Critical Infrastructure Electrical Service

Critical facilities are buildings or structures which are essential for the health, safety, and economic well-being of a population—and where the loss of electrical service would disrupt a critical public safety function. Examples of critical facilities include, but are not limited to, hospitals, medical facilities with life-sustaining equipment, fire stations, police facilities, emergency operation centers and management agencies, public drinking water facilities, sewer and wastewater facilities, pump stations, airports, evacuation centers, and national defense facilities. Some jurisdictions require certain critical facilities to have emergency generation onsite in order to address safety concerns.

Regulators can request information on the location of critical facilities, along with performance metrics for the facilities or for circuits where the facilities are located. Some information about critical facilities is sensitive and will not be shared with stakeholders.

To ensure consistency between utilities in the same jurisdiction, regulators can clearly define which types of facilities fall under the definition of "critical." A number of utility resilience plans incorporated consideration of critical facilities. For example, allowing critical facilities to maintain electrical service is one of three criteria that O&R (2023) established for prioritizing resilience projects. NYSEG (2023), RG&E (2023), and National Grid (2023b) assigned a score to avoided impacts to critical facilities, based on the population served by the facility and the duration of the avoided interruption. In California, IOUs report quarterly on critical infrastructure damaged or destroyed by utility-related ignitions (COEIS, 2024).

Considerations for Critical Infrastructure Electrical Service

- Utility resilience plans do not reflect a universally accepted definition of critical infrastructure, limiting the ability to compare specific metrics across jurisdictions. Lack of standardization between utilities in the same jurisdiction may be an issue for regulators and stakeholders involved in resilience planning processes.
- Data quality for critical facilities varies between utilities. That can limit the ability for PUCs and other state agencies to address critical facilities effectively for their jurisdictions.
- Specific information on critical facility locations and grid connections may be sensitive, and access should be controlled and monitored accordingly.

7.3 Asset Damage and Failure

Asset damage and failure metrics are divided into three main categories: asset damage, asset performance, and asset repairs and replacements. Utilities track asset damage and failure metrics to understand physical impacts from hazard events on their infrastructure and to assess the resilience of

[30] In addition, if operational work-arounds are used to protect public safety (see Section 7.7) while long-term resilience measures are being put in place, some reliability statistics may temporarily degrade.

their systems. Tracking these metrics allows utilities to identify patterns in asset vulnerabilities, prioritize maintenance and upgrades, and better allocate resources for future resilience efforts. (Section 7.5.1 covers financial impact metrics for asset damage.) Table 7.4 lists Asset Damage and Failure Metrics.

Table 7.4. Performance Metrics for Asset Damage and Failure

Metric Type	Metrics	Units	Description
Asset Damage	Critical facility asset damage from resilience events	Number of assets	Extent and characteristics of damages to key assets from a resilience event
	Asset damages from resilience events	Number of assets	Extent and characteristics of damages to assets from a resilience event
Asset Performance	Overloaded equipment as a result of a resilience event	Number of assets	Number of overloaded pieces of equipment during a resilience event
	Failed equipment as a result of a resilience event	Number of assets	Number of pieces of equipment that failed during a resilience event
	Failed hardened equipment as a result of a resilience event	Number of assets	Number of pieces of hardened equipment that failed during a resilience event
Asset Repairs and Replacements	Asset replacement and repair rates after major events	Number of replacements or repairs	Number of asset replacements or repairs required after a resilience event

Asset Damage

Utilities track the extent and characteristics of asset damage from severe weather events to monitor the evolving impacts of extreme weather on their systems (Con Edison, 2019), categorize root-causes of equipment failures (TECO, 2023), inform flexible adaptation pathways and indicate infrastructure or areas in need of resilience upgrades (Con Edison, 2019; SCE, 2022), and estimate or monitor the benefits of resilience investments (RG&E and NYSEG, 2023; CenterPoint Energy, 2024; National Grid, 2023b). For example, following major weather events, TECO conducts random sampling of system damage to identify and categorize the root causes of equipment failures. The company uses these data to make informed decisions on engineering practices, equipment selection, and construction standards and specifications.

Asset Performance
Utilities measure asset performance by tracking overloaded or failed equipment during hazard events. Examples of these metrics include:

- Outages and structure failures during a hurricane (FPL, 2022)
- Infrastructure performance after a hurricane (FPL, 2022)
- Conductor performance during major events (PSE&G, 2018)
- Number of overloaded pieces of equipment resulting from an event (Consumers Energy, 2023)
- Total overhead equipment failures in wildfire risk tiers (NV Energy, 2023)

These metrics inform utilities where to make targeted infrastructure investments and enable assessment of their effectiveness (FPL, 2022). PSEG maps the benefits of performance improvements during major events to CMI reductions on a project-by-project basis, illustrating the impacts of resilience initiatives on both the utility and its customers (PSE&G, 2018).

Some utilities track failure rates of hardened equipment, which can help assess the effectiveness of resilience measures, identify areas for improvement, and guide future investments in climate adaptation strategies. For example, CenterPoint Energy proposed tracking flood impacts to its backup control center after construction of flood walls had been implemented at the facility. The company planned to measure water elevation and equipment at risk during future flood events and report on averted damages to communicate program effectiveness. CenterPoint Energy and Central Hudson proposed tracking similar metrics, such as the total number of replacement/braced poles that failed during hazard events, failure rates of hardened transmission structures during hazard events, and number of transmission trip-outs due to trees in the identified sections where mitigation work was performed.

Asset Repairs and Replacements
Tracking asset replacement and repair rates after major events enables utilities to measure the impacts of resilience initiatives and support asset management planning. For example, FPL (2022) tracked total hurricane-driven distribution pole replacements before and after the implementation of its inspection program, allowing the company to quantify the resilience benefits of the program through improved replacement rates (FPL, 2022). Duke Energy proposed utilizing a combination of decision analytics software, equipment condition data, and climate exposure data to evaluate climate change impacts on asset replacement rates. The company proposed leveraging these data to inform its asset management processes.

7.4 Response and Restoration

Performance metrics in this category measure utility response and timing of interruption restoration. Regulators and utilities can assess utility response to resilience events along several dimensions, including resourcing (i.e., labor), timing, efficiency, and effectiveness. Restoration metrics cover timing and cost (Section 7.5.1 covers restoration cost metrics). Table 7.5 contains examples of restoration performance metrics.

Table 7.5. Response and Restoration Performance Metrics

Metric Type	Metrics	Units	Descriptions
Response	Resource engagement during an event	Assets repaired or replaced, teams deployed	Total resources engaged during an event response—may include physical equipment repair or replacement items, teams deployed and their needs
	Restoration efforts	Person-hours	Total restoration person hours required to restore power after an event
	System inefficiencies during event response	Minutes	Measures system inefficiencies during an event response, often through the lens of unproductive crew time (which drives up mutual aid costs and interruption times)
	Emergency response measures	Evacuations	These may include, for example, community evacuations as a result of a utility-ignited fire
	Downed wire response	Time	Time to detect and de-energize downed wires (details of metric not specified)
Restoration	Time to Restore X% of Customers (or CR-X)	Hours	Hours from onset time to restore X% of customers impacted (usually 50%, 90%, or 100%)
	National Grid (cite)	Hours	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	Percent	Among customers impacted by a major storm (or other major event designation), the percent restored within X hours of interruption onset time

Response

A number of utilities tracked resource engagement during major events to ensure effective allocation and utilization of crews and resources, streamline operations, and optimize storm response efforts (O&R, 2023; Consumers Energy, 2023). Consumers Energy leveraged an in-house program called

Catastrophic Crewing (CatCrew) for resource management during storm restoration. The tool captured which crews were engaged for storm restoration, where the crews are headquartered, duration of work and rest periods, and lodging and food requirements.

Utilities also may track crew deployment response metrics from a productivity perspective. O&R (2023) measured unproductive crew time involved in storm response mobilization in the context of its proposed Storm Resilience Center. This metric was linked to others that described its financial and electrical service implications, as reductions in unproductive crew time drive lower mutual aid costs and increase the efficiency of storm response activities. In addition, Nevada Energy tracked the number of community emergency evacuations as a result of utility-owned infrastructure wildfire ignition.

Restoration Timing

Performance metrics that measure a utility's ability to recover from a hazard are often centered around restoration timing. A number of utilities mention tracking recovery performance in their resilience plans, primarily through metrics measuring partial or total restoration timing (e.g., CenterPoint, 2024; Consumers Energy, 2023; FPL, 2022; O&R, 2023; Oncor, 2024). Some utilities define restoration timing metrics as being explicitly customer- or utility-focused. For example, as part of its Resilience Analysis Process, O&R proposed tracking restoration timing using the metric Customer Restoration Time (CR-X). This metric would measure the number of hours transpiring between the beginning of an interruption event and a point at which power was restored to a certain percent of customers. Other utilities tracked restoration efforts and resources from a more utility-centric perspective. FPL (2022) tracked restoration construction person hours, noting that this metric would have been significantly higher without existing hardening programs in place.

National Grid proposed a recovery metric measuring the time to restore service from the time of peak customers interrupted to 95% restoration, with the results plotted using an average and standard deviation to establish a benchmark. Under such a framework, utilities could link restoration times to interrupted customer counts to develop a graph as in Figure 7.2. This illustrative graph shows small gray x marks representing major historical storms, plotted by peak customers interrupted and hours to restore service to 95% of customers. According to National Grid, any storms plotted above the red line indicate the need for further investigation and reflections on lessons learned. Storms plotted below the green line represent cases of potential best practices to be analyzed and shared throughout the company.

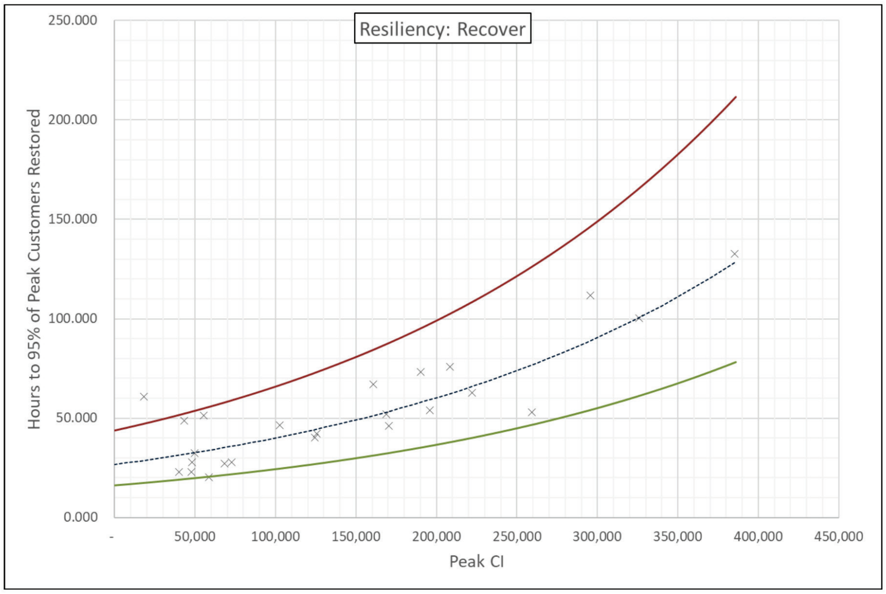


Figure 7.2. Visual Representation of National Grid's Recovery Metric, Hours to Restore Customers Interrupted During High Impact Storms

Considerations for Restoration Metrics

- National Grid noted that its custom restoration metric is challenged by low baseline data availability. The infrequency and high variance of major events make it difficult to develop a robust baseline. In addition, specific factors related to resilience events, such as conditions that follow the initial hazard event, impact restoration activities significantly.
- In joint comments to the Massachusetts DPU, Unitil expressed reservations about using recovery time as a resilience metric for the reason that "many of the projects currently being deployed to improve the resiliency of the system, or reduce the frequency of events, could result in lengthier restorations should an outage occur on the improved portion of the system." (JIC, 2024)

7.5 Monetary Impact

Monetary Impact performance metrics measure utility and customer costs from hazard events and associated power interruptions. This report organizes Monetary Impact metrics into three categories: utility costs, customer interruption costs, and economy-wide impacts. Table 7.6 shows examples of these metrics.

Table 7.6. Monetary Impact Metrics

Metric Type	Metrics	Units	Description
Utility Costs	Loss of revenue	Dollars	Loss of revenue
	Value of assets damaged and destroyed by major events	Dollars	Remaining undepreciated value of assets and structures damaged or destroyed from a resilience event
	Post-event O&M restoration costs	O&M dollars	Total O&M restoration costs after an event
	Post-event capital restoration costs	Capital dollars ($)	Total capital costs for restoration, repair, and replacement after an event
Customer Interruption Costs	Cost per event	Dollars per event	Average cost per customer resulting from each interruption event
	Cost per average kW	Dollars per kW	Cost per interruption event normalized by average customer demand (in kW)
	Cost per unserved kWh	Dollars per kWh	Cost per interruption event normalized by the expected amount of unserved energy (in kWh)
	Total cost	Dollars	Aggregate cost to customers
Economy-wide Impacts	Gross output	% and dollar	% change and dollars of gross output by industry sector, geographic extent of interruption, impacted region, and interruption duration
	Gross (regional) Domestic Product	% and dollar	% and dollar change in gross domestic product by geographic extent of interruption, impacted region, and interruption duration
	Change in household consumption	% and dollar	% and dollar change in consumption by geographic extent of power disruption, impacted region, nine household income categories, and interruption duration

7.5.1 Utility Costs

Resilience performance metrics representing utility costs measure costs incurred due to power interruptions and damage from hazard events. Utilities can estimate lost revenue based on the extent and duration of the interruptions and the types of customers that lost power (e.g., residential versus commercial). Utilities also can provide information to regulators and stakeholders on the value of assets damaged or destroyed, which would account for asset depreciation. Other utility costs include O&M and capital restoration and recovery costs. O&M includes expenses such as labor, while capital generally includes the replacement cost of the assets.

7.5.2 Customer Interruption Costs

Customer interruption cost (CIC) estimates are central to evaluating economic benefits of reliability and resilience investments. CIC is "The economic cost that customers incur when they experience an interruption in electricity service. It is also referred to as the value of lost load (VOLL) or the value of service (VOS)" (Sullivan et al., 2018). Utilities use various methods to estimate CICs, including surveys, market analyses, regional economic modeling, and blackout studies. Among these, survey-based methods are common for estimating costs of short-duration interruptions because of the historical precedent, accuracy, and versatility of these methods for estimating interruptions lasting 24 hours or less.

Utilities have been incorporating CICs into planning for decades, with the support of Berkeley Lab's Interruption Cost Estimate (ICE) Calculator. Berkeley Lab first released the ICE Calculator in 2011 and updated the tool in 2015 based on CIC data from 34 studies (total of 105,000 customer surveys) completed by 10 utilities between 1989 and 2012 (Sullivan et al., 2015). The ICE Calculator is an interactive tool for estimating interruption costs using data from such studies. Users of the tool enter a number of parameters, including the number of customers of each type and the geographic location, as well as reliability changes in terms of SAIFI, SAIDI, and CAIDI and the timeframe over which the changes will occur. The ICE Calculator uses the CIC estimates to calculate four key interruption cost metrics (Sullivan et al., 2018):

- **Cost Per Event** – average cost per customer resulting from each interruption event
- **Cost Per Average kW** – cost per interruption event normalized by average customer demand (in kW)
- **Cost Per Unserved kWh**[31] – cost per interruption event normalized by the expected amount of unserved energy (in kWh)
- **Total Cost** – aggregate cost to customers

Utilities also are increasingly using Cost per CMI to value reliability and resilience investments based on the estimated reduction in customer minutes interrupted.

[31] Also known as Cost of Expected Unserved Energy, or EUE, which is a term used in bulk power system planning.

In 2022, Berkeley Lab initiated a national public-private partnership to update and upgrade the ICE Calculator. Through the ICE Calculator 2.0 initiative, Berkeley Lab and partners administered a consistent set of modern interruption cost surveys for a statistically representative sample of customers for each sponsoring utility.[32] These updates will enable states and utilities to better understand the impacts of power interruptions and assess the benefits of grid investments. ICE Calculator 2.0 will launch in early 2025.

ICE Calculator 2.0 will continue to have limitations related to estimating the economic impacts of long-duration interruptions, given that survey-based CIC methods focus on estimating interruptions lasting 24 hours or less. (Berkeley Lab's Power Outage Economics Tool, focused on resilience events, is discussed in Section 7.5.3.) Nonetheless, planners have used the ICE Calculator to estimate CICs for long-duration interruptions by making simplifying assumptions that apply the estimates to long duration interruption scenarios, which is generally preferable to disregarding CICs in resilience plans. A number of utilities reported using ICE Calculator estimates in their resilience planning processes (Entergy New Orleans, 2022; FPU, 2022; TECO, 2022; Oncor, 2024).

7.5.3 Economy-wide Impacts

CIC surveys are effective for evaluating the costs of short, localized interruptions, but are less suitable for assessing the impacts of widespread, long-duration (WLD) power interruptions (Larsen et al., 2024). This limitation arises primarily because respondents struggle to envision the direct effects of such extensive interruptions, especially when respondents have never experienced them, and the broader economic impacts across regions that WLD interruptions cause. For example, manufacturing facilities use inputs and produce outputs, with the outputs for some businesses becoming the inputs for others. In the event of a long-duration interruption, the business would incur direct costs from limited or no production capacity and also would cause disruptions to other businesses by not producing their inputs. It is difficult for respondents to estimate these spillover effects across industry sectors and regional economies. As a result, survey-based estimates often fall short in capturing customer costs for interruptions lasting several days or affecting entire utility service areas, multiple utilities, or multi-state regions (Larsen et al., 2024).

Regional economic models can estimate direct and spillover effects from interruptions at larger scales and over longer durations (Sullivan et al., 2018). Examples of regional economic models are input/output models, computable general equilibrium models, and macro-economic models (Sanstad, 2016). An advantage of regional economic models is that they can account for the connections between firms and sectors and account for economic production disruptions that propagate across businesses and industries. They also can model adaptive behavior by firms to mitigate economic losses during interruptions. A disadvantage is that they rely on assumptions about household and business behaviors that are difficult to observe, including the specific adaptive behaviors that customers may undertake.

[32] See icecalculator.com/recent-updates.

One example of a method for estimating the impact of WLD power interruptions is a prototype Power Outage Economics Tool (POET) developed and piloted by Berkeley Lab and partners. POET utilizes a hybrid valuation approach which relies on CIC surveys to collect information on household and business customer behavior and uses the data to calibrate a computable general equilibrium model of the regional economy. The economic impact estimates are thus grounded in empirical survey data and also based on an integrated representation of the regional economy (Larsen et al., 2024).

Table 7.6 contains three of the key economic impact metrics generated by POET. Gross output reflects the change in business revenue. Gross (regional) Domestic Product is the change of the total value of final goods and services generated by the regional economy. The change in household consumption metric is the average lost consumption from the power disruption, or the subsidy to households to make them indifferent to the power disruption.

Figure 7.3 summarizes prototype POET results for Commonwealth Edison (ComEd). If its entire service territory lost power, the estimated Gross Domestic Product (GDP) losses would be $2.2 billion for a one-day interruption, $4.3 billion for a three-day interruption, and $17.1 billion for a 14-day blackout. As discussed in Larsen et al. (2024), POET could be deployed in other parts of the country to estimate the economic value of investments in power system resilience. This tool starts to fill an important gap related to estimating resilience benefits for utilities and their customers as part of a broader BCA that informs prioritization of resilience solutions.

Figure 7.3. Change in Overall Gross Domestic Product for All of ComEd's Service Territory
Source: Larsen et al. (2024)

7.6 Customer Communications and Engagement

Utilities generally have existing initiatives to track overall customer satisfaction with the utility, customer satisfaction with utility transactions (e.g., online bill pay), and accuracy and effectiveness of interruption communications. Resilience plans reviewed for this report did not contain performance metrics for customer satisfaction and had limited metrics for measuring communications and engagement related to resilience. Utilities could add resilience-related questions to customer satisfaction survey instruments.

Table 7.7 contains metrics for measuring customer communications and engagement. Metrics can measure the effectiveness of customer communications using email open and click-through rates and customer information recall measures. They can also measure effectiveness of critical communications, which California requires of IOUs when utility-ignited wildfires occur (COEIS, 2024). Utilities track customer complaints as part of normal operations, and regulators can request this information as it relates to utility performance during extreme events.

Table 7.7. Customer Communications and Engagement Performance Metrics

Metric Type	Metrics	Units	Descriptions
Customer Communications	Customer engagement with resilience plans or initiatives	Email open rates, ad click-through rates, audio listen-through rates, etc.	Customer engagement with resilience initiatives, including social media, ads, audio and email campaigns, phone calls, face-to-face interactions, and stakeholder meetings
	Customer recall of hazard preparedness communications	N/A	Customer recall of hazard preparedness communications
	Community outreach	%	% of customers notified of evacuation in evacuation zone of a utility-ignited wildfire
Customer Satisfaction	Customer complaints about extreme weather events	Number of customer complaints	Customer complaints received in relation to a resilience event

7.7 Public Safety Power Shutoffs

A number of western states have procedures in place to preemptively shut off power to reduce wildfire risks. California calls the events Public Safety Power Shutoffs (PSPS) and Nevada calls them Public Safety Outage Management (PSOM). This report adopts the PSPS nomenclature for convenience. Utilities typically trigger these events during extreme weather conditions, such as high winds, low humidity, and dry vegetation. PSPS events are both a mitigation measure for improving community resilience to wildfires and also a negative impact of severe climate conditions.

California and Nevada have implemented reporting procedures for PSPS events, including performance metrics. Table 7.8 shows a sample of performance metrics specific to PSPS events. Metrics for electrical service to specific customers include impacts to Medical Baseline customers, who have a higher risk of negative consequences from an interruption, and critical facilities, which may require additional assistance and planning for events. Understanding performance of communication procedures is important. Weather conditions determine the timing of PSPS events, and the lead time for planning and communication may be limited prior to the shutoff. For restoration metrics, obtaining the median and 95th percentile time value for circuit segments gives stakeholders a sense of a typical restoration time and a longer one.

Table 7.8. Performance Metrics Specific to Public Safety Power Shutoff Events

Metric Type	Metric
Electrical Service	SAIDI and SAIFI—including and excluding PSPS
	Duration of PSPS events during different wind warning statuses (Red Flag Warning, High Wind Warning)
Electrical Service to Specific Customers	Critical infrastructure impacted by PSPS
	Medical Baseline customers impacted by PSPS
Customer Communications	Number of customers notified prior to PSPS
	Number of Medical Baseline customers notified prior to PSPS
Restoration	Median and 95th percentile of time between de-energization due to PSPS and inspection of a circuit segment

7.8 Equity

In the context of resilience planning, equity can refer to ensuring that all communities, particularly those historically underserved or disproportionately affected by power interruptions or increasingly severe weather events, have fair access to resilient energy infrastructure and the benefits of resilience investments. Equity emphasizes addressing systemic disparities and prioritizing investments in vulnerable and marginalized communities. Chapter 4 (Adaptive Capacity in the context of Vulnerability

Assessments) and Section 6.3 (Adapt phase Attribute Metrics) addressed the ability of communities to adapt to hazard impacts and the social indicators associated with that ability.

Utility resilience plans may further consider equity in vulnerability ratings or measure prioritization by:

- Understanding economic impacts for vulnerable populations
- Including equity considerations in prioritization rankings
- Ensuring equitable distribution of resilience benefits

State legislatures, state regulators, or utilities may designate certain populations for equity considerations.[33] Each designation has its own set of criteria. For example, Washington state considers Highly Impacted Communities and Vulnerable Populations, which fall under the umbrella of Named Communities.[34] New York and California designate "Disadvantaged Communities," which are Census tracts that meet a set of criteria associated with economic, health, and environmental burdens. Figure 7.4 shows maps from portions of New York (left) and California (right) created by using online tools provided by each state.

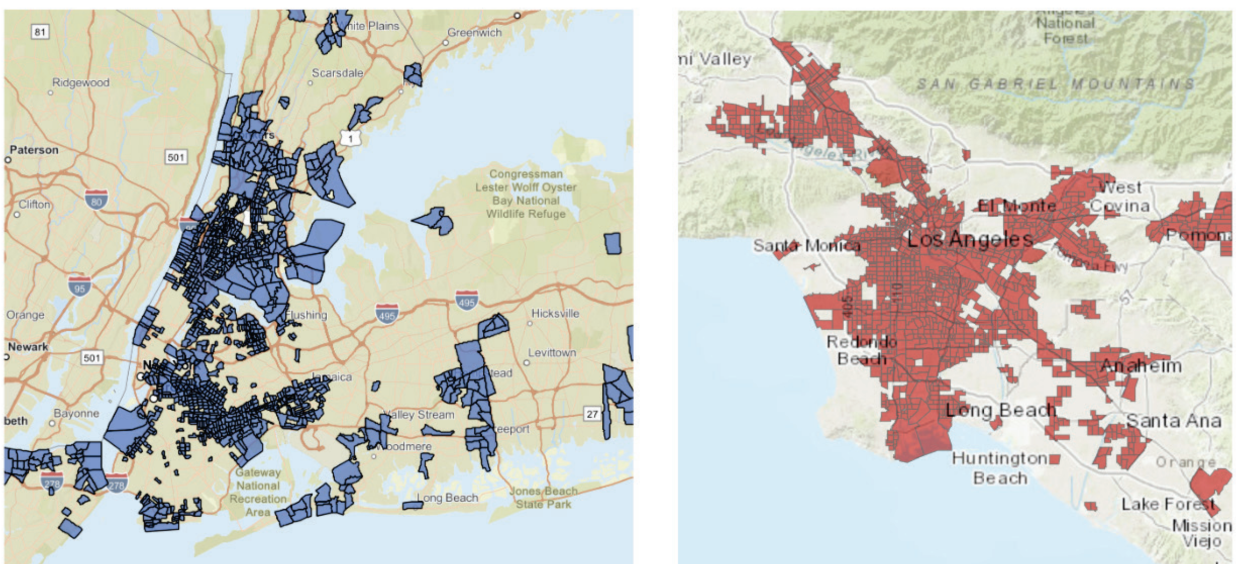


Figure 7.4. Disadvantaged Communities in Portions of New York (Left) and California (Right)
Source: NYSERDA (left), OEHHA (right)

Duke Energy used a publicly available index to measure community resilience in its climate vulnerability assessment for the Carolinas (Duke Energy Carolinas, 2022). The Social Vulnerability Index (SVI) uses 16 variables at the Census tract level to identify communities that may need support before, during, or after disasters. These variables are grouped into four major areas of social vulnerability—

[33] See Hanus, N. et al. (2024), *Database of Current State of U.S. Energy Equity Regulation and Legislation*.
[34] https://www.pse.com/en/about-us/energy-equity#:~:text=Named%20Communities%20is%20being%20used,Impacted%20Communities%20and%20Vulnerable%20Populations.

socioeconomic status, household characteristics, racial and ethnic minority status, and housing type and transportation—and then combined into a single measure of overall social vulnerability. Figure 7.5 summarizes an illustrative example overlaying FEMA flood plains and SVI counties. Duke Energy noted that “Further analysis would be required to understand how best to leverage the SVI as an additional factor in the larger prioritization of resilience efforts.”

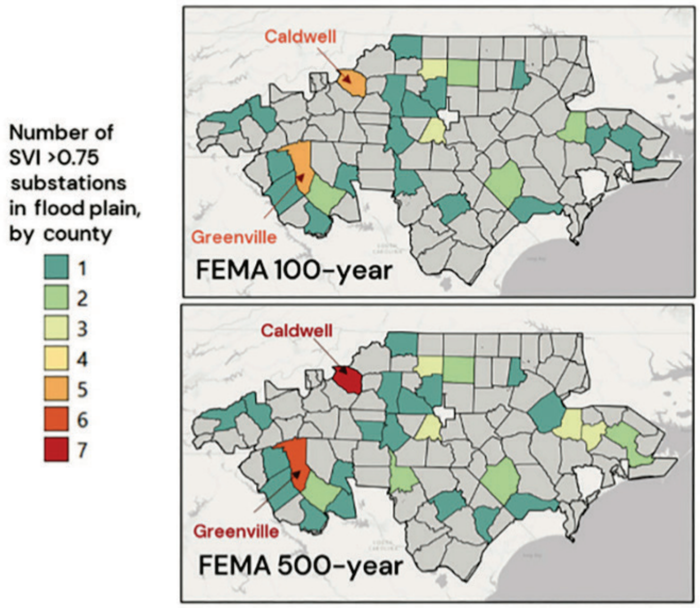


Figure 7.5. Illustrative Example Overlaying Vulnerability Index with Asset Exposure Data
Source: (Duke Energy Carolinas, 2023)

Utilities can include equity as a factor in prioritizing resilience investments. A number of utility plans include prioritization frameworks that incorporate criteria related to vulnerable populations.[35] Section 8.2 provides details on prioritization analyses in utility resilience plans.

Utilities can ensure equitable distribution of resilience benefits by analyzing the impacts of resilience investments on specific vulnerable populations or specific socioeconomic factors for which data are available—such as low-income, minority-populated, or geographically isolated areas. Figure 7.6 shows results using POET Larsen et al. (2024) to model economic losses, by income group, from power interruptions in Commonwealth Edison’s service territory. The bar graph on the left shows the change in household consumption from a one-day interruption. The bar graph on the right shows the same information for a two-week interruption. Higher-income households (red bar) show a greater consumption loss than lower-income households (green bar) for a one-day interruption, but for a two-week interruption, lower-income households have greater losses for most geographic areas. This could be due to the ability of higher-income households to relocate during long-duration interruptions. While these figures show economic losses, investments to mitigate these types of interruptions would yield

[35] See, for example, SCE (2022), PG&E (2024), and DTE Electric (2024).

economic benefits. These types of analyses can provide utilities, regulators, and stakeholders with a better understanding of equity impacts.

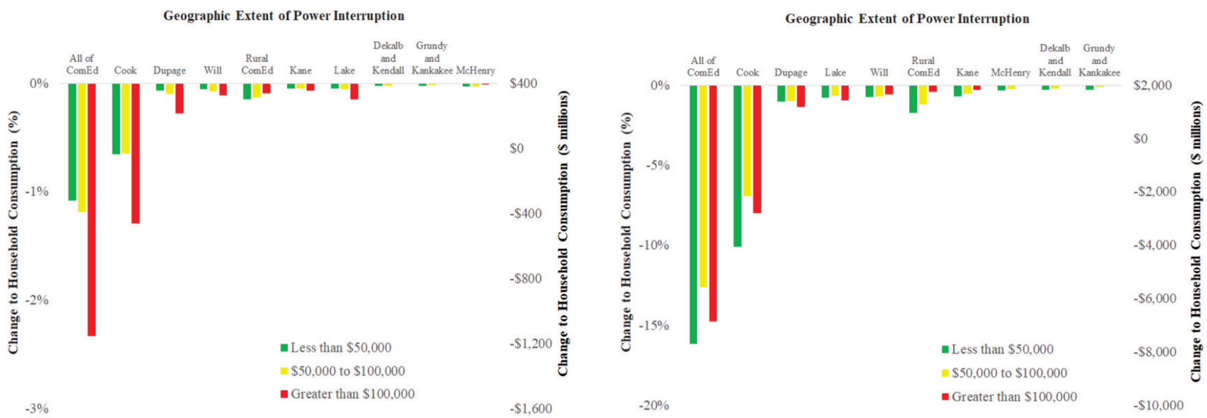


Figure 7.6. Losses to Annual Household Consumption During a One-Day (Left) and Two-Week (Right) Power Interruption by Income Grouping

Source: (Larsen et al., 2024)

8. Evaluation and Prioritization Analyses

Resilience planning raises two key questions:

1) How effective are the resilience measures?
2) Which measures should the utility implement?

This chapter covers the types of analyses that utilities conduct to answer those questions. Section 8.1 covers analyses that utilities undertake to estimate impacts from resilience measures—pre- and post deployment. Section 8.2 discusses analyses utilities perform to determine which measures to implement based on estimated costs and impacts.

8.1 Evaluation Analyses

8.1.1 Ex Post Analyses

Ex post analyses compare performance of the electric grid before and after implementing resilience measures. These analyses are helpful for assessing the effectiveness of deployed measures. By tracking key metrics over time as resilience solutions are implemented, utilities, state agencies, and stakeholders can better understand how investments have impacted grid performance, particularly during extreme weather events such as hurricanes and high wildfire risk days. This section describes several examples. Best practices are emerging. For example, researchers have collaborated with utilities to analyze grid performance data to improve ex post analyses using comparison groups, including for wildfire prevention (Warner et al., 2024) and enhanced vegetation management (Taylor et al., 2022). Grid performance trends vary significantly depending on storm severity, climate factors, and geographic scope. Ex post analyses critical to more accurately measure the impact of specific resilience investments.

DTE Electric

DTE Electric (2023) used ex post analysis to summarize performance improvements from its short-cycle preventative maintenance programs (Figure 8.1). These programs give regional engineers the flexibility to quickly diagnose and resolve issues for affected customers and communities prior to storm season. In response to historic summer storms in 2021, the company implemented a new process called Pre-Storm Season Strengthening to prioritize preventative maintenance work by identifying circuits with characteristics that make them prone to storm-related failures. DTE Electric's short-cycle maintenance programs now receive their work plans from the process. Ex post analysis showed that these programs had resulted in significant improvements in SAIDI and SAIFI during summer storm months in 2022, including a 56.6% reduction in SAIDI under all weather conditions. This type of analysis allows utilities, regulators, and stakeholders to understand the benefits of preventative maintenance, including improving prioritization of projects and circuits.

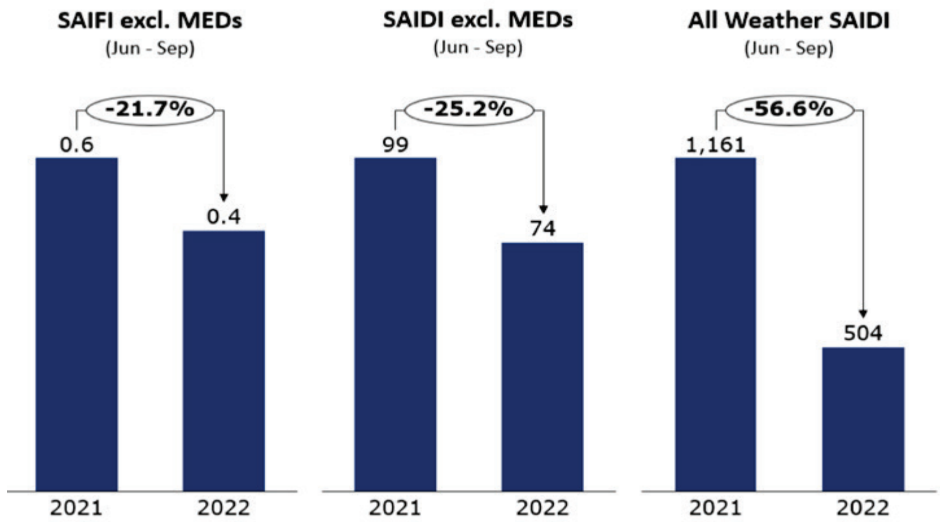


Figure 8.1. Performance Improvements from Short Cycle Preventative Maintenance Programs
Source: DTE Electric (2023)

Florida Power & Light

The FPL 2022 Storm Protection Plan included an ex post analysis for hurricane data. The analysis indicated that the utility's Distribution Inspection Program had significantly enhanced the performance of distribution poles during severe weather, leading to reduced storm damage, quicker restoration times, and lower restoration costs. A comparison of pole performance between Hurricane Wilma in 2005, before the program's implementation, and Hurricane Irma in 2017, after the program began, illustrates these improvements (Table 8.1). FPL indicated that this program had played a key role in strengthening the distribution system, directly enhancing storm resilience of pole infrastructure. The Storm Protection Plan also included an ex post analysis of transmission facility performance during the same hurricanes (Table 8.2), suggesting that the transmission inspection program also significantly enhanced storm resilience and resulted in cost savings for storm restoration.

Table 8.1. Pre/post Analysis of Distribution Pole Performance during Hurricanes

	Hurricane Wilma	Hurricane Irma
Hurricane Strength (Category)	3	4
Customer Outages (Millions)	3.2	4.4
Distribution Poles Replaced	>12,400	<2,900[13]
Total Days to Restore	18	10
Average Days to Restore	5.4	2.1

Source: Florida Power & Light (2022)

Table 8.2. Pre/post Analysis of Transmission Facility Performance during Hurricanes

Transmission Facilities	Hurricane Wilma	Hurricane Irma	Improvement
Line Section Outages	345	215	38%
Substation Outages	241	92	62%
Structures Failed	100	5	95%

Source: Florida Power & Light (2022)

Idaho Power

In 2023, Idaho Power began using ex post analysis with a comparison group of "baseline feeders" to assess the effectiveness of overhead circuit hardening by measuring reliability performance and interruption rates per 100 line-miles for feeders before and after hardening work was completed. As summarized in its Wildfire Mitigation Plan, hardened feeders were compared to baseline feeders, defined as all other distribution feeders without completed hardening projects. Initial analysis indicated significant reliability improvements (Table 8.3), with more comprehensive evaluations planned in the coming years as additional post-hardening data are available. The plan does not indicate whether MEDs were included in the analysis of SAIFI, SAIDI, and interruption rate, which could indicate that improvements were indicative of performance in all conditions and not just blue-sky conditions.

Table 8.3. Overhead Circuit Hardening Reliability Improvements

Overhead Circuit Hardening Reliability Improvements	
SAIFI % improvement with WMP hardening	15%
SAIDI % improvement with WMP hardening	27%
Outage rate % improvement with WMP hardening	13%

Source: Idaho Power (2023)

Portland General Electric

Since 2021, PGE has implemented safety-adjusted protection settings on devices within a High Fire Risk Zone (HFRZ) to reduce ignition risk during the fire season, including operational protocols requiring ground patrols before re-energizing following device operations. To analyze the systemwide reliability impact of this mitigation measure, PGE conducted an ex post analysis to compare SAIDI, SAIFI, and MAIFI during the wildfire season in 2019 and 2020 (before implementation) with 2021 and beyond (after implementation) (Table 8.4). Despite the protection settings causing slightly longer interruptions during extreme weather days, the analysis showed that this wildfire mitigation measure had a negligible impact on overall reliability, given that HFRZs represent only a small portion of PGE's service area, and Red Flag Warning (RFW) days in the area are infrequent. MAIFI increased by 74% on RFW days, but the absolute increase of about 0.003 momentary interruptions was minimal. PGE plans to continue monitoring these impacts amid uncertainties related to weather and reliability trends. Assuming that the safety-adjusted protection settings for HFRZs on RFWs significantly reduce wildfire ignition risk, this resilience measure could be more cost-effective than undergrounding and enhanced vegetation management (Warner et al. 2024).

Table 8.4. Ex Post Analysis of Systemwide Reliability Performance (June 1-October 31) on RFW and Non-RFW Days (Excluding MEDs)

Timeframe	SAIDI		SAIFI		MAIFI	
	Non RFW	RFW Day	Non RFW	RFW Day	Non RFW	RFW Day
2019-2020	0.29897	0.32451	0.00182	0.00250	0.00545	0.00345
2021-2023	0.29167	0.33027	0.00176	0.00211	0.00505	0.00601
% Difference	Negligible	2%	Negligible	Negligible	Negligible	74%

Source: Portland General Electric (2023)

National Grid

Resilience plans also may propose ex post analyses and metrics to track resilience plan performance. In its Climate Change Resilience Plan, National Grid proposed ex post analyses for several programs, including distribution line design upgrades (see hypothetical example in Table 8.5). The utility proposed to report interruption metrics—including frequency—aggregated for all lines or feeders, for three years before and after implementing resilience enhancements. The plan defined interruption frequency as the total number of customer interruptions divided by the total number of customers served, including major storm events, and excluding substation and supply-related interruptions. NYSEG (2023) and RG&E (2023) proposed similar ex post analyses and metrics for their distribution circuit resiliency programs, with a report on circuit customer interruptions experienced, including storms, for three years before and after the completion of a distribution circuit resiliency project, excluding interruptions related to transmission infrastructure and substations.

Table 8.5. Hypothetical Example of Ex Post Analysis Metrics for Distribution Line Design Upgrades

Performance Metric	Outage Frequency – Post 3 Years	% Change	Comments
Distribution Line Design Upgrades	1.214	-6.5%	No events caused by failure of pole recently upgraded to Class 1

Source: National Grid (2023b)

8.1.2 Ex Ante Analyses

Utilities perform ex ante analyses to estimate the effect that resilience measures will have on performance metrics. The analyses can be deterministic or stochastic, or they can leverage machine learning algorithms to make predictions. Ex ante studies often leverage information learned in ex post studies about statistical associations between hazard events, resilience measures, and negative outcomes to the grid. For example, if an ex post analysis determines that vegetation management can reduce tree-caused interruption frequency by 25%, then ex ante analysis could use this relationship to estimate the impact of future investments on other circuits. Undertaking such analyses can be challenging for two key reasons. One is the difficulty of predicting the likelihood and severity of extreme weather events. Two is the difficulty of predicting the impacts of these events on a utility's assets and its ability to continue serving load, both under present conditions and a planned future condition following implementation of resilience investments. Many utilities lack data on the current condition of assets and effectiveness of measures for preventing interruptions. Utilities and researchers are advancing capabilities for predicting measure effectiveness. Avangrid and TECO are examples of utilities estimating resilience improvements using advanced modeling techniques.

Avangrid is using AI to gain a better understanding of electric grid performance, both during calm and stormy weather (RG&E, 2023). By using a tool called GeoMesh, Avangrid breaks down its service areas into smaller sections and analyzes millions of data points, such as wind speed, precipitation, interruption history, and vegetation density. This helps the utility to identify areas that need upgrades, improve storm response, and predict which customers are most likely to be affected by storms. The goal is to tailor investments to strengthen the grid and address the impacts of extreme weather.

TECO and Entergy used a storm resilience model to evaluate a suite of grid hardening projects and estimate their ability to reduce utility restoration costs and impacts to customers. They then used the results to prioritize projects based on cost-effectiveness. For TECO, the model used NOAA's major storm event database to classify storms into 13 different categories based on strength and whether the storm was a direct hit, partial hit, or peripheral hit on the service territory. The utility used stochastic modeling to simulate the impact of 1,000 potential storms on its grid. The model calculated the likelihood of failure for each TECO asset as a function of the vegetation, wind zone, and age and condition of the asset. To estimate interruption durations, the model ranked grid projects based on restoration prioritization metrics and assumed the projects were completed in rank order. The model calculated restoration costs and customer interruption costs for each suite of grid hardening projects to estimate benefits of resilience measures and compare them to project costs. This type of approach can address the difficulty of predicting the probability of rare, catastrophic events by evaluating a range of possible storm scenarios, rather than simply relying on historical averages. The scenarios account for variations in storm intensity, frequency, and geographic impact.

8.2 Prioritization Analyses

Identifying and prioritizing resilience solutions that mitigate vulnerabilities to extreme weather hazards is a key part of the resilience planning process. While the specific names and technical details of prioritization approaches vary by utility plan, they generally fall into one of three categories: BCA, RBA, or MCA. Table 8.6 summarizes these categories, which are generally associated with certain key planning indicators, methods, and tools. Specific approaches vary, particularly given active development of best practices. A utility may use multiple approaches—for example, applying RBA to prioritize solutions and then comparing the resulting costs and benefits using BCA, such as Duke Energy Florida (2022). The following subsections provide details on each analysis category and examples that reflect emerging utility practices.

Table 8.6. Prioritization Analysis Categories in Utility Resilience Plans

Analysis Category	Explanation	Key Planning Indicators	Methods & Tools	Utility Plan Examples
Benefit-Cost Analysis (BCA)	Compares and prioritizes resilience measures based on present value of monetized benefits and costs	Benefit-Cost Ratio (BCR)	Interruption Cost Estimate (ICE) Calculator, Power Outage Economics Tool (POET)	Entergy New Orleans (2023) TECO (2022) United Illuminating (2022)[36] Xcel Energy (2019)
Risk-Based Analysis (RBA)	Estimates cost-effectiveness based on risk reduction benefits (calculated by probability and associated consequences) and costs for a specific solution	Risk-Spend Efficiency (RSE), Value-Spend Efficiency (VSE)	Bowtie Method, Geospatial Analysis	Duke Energy Florida (2022) FPU (2022) Idaho Power (2023) NV Energy (2023) Oncor (2024) – with BCA Pacific Power (2023) PGE (2023) RMP (2023)
Multi-Criteria Assessment (MCA)	Compares benefits that are difficult to quantify or monetize, using composite indices, or that may not be effectively highlighted in financial analysis	Composite Indices	Index Calculation, Weighting	Con Edison (2023b) Consumers Energy (2023) DTE Electric (2023) National Grid (2023b) NYSEG (2023) O&R (2023b) PGE (2022) RG&E (2023)

8.2.1 Benefit-Cost Analysis

BCA compares and prioritizes resilience measures based on the present value of monetized benefits and costs. Benefits flow to the utility, its customers and society more broadly,[37] based on how the resilience

[36] This analysis was submitted as part of United Illuminating's general rate case and not in response to Connecticut's resilience planning requirements cited in this report.

[37] Utility benefits include avoided O&M and capital costs. Customer benefits include avoided damages, spoilage, and other costs for the customers that directly benefit from a reduction in outage frequency and/or duration for their own electric service. Societal benefits include the "spillover" benefits for other entities that indirectly benefit from the customers with improved resilience, even though the resilience program does not impact their own electric service. For example, a business in a neighboring, unaffected region benefits from being able to continue delivering goods to a grocery store that does not lose power during a major storm.

program impacts the prevention of, response to, and recovery from events, relative to the counterfactual scenario in which the program is not implemented. The effective useful life of a resilience investment could span several decades, so the BCA approach estimates the present value of projected costs and benefits by applying an annual discount rate, typically based on the utility's Weighted Average Cost of Capital. The Benefit-Cost Ratio (BCR) is the estimated benefits divided by costs (in present values), a key planning indicator for prioritizing resilience solutions that mitigate vulnerabilities to extreme weather hazards. The difference in benefits and costs equals net benefits, which also may factor into prioritization decisions as a complement to the BCR.

Importantly, a BCA may not capture all potential benefits, given the complexity and deep uncertainty associated with estimating the value of reducing the frequency and severity of interruptions under projected extreme weather conditions. Many resilience solutions also may deliver benefits under blue-sky conditions, such as grid monitoring and control technologies. Nonetheless, the primary resilience benefit categories—most notably avoided restoration costs and avoided customer interruption costs—may be sufficient for achieving a BCR greater than 1.0 and for prioritizing investments. As discussed in Section 7.5.3, utilities have used Berkeley Lab's ICE Calculator to estimate long-duration interruption scenarios, with simplifying assumptions that conservatively apply ICE Calculator estimates for customer interruption costs for short duration interruptions. If the overall BCR for a proposed set of resilience solutions is above 1.0 under conservative assumptions using ICE Calculator estimates, and the BCR is higher than competing options using a consistent BCA approach, the analysis supports the resilience plan prioritizing the solutions as high value measures.

BCA is particularly useful for targeting specific measures within a resilience plan based on cost and characteristics of the grid, climate, geography, or community. For example, United Illuminating (2022) uses the ICE Calculator, customer data, and historical interruption data for nine priority circuits to estimate the costs and benefits of three competing resilience proposals:

- **Proposal 1** – Lowest-cost solution for each circuit is mixed automation and topology upgrades
- **Proposal 2** – Second least-cost proposal encompasses all measures in Proposal 1 plus hardening efforts, including undergrounding portions of the line
- **Proposal 3** – Costliest proposal, including undergrounding the entire mainline of the circuit

Figure 8.2 summarizes the results of the BCA by storm scenario and proposal, including the optimal set of proposals for each of the nine priority distribution circuits. The BCA found that the most cost-effective solution was Proposal 1 for six circuits. Proposal 2 had the highest BCR for three circuits, including undergrounding the portions of each line that would deliver the largest net benefits. This optimal set of proposals had a BCR of just above 1.0 under scenario 1 (lower storm scenario) and a BCR of 1.6 under scenario 2 (higher storm scenario). None of the proposals would have been cost-effective if applied to all nine priority circuits. While undergrounding eliminates the vulnerability of power lines to ice, high winds, and other hazards, it is a particularly costly measure ($9 million per mile in this example). Proposal 3, which would underground the entire mainline, would cost $551 million, with a BCA of 0.34

Schellenberg and Schwartz (2024).

to 0.5, resulting in net *losses* of at least $275 million. As this example demonstrates, a variety of targeted measures can together cost-effectively mitigate a given vulnerability, highlighting the ability of BCA to inform prioritization for specific circuits (or portions thereof).

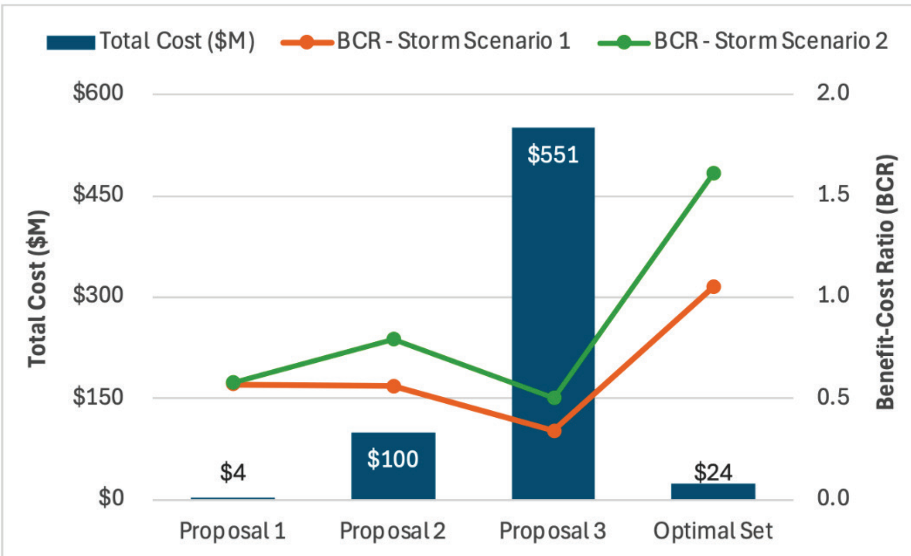


Figure 8.2. United Illuminating Resilience Plan Benefit-Cost Analysis (BCA) Results

Source: Summary of United Illuminating (2022) Results

8.2.2 Risk-Based Analysis (RBA)

Many resilience plans have applied RBA, which estimates cost-effectiveness based on risk reduction benefits, calculated by probability of exposure and its associated consequences, and costs for a specific solution. This prioritization approach is common for WMPs, which generally have detailed modeling of wildfire ignition probability and spread based on characteristics of the grid, climate, geography, or community. This type of risk modeling, along with a focus on one hazard and the short planning horizon for WMPs (typically 3 years), are conducive to RBA. Applying RBA to multiple extreme weather hazards and the significantly longer planning horizon for climate vulnerability assessments (10 to 50 years) is more challenging and subject to deep uncertainty in risk modeling.

The Bowtie method can support the development of RBA to prioritize investments in WMPs and other resilience plans. Idaho Power (2023) uses the Bowtie method as a visual representation of risk (Figure 8.3) to assess wildfire risk across its service area. The analysis consists of three key components: the triggering event, risk drivers, and risk impacts. The triggering event is the potential occurrence Idaho Power seeks to prevent—ignition from utility equipment that leads to a wildfire. Risk drivers, listed on the left side of the Bowtie, are factors that could lead to an ignition. The right side of the Bowtie lists potential risk impacts. Idaho Power has prioritized strategies that mitigate the top risk drivers, including overhead circuit hardening, underground conversions, enhanced vegetation management and asset inspections, and PSPS. The company plans to review and update these measures annually to ensure continuous improvement.

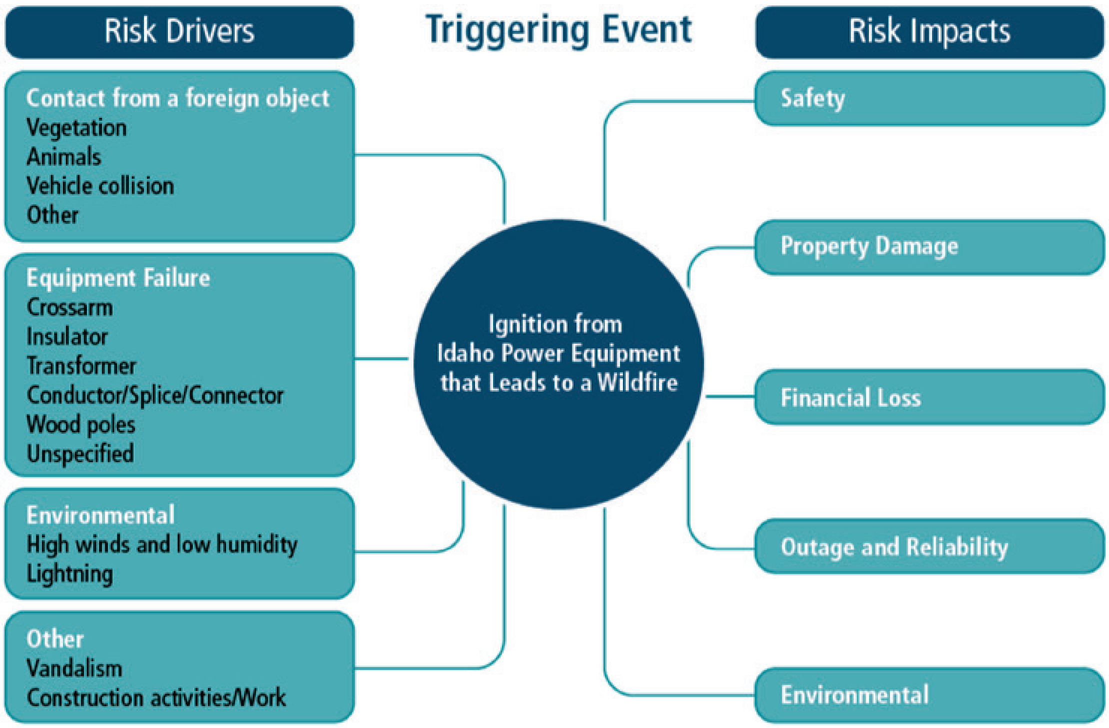


Figure 8.3. Idaho Power Risk Bowtie to Support RBA Development

Source: Idaho Power (2023)

PGE (2023) used both Risk-Spend Efficiency (RSE) and Value-Spend Efficiency (VSE) indicators as part of the RBA for its WMP. Figure 3.14 is an illustrative RSE assessment for undergrounding based on the pre-mitigation wildfire feeder risk (counterfactual), post-mitigation wildfire feeder risk, and annual cost from mitigation. As this hypothetical example illustrates, undergrounding the line would result in an RSE of 90, which represents a 90-to-1 risk reduction per dollar of investment. PGE has further developed the RSE concept with a measure of risk called Value-spend Efficiency (VSE), which adjusts for qualitative impacts that are not easily monetized. RSE and VSE "directionally inform the selection of wildfire mitigation options for inclusion in the mitigation strategies within the [High Fire Risk Zone]." This prioritization approach aims to maximize the estimated risk reduction value per dollar invested.

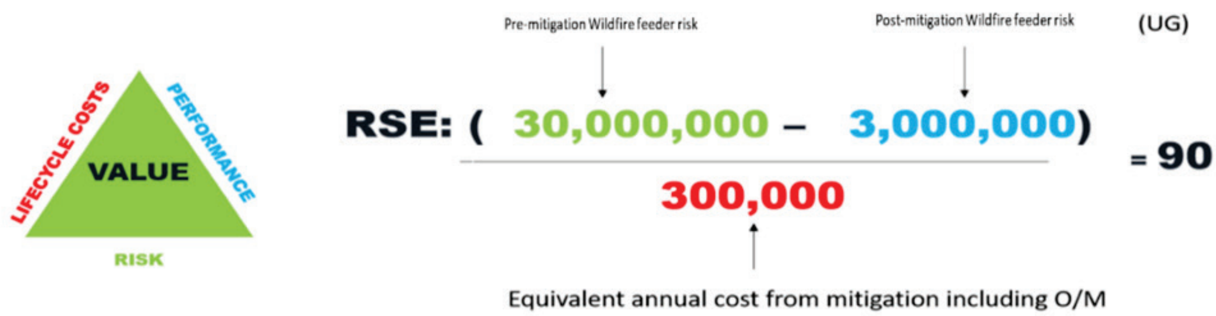


Figure 8.4. Illustrative Risk-Spend Efficiency Assessment for Undergrounding

Source: Portland General Electric (2022)

Oncor (2024) combines data-driven RBA with estimation of a BCR to identify and prioritize resilience investments (Figure 8.5). The Integrated Resilience and Risk Investment Model transforms potential risk management strategies into actionable investment plans. The model quantifies improvements in system resilience and risk at the investment, program, substation, and measure levels, allowing for a targeted analysis of how specific measures mitigate risks. The model calculates risk-related benefits, such as reducing system restoration costs and minimizing the number of customers affected by interruptions, using a data-driven methodology. The RBA includes customer-centric metrics, assessing the reduction in interruption impacts, and applies a BCA with a 50-year effective useful life for infrastructure investments.

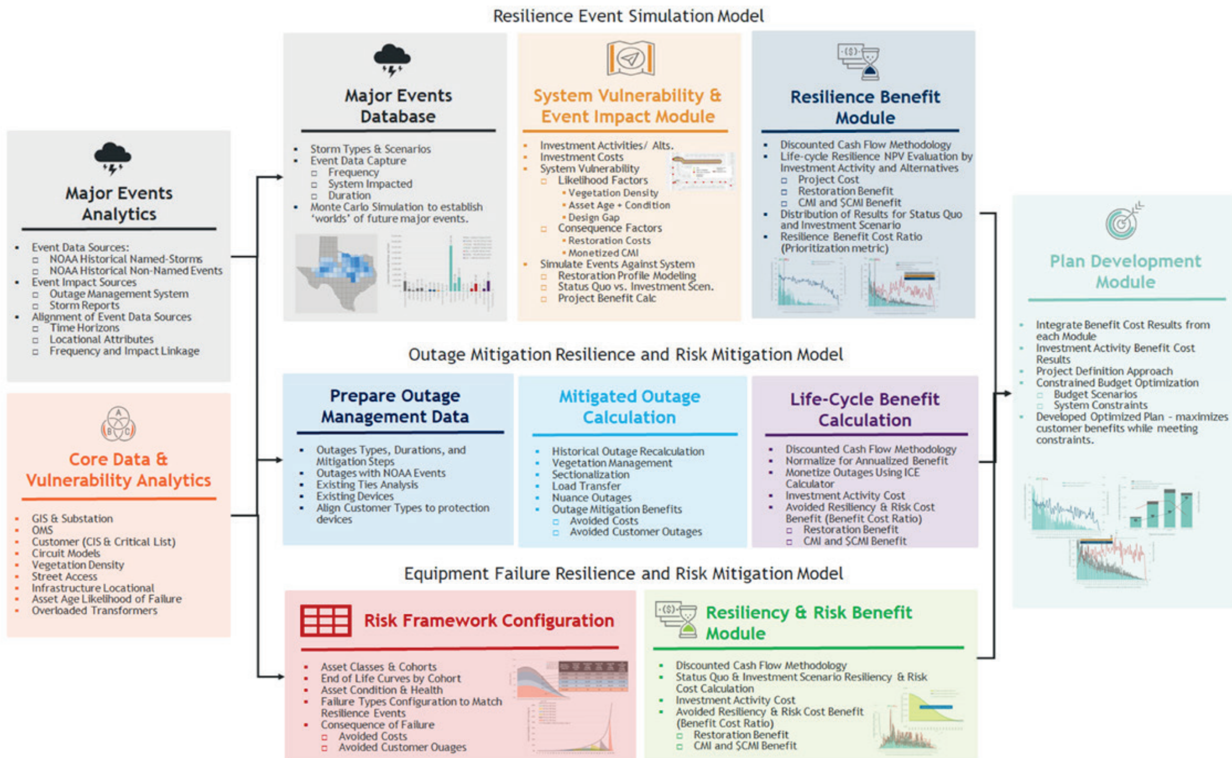


Figure 8.5. Integrated Resilience & Risk Investment Model

Source: Oncor (2024)

8.2.3 Multi-Criteria Assessment (MCA)

For many extreme weather hazards, estimating the probability and consequence over 10 to 50 years under one or more climate change scenarios is challenging and subject to deep uncertainty in risk modeling. MCA compares benefits that are difficult to quantify or monetize or that may not be effectively highlighted in financial analysis. Resilience plans use the composite indices or scores from MCA to rank resilience investments in a transparent manner, with input from SMEs and stakeholders, similar to how climate vulnerability assessments identify priority vulnerabilities.

MCA composite indices have varying names, components, and scoring methods. For example, National Grid (2023b) calculates a Business Case Justification (BCJ) score to characterize the benefits of resilience projects and programs. The BCJ score includes three components: system reliability, criticality, and community resilience (Figure 8.6). After these scores from 1 to 5 are determined, the scores for each of the three components are summed and used to calculate the BCJ score (as a percentage of 15), representing a relative comparison of potential benefits across projects and programs. The BCJ framework also considers whether a proposed project serves disadvantaged communities, which are more vulnerable to the impacts of climate change than other communities.

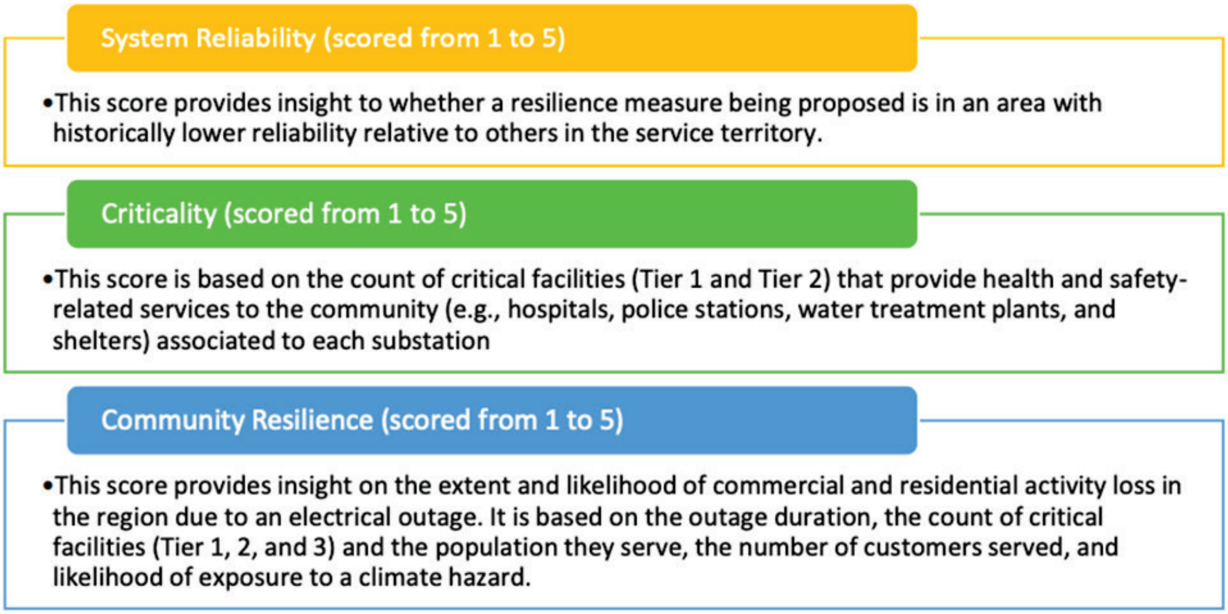


Figure 8.6. Business Case Justification (BCJ) Framework

Source: National Grid (2023)

DTE Electric (2023) also uses MCA as part of its Global Prioritization Model to evaluate projects and programs by measuring ten distinct customer benefits, known as "impact dimensions," based on specific planning indicators or "drivers" (Table 8.7). Projects receive scores (generally 0 to 100) in each dimension based on the expected benefit per dollar invested, with higher scores given to those delivering more value. These scores are then adjusted by weighting factors that prioritize core areas like reliability and safety. The total project score is calculated by summing the weighted dimension scores, with higher-scoring projects prioritized for implementation. Recently, the Global Prioritization Model was updated to include investment in Environmental Justice communities, reflecting input from stakeholders and the Public Service Commission. This approach ensures that projects providing the most value in terms of safety, reliability, and load relief are prioritized, particularly for these communities.

Table 8.7. Global Prioritization Model Scoring

Impact Dimension	Drivers	Weight
Reduce Electrical Hazards	• Reduction in wire down events • Reduction in secondary network cable manhole events	3
Overload Relief	• Elimination of overloaded equipment	
SAIDI	• Reduction in duration of outage events	
SAIFI	• Reduction in frequency of outage events	
Regulatory Compliance	• MPSC staff's recommendation (March 30, 2010 report) on utilities' pole inspection program • Docket U-12270 – Service restoration under normal conditions within 8 hours • Docket U-12270 – Service restoration under catastrophic conditions within 60 hours • Docket U-12270 – Service restoration under all conditions within 36 hours • Docket U-12270 – Same circuit repetitive interruption of fewer than five within a 12-month period	2
Major Event Risk	• Reduction in extensive substation outage events that lead to a large amount of stranded load for more than 24 hours	
Capacity Relief	• Elimination of system capacity constraints	
Investment in EJ Communities	• Percent of customers impacted by investment in EJ communities	
O&M Avoidance	• Trouble event reduction and truck roll reduction • Preventive maintenance investment reduction	1
Capital Avoidance	• Trouble event reduction and truck roll reduction • Reduction in capital replacement either during equipment failures or avoided planned capital work	

Source: DTE Electric (2023); EJ – Environmental Justice

8.2.4 Incorporating Climate Change into Existing Utility Analyses

Utilities conduct many analyses as part of standard business practices for ongoing planning and operational processes and to meet regulatory requirements. Among these analyses are load forecasting, asset health analytics, and contingency analysis. Utilities are starting to recognize that certain processes may be vulnerable to climate change, requiring enhancements that commonly include data quality and analytical advancements. For example, Duke Energy Carolinas (2023) found that its asset management processes are highly vulnerable to climate change, due in part to limited data and insight on the impact of climate change on asset health. The utility's load forecasting process had a medium vulnerability rating due to the need to incorporate climate projections and ensure consistency with how extreme temperatures are considered across forecasting processes. As with infrastructure-related vulnerabilities, climate change could expose these process-related vulnerabilities, resulting in power interruptions and other adverse consequences.

To mitigate process-related vulnerabilities, Duke Energy plans to improve analyses that quantify the impact of climate change on asset failure and replacement rates, including potential enhancements to asset health analytics applications, equipment condition data, and climate exposure data. Similarly, the utility is continuing efforts to incorporate climate projections into the load forecasting process, including consistently considering extreme temperatures across top-down and circuit-level forecasts, using the RCP 4.5 scenario. These enhanced analyses provide input into ongoing prioritization of asset replacement and T&D capacity expansion, informed by asset health analytics and load forecasting that effectively account for climate change.

Resilience planning processes can also incorporate enhanced analyses to inform prioritization of measures as part of long-term plans. For example, Southern California Edison (2022) applied an improved contingency analysis approach to interruption scenarios for substations vulnerable to climate hazards such as wildfire and flooding to understand reliability impacts to customers. Using steady state power flow analyses for 10 interruption scenarios, Southern California Edison conducts contingency analysis by taking one vulnerable transmission substation out of service at a time. These simulations allow planners to identify transmission lines that would overload under each interruption scenario. The plan then develops climate adaptation strategies to be considered as part of its general rate case.

9. Key Findings and Emerging Best Practices and Research Areas

To gather information on resilience data, metrics, and analyses for this report, the research team reviewed state resilience planning requirements, utility resilience plans, academic literature, and materials from industry resilience initiatives and working groups. The team also conducted interviews with staff at utilities, PUCs, and state energy offices. This chapter presents key findings (Section 9.1), emerging best practices (Section 9.2), and areas for future research (Section 9.3).

9.1 Key Findings

The following list summarizes key findings of this study.

1. **Resilience planning presents unique challenges for utilities and regulators.** Planning approaches vary by utility and state. Some states established resilience planning requirements several years ago, while other states are exploring potential requirements or have not yet taken action. Various approaches aim to overcome several challenges of resilience planning that make it more difficult than traditional reliability planning.
    - Severe weather hazards pose diverse threats to the electrical system. They are infrequent, hard-to-predict, and have the potential to be catastrophic.
    - Resilience events may be experienced unevenly across a utility service territory. For example, wealthier residential customers may leave town, while less well-off customers may have fewer options and experience greater hardships.
    - Resilience measures may be expensive, yet may never be put to the test by a resilience event.
    - Resilience planning requires considerations that extend beyond routine economic factors considered in traditional planning. These additional factors include health, safety, community well-being, and critical infrastructure.
    - Planning activities must be coordinated across state and local agencies, stakeholders, and customers responsible for critical infrastructure.

    Utilities, regulators, researchers, and working groups are experimenting with solutions to these challenges, such as standardized methodologies and tools to better evaluate and enhance grid resilience.

2. **Utility methods for approaching risk and vulnerability assessments vary in nomenclature but have a similar framework.** Generally, they involve projecting various extreme weather hazards, identifying critical assets, and evaluating the potential impacts on service reliability and recovery. Some utilities also account for the adaptive capacity of the population. Differences in terminology and specific methodologies may reflect regional priorities or organizational preferences, but the underlying principles remain consistent.

3. **An increasing number of indices are in use for characterizing resilience attributes or performance.** Multi-component indices for assessing risk and prioritizing investments include innovative approaches that combine different components of resilience (e.g., IEEE, 2020) as well as approaches tailored to specific utilities. Utility-specific models could serve as valuable references or templates for other utilities and for state-level decision-making, fostering a collaborative exchange of best practices.

4. **Utilities and regulators acknowledge the need to augment standard reliability metrics with metrics tailored to measure resilience.** Through filed resilience plans and interviews for this report, utilities expressed that adapting traditional systemwide reliability metrics alone does not capture the complexity of resilient utility systems. While SAIDI and SAIFI communicate electrical service quality and continuity, these metrics are normally calculated as averages over the course a year. They were not designed to capture singular instances when large numbers of customers may experience extended power interruptions. Even when MEDs are included in the analysis, most of the measurement time period comprises blue-sky days where grid resilience does not play a factor. Reporting SAIDI and SAIFI with more granularity in regards to location (i.e., circuit) and weather conditions can make the metrics more useful, while using them in combination with other metrics (such as CI, CMI, CEMI, and CELID) can improve understanding of interruption events (see Section 4.2).

5. **Regulators and stakeholders face a tradeoff between more granular utility data and limited resources to analyze and interpret the data.** While detailed information can enhance decision-making, analyzing it requires funding, resources, and IT infrastructure, which may be limited for PUCs, state energy offices, other government agencies, and other organizations involved in resilience planning processes. Finding the right balance between data granularity and practical feasibility remains an ongoing challenge. Some jurisdictions expressed a desire for more data, while others expressed that the amount of existing data was more than staff could effectively process. Developing combinations of useful metrics and visualizations could help target the information requested and reduce the volume of data that is reported, focusing on data, metrics, and analyses most critical for planning and decision-making purposes.

6. **Utilities and regulators are increasingly defining and considering vulnerable populations in planning efforts.** Utility plans reflect the recognition that certain groups, such as the elderly and low-income households, are disproportionately affected by power interruptions and extreme weather events. Efforts to incorporate equity into resilience planning include mapping vulnerable populations, tracking communication and support strategies, and incorporating equity considerations into prioritization processes.

7. **Utilities and regulators are increasingly taking steps to systematically measure and track performance of resilience investments, such as measuring ex post impacts.** These efforts include measuring performance of hardened circuits and comparing them to unhardened circuits to determine the effectiveness of resilience initiatives. For example, the Connecticut

PURA has discussed collecting interruption data by storm intensity level and "Resilience Zone," or whether the area has been previously hardened, remains unhardened, or relies only on vegetation management (PURA, 2022a). The intent is to establish a framework for conducting ex-post analyses on resilience projects. Tracking performance over time enables utilities to refine strategies, allocate resources more efficiently, and justify future investments.

9.2 Emerging Best Practices

Research for this report revealed a number of methods, processes, and approaches that show strong potential for improving and advancing the use of data, metrics, and analyses in resilience planning, such as the following practices.

1. **Select or establish a clear analysis framework based on capabilities, regional preferences, and resilience objectives.** It is important for regulators and utilities to have a mutual understanding of the resilience planning framework, which guides the development and sharing of data, metrics, and analyses to support the resilience planning process. A core component of the framework is an explicit articulation of the state's resilience planning objectives, if established, as well as additional utility objectives. This includes a description of the resilience hazards to be addressed and how they will be addressed in each of the four phases of a resilience event, including performance assessment. This report calls these phases *anticipate, withstand, adapt*, and *recover*. Utilities use variations of these categories and specific definitions appropriate for their service area.

2. **Generate and maintain consistent definitions and accurate location data for critical facilities.** Consistent definitions for critical facilities within jurisdictions can improve resilience planning and emergency response processes. Utilities already prioritize restoration activities and coordinate with emergency management agencies to ensure critical facilities remain operational. A standardized definition of critical facilities between utilities in the same jurisdiction can help regulators and other state agencies coordinate with multiple utilities using a consistent understanding of which types of facilities are deemed critical--particularly when emergency response resources may be limited during a major event. It can also facilitate comparisons of critical facility-related performance metrics between utilities.

3. **Consider the key socioeconomic factors that define populations that are more vulnerable to the adverse impacts of power interruptions and severe weather.** Developing a more thorough understanding of vulnerable populations and their capacity to adapt to power interruptions of varying durations enables more effective strategies for reducing negative impacts when conducting vulnerability analyses, developing mitigation strategies, and prioritizing investments. For example, decisions about where to locate resilience hubs should account for the distribution of vulnerable populations within the service territory. Additional measures may be necessary to ensure that vulnerable populations receive communications about resilience hubs and are able to access them in the case of an extended interruption.

Online mapping tools, such as those for New York and California (Section 7.8), allow access to geospatial data and designations for disadvantaged or vulnerable populations by Census tract. These tools can be useful for utilities, researchers, and other stakeholders to connect geospatial socioeconomic data with data for the utility service territory.

4. **Measure service impacts at a granular level and be consistent in tracking interruption causes.** Utilities can use IEEE Standard 1782-2022 for guidance on tracking and classifying interruptions through a specific set of variables. Utility OMS data contain a wealth of information about the causes and locations of interruptions, as well as affected equipment. Tracking and analyzing interruption data at a granular level can provide insight into potential resilience strategies.

5. **Advance efforts to address uncertainty associated with the likelihood and magnitude of resilience events.** Utilities and third parties are developing methods and tools for addressing the uncertainty inherent in planning for low-frequency, high-impact weather events. Examining large numbers of hazard impact scenarios can provide a more comprehensive assessment of risk (Wall, 2024). Such an approach also can enable utilities and stakeholders to improve resilience planning by evaluating resilience measures and strategies that perform well over a range of plausible future scenarios.

6. **Use combinations of metrics to understand system performance**. Major interruption events from severe weather can be viewed as frequency distributions, with interruption duration on the x-axis and frequency on the y-axis. Metrics that reflect system or circuit-level averages—such as SAIDI—are useful for understanding the mean of the distribution. Including other metrics such as CELID-8, CELID-24, and CELID-48 can reveal the length of the tail of the distribution and the portion of customers impacted over time. Using combinations of metrics is an emerging best practice that is echoed in the academic literature (Raoufi et al., 2020).

7. **Conduct regular, systematic ex post analyses following resilience events.** Ex post analyses have tended to be ad hoc, limiting the comparability of results across regions and years. An emerging opportunity is to conduct ex post analyses more systematically on a regular basis, including with the use of statistically representative comparison groups, to improve the ability of states and utilities to evaluate the cost-effectiveness of future resilience investments. Furthermore, combining data across utilities and major storms can allow utilities and researchers to develop grid performance improvement estimates that account for geography, weather, climate, and other factors. This would improve the evaluation of past and future resilience investments for all states and utilities evaluating solutions that mitigate the impacts of extreme weather.

8. **Align grid resilience planning with other applicable plans.** Resilience plans can align with, or be incorporated into, a utility's Integrated Distribution System Plan. In addition, the utility's grid resilience plan can align with regional transmission plans, local and state emergency response

plans, and methods, data sources, and priorities in the State Energy Security Plan. These security plans are the foundation of resilience planning for grid investments supported by the Infrastructure Investment and Jobs Act. State Energy Security Plans highlight resilience risks, discuss investment priorities for enhancing the grid, and provide insights into potential priority investments by utilities. For example, DOE guidance for these plans includes wildfire mitigation measures.[38]

[38] See DOE. 2024. *Risk Mitigation Approach Guidebook for State Energy Security Plans*.

9.3 Areas for Future Research

Resilience planning practices are still in a relatively nascent stage for many utilities and states. As practices evolve, gaining a greater understanding of the performance of the electrical system—and measures to enhance resilience—will be critical to ensure that the electrical system and the communities it serves are prepared for more frequent and severe weather events. Data, metrics, and analyses required for effective planning will continue to evolve and improve over time. Collecting more granular data on a systematic basis—and developing tools for utilities and states for use in planning and performance tracking—will be important elements of the improvement process. The following recommendations address areas where further research would be particularly useful for utilities and states.

1. **Collect and analyze infrastructure failure data consistently and systematically.** Analysis of such a dataset across utilities and jurisdictions would help utilities and industry researchers understand what assets are failing, how often, and why. It would enhance ex post analyses by developing a broader control group and having more data for the pre-implementation comparison condition.

   The Outage Data Initiative Nationwide (ODIN) is an existing collaborative effort between the U.S. Department of Energy, Oak Ridge National Laboratory, electric utilities, and OMS vendors to create a source of standardized data on power interruptions that utilities can share with stakeholders. The initiative is open to utility participation and can provide a model for future efforts aimed at collecting, analyzing, and sharing data.

2. **Track and analyze interruption restoration strategies and approaches to understand how they affect interruption durations.** Utilities could use this information to identify which strategies and actions lead to faster restorations, better resource optimization (crew assignments, equipment, materials), and better predictions of restoration times.

3. **Track and analyze the effectiveness of preventive maintenance activities for grid assets**. Such information would allow researchers to study statistical relationships between preventive maintenance practices and asset failure information and assess whether more expansive preventive maintenance could reduce failure rates for certain types of grid assets.

4. **Improve physical models for how networks and assets generally fail.** Researchers could calibrate models based on infrastructure failure data (see research area #1) and use the model to simulate the effectiveness of potential resilience measures. This type of model would be particularly useful when resilience metrics extend beyond the grid to the communities and economies they serve.

5. **Develop publicly-available resources for estimating effectiveness of resilience measures.** These resources could be as simple as a collection of analytical results from other studies,

accessible to states and utility planners in the form of a collection of relevant data or studies. A more advanced solution could be a set of peer-reviewed models or tools for predicting the performance of resilience measures that could leverage efforts in research area #4.

6. **Continue to advance efforts for understanding impacts of WLD interruptions to regional economies.** Utilities, researchers, regulators, and state energy offices can conduct research to gain insight into issues stemming from WLD interruptions and enable more-informed decision-making. Insights could include:
    - *The response of different types of customers to WLD interruptions.* For example, would residential customers stay in place or leave their homes? Would commercial and industrial customers temporarily relocate operations?
    - *The prevalence and potential use of backup generators and energy storage by residential and non-residential customers.* For example, to what extent would solar plus storage enable residential customers to remain safely in their homes? Would backup power allow commercial and industrial customers to continue operations?
    - *Key dependencies between customers and industries in the regional economy.* For example, how do disruptions in one market sector affect customers in other sectors?

The Power Outage Economics Tool (POET) evaluates the economic impacts of interruptions lasting longer than 24 hours. It is one approach that is beginning to fill a gap in the resilience planning analytical toolkit. The tool combines macroeconomic modeling of widespread, long duration power interruptions with customer survey data responses that include information about customer preparedness for WLD interruptions. Future research to extend and enhance POET involves conducting additional surveys across the country to identify customer behaviors when confronted with WLDs. In addition, incorporating a range of resilience-enhancing strategies into the tool will allow stakeholders to assess the value of past or proposed investments.

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APPENDIX A. Hazard Data Variables in Resilience Plans

Inland Flooding Data Variables	Examples
100- and 500-year floodplains: extent	PG&E (2024b), National Grid (2023a), SCE (2022), TEC (2022), NV Energy (2023a), Duke Energy (2023)
100- and 500-year floodplains: extent and depth	O&R (2023a), Con Edison (2023a), RG&E and NYSEG (2023)

Coastal Flooding Data Variables	Examples
Sea Level Rise + 100-year Storm Condition	PG&E (2024b), SCE (2022), Duke Energy (2023)
Coastal Flood and Storm Surge potential	FPU (2022)
Sea Level Rise	O&R (2023a), Con Edison (2023a), Duke Energy (2023)

High Wind Speed Data	Examples
Extreme Wind Loading Zones	TEC (2022), FPU (2022)
High Wind Event Risk	NV Energy (2023a),
High Wind Gust Hours	Consumers Energy (2022), Consumers Energy (2023)
1-in-x-year Wind Speeds	National Grid (2023a), O&R (2023a), RG&E and NYSEG (2023)
Xth Percentile Wind Speeds	Duke Energy (2023)

Wildfire Data Variables	Examples
Burn Probability	PG&E (2024a)
Days of Extreme Fire Danger/High Fire Weather Index	SCE (2023), SDG&E (2023)
Fire High Consequence Areas (FHCA)	RMP (2023)
Fire Potential Index (FPI)	Idaho Power (2023)
Fire Propagation and Fire Behavior	PGE (2023)
Fuel or Soil Moisture	SCE (2022), SCE (2023), Pacific Power (2023)
High Fire Risk Areas	PG&E (2024a)
High Fire Threat Districts	PG&E (2024a), SCE (2023), SDG&E (2023)
Historical Fire Records	PG&E (2024a), SCE (2023), SDG&E (2023), PGE (2023)
Ignition Risk	PG&E (2024a)
Keetch-Byram Drought Index	SCE (2022),
Relative Humidity	SCE (2022),
Wildfire Area Burned	PG&E (2024b), SCE (2022), Duke Energy (2023), PGE (2023)
Wildfire Exposure Rating	SCE (2022),
Wildfire Risk Ratings	NV Energy (2023a),

Extreme Storm Data	Examples
Frequency and Intensity of Severe Storms	Con Edison (2023a), Consumers Energy (2022)
Historical Storms	O&R (2023a)
Major Event Days	Consumers Energy (2023)
Major Storms Event Database	TEC (2022), Oncor (2024), Entergy New Orleans (2023)
Storm Days and Thunderstorm Occurrence	Consumers Energy (2023)
Thunder Storm Risk	NV Energy (2023a),
Winter Storm Risk	NV Energy (2023a),

Precipitation and Drought Data	Examples
Drought Risk	NV Energy (2023a),
Average Precipitation	SCE (2022), Con Edison (2023a), Consumers Energy (2022)
Annual Peak Precipitation Days	SCE (2022), O&R (2023a), Con Edison (2023a), Duke Energy (2023)
Extreme Precipitation Events (Multi-day)	PG&E (2024b), SCE (2022), O&R (2023a), Con Edison (2023a), RG&E and NYSEG (2023), Duke Energy (2023), Consumers Energy (2022)
Groundwater and Runoff	SCE (2022), Consumers Energy (2022)
1-in-x-year Precipitation	SCE (2022), Con Edison (2023a),
Keetch-Byram Drought Index	SCE (2022),

High Heat Data Variables	Examples
Average Maximum Temperatures	National Grid (2023a), SCE (2022), Con Edison (2023a), RG&E and NYSEG (2023), SCE (2023), SDG&E (2023)
Average Minimum Temperatures	SCE (2022), O&R (2023a), Con Edison (2023a), RG&E and NYSEG (2023), SCE (2023), SDG&E (2023)
Average Temperatures	Con Edison (2023a), Duke Energy (2023), PG&E (2024a), SCE (2023), PGE (2023), Consumers Energy (2022)
Xth Percentile Temperatures	PG&E (2024b), PG&E (2024a)
Days over Temperature Thresholds	National Grid (2023a), O&R (2023a), Con Edison (2023a), RG&E and NYSEG (2023), Duke Energy (2023), Consumers Energy (2022)
Peak Heat Days	National Grid (2023a), SCE (2022),
Trough Cold Days	SCE (2022), Con Edison (2023a), Duke Energy (2023)
Heatwave Events	SCE (2022), O&R (2023a),
Warm Night Events	SCE (2022),
Degree Days (Heating and Cooling)	SCE (2022), O&R (2023a), Con Edison (2023a),
Heat Index/Humidity-Temperature Combinations	SCE (2022), O&R (2023a), Con Edison (2023a), RG&E and NYSEG (2023),
Relative Humidity	RG&E and NYSEG (2023)
1-in-x-year Maximum Temperatures	PG&E (2024b), SCE (2022), Duke Energy (2023), PG&E (2024a)

APPENDIX B. Examples of External Hazard Data Sources

Inland flooding

- Utilities conducting inland flooding analyses commonly used the **100- and 500-year floodplains generated by the Federal Emergency Management Agency (FEMA)** (e.g., PG&E, Duke, O&R). FEMA floodplain data are generated using historical data at a local scale.
- RG&E and NYSEG used **FloodFactor flood depth projections generated by First Street.** These data are spatially cohesive across the United States and forward-looking, generated across a range of storm scenarios.

Coastal flooding/sea level rise

- California utilities conducting coastal flood analyses typically used the **United States Geological Survey (USGS) Coastal Storm Modeling System (CoSMoS)**, which provides granular coastal flood depth data across a number of sea level rise scenarios and storm types (e.g., PG&E 2024, SCE 2022). These data are currently available for almost the entire California coastline.
- A number of other utilities used coastal flood data from the **National Oceanic and Atmospheric Association (NOAA).** These data can be accessed through the NOAA Sea Level Rise Viewer or through geospatial file downloads (e.g., PG&E 2024, Duke Interim Report 2022). The data are spatially complete across both the east and west coastlines of the United States.
- Some utilities leveraged local coastal flooding datasets, especially for coastal flooding with highly local dynamics (e.g., coastal river and delta systems): for example, O&R used **Columbia University's Hudson River Decision-Support Flooding Tool** (O&R 2023), and PG&E used the **Delta Stewardship Council's Delta Flood Hazard Dataset** (PG&E 2024).

Wind

- Trends and projections for severe winds are more uncertain than those identified for other hazards (Easterling et al 2018). Utilities generally used historical and present-day data to describe potential wind conditions in their service area. For example, Florida Public Utilities Company used the American Society of Civil Engineers' Extreme Wind loading zones in its Resiliency Risk Model. Nevada Energy presented maps of high wind risk zones, which were determined using wind event observation data from 2006-2022.
- Some utilities leveraged forward-looking wind gust data to understand potential future trends in severe winds. For example, National Grid used 1-in-10-year and 1-in-100-year high wind projections developed by the Massachusetts Institute of Technology Joint Program on the Science and Policy of Global Change. Duke Energy used downscaled wind projections to project changes in average daily windspeeds and high wind days and supplemented these data with an extensive literature review (Duke Interim Report 2022).

Wildfire

- California utilities typically used projections showing wildfire burn acreage (Westerling et al.,

2018) and wildfire probability (Thomas et al., 2018), which are readily accessible through the state climate data portal, **Cal-Adapt** (PG&E 2024, SCE 2022). These datasets are available for viewing and manipulating through Cal-Adapts tool suite, and are downloadable as GIS files. They are spatially complete for areas of fire risk across California.

- Per state guidance, California utilities also include records of historical catastrophic fires, as well as information on the locations of the **High Fire Threat Districts (HFTDs)** within their service territories. Similarly, PGE includes a list of large historical fires in its service territory, and Rocky Mountain Power and Nevada Energy map zones of fire risk analogous with the California HFTDs.

Storms

- Tampa Electric, Entergy New Orleans, and Oncor all leverage the Major Storms Event Database, which draws on the National Oceanic and Atmospheric Administration's (NOAA) records of major storms since 1852 to reflect present-day and potential future storm scenarios.
- Several east coast utilities use the **Sea Lake and Overland Surges from Hurricanes (SLOSH) model** to represent flooding driven by hurricanes (e.g., Duke Interim Report 2022, Con Edison 2019, Con Edison 2023). These data provide hurricane category-specific modeled flood depth information across the entire east coast of the United States.
- Several utilities present more qualitative assessments of trends in extreme storms, noting that their relative rarity, as well as the fact that they occur on small space and time scales, makes them hard to resolve using GCMs (e.g., O&R CVA, Avangrid - NYSEG and RG&E CVA). These narrative-form projections usually build on historical information on large disruptive storm events, included in-text (e.g., Avangrid - NYSEG and RG&E CVA) or in tabular form (e.g., O&R CVA).

Precipitation and drought

- The majority of utilities use downscaled GCM precipitation projections to understand potential future changes in average and extreme precipitation (e.g., PG&E 2024, National Grid 2023, Duke 2023, O&R 2023, Central Hudson 2023, PSEG-LI 2024). Use of downscaled GCM data allows these utilities to flexibly derive relevant precipitation variables such as maximum 5-day precipitation and 100-year 1-day precipitation totals.
- Nevada Energy uses the **US Drought Monitor** to represent drought risk in its Natural Disaster Protection Plan. The Drought Monitor shows present-day and recent drought conditions, as well as historical drought trends.

High heat

- Similar to precipitation, the majority of utilities use downscaled GCM temperature projections to understand potential future changes in average and extreme heat (e.g., PG&E 2024, National Grid 2023, Duke 2023, O&R 2023, Central Hudson 2023, PSEG-LI 2024). Use of downscaled GCM data allows these utilities to flexibly derive relevant high heat variables such as total annual days over a given threshold and heatwave duration and intensity.

APPENDIX C. Attribute and Performance Metrics

Metric Name	Metric Type	Metric Subtype	Plans that Include Metric
Level of resiliency at each location as it relates to the risk each measure is developed to mitigate	Attribute	Absorb	- Oncor (2024)
Set of indicators measuring the positive, negative, or neutral effect of an adaptation action on the community it is deployed in. The objective of the CIM is to factor in equity considerations when selecting adaptation options and/or prioritizing and refining these options. The CIM is a set of indicators that capture various impacts that an adaptation action can have on the community it takes place in. Adaptation options proposed to address a climate vulnerability may be evaluated using CIM among other factors before being selected.	Attribute	Adapt	- SCE (2022)
Set of scores measuring the sensitivity and corresponding adaptive capacity of a particular community to potential loss of utility service	Attribute	Adapt	- SCE (2022)
Network Resiliency Index	Attribute	Adapt	- Con Edison (2023)
Number of distribution and transmission Inspection Findings HFTD	Attribute	Anticipate	- SDG&E (2023)
90th percentile maximum ambient temperatures	Attribute	Anticipate	- SCE (2022)
Asset exposure to high intensity heat waves	Attribute	Anticipate	- SCE (2022)
Overhead transmission conductor line-miles exposed to temperatures at or above 1 in 10 -year annual maximum temperatures over planning standard	Attribute	Anticipate	- Duke (2022)
Overhead transmission conductor line-miles by region exposed to temperatures at or above the asset rating threshold for 7 or more total days	Attribute	Anticipate	- PG&E (2024)
Substation exposure to 1-in-2 and 1-in-10 temperatures over regional temperature ratings	Attribute	Anticipate	- PG&E (2024)
Substation exposure to days per year over with avg temperatures over 32C	Attribute	Anticipate	- National Grid (2023a)
Distribution line exposure to summer maximum temperatures	Attribute	Anticipate	- National Grid (2023a)
Distribution line exposure to days per year with maximum temperatures over 40C	Attribute	Anticipate	- National Grid (2023a)
Transmission line exposure to future equivalent temperatures to present day 35°C (95°F)	Attribute	Anticipate	- National Grid (2023a)
Total substations, miles of transmission lines, and miles of distribution lines experiencing between 5 and 15 days with average temperatures above 86F	Attribute	Anticipate	- RG&E and NYSEG (2023)

Metric Name	Metric Type	Metric Subtype	Plans that Include Metric
Assets in the 100- and 500-year floodplains	Attribute	Anticipate	- National Grid (2023a) - RG&E and NYSEG (2023) - SCE (2022) - PG&E (2024) - PGE (2022) - O&R (2023) - NV Energy (2023)
Assets exposed to areas of high landslide risk	Attribute	Anticipate	- PG&E (2024) - NV Energy (2023)
Assets exposed to the 100-year storm and sea level rise	Attribute	Anticipate	- Con Edison (2023a) - SCE (2022) - PG&E (2024)
Asset exposure to category 4 hurricanes	Attribute	Anticipate	- Con Edison (2023a)
Assets falling within High Fire Risk Areas or the High Fire Threat Districts	Attribute	Anticipate	- PG&E (2024)
Index of the expected damage to, or loss of, housing units due to wildfire in a year	Attribute	Anticipate	- PGE (2022)
Wildfire burn area	Attribute	Anticipate	- SCE (2022)
Dryness indicators: relative humidity, soil moisture, keetch-byram drought index	Attribute	Anticipate	- SCE (2022)
Total distribution and transmission Line Miles in the Fire Hazard Consequence Areas (FHCA)	Attribute	Anticipate	- Pacific Power (2023)
Wildfire Risk to Potential Structures (RPS)	Attribute	Anticipate	- NV Energy (2023)
Wildfire Conditional Risk to Potential Structures (CRPS)	Attribute	Anticipate	- NV Energy (2023)
Wildfire Burn Probability (BP)	Attribute	Anticipate	- NV Energy (2023)
Wildfire Conditional Flame Length (CFL)	Attribute	Anticipate	- NV Energy (2023)
Wildfire Hazard Potential (WHP)	Attribute	Anticipate	- NV Energy (2023)
Total distribution poles exposed to high 1-in-10-year windspeeds	Attribute	Anticipate	- National Grid (2023a)
Total sub-transmission structures exposed to high 1-in-100-year windspeeds	Attribute	Anticipate	- National Grid (2023a)
Total transmission structures exposed to high 1-in-100-year windspeeds	Attribute	Anticipate	- National Grid (2023a)
Overhead asset thunderstorm wind risk	Attribute	Anticipate	- NV Energy (2023)
Highest daily peak wind gusts at transmission and distribution lines	Attribute	Anticipate	- RG&E and NYSEG (2023)

Metric Name	Metric Type	Metric Subtype	Plans that Include Metric
Coastal Flooding Extent and Depth	Attribute	Anticipate	- O&R (2023) - FPU (2022)
Drought	Attribute	Anticipate	- NV Energy (2023)
Extreme Event Characteristics	Attribute	Anticipate	- Con Edison (2019)
Major Storm Event Database	Attribute	Anticipate	- Entergy (2022) - Tampa (2022) - Oncor (2024)
Characteristics/Instances of Catastrophic Wildfires	Attribute	Anticipate	- SCE (2023) - PG&E (2024)
Extreme event counts (flood, tornado, wind, heat, winter, cold)	Attribute	Anticipate	- Oncor (2024)
Heating and Cooling Degree Days	Attribute	Anticipate	- Consumers Energy (2023) - O&R (2023)
Number of days per year over specified reference temperatures	Attribute	Anticipate	- Con Edison (2019)
Rate of change in key temperature climate variables	Attribute	Anticipate	- Con Edison (2019)
Total days per year over 86°F across the service area	Attribute	Anticipate	- Consumers Energy (2023)
Present day and future changes in average and extreme temperatures and heat index in the service area	Attribute	Anticipate	- O&R (2023)
Total hours per year of sustained high windspeeds and high wind gusts	Attribute	Anticipate	- Consumers Energy (2023)
Extreme wind loading zones	Attribute	Anticipate	- FPU (2022)
Present day and future data showing projected windspeeds during a high wind event	Attribute	Anticipate	- O&R (2023)
FEMA 100- and 500-year floodplains	Attribute	Anticipate	- O&R (2023)
Days with higher Convective Available Potential Energy (CAPE)	Attribute	Anticipate	- DTE Electric (2023)
Total number of Major Event Days per year	Attribute	Anticipate	- Consumers Energy (2023) - PGE (2022) - O&R (2023)
Vegetation ignitions	Attribute	Anticipate	- SDGE (2023)

Metric Name	Metric Type	Metric Subtype	Plans that Include Metric
Trees with pending work	Attribute	Anticipate	- SDGE (2023)
Trees inspected in the HFRA, tree-caused circuit interruptions, wire downs, outages in the HFRA	Attribute	Anticipate	- SDGE (2023)
Average Time for Vegetation Clearance Permissions from Local Agencies	Attribute	Anticipate	- NV Energy (2023)
Vegetation response times - the time between vegetation inspection finding and resulting trimming activities (in HFTD)	Attribute	Anticipate	- PG&E (2024)
Total acreage within the service area burned by ignition events	Attribute	Anticipate	- NV Energy (2023)
High Fire Risk Areas	Attribute	Anticipate	- PG&E (2024)
Fire Potential Index, which quantifies the potential for large or consequential wildfires based on weather, fuels, and terrain. PP also tracks additional fire metrics, including fire weather forecasts, fuel data, drought index, weather service warnings, etc.	Attribute	Anticipate	- Pacific Power (2023)
Wildfire	Attribute	Anticipate	- NV Energy (2023) - PG&E (2024) - Pacific Power (2023)
Number of Electric Infrastructure-Caused Ignition Events and/or Fires that Occur within the Vicinity of Utility Electrical Equipment	Attribute	Anticipate	- NV Energy (2023)
Number of Vegetation Contacts with Lines in Wildfire Risk Tiers - instances, outages	Attribute	Anticipate	- NV Energy (2023)
Annual probability of asset-caused ignition	Attribute	Anticipate	- PGE (2023)
Number of CPUC Reportable ignitions in the HFRA	Attribute	Anticipate	- SCE (2023)
Number of risk events (ignitions, wire-downs and outages in the HFTD)	Attribute	Anticipate	- PG&E (2024)
Fires Originating from Utility Equipment	Attribute	Anticipate	- Pacific Power (2023)
Winter Storms and Ice	Attribute	Anticipate	- NV Energy (2023)
Establishes the number of outages per mile in identified high risk WMZs	Attribute	Anticipate	- Oncor (2024)
Future flood events that impact the backup control center, including water elevation and equipment at risk for each event	Attribute	Anticipate	- CenterPoint Energy (2024)
Facility Development and Use	Attribute	Recover	- O&R (2023)
Number of assets inspected using new technological tools	Attribute	Withstand	- SDG&E (2023)
Asset condition related to joint-use poles	Attribute	Withstand	- Duke Energy (2023)
Total number of transformers that meet the latest temperature specification	Attribute	Withstand	- RG&E and NYSEG (2023)
Total number of upgraded transformers	Attribute	Withstand	- National Grid (2023b)
Total transmission assets upgraded/costs of projects	Attribute	Withstand	- TECO (2023)

Metric Name	Metric Type	Metric Subtype	Plans that Include Metric
Status of flood protection projects at specific substation locations	Attribute	Withstand	- O&R (2023)
Completion of planned targeted covered conductor and/or sectionalization devices each year	Attribute	Withstand	- SCE (2023)
Measurement of how much of grid hardening mitigation deployed (e.g., number of circuit miles, number of units, number of structures, etc.) is aligned with IWMS	Attribute	Withstand	- SCE (2023)
Distribution line miles converted to underground as part of the Storm Protection Plan	Attribute	Withstand	- TECO (2023) - PSEG Long Island (2024)
Distribution OH feeders hardened	Attribute	Withstand	- TECO (2023)
Miles of circuit undergrounded for selective undergrounding	Attribute	Withstand	- O&R (2023)
Total number of transmission overhead structures replaced per year	Attribute	Withstand	- O&R (2023)
Number of devices installed per year under the NY accelerated Smart Grid Distribution Automation Program	Attribute	Withstand	- O&R (2023)
Number of physical mitigation measures implemented per year as part of the shoreline erosion protection program	Attribute	Withstand	- O&R (2023)
Circuit miles undergrounded for wildfire hardening	Attribute	Withstand	- PG&E (2024)
The increase in: a) DER hosting capacity, and b) load serving capacity by substation demonstrated by an increase in transformer rating installed.	Attribute	Withstand	- Eversource (2024) - Unitil (2024)
Elevated equipment at substations in floodplains	Attribute	Withstand	- PSEG Long Island (2024)
Distribution poles replaced	Attribute	Withstand	- PSEG Long Island (2024)
Covered "tree" wire installed	Attribute	Withstand	- PSEG Long Island (2024)
Poles hardened	Attribute	Withstand	- PSEG Long Island (2024)
Number of overloaded pieces of equipment	Performance	Asset Damage and Failure	- Consumers Energy (2023)
Quantification of the impact of climate change on asset failure and replacement rates	Performance	Asset Damage and Failure	- Duke Energy (2023)
Number of facilities requiring repair or replacement after an event	Performance	Asset Damage and Failure	- FPL (2022)
Post-storm asset damage	Performance	Asset Damage and Failure	- TECO (2022)
Total flood damage after flood wall implementation	Performance	Asset Damage and Failure	- National Grid (2023b)
Number of Overhead Equipment Failures with Lines in Wildfire Risk Tiers	Performance	Asset Damage and Failure	- NV Energy (2023)

Metric Name	Metric Type	Metric Subtype	Plans that Include Metric
Failure Rate of Hardened Transmission Structures During a Resiliency Event	Performance	Asset Damage and Failure	- CenterPoint Energy (2024)
Total number of new towers that fail during major storms	Performance	Asset Damage and Failure	- CenterPoint Energy (2024)
Total number of replacement/braced poles that fail during resiliency events	Performance	Asset Damage and Failure	- CenterPoint Energy (2024)
Number of replaced poles that fail under the current NESC design standards	Performance	Asset Damage and Failure	- CenterPoint Energy (2024)
Monitoring of the upgraded freeway crossings that fail during resiliency events	Performance	Asset Damage and Failure	- CenterPoint Energy (2024)
Number of substations that have equipment elevated and yet experience water damage to substation equipment (e.g., control house, circuit breakers, transformers) for actual flood events.	Performance	Asset Damage and Failure	- CenterPoint Energy (2024)
Degree and characteristics of substation flood impacts	Performance	Asset Damage and Failure / Critical Facilities	- RG&E and NYSEG (2023)
Key Asset Damages	Performance	Asset Damage and Failure / Critical Facilities	- Con Edison (2019)
Total Number of Assets Damaged and Customers Unable to be Restored Through Adaptive Capacity for Each Hazard Scenario	Performance	Asset Damage and Failure / Critical Facilities	- SCE (2022)
Infrastructure Performance after a Hurricane	Performance	Asset Damage or Failure	- FPL (2022)
Transmission outages/failures during a storm	Performance	Asset Damage or Failure	- FPL (2022)
Conductor performance during major events	Performance	Asset Damage or Failure	- PSE&G (2018)
Avoided impact to Critical Facilities (AIC)	Performance	Critical Facilities	- RG&E and NYSEG (2023)

Metric Name	Metric Type	Metric Subtype	Plans that Include Metric
Ad click through rates, impressions, radio number of spots, streaming audio impressions and listen-through rate, customer emails sent and opened	Performance	Customer Communications and Engagement	- Pacific Power (2023)
Number of customers notified prior to initiation of a PSPS event.	Performance	Customer Communications and Engagement	- PG&E (2024)
Social media engagement, video completion rate, email campaign, customer bill inserts, phone engagement, face to face engagement	Performance	Customer Communications and Engagement	- PGE (2023)
customer recall of SCE wildfire and preparedness communications	Performance	Customer Communications and Engagement	- SCE (2023)
Customer Complaints	Performance	Customer Communications and Engagement	- Con Edison (2019) - NV Energy (2023)
Net Promoter Score	Performance	Customer Communications and Engagement	- Duke (2023)
The number of outreach and involvement meetings about the respective EDCs ESMP and about specific ESMP infrastructure projects filing with stakeholders, including EJCs, municipal leaders, community-based organizations, and customers (i.e., residential, commercial, and industrial, as well as DER customers).	Performance	Customer Communications and Engagement	- Eversource (2024) - Unitil (2024)
The number and category of requests made as part of stakeholder feedback on specific ESMP infrastructure projects, classified into visual mitigation, access accommodations, work hours, right-of-way maintenance, informational accommodations, engineering accommodations, and damage prevention, as well as the EDC's response to these requests classified as under consideration, implemented, not accepted with reason, and other.	Performance	Customer Communications and Engagement	- Eversource (2024) - Unitil (2024)
Customer outages (storm and non-storm) at distribution circuits before and after resiliency project completion	Performance	Electrical Service	- RG&E and NYSEG (2023)
Outages avoided from NY accelerated Smart Grid Distribution Automation Program	Performance	Electrical Service	- O&R (2023)
Avoided outages during a storm event	Performance	Electrical Service	- O&R (2023)
Total transmission line outages before and after upgrades	Performance	Electrical Service	- National Grid (2023b)

Metric Name	Metric Type	Metric Subtype	Plans that Include Metric
Business Impact Analysis Disruption Score	Performance	Electrical Service	- PG&E (2024)
CPI = Index*((SAIDI*WF*NF)+(SAIFI*WF*NF)+(MAIFI*WF*NF)+(Lockouts*WF*NF)) Index = 10.645 SAIDI: Weighting Factor 0.30, Normalizing Factor 0.029 SAIFI: Weighting Factor 0.30, Normalizing Factor 2.439 MAIFI: Weighting Factor 0.20, Normalizing Factor 0.70 Lockouts: Weighting Factor 0.20, Normalizing Factor 2.00"""	Performance	Electrical Service	- RMP (2023)
Customer Minutes Interrupted (CMI) - during Storms, Extreme Weather, Blue-Sky Conditions, Not Specified	Performance	Electrical Service	- TECO (2022) - Entergy (2023) - Duke (2022) - PSE&G (2018) - PGE (2022) - National Grid (2023b) - Centerpoint Energy (2024) - SCE (2022) - Indiana Michigan Power (2023) - SCE (2022) - Con Edison (2023b)
Customers Experiencing Long Interruption Durations (CELID)	Performance	Electrical Service	- O&R (2023) - Indiana Michigan Power (2023) - PGE (2022) - Xcel (2019)

Metric Name	Metric Type	Metric Subtype	Plans that Include Metric
Customers Experiencing Multiple Interruptions (CEMI)	Performance	Electrical Service	- DTE Electric (2023) - Indiana Michigan Power (2023) - PGE (2022) - PGE (2023) - Xcel (2019)
CAIDI	Performance	Electrical Service	- National Grid (2024) - Indiana Michigan Power (2023) - National Grid (2023b) - O&R (2023) - Consumers Energy (2023) - DTE Energy (2023) - PG&E (2024) - Xcel (2019) - SCE (2022) - SDG&E (2023) - Eversource (2024) - Unitil (2024)
MAIFI - Major Event Days excluded or not specified	Performance	Electrical Service	- Indiana Michigan Power (2023) - PGE (2023) - DTE Electric (2023) - Xcel (2019)
Establishes the performance for each area across the system for various intensities and types of extreme weather events	Performance	Electrical Service	- Oncor (2024)
Five-Year Average Outage Events by Cause	Performance	Electrical Service	- DTE Electric (2023)
Major and minor outage causes	Performance	Electrical Service	- Indiana Michigan Power (2023)

Metric Name	Metric Type	Metric Subtype	Plans that Include Metric
Wildfire Risk Zone Outage Metrics–Leading Drivers of Ignition by Cause Code	Performance	Electrical Service	- Idaho Power (2023)
Weather conditions at the time of an outage	Performance	Electrical Service	- National Grid (2023b) - Oncor (2024)
Outages from high wind events	Performance	Electrical Service	- Consumers Energy (2023)
Outages and their Characteristics during MEDs and CEDs (Catastrophic Event Days)	Performance	Electrical Service	- NV Energy (2023)
Major Outage Events (MOE) - MOE can more specifically measure resilience by defining the most extreme events and measuring outage events based on a percentage of customers with outages and the length of outages.	Performance	Electrical Service	- O&R (2023)
De-energization events at substations that see substantial flooding	Performance	Electrical Service	- PG&E (2024)
Number of Outages in HFRA	Performance	Electrical Service	- SCE (2022)
SAIDI/SAIFI - Major Event Days excluded or not specified	Performance	Electrical Service	- National Grid (2023b) - National Grid (2024) - Idaho Power (2023) - Consumers Energy (2023) - O&R (2023) - PGE (2023) - Oncor (2024)
SAIDI/SAIFI - Major Event Days included	Performance	Electrical Service	- Con Edison (2019 Appendices) - Consumers Energy (2023) - DTE Electric (2023) - Indiana Michigan Power (2023) - Tampa Electric (2022) - FPL (2022) - National Grid (2024) - Xcel (2019) - Eversource (2024)
Vegetation outages	Performance	Electrical Service	- SDGE (2023)

Metric Name	Metric Type	Metric Subtype	Plans that Include Metric
Identifies the number of underperforming areas across the system	Performance	Electrical Service	- Oncor (2024)
Total customers impacted by a resilience event (includes extreme weather, physical security, and technology-specific events)	Performance	Electrical Service	- CenterPoint Energy (2024)
Total number of line outages on converted 69kV transmission lines resulting from resiliency events	Performance	Electrical Service	- CenterPoint Energy (2024)
Percent of customers covered by/benefiting from incremental resiliency investments outlined in the EDC's ESMPs	Performance	Electrical Service	- Eversource (2024) - Unitil (2024)
Decrease in incidents per mile	Performance	Electrical Service	- PSEG Long Island (2024)
Decrease in the frequency of outages	Performance	Electrical Service	- PSEG Long Island (2024)
Decrease in the duration of outages	Performance	Electrical Service	- PSEG Long Island (2024)
Decrease in outages less than 5 minutes	Performance	Electrical Service	- PSEG Long Island (2024)
Decrease in the frequency of vegetation-related outages	Performance	Electrical Service	- PSEG Long Island (2024)
Total number of outages and interruptions of supply avoided	Performance	Electrical Service / Asset Damage and Failure	- CenterPoint Energy (2024)
Outages avoided and damage averted for each future transformer failure where transformer fire protection barriers are installed	Performance	Electrical Service / Asset Damage and Failure	- CenterPoint Energy (2024)
Total avoided O&M and/or CapEx during major events	Performance	Monetary Impacts	- PSE&G (2018)
Post-storm restoration costs	Performance	Monetary Impacts	- FPL (2022) - Entergy (2022) - TECO (2022)
Cost of extreme weather events on the distribution and transmission system annually	Performance	Monetary Impacts	- Duke Energy (2022)
Value of all assets and structures destroyed by ignition events	Performance	Monetary Impacts	- NV Energy (2023)
Average O&M restoration cost per incident	Performance	Monetary Impacts	- Consumers Energy (2023)

Metric Name	Metric Type	Metric Subtype	Plans that Include Metric
Interruption Cost Estimate (ICE) Calculator	Performance	Monetary Impacts	- Duke (2023) - Entergy (2022) - FPU (2022) - TECO (2022) - Oncor (2024)
Value Spend Efficiency (VSE)	Performance	Monetary Impacts	- PGE (2023)
Risk Spend Efficiency (RSE)	Performance	Monetary Impacts	- Idaho Power (2024) - Pacific Power (2023) - Duke (2023)
Value of Lost Load (VoLL)	Performance	Monetary Impacts	- PSE&G 2028
Wildfire: cost metrics	Performance	Monetary Impacts	- NV Energy (2023)
Frequency, Scope, and Duration of PSPS Events	Performance	Power Shutoffs	- PG&E (2024) - SCE (2023)
Customer Hours of PSPS per Red Flag Warning	Performance	Power Shutoffs	- PG&E (2024)
Number of Customers Impacted by PSPS	Performance	Power Shutoffs	- SCE (2023)
Overall Wildfire and PSPS Risk	Performance	Power Shutoffs	- SDG&E (2023)
Number of PSOM events and duration of power outage during PSOM (Public Safety Outage Management) events	Performance	Power Shutoffs	- NV Energy (2023)
Number of unplanned outages outside of PSOM events,	Performance	Power Shutoffs	- NV Energy (2023)
Duration of unplanned outages in minutes/hours outside PSOM (Public Safety Outage Management) events	Performance	Power Shutoffs	- NV Energy (2023)
Number of minutes/hours to re-energize after hazardous conditions are cleared during a PSOM event	Performance	Power Shutoffs	- NV Energy (2023)
Number of Community Emergency Evacuations	Performance	Response and Restoration	- NV Energy (2023)
Restoration time regardless of cause	Performance	Response and Restoration	- Indiana Michigan Power (2023)

Metric Name	Metric Type	Metric Subtype	Plans that Include Metric
Post-Storm Restoration Timing	Performance	Response and Restoration	- Consumers Energy (2023) - FPL (2022) - O&R (2023)
Catastrophic Crewing ("CatCrew") is the Company's 15-year-old home-grown resource management software tool used during storm restoration	Performance	Response and Restoration	- Consumers Energy (2023)
Number of distribution poles replaced after a storm	Performance	Response and Restoration	- FPL (2022)
Downed wire response	Performance	Response and Restoration	- DTE Electric (2023)
Total restoration time from a resilience event (includes extreme weather, physical security, and technology-specific events)	Performance	Response and Restoration	- Centerpoint Energy (2024)
Number of successful load transfers achieved by Intelligent Grid Switching Device (IGSD) schemes during resiliency events	Performance	Response and Restoration	- Centerpoint Energy (2024)
Avoided outage restoration times and costs	Performance	Response and Restoration / Monetary Impacts	- PSE&G (2018)

APPENDIX D. Adaptive Capacity Indicators and Associated Datasets

Adaptive Capacity Metric	Category	Importance, Notes, Additional Detail	Data Sources that can be Leveraged to Describe Metric	Studies or Literature that Cite Metric
Percent of Population in Workforce	**Human and Civic Resources**	• Economic stability and financial resources • Development of skills • Social capital • Institutional support	ACS: Selected Economic Characteristics (DP03): Employed vs. Unemployed Totals EJ Screen: Unemployment	Weis et al, 2016 Moss et al, 2001 PG&E, 2024b
Access to Social Networks, Participation or Support from Community Organizations, Language	**Human and Civic Resources**	• Sharing information and resources • Collective action, empowerment, advocacy • Relationships of trust and exchange among community members • Emotional/psychological support systems	ACS: Selected Social Characteristics (DP02): School Enrollment, Computers and Internet Use EJ Screen: Limited English Speaking, Broadband Gaps	Weis et al, 2016 Ofoegbu et al, 2016 Ruiz Meza, L.E., 2015 Moss et al, 2001 PG&E, 2024b Dugan et al, 2023
Education Level	**Human and Civic Resources**	• Improved ability to make informed decisions • Ability to anticipate changes and appropriately modify their livelihood opportunities • Better economic opportunities and higher potential to be part of governing bodies	EJ Screen: Less than High School Education	Weis et al, 2016 Ofoegbu et al, 2016 Moss et al, 2001 Brooks at al, 2005 PG&E, 2024b Dugan et al, 2023
Percent of Population with Health Insurance/Healthcare System	**Healthy Population**	• Better healthcare access, improved resilience to health impacts • Financial protection	ACS: Selected Economic Characteristics (DP03): Health Insurance Coverage EJ Screen: Lack of Health Insurance	Weis et al, 2016 Alberini et al, 2006 Brooks at al, 2005 PG&E, 2024b
Level of Disabilities	**Healthy Population**	• Potential higher sensitivity to climate impacts • Barriers to resource access • Potential for social isolation • Higher healthcare needs	EJ Screen: Disabilities	Weis et al, 2016 PG&E, 2024b Dugan et al, 2023
Infant Mortality Rate	**Healthy Population**	• Quality of and access to healthcare • Economic stability	EJ Screen: Low Life Expectancy	Weis et al, 2016 Yohe & Tol, 2002
Percent of Population with Property Insurance	**Economic Resources**	• Financial protection • Access to reconstruction services		Weis et al, 2016 PG&E, 2024b
Wealth and Financial Inequality	**Economic Resources**	• Access to resources (financial, material, technological) • Buffer during a crisis, ability to afford relief • Capacity of community to provide social services and invest in infrastructure • Disparities in access to adaptation resources • Investments in innovative solutions	ACS: Selected Economic Characteristics (DP03): Median Household Income	Alberini et al, 2006 Brooks at al, 2005 Moss et al, 2001 PG&E, 2024b

Adaptive Capacity Metric	Category	Importance, Notes, Additional Detail	Data Sources that can be Leveraged to Describe Metric	Studies or Literature that Cite Metric
Access to Supplemental Livelihood/Access to Financial and Natural Resources/Income	**Economic Resources**	• Financial stability from employment and/or diverse income sources • Economic resilience • Ability to invest in adaptation • Capacity to support community efforts • Means to support healthcare/wellbeing costs	ACS: Selected Economic Characteristics (DP03): Median Household Income EJ Screen: Unemployment, Low Income	Weis et al, 2016 Smit & Wandel, 2006 Ruiz Meza, L.E., 2015 Moss et al, 2001 Alberini et al, 2006 Brooks at al, 2005 Dugan et al, 2023
Managerial ability/ Local Skill in Dealing with Risks	**Human and Civic Resources**	• Resource procurement and allocation • Strategic planning and risk management • Leadership during extreme events • Fostering stronger stakeholder engagement		Smit & Wandel, 2006 Ruiz Meza, L.E., 2015 Moss et al, 2001 Brooks at al, 2005 PG&E, 2024b
Access to Technological Resources	**Economic Resources**	• Better early warning systems • Improved infrastructure • Data collection/monitoring • Innovative adaptation measures	EJ Screen: Broadband Gaps	Smit & Wandel, 2006 Ruiz Meza, L.E., 2015 Moss et al, 2001
Access to Information	**Economic Resources**	• Informed decision-making • Education/awareness • Participation in community adaptation efforts • Efficient resource allocation	EJ Screen: Limited English Speaking, Less than High School Education	Smit & Wandel, 2006 Yohe & Tol, 2002 Ofoegbu et al, 2016 Moss et al, 2001 Alberini et al, 2006
Permeable Surface Cover	**Community Built Environment**	• Flood mitigation • Reduced UHI • Better ecosystem health		SCE, 2022 PG&E, 2024b
Tree Canopy/Green Space	**Community Built Environment**	• Reduced UHI • Better ecosystem health • Better air quality • Mental health benefits		SCE, 2022
Cooling Center	**Community Built Environment**	• Protection from extreme heat • Community resource hub		SCE, 2022
Medical Facilities/Access to Medical Professionals	**Community Built Environment**	• Emergency response/healthcare access during an event • Capacity to manage medical issues within a community (both acute and chronic)		SCE, 2022 Ofoegbu et al, 2016 Alberini et al, 2006 Brooks at al, 2005
Supermarket Access/General Food Availability	**Community Built Environment**	• Food security • Nutrition/health	EJ Screen: Food Desert Map the Meal Gap	SCE, 2022 Ofoegbu et al, 2016 Brooks at al, 2005 PG&E, 2024b

Adaptive Capacity Metric	Category	Importance, Notes, Additional Detail	Data Sources that can be Leveraged to Describe Metric	Studies or Literature that Cite Metric
Voters	**Governance and Services**	• Influencing resilient policies • Social cohesion and engagement • Leadership accountability • Community and individual empowerment/advocacy	ACS: Demographic and Housing Estimates (DP05): Citizen Voting Age Population	SCE, 2022 PG&E, 2024b
Emergency Services/Responders	**Governance and Services**	• Immediate response mechanisms during a crisis • Public health and safety • Infrastructure and community protection		SCE, 2022 PG&E, 2024b
Planning Level	**Governance and Services**	• Proactive risk management • Resource allocation • Resilience strategy integration across sectors • Community engagement		SCE, 2022 Moss et al, 2001 Brooks at al, 2005 PG&E, 2024b Dugan et al, 2023
Quality of Infrastructure	**Community Built Environment**	• Protection against hazards/better equipped to handle hazards • Better emergency response programs • Improved economic stability and ability to recover after an event		Brooks at al, 2005
Air Conditioning	**Individual Built Environment**	• Protection from extreme heat		SCE, 2022
Telecommunications Access	**Individual Built Environment**	• Real-time information distribution during an event • Early warning systems • Coordination of emergency services • Heightened public awareness	ACS: Selected Social Characteristics (DP02): Computers and Internet Use EJ Screen: Broadband Gaps	SCE, 2022 Alberini et al, 2006 PG&E, 2024b
Population Density/housing (multi-family vs. single family)	**Community Environment**	• Resource Pressure • Well-developed infrastructure and overburdened systems • Environmental Stress • Political Challenges		Moss et al, 2001 Dugan et al, 2023
Transit Access/Mobility	**Transportation**	• Ability to evacuate during a crisis	ACS: Communiting Characteristics by Sex (DS0801): Means of transportation to work, vehicles available EJ Screen: Transportation Access Burden	SCE, 2022 PG&E, 2024b
Vehicle Access/Mobility	**Transportation**	• Ability to evacuate during a crisis	EJ Screen: Transportation Access Burden	SCE, 2022 PG&E, 2024b Dugan et al, 2023
Nutrition	**Healthy Population**	• Health and wellbeing • Food security, risk of hunger • Physical and cognitive development	EJ Screen: Food Desert, Low Income Map the Meal Gap	Yohe & Tol, 2002 Brooks at al, 2005
Sanitation	**Community Built Environment**	• Problems caused by faulty sanitation	EJ Screen: Toxic Releases into Air, Superfund Proximity, Hazardous Waste Proximity, Wastewater Discharge	Yohe & Tol, 2002

Adaptive Capacity Metric	Category	Importance, Notes, Additional Detail	Data Sources that can be Leveraged to Describe Metric	Studies or Literature that Cite Metric
Life Expectancy/Population Health	**Healthy Population**	• Related to infant mortality but includes health risks later in life	EJ Screen: Low Life Expectancy	Yohe & Tol, 2002 Alberini et al, 2006 Dugan et al, 2023
Drinking Water Treatment	**Community Built Environment**	• Safe drinking water • Water scarcity management/mitigation • Reduced pollution and environmental degradation	EJ Screen: Drinking Water Non-Compliance, Wastewater Discharge	Yohe & Tol, 2002
Natural Disasters	**Climate Risk**	• Emergency response procedures • Resilient infrastructure • Healthy and safe populations • Economic stability	EJ Screen: Wildfire, Flood, Sea Level Rise, Extreme Heat Risk	Yohe & Tol, 2002 Ruiz Meza, L.E., 2015

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APPENDIX E. Organizations Interviewed

Avangrid
California Energy Commission
Massachusetts Department of Energy Resources
Michigan Public Service Commission
National Grid
Pacific Gas & Electric
Public Utility Commission of Texas
Tennessee Department of Environment and Conservation, Office of Energy Programs
Wisconsin Public Service Commission, Office of Energy Innovation