Current Practices in Distribution Utility Resilience Planning for Hurricanes and Non-Winter Storms

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List of Acronyms

BRIC	Building Resilience Infrastructure and Communities Program
CAIDI	Customer Average Interruption Duration Index
CBA	Cost Benefit Analysis
CELID	Customers Experiencing Long Interruption Durations
CEMI	Customers Experiencing Multiple Interruptions
CIC	Customer Interruption Costs
CMI	Customer Minutes Interrupted
CMP	Central Main Power
DEI	Diversity, Equity, and Inclusion
DSPx	Next-Generation Distribution System Platform
DTEE	Detroit Edison Electric
EAL	Expected Annual Losses
EJ	Energy Justice
EPRI	Electric Power Research Institute
FAC	Florida Administrative Code
FEMA	Federal Emergency Management Agency
FPSC	Florida's Public Service Commission
GRC	General Rate Case
ICE	Interruption Cost Estimate
IEEE	Institute of Electrical and Electronics Engineers
IOU	Investor-Owned Utility
ISO	International Organization for Standardization
kV	Kilovolt
LBNL	Lawrence Berkeley National Laboratory
LLC	Limited Liability Corporation
LOF	Likelihood of failure
MAIFI	Momentary Average Interruption Frequency Index
MED	Major Event Day
MPSC	Michigan Public Service Commission
NOAA	National Oceanic and Atmospheric Administration
NRI	National Risk Index
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SECO	Sumter Electric Cooperative
URD	Underground Residential Distribution

1 Introduction

This report is part of a series of hazard-focused case studies examining common practices in electric utility resilience planning. We use standard terminology defining resilience as the ability to anticipate, withstand, absorb, and recover from hazards that cause long duration outages. We distinguish between reliability and resilience using IEEE 1366-2022,[1] which defines major events as "an event that exceeds reasonable design and/or operational limits of the electric power system." Resilience planning is focused on major event days and reliability planning is focused on non-major event days. Utility resilience plans are assessed according to common resilience components that we have identified in existing resilience frameworks. The focus of this report is on hurricanes and severe storms in which the primary hazards are precipitation or high winds. We exclude winter storms with primary hazards of ice and extreme cold, as they are a unique set of hazards with different resilience considerations. Standalone reports focusing on *wildfires* and *winter storms* have been published in parallel with this report. This report can be used as a starting point for understanding potential investment prioritization processes and investment options. This report is intended to improve utility resilience planning by supporting constructive dialogue among utilities, regulators, and other stakeholders.

1.1 Approach

The hazard-focused resilience reports are based on a review of each utility's publicly available distribution resilience plan or hazard-specific planning report and interviews with utility representatives (see Appendix A).

All utilities reviewed in this report were contacted. Utilities that responded were asked for feedback on our approach and the accuracy of our findings. All utilities were assessed according to six resilience planning components: 1) Preliminary Hazard Characterization, 2) Attribute Metrics, 3) Performance Metrics, 4) Threat Risk Analysis, 5) Investments, and 6) Investment Prioritization. These components were adapted from those identified in existing resilience frameworks, as described by EPRI,[2] Sandia,[3] and others.[4] Section 1.3 describes the utilities that were selected for this report and the remainder of this report considers the utilities' resilience planning practices according to the six resilience components. We first provide a brief description of these components. Further details on resilience components and resilience investment prioritization can be found Appendix C. This report is focused on resilience *planning*, so we do not include detailed information on *operating* procedures during major event days (such as event response management, training, situational awareness, and coordination between utilities in mutual assistance programs).

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1 "IEEE Std 1366TM-2022, IEEE Guide for Electric Power Distribution Reliability Indices," 2022.
2 J Tripolitis, S Martino, and J Wharton, "Distribution Grid Resiliency: Prioritization of Options" (Electric Power Research Institute, 2015).
3 Jean-Paul Watson et al., "Conceptual Framework for Developing Resilience Metrics for the Electricity, Oil, and Gas Sectors in the United States," September 1, 2014, https://doi.org/10.2172/1177743.
4 Paul De Martini, Newport Consulting, and Jeff Taft, "Distribution Resilience and Reliability Planning" (Pacific Northwest National Laboratory, January 2022).

Preliminary hazard characterization is a process used by utilities to determine the relative risk of different hazards and to determine where to focus resilience investments. Because there are many hazards, this preliminary hazard characterization tends to be qualitative and based on engineering judgement more than detailed analysis. For example, a utility might perform a climate change risk assessment and determine that rising temperatures carry a “low risk,” and increased flooding carries a “high risk.”

Attribute metrics measure system characteristics that may be beneficial to resilience.[5] We suggest that utilities collect metrics for each resilience phase, and we refer to anticipate, absorb, withstand, and recovery metrics throughout this report. These phases are further described in Appendix C.2, and system resilience curves illustrating the effect of investments to address each phase are shown in Figure 1. Attribute metrics can provide utilities with options to improve their performance metrics. For example, the percentage of underground laterals is a metric that describes the ability of a utility to *withstand* strong winds. If a utility has a poor Tree-SAIDI score, they might consider increasing the number of underground laterals.

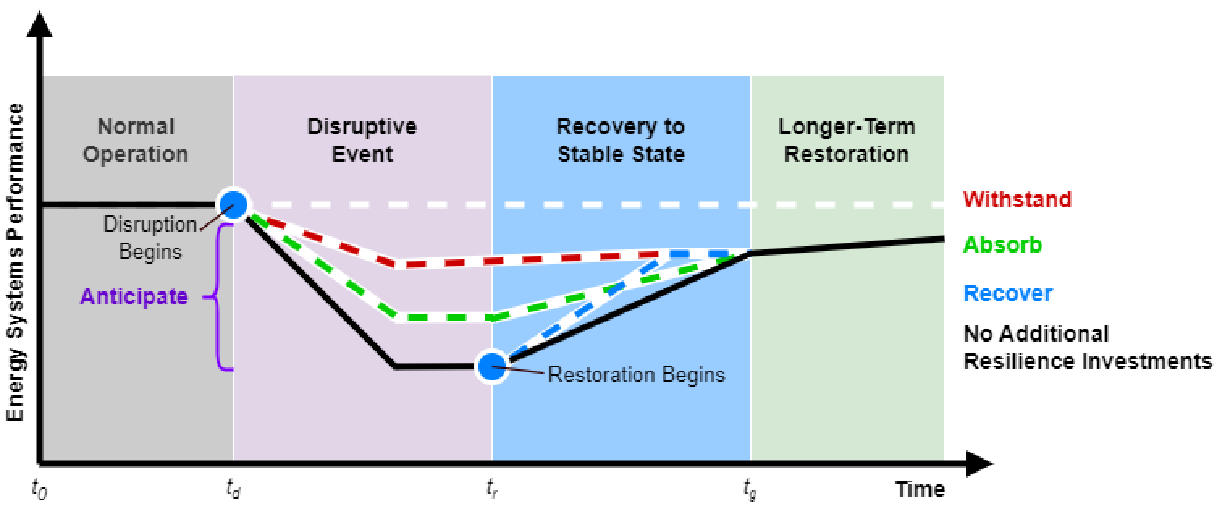


Figure 1. System resilience curves for the effects of investments to withstand, absorb, recover, or anticipate. Investments to withstand result in the system performance avoiding some impacts altogether, while not necessarily improving recovery rates. Investments to absorb the impact of an event will arrest the decrease in system performance and reduce impacts to system users until a stable state can be attained. Unlike investments to withstand, investments to absorb may limit a reduction in performance or allow for accelerated recovery without altogether avoiding hazard impacts. Investments to recover accelerate the rate of recovery but may not result in an impact reduction at the time of the event. Investments to anticipate can support the system’s abilities to withstand, absorb, or recover.

[5] Caitlin Murphy et al., “Adapting Existing Energy Planning, Simulation, and Operational Models for Resilience Analysis,” February 25, 2020, https://doi.org/10.2172/1602705; Laura Leddy et al., “Measuring and Valuing Resilience: A Literature Review for the Power Sector,” September 5, 2023, https://doi.org/10.2172/1999382.

Performance metrics measure a utility's status in achieving its core objectives (e.g., affordability, safety, reliability, resilience, equity). Major event day (MED)-SAIDI is an example of a resilience performance metric.

Threat Risk Analysis is analysis used to quantify the probability, consequence, and vulnerability (i.e., risk) of a threat. It can be performed using historical data or simulations and can be used to determine how system changes (e.g., a new investment) affect risk. A historical risk analysis might assess customer outages caused by strong winds on single-phase laterals and recommend undergrounding. A forward-looking simulation might analyze the same threat but could also consider expected increases in wind speeds from climate change. Threat Risk Analyses can include simulation to quantify the effects of various investment on system performance.

Investment considerations are provided in this report. We provide common categories (e.g., vegetation management) and examples of investments that utilities are making to improve resilience in their service territory. A utility that has considered a variety of investments is likely to achieve more cost-effective solutions.

An *Investment Prioritization* process identifies cost-effective investments for minimizing risk. Ideally, this prioritization process will demonstrate the cost and effectiveness of investments with respect to specific performance metrics. It is also important that these investments are not made in isolation. Resilience investment prioritization is more effective when integrated into existing planning processes (e.g., capacity planning or asset management) and when it considers multiple utility objectives (e.g., reliability, cost, equity, etc.). Cost benefit analysis is one form of investment prioritization.

There are overlaps and relationships between the resilience components listed here. *Preliminary Hazard Characterization* and *Threat Risk Analysis* exist on a spectrum. *Preliminary Hazard Characterization* is primarily needed to focus the *Threat Risk Analysis* on hazards with the greatest risk. *Attribute Metrics* and *Performance Metric* also exist on a spectrum. For example, "Tree-SAIDI" is a popular performance metric that also provides insight into system characteristics (i.e., high Tree-SAIDI scores imply high tree coverage and a need for improved vegetation management). A resilience workflow often exists between *Attribute Metrics, Threat Risk Analysis,* and *Performance Metrics. Attribute Metrics* can provide actionable changes that can be evaluated with a *Threat Risk Analysis* tool, which then outputs predicted changes in *Performance Metrics.* The cost of achieving a given *Performance Metric* improvement can be used to rank the cost effectiveness of the investment. If the performance metric is associated with a monetary benefit, a cost-benefit analysis (CBA) can be done. Both cost-effectiveness and CBA can be used to support *Investment Prioritization*.

Table 1 lists the resilience components and describes some of the questions that can help evaluate utility resilience planning. The resilience components are agnostic to hazard type and can be used as a template for analyzing resilience reports for any hazard.

Table 1. Rubric for assessing utility resilience plans. Resilience components and suggested questions are provided that can help utilities develop cost-effective resilience strategies.

Resilience Component	Suggested Questions
Preliminary Hazard Characterization	• Is risk defined? • Does the definition of risk include the probability, vulnerability, and consequence of each hazard? • Are multiple hazards considered in the characterization? • Does the characterization identify high risk hazards? • Are emerging risks considered proactively?
Attribute Metrics	• Are attribute metrics used to characterize system strengths and weaknesses in the face of specific hazards? • Are attribute metrics collected that describe the system's ability to anticipate, withstand, absorb, and recover? • Are attribute metrics collected in a manner consistent with utility and industry standards? • Are attribute metrics used to guide investment decisions? • Data hygiene: Are data of sufficiently high resolution? Is data coverage sufficient?
Performance Metrics	• Are performance metrics defined? • Are the performance metrics used to measure how well a utility is meeting its resilience objectives? • Are the performance metrics used to track how well a utility is meeting other objectives, such as equity, clean energy, and reliability? • Are the resilience performance metrics applicable to all hazards or are they developed specifically for one hazard? • Data hygiene: Are data of sufficiently high resolution? Is data coverage sufficient?
Threat Risk Analysis	• Is risk defined? • Does the definition of risk include the probability, vulnerability, and consequence of each hazard? • Does the risk analysis use historical data? • Does the risk analysis use forward-looking simulation? • Data hygiene: Are data of sufficiently high resolution? Is data coverage sufficient? • Are customers and communities engaged to determine or validate consequence valuation?
Investments	• Are there investment considerations in multiple categories of investment types? Categories may include vegetation management, overhead hardening, undergrounding, network redundancy, grid modernization, operations, advanced resource planning, forward looking analysis, and non-electric grid physical infrastructure. • Are utility or industry standards used to guide investments?

Investment Prioritization	• Are investments prioritized according to their cost effectiveness? • Does the investment valuation consider multiple objectives that are supported by a single investment? • Do investment decisions reflect feedback from community engagement efforts? • Are investment decisions made in isolation or as part of the regular planning process?

1.2 Takeaways

The following takeaways reflect themes observed among the six utilities reviewed.

- **Preliminary hazard characterizations tend to focus on a single hazard, rather than multiple hazards:** The utilities reviewed in this report are facing intense storms such as hurricanes or nor'easters as their primary threat, but few look at other hazards. However, many of the utilities do characterize different types of storms and qualitatively assess different threats that may be associated with them. Evaluating multiple hazards can expand considerations for intensifying and cascading impacts from overlapping hazards.
- **Utilities use individualized processes for collecting outage information and performing risk assessments; data standardization opportunities exist:** While standards for collecting outage data exist (e.g., IEEE 1782-2022[6]) and for defining risk exist (e.g., ISO 31000[7]), no references were found in the reviewed utility reports. Data standardization can improve information sharing.
- **Standardized nationwide metrics for utility losses and risks from various hazards can benefit from further development:** The Federal Emergency Management Agency's (FEMA's) National Risk Index (NRI) and Expected Annual Loss (EAL) are indicators of the expected risk of natural hazards but do not reflect losses to utility assets or many of the indirect losses to the communities they serve. An alternative metric that uses sufficiently high-resolution data, includes forward-looking considerations, and compares different hazards was not identified. See Appendix B for more information on EAL, opportunities for improvement, and comparisons of EAL by hazard.
- **Attribute metrics are not used to their full potential throughout resilience planning processes:** Some utilities have very advanced modeling and analysis for specific storm types, but these models do not use attribute metrics associated with storm types to help anticipate resilience performance (e.g., hail associated with longer restoration times than rain or heavy winds). We also observe a lack of attribute metrics describing recovery capabilities, which appears to lead to fewer recovery-oriented investments (e.g., mobile substation and transformer fleets).

[6] https://ieeexplore.ieee.org/document/9882080
[7] Grant Purdy, "ISO 31000:2009—Setting a New Standard for Risk Management," *Risk Analysis* 30, no. 6 (2010): 881–86, https://doi.org/10.1111/j.1539-6924.2010.01442.x.

- **There are opportunities to improve performance metrics:** Where investments are made, performance metrics are rarely used to predict or track the effectiveness of those investments in reducing risk.
- **No out-of-the-box tools for forward-looking analysis are available to utilities:** While recording historical data and the use of in-house modeling tools will always be necessary, all utilities could benefit from having an industry-standard, openly available tool to perform storm-focused forward-looking analysis.
- **Utility resilience investment prioritization would benefit from research on the impacts of long duration outages:** We observe several utilities that report customer interruption costs and other performance metrics using methods and data based on short duration outages. The impact of long-duration outages is an important gap in the field, especially how to account for the social and economic consequences of associated cascading impacts.
- **Multi-objective planning is not done by most utilities:** In many of the utility reports reviewed here, utility planning does not include objectives beyond storm resilience which could include clean energy integration, energy justice, equity, or community impacts. DTE Electric and Ponca City do use multi-objective planning principles. DTE Electric targets vulnerable communities for distribution grid investments. Ponca City has a comprehensive but qualitative multi-objective planning and investment prioritization process.

1.3 Utility Selection

Utilities were selected based on the relevance of storms as a hazard for their service territory, availability of published materials regarding utility storm resilience investments, and diversity in the group of utilities selected. Investor-owned utilities (IOU), municipal utilities, and cooperatives were represented in each hazard report. The service territories of these utilities are shown in Figure 2 with their EAL, calculated from the census tract EAL provided by FEMA. We recognize the limitations of the EAL (or any one metric) in accurately capturing storm risk, but we use it here to convey the diversity of included utilities and the risk they face. These comparisons are not intended for utilities to comprehensively assess risk, or to support or oppose the prudence of utility spending. See Appendix B for more information on the EAL metric, opportunities for improvement, and comparisons of EAL by hazard.

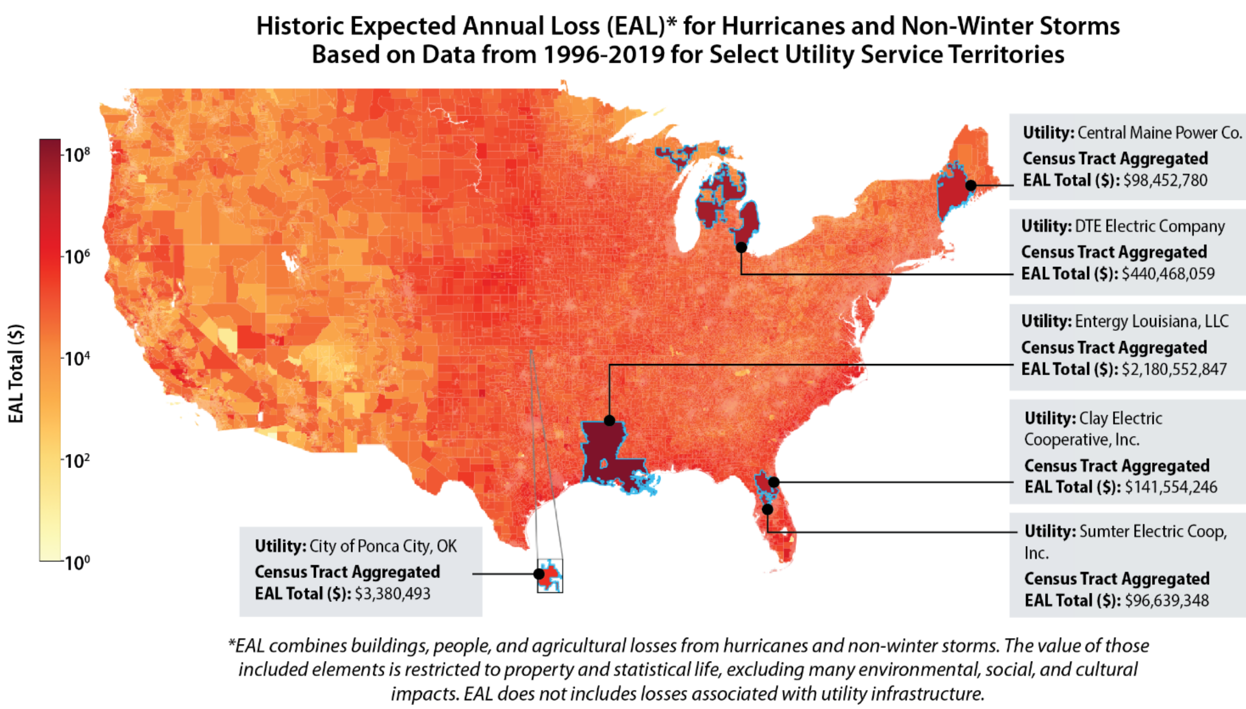


Figure 2. FEMA Expected Annual Loss (EAL) for the U.S.[8] EAL is a relative measure of risk that estimates the average economic loss in dollars resulting from natural hazards each year. The EAL quantifies economic losses from consequences of buildings, agriculture, and people. See Appendix B for more detail.

Context for the storm hazards facing each utility is provided in Table 2. The motivation and context for the resilience reports used as sources in this case study are given in Table 7 in Appendix A.

[8] "Map | National Risk Index," accessed April 7, 2023, https://hazards.fema.gov/nri/map#.

Table 2. Selected utilities, resilience report context, and reported spending. Information here is provided by the utility documents listed in FEMA's NRI and the NOAA Storm Events Database.[9]

Utility	Utility Hazards and Spending
CMP	• CMP reports that storms are increasing in intensity and frequency in CMP's service territory. An average of five major storms per year have occurred in CMP's service territory, each resulting in restoration periods of at least two days and 88,000 customers with service interruptions. CMP defines "major storms" using IEEE Standard 1366.[10] • CMP's territory contains counties with a hurricane risk index in the 83rd percentile and flooding in the 79th percentile. • The year that CMP's report was published, Maine had experienced 48 storm event days documented in the NOAA Events Database. • CMP's Expected Annual Loss (EAL) is $98 million.
Detroit Edison Electric (DTEE)	• DTEE experienced twelve storms (roughly defined as weather impacting at least 25,000 customers), including four CAT-1 storms (110,000 customers impacted), and one CAT-2 storm (220,000 or more customers impacted) in 2018. The storm in 2020 impacted almost 500,000 customers and was one of the largest storms in company history. Their five-year (2018-2022) distribution investment and maintenance plan reflects this experience. • Several of the counties in DTEE's territory have a high-risk index for strong winds, with Wayne County, containing Detroit, in the 100th percentile. Counties in DTEE's territory are also in the 99th percentile for tornadoes, flooding, and lightning. • The year that DTEE's report was published, Michigan had experienced 58 storm event days documented in the NOAA Events Database. These events resulted in 10 injuries. • DTEE's EAL is $440 million.

[9] https://www.ncdc.noaa.gov/stormevents/
"The Storm Events Database contains the records used to create the official NOAA Storm Data publication, documenting:

a. The occurrence of storms and other significant weather phenomena having sufficient intensity to cause loss of life, injuries, significant property damage, and/or disruption to commerce;
b. Rare, unusual, weather phenomena that generate media attention, such as snow flurries in South Florida or the San Diego coastal area; and
c. Other significant meteorological events, such as record maximum or minimum temperatures or precipitation that occur in connection with another event."

[10] IEEE 1366-2022 section 4.5 includes a method for Major Event Day classification.

Entergy Louisiana	• Entergy is impacted by hurricanes in Louisiana, some of which require years of recovery time. • Of all the utilities reviewed, Entergy's territory includes counties with the highest hurricane risk in the 99th percentile. These counties are also in the 100th percentile of risk of riverine flooding and the 99th percentile for tornadoes. • The year that Entergy's report was published, Louisiana experienced 67 storm event days documented in the NOAA Events Database. These events resulted in four deaths and 60 injuries. • Entergy's EAL is $2 billion.
Ponca City, Oklahoma	• Kay County, where Ponca City is located, has experienced 33 major disaster declarations between 1955 and 2021. Many of these include severe storms, heavy rain, flooding, and tornadoes. • Kay County is at the 71st percentile for risk of hail, 68th for flooding, 70th for strong wind, and 93rd for tornadoes. • The year that Ponca City's report was published, Kay County experienced 28 storm event days documented in the NOAA Events Database. • Ponca City's EAL is $3 million.
Sumter Electric Cooperative (SECO)	• Sumter county is at a relatively low risk of flooding with a risk index at the 40th percentile. Sumter has a moderate tornado risk index at the 84th percentile. • The year that SECO's report was published, Sumter County had experienced two storm event days documented in the NOAA Events Database. • SECO's EAL is $97 million.
Clay Electric	• Clay county is at a moderate risk of coastal flooding and riverine flooding with respective risk indices of 63 and 77. Clay has a moderate tornado risk index at the 87th percentile. • The year that Clay Electric's report was published, Clay County had experienced eight storm event days documented in the NOAA Events Database. • Clay Electric's EAL is $41 million.

2 Preliminary Hazard Characterization

In this section, we review the preliminary hazard characterization process for all utilities. Appendix C.1 contains additional details on the preliminary hazard characterization process and Appendix D.1 describes how preliminary hazard characterization is included in different resilience frameworks.

Ponca City is the only utility we observed that performs a complete preliminary hazard characterization, as described in Table 2. Ponca City performed their hazard identification process using historical data, subject matter experts, stakeholder input and hazard risk. They considered dam incidents, drought, earthquakes, extreme heat, fire, flooding, hail, hazardous material, lightning, tornadoes/high wind, severe winter storms, public health, cybersecurity, and electric magnetic pulses.

DTEE, Entergy, and CMP resilience plans include some elements of *Preliminary Hazard Characterization*. For instance, these utilities do characterize different storm types and different threat types that accompany storms. Storms may be separated by category, as is the case for DTEE and Entergy, or type like hurricanes and blizzards, as is the case for CMP. Entergy's storm classification is robust: they use a Major Storm Events database of 49 different storm types, based on historical hurricane data from NOAA. This database is discussed further in Section 4, where it is used for *Threat Risk Analysis*. Table 3 lists the specific threats identified by utilities that could be associated with different types of storms.

DTEE performs plausible scenario planning, suggesting they have considered other hazard types. However, DTEE does not describe the criteria for identifying plausible scenarios and the scenarios are limited to increasing CAT storms and several non-resilience scenarios, such as increased electrification and high adoptions of distributed generation.

In their report, CMP discusses some elements that fall under risk assessment. They note that combinations of threats may be more damaging than these threats in isolation, such as heavy snow and rain accompanied by strong winds. CMP also identifies some initial vulnerabilities of their system, citing their relatively long circuits as a resilience challenge.

Table 3. Storm-related hazards identified in the reviewed utility reports.

Threats (Storm Attributes or Impacts)	Utilities Addressing Threats
Flooding	Clay Electric, DTE, Entergy Louisiana, Ponca City, SECO
Severe/high winds	Clay Electric, DTEE, Entergy Louisiana, Ponca City, SECO
Tornadoes	Ponca City
Hail	Ponca City
Lightning	Ponca City
Heavy, wet snow	CMP
Heavy winds accompanied by rain	CMP

3 Metrics

In this section, we summarize the attribute and performance metrics used by the utilities identified in Table 2.

3.1 Attribute Metrics

We identified attribute metrics detailed in Table 4 used by CMP, Entergy and DTEE. Attribute metrics were not identified in the reports by Ponca City, SECO and Clay Electric. If attribute metrics are not used in a utility's investment prioritization process, this may prevent these utilities from identifying cost-effective solutions for storm-related resilience investments. CMP primarily collects anticipation metrics by using historical data. In addition to anticipation metrics, Entergy and DTEE collect withstand metrics all of which are needed to run the forward-looking threat analysis described in Section 4.2. Attribute metrics describing utilities' ability to absorb and recover from a severe storm are generally lacking and may result in less effective resilience investments in these areas.

Table 4. Attribute metrics identified in the utility reports. Metrics with an asterisk(*) are both performance and attribute metrics.

Utility	Attribute Metrics	Resilience Category
CMP	Storm type of each major storm *Associated restoration costs and customer impacts are also tracked. These are listed in Table 5.*	Anticipate
	Tree-related outages (inside right-of-way), non-storm*	Anticipate
	Tree-related outages (outside right-of-way), non-storm*	Anticipate
	Tree-related outages (inside right-of-way), storm*	Anticipate
	Tree-related outages (outside right-of-way), storm*	Anticipate
	Storm outages (vs. non-storm outages)*	Anticipate
	Pole age	Withstand
Entergy Louisiana	Storm type of each major storm	Anticipate
	Vegetation density	Anticipate
	Substation flooding probability	Anticipate
	Likelihood of Failure (LOF)—LOF is calculated for each asset based on attributes such as vegetation density, actual wind loading versus wind loading standard, and age.	Anticipate
	Overhead structure wind design differential	Withstand
	Asset age	Withstand
	Asset accessibility and terrain	Recover
DTEE	Storm type of each major storm	Anticipate
	Asset age	Withstand
	Major equipment failure	Anticipate
	Expected weather related jobs in 24-hour period	Anticipate
	Recorded wire downs per overhead line mile	Anticipate/Withstand
SECO	Not listed in publicly available documents.	n/a
Clay Electric	Not listed in publicly available documents.	n/a
Ponca City	Not listed in publicly available documents.	n/a

3.2 Performance Metrics

The performance metrics calculated during a storm response are identified and presented in Table 5 for Entergy, CMP and DTEE. Ponca City, SECO, and Clay Electric did not report any performance metrics. A lack of performance metrics will make it difficult to track the effectiveness of their investments. For example, DTEE reports that performance metric tracking helped increase the accuracy of their customer outage restoration estimates from 60% to 87% in 2020, while Entergy tracks the reduction in restoration cost from investments. Entergy and DTEE both track customer interruption costs (CIC), but this performance metric is calculated using Lawrence Berkeley National Laboratory's (LBNL's) Interruption Cost Estimate (ICE) tool, which is currently designed only for outages with durations less than 24 hours.[11] CMP tracks Storm CAIDI, Storm SAIFI, and Storm SAIDI in accordance with major event day definitions in IEEE 1366.

Table 5. Performance metrics identified in the utility reports. Metrics with an asterisk(*) are both performance and attribute metrics.

Utility	Performance Metrics
Entergy Louisiana	Customer Minutes Interrupted (CMI)
	Reduced restoration cost
	CIC – economic cost a customer incurs when they experience an interruption in electricity service. Calculated using LBNL's ICE Tool, which is currently designed only for short duration outages.
CMP	Storm CAIDI – the average time required to restore service during a storm event.
	Storm SAIFI – indicates how often the average customer experiences a sustained interruption over a predefined period of time, during a storm event.
	Storm SAIDI – indicates the total duration of interruption for the average customer during a predefined period of time, during a storm event. MED-SAIDI is a day in which SAIDI exceeds a certain threshold.
	Number of customer impacts (for each major storm)
	Days of customer impacts (for each major storm)
	Total hours of customer impacts (for each major storm)
	Restoration costs, capital (for each major storm)
	Restoration costs, expense (for each major storm)
	Tree-related outages (inside right-of-way), non-storm*
	Tree-related outages (outside right-of-way), non-storm*
	Tree-related outages (inside right-of-way), storm*
	Tree-related outages (outside right-of-way), storm*
	Storm outages (vs. non-storm outages)*

[11] Long duration outages are an expected consequence of hazards considered in resilience planning. There is no single accepted best practice for assigning value to long duration outages. See Madeline Macmillan et al., "Shedding Light on the Economic Costs of Long-Duration Power Outages: A Review of Resilience Assessment Methods and Strategies," *Energy Research & Social Science* 99 (May 2023): 103055, https://doi.org/10.1016/j.erss.2023.103055. for more on addressing this challenge.

DTEE	SAIDI – indicates the total duration of interruption for the average customer during a predefined period of time.
	SAIFI – indicates how often the average customer experiences a sustained interruption over a predefined period of time.
	CAIDI – represents the average time required to restore service.
	CEMI – percentage of customers experiencing multiple interruptions/outages in a calendar year. Provided for 1-10 interruptions.
	CELID – percentage of customers experiencing long interruptions/outages in a calendar year. Provided for 8-, 36-, and 60-hour interruptions.
	MAIFI – indicates the average frequency of momentary interruptions.
	CIC – economic cost a customer incurs when they experience an interruption in electricity service. Calculated using LBNL's ICE Tool, which is currently designed only for short duration outages.
SECO	Not listed in publicly available documents.
Clay Electric	Not listed in publicly available documents.
Ponca City	Not listed in publicly available documents.

4 Threat Risk Analysis

In this section, we review the historical and simulated threat analyses used by the utilities. A clear definition of risk is important for performing threat risk analysis. DTEE, Entergy, CMP, and Ponca City each perform threat risk analysis that includes probability, vulnerability, and consequence, as defined in Appendix C.3 Threat Risk Analysis. SECO and Clay Electric did not define risk or perform any threat risk analysis. Other than Ponca City, which relies on FEMA's Local Mitigation Planning Handbook,[12] we did not identify the use of any threat risk assessment standards or frameworks (e.g., ISO-31000). See Appendix D. Distribution Utility Resilience Frameworks for more information on resilience frameworks.

4.1 Historical Analysis

CMP and Ponca City collect historical data to inform resilience investment decisions. CMP follows a historical threat risk analysis that is similar to the process suggested in EPRI's Distribution Grid Resilience Investment Prioritization Report (see Appendix D. Distribution Utility Resilience Frameworks for more information on this report). CMP also observed that long circuits were a vulnerability and have therefore examined investments in network redundancy (see Appendix C.4 Investments for investment categories and Table 6 for specific investments described in CMP's report). CMP tracks outage causes (e.g., tree-related and storm-related), storm type, days of customer impacts, number of customers impacted, customer outage hours, and restoration costs. CMP uses these historical attribute metrics, information about high-risk

[12] https://www.fema.gov/sites/default/files/2020-06/fema-local-mitigation-planning-handbook_03-2013.pdf

sections of their network, and historically effective investments to inform new resilience investments. For example, they identify their worst performing circuits with a weighted storm SAIFI and prioritize these for hardening (more in Section 6).

Ponca City collects historical data on flooding, high winds, dam incidents hail and lightning to perform a qualitative risk assessment. They use subject matter experts, stakeholder feedback and the intersection of historical threat data with city infrastructure to perform a risk assessment.

DTEE and Entergy also collect historical data, but these are primarily used as inputs to their forward-looking analysis.

4.2 Forward-Looking Analysis

DTEE and Entergy use historical data as inputs to several types of forward-looking analyses that evaluate storm hazards. DTEE compiles weather and outage data from the past 10 years, uses it to identify impactful weather parameters and creates a predictive outage model for 13 different sections in their service territory. A unique feature of DTEE's threat risk analysis tool is that it is also used for near-term storm planning to inform resource positioning. The output from DTEE's model shows how many weather-related jobs different network sections can expect in a 24-hour period, based on forecasted weather conditions. Examples of these weather-related jobs include crew dispatch, updating crew status, damage assessment, and creating notes associated with an event. DTEE also identifies plausible forecasts and impacts in two-day and five-day timeframes. Forecasted weather threats may be classified as high-impact and tracked more closely. This forecast is complemented by a customer outage prediction modeling tool, created in partnership with the University of Michigan-Dearborn.

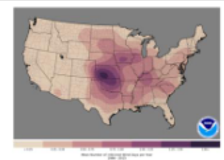
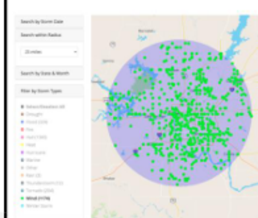
Entergy retrieves historical hurricane records from NOAA to understand the frequency of major storm events, system impacts, and restoration costs. Historical events in different areas of the system were input to create the Major Storms Event Database of 49 different storm types. This database is used to generate scenarios, which are used in Monte Carlo simulations to predict impacted assets and customer outages for 31 different sections of their network. Asset impacts are estimated using the Likelihood of Failure (LOF) attribute metrics described in Table 4. Entergy also uses a "Storm Impact Model" to identify which substations are most likely to experience flooding during major storm events. A unique feature of Entergy's threat risk assessment is that their forward-looking models output restoration cost and CMI[13]. The probability of each storm type and impact are then used to perform a Resilience Benefit Calculation. This feeds directly into investment prioritization, described in greater detail in Section 6.

Ponca City uses the "Simple Planning tool for Oklahoma Climate Hazards"[14] to perform its forward-looking analysis, which is a collection of data sets and tools for assessing various hazards. Each hazard also includes a climate change impact. The result is a set of geospatial maps allowing Ponca City to intersect various hazards with parcels, critical facilities,

[13] This uses the ICE Calculator from LBNL to monetize CMI.
[14] http://www.southernclimate.org/wp-content/uploads/SPTOK.pdf

infrastructure and more. Figure 3 shows an example of these data sets, tools, and climate change trends for Severe Thunderstorm Wind.

Figure 3. Description of data and forecasting resources presented in the "Simple Planning Tool for Oklahoma Climate Hazards" used by Ponca City.

Severe Thunderstorm Wind			
Data Limitations: Population and temporal biases (i.e., greater number of reports in recent decades), a limited number of weather stations that record wind speed, and the fact that severe thunderstorm winds can be very localized, mean that data are not of sufficient quality to robustly determine whether there have been trends over a long period of time (e.g., 100+ years).			
Historical Data	**Severe T-Storm Wind Days Per Year** (1986-2015) NOAA/National Weather Service Storm Prediction Center	This map shows you the average number of days per year in which severe thunderstorm wind reports were received in your area. The map gives you a sense of the approximate number of days each year that you can expect to see severe thunderstorm winds (57 mph or greater) in your area. **1.** Click on the link to access the Oklahoma Climatological Survey's *Tornadoes & Severe Storms* climatology page. **2.** Select *50 Knot Wind Days* or *65 Knot Wind Days*. Tool Link: http://climate.ok.gov/index.php/climate/category/tornadoes_severe_storms	
	Severe T-Storm Wind Reports Wind: (1955-present) Southern Regional Climate Center	This interactive tool shows you the historical record for individual severe thunderstorm wind reports (gust of 57 mph or greater) in your area. It can be used to determine severe thunderstorm wind events that have impacted your area or close to your area. **1.** On left side of screen, click on *Search within Radius*. **2.** Choose the diameter of the area of which you want to investigate (25 or 50 miles). **3.** Select *Wind* (de-select Torn and Hail). **4.** Pan, zoom, and then click on the map area of interest. **5.** Reports are displayed on the map and in two tables below the map. **6.** Map: Mouse over individual storm reports for details. **7.** Tables: There are two tables, *Recent Storm Reports* and *Historical Storm Reports*. Click on column header to sort by column of interest. For example, to view the dates in which the highest wind occurred, click on the *Scale* column headers to sort by the highest wind value. Tool Link: https://www.srcc.tamu.edu/storm_reports/	
	Severe T-Storm Watch Climatology Map (1993-2012) NOAA/National Weather Service Storm Prediction Center	This map shows you a 20-year climatology of severe thunderstorm watches. From this map you can get a sense of the approximate number of days each year you can expect to have a severe thunderstorm watch issued for your county(ies). **1.** Under the *Storm Prediction Center WCM Page* banner near the top of the page, click on the *Watch Frequency Maps* link. **2.** Scroll down a bit until you see *20y SPC Watch Climatology*. **3.** Click on the *average number of severe thunderstorm watches per year* image to view it in larger form. **4.** Note: this WCM page contains a lot of other statistics about the hail, severe thunderstorm, and tornado products that come out of the NWS Storm Prediction Center if you are interested in digging deeper into data. Tool Link: http://www.spc.noaa.gov/wcm/	
Future Trends	Damaging winds in Oklahoma are associated with severe thunderstorms. More favorable environments for severe thunderstorms are expected and increases in severe wind occurrences are projected. Climate models project an increase in the frequency and intensity of severe thunderstorms over the Southern Great Plains, especially during the peak storm season (March, April, May). Uncertainty remains, however, in the assumption that the favorable environments will reach their potential of producing damaging winds (Kossin et al. 2017).		

SCIPP, 2023: *Simple Planning Tool for Oklahoma Climate Hazards v 1.7,* L. T. Kos, R. E. Riley, M. Shafer, and D. Bertrand, eds., Southern Climate Impacts Planning Program, 40 pp,

https://www.southernclimate.org/wp-content/uploads/SPTOK.pdf (p. 18).

5 Investments

Utilities categorize their investments in different ways; these investments generally fit into the categories listed in Table 7 in Appendix C.4. These are the specific actions and infrastructure investments the utility can make to improve system resilience. We categorize these investments as Vegetation Management, Overhead Hardening, Undergrounding, Network Redundancy, Non-Electric Grid Infrastructure, Grid Modernization, Forward-Looking Analysis, Advanced Resource Planning, and Operations. These investments generally fit into the categories listed here and further described in Table 8 in Appendix C.4.

Specific storm-related resilience investments cited by the utility resilience reports are listed in Table 6. This table can also be used to see which investment categories are most common. For example, all reviewed utilities use vegetation management. Most utilities are focusing efforts on overhead hardening and grid modernization; some are investing in operations and undergrounding. Few are considering forward-looking analysis and network redundancy. Advanced resource planning and non-electric grid infrastructure are absent from the documentation of all reviewed utilities.

Table 6. Resilience investments made, considered, or proposed by utilities reviewed and their corresponding investment categories.

Utility	Investment	Category
CMP	Enhanced vegetation management: five-year trimming cycle with targeted additional trimming in "hot-spots." • "Ground-to-sky" clearances, versus the current standard of 8' side clearance, 15' overhead clearance, and 10' of clearance below a conductor. • Increased hazard tree removal (currently under-resourced). Distribution Line Inspections within a year of tree trimming.	Vegetation management
	Tree wire to replace "bare primary conductors with covered conductors capable of withstanding temporary contact with tree branches."	Vegetation management
	Changes to network configuration: increased automated feeder ties and switching capabilities	Network redundancy
	Adding reclosers	Network redundancy
	Adding new lines and circuit breakers to establish new circuits, possibly increasing tie capabilities	Network redundancy
	Voltage conversions or transformers to facilitate power flow between circuits, combined with added circuit ties	Network redundancy
	Diesel generators	Network redundancy
	Upgrading or adding substations	Network redundancy
	Selective undergrounding (will be considered for 2021-2028, excluded from 2019-2020)	Undergrounding
	Distribution automation for isolation of outage (via switches, reclosers, RTUs and other communication technologies)	Grid modernization
	Substation automation	Grid modernization
	Distribution hardening: poles, crossarms, wires, replace poles that are 75 years old or fail inspections	Overhead hardening
	Upgrading lines to 3-phase	Overhead hardening

Entergy Louisiana	Distribution feeder and lateral hardening: Rebuilding structures	Overhead hardening
	Transmission rebuilds	Overhead hardening
	Substation control house roof remediation	Overhead hardening
	Distribution feeder and lateral hardening: Overhead to underground conversion	Undergrounding
	Substation storm surge mitigation	Non-electric grid physical infrastructure
DTEE	Tree trimming	Vegetation management
	Circuit switches	Network redundancy
	4.8 kV hardening (with long-term goal of conversion and consolidation to phase out the 4.8 kV system)	Overhead hardening
	Overhead system equipment replacement	Overhead hardening
	Adoption of National Electric Safety Code Grade B construction (previously Grade C construction) to help account for higher wind loads.	Overhead hardening
	Strategic undergrounding	Undergrounding
	Underground system equipment replacement	Undergrounding
	Mobile fleet investments	Operations
	Outage credits	Operations
	Customer communications about outage status	Operations
	Substation equipment replacement	Operations
	Short cycle maintenance programs for poor reliability circuits	Operations
	Distribution load relief projects (primarily load relief prioritization and consideration of non-wire alternatives)	Operations
	Analysis of the impact of peaking generation on the distribution system	Operations
	Pole and pole-top maintenance and modernization	Grid modernization
	ADMS/distribution and grid automation	Grid modernization
	Installation of fiber backbone communications	Grid modernization
	Underground residential distribution (URD) fault indicators	Grid modernization

Ponca City, OK	Tree trimming (ongoing)	Vegetation management
	Construct lightning rods or air terminals to protect critical infrastructure and schools	Overhead hardening
	Hardening, strengthening, and/or burying electrical infrastructure (ongoing)	Overhead hardening
	Replace existing power supplies in critical facilities	Operations
	Engineering inspection and testing of grounding system and lightning protection of publicly owned communication and water towers (not started)	Operations
	StormReady certification and communication system.[15]	Operations
	NOAA Weather Radio	Operations
	Remote weather cameras (not started)	Grid modernization
	Correction and installation of surge protection (not started)	Grid modernization
	Backup generator testing	Operations/Network redundancy
	Additional weather stations (not started)	Grid modernization
	Backup battery for traffic signals on arterial streets (ongoing)	Grid modernization
SECO	Tree trimming and removal	Vegetation management
	Replacement of transmission and distribution poles/structures	Grid modernization
Clay Electric	Vegetation management for transmission and distribution rights-of-way Mowing, spraying herbicide, systematic recutting	Vegetation management
	Storm hardening research: “Report on Collaborative Research for Hurricane Hardening” provided to Florida’s Public Service Commission (FPSC) by the University of Florida’s Public Utility Research Center	Forward-looking analysis
	Transmission and distribution pole inspections	Hardening/Operations

[15] See https://www.weather.gov/stormready/

6 Investment Prioritization

The investments listed in Table 6 represent some of the possible investments a utility can make to improve non-winter storm resiliency. How utilities select investments varies; considerations found in the reviewed documents include storm risk reduction, utility worker safety, cost, community input, and other multi-objective considerations.

Entergy conducts storm simulations and cost-benefit analyses to optimize investments for resilience-based projects. Their Storm Resilience Model uses a Project Scheduling and Investment model based on Monte Carlo simulations that calculates a resilience benefit-to-cost ratio and any logistical constraints, e.g., contractor and material availability, to prioritize investments.

CMP uses a cost-effectiveness investment prioritization that mirrors EPRI's "Distribution Grid Resiliency Framework." CMP is primarily focused on improving resilience against storms by investing in the worst performing circuits. A cost-effective plan is established for each of these circuits by examining past issues and outages associated with each individual circuit. Costs of circuit-specific projects, in which multiple types of investments are made for each circuit, the feasibility of implementing upgrades in the near-future and expected improvement in SAIFI determine how circuits are prioritized.

DTEE prioritizes investments using their Global Prioritization Model (GPM). The GPM prioritizes investments based on cost-effectiveness relative to various metrics including safety, load relief, regulator compliance, major event risk, reliability and O&M cost avoidance, and reactive capital avoidance, i.e., reduction in capital replacements caused by equipment failure. DTEE's investment selection process also integrates the DOE's Next-Generation Distribution System Platform (DSPx) framework, which describes least-cost best-fit methods as a practical approach for core distribution investments that have many benefits.[16] DTEE has incorporated environmental justice considerations into their GPM by prioritizing vulnerable communities in their GPM. The measures that DTEE has taken to incorporate environmental justice into distribution planning include: 1) use of the State of Michigan's MiEJScreen[17] tool to identify vulnerable communities within DTEE service territory and create a geographic representation of reliability data; 2) an analysis of the reliability performance of vulnerable census tracts versus the system average; 3) community engagement on the subject of distribution planning; and 4) the addition of "Investment in EJ communities" as a new GPM impact dimension.

[16] Joe Paladino, et al., "Modern Distribution Grid Volume I: Objective Driven Functionality" (U.S. Department of Energy, Office of Electricity, November 2019); Joe Paladino, et al., "Modern Distribution Grid Volume II: Advanced Technology Maturity Assessment" (U.S. Department of Energy, Office of Electricity, November 2019); Joe Paladino, et al., "Modern Distribution Grid Volume III: Decision Guide" (U.S. Department of Energy, Office of Electricity, November 2019); Joe Paladino, et al., "Modern Distribution Grid Volume IV: Strategy & Implementation Planning Guidebook" (U.S. Department of Energy, Office of Electricity, November 2019).

[17] "MiEJScreen: Environmental Justice Screening Tool (DRAFT)," accessed November 21, 2023, https://www.michigan.gov/egle/maps-data/miejscreen.

Ponca City performs an informal cost-benefit analysis that is intended to reflect the guidelines created by FEMA.[18] The CBA provides scores of low, medium, and high to incorporate considerations for life, safety, property protection, technical feasibility, political support, and legal authority. This is a qualitative method of prioritization that reflects multi-objective decision-making.

SECO, Clay Electric, and the other Florida utilities began work with the University of Florida in 2011 to develop a more analytical approach for resilience investment prioritization. This work is ongoing.

7 Conclusion

This report analyzes the storm resilience of several utilities according to the resilience components shown in Table 1. Key takeaways are listed in Section 1.2. The utilities that we reviewed varied widely in their size and sophistication, but there are opportunities for improvement for all utilities. Standardized, comprehensive data collection covering each aspect of resilience (i.e., anticipate, withstand, absorb, and recover) can support the creation of attribute metrics that inform historical and forward-looking risk threat analysis. Utilities could benefit from standardized risk analysis approaches, off-the-shelf tools, and estimates of customer interruption costs for long duration outages. Resilience planning can benefit from a more multi-objective approach that is supported and quantified by setting targets for performance metric improvements.

[18] https://www.fema.gov/grants/tools/benefit-cost-analysis

Appendix A. Utility Sources

Our literature reviews focused on one document per utility. We relied on utility interviews to provide additional context and available resources, such as updated documents that were made available during the course of the project. Many utilities do not share all relevant information in public-facing documents.

Table 7. Selected utilities, sources, and resilience report context.

Utility	Source and Document Context
CMP	• CMP's "2019-2020 Resiliency Plan" results from storms experienced in CMP's territory as well as legislation requiring the PUC to assess investor-owned utility resilience efforts and if hardening requirements serve customer interests.
DTEE	• DTEE is the electric generation, transmission, and distribution subsidiary of DTE Energy. • DTEE's 2021 Distribution Grid Plan Final Report is released in coordination with its "Distribution Operations Five-Year (2018-2022) Investment and Maintenance Plan", as required by the Michigan Public Service Commission (MPSC). • DTEE representatives were interviewed and feedback was included. Per the utility's recommendation, we also conducted a targeted review of DTEE's 2023 Distribution Grid Plan for additional information on environmental justice, resilience investments, and investment prioritization.
Entergy Louisiana	• The "Resilience Investment and Benefits Report" was submitted as an exhibit (Exhibit JDD-2) in support of the "Application of Entergy Louisiana, LLC for Approval of the Entergy Future Ready Resilience Plane (Phase I)." It is tracked under Docket U-36625 and will be under review by the Louisiana Public Service Commission until at least January 2024.
Ponca City, Oklahoma	• Ponca City's "2022 Hazard Mitigation Plan Update" is an update to a 2017 hazard mitigation report. The 2022 report was submitted to FEMA as a requirement for the "Building Resilience Infrastructure and Communities Program" (BRIC) and the "Hazard Mitigation Grant Program." • Ponca City representatives were interviewed and feedback was included.
Sumter Electric Cooperative (SECO)	• This report details SECO's storm hardening initiatives as they relate to construction standards, inspection cycles, and vegetation management pursuant to the Florida Public Service Commission Rule 25-6.0343, Florida Administrative Code (FAC) for calendar year 2022.
Clay Electric	• This is a storm outage report submitted to Florida Public Service Commission as required by Rule 25-6.0343, FAC based on their reliability data for calendar year 2022.

Appendix B. Expected Annual Loss Calculation for Utilities

B.1 Definition:

Expected Annual Loss (EAL) total represents the average economic loss in dollars resulting from natural hazards each year. It is calculated for each hazard type and quantifies loss for the following consequence types: buildings, people, and agriculture.[19] The EAL data is from FEMA's National Risk Index (NRI) data resources.[20] The EAL data corresponds to specific threats while a hazard type can consist of multiple threats, e.g., the threats associated with storms can include hail, strong winds, and flooding.

EAL spans a very large range for all hazards reviewed in this series of reports. The average EAL of the service territories reviewed for winter storms are lower than that of wildfires and non-winter storms, but the range of winter storm EALs are comparable to that of other wildfires and non-winter storms. EAL is an indicator of the expected severity of hazards but does not reflect losses to utility assets or revenue.

Several limitations of EAL restrict this metric's ability to capture risk:

- Loss data from 1996 to 2019 is captured to calculate EAL. For many hazards, this dataset does not capture the range of values that has been seen historically. For example, the fire regime of certain areas, such as those west of the Cascades, exceeds this time frame.
- EAL is limited to buildings, people, and agriculture. The value of those included elements is restricted to property and statistical life, excluding many environmental, social, and cultural impacts.
- More precise and accurate modeling can be and has been performed. This can include higher flame length resolution, dead fuel accumulation for wildfires, the incorporation of predictive weather and climate models.

[19] Federal Emergency Management Agency. (n.d.) Expected Annual Loss. Retrieved 11 July 2023 from https://hazards.fema.gov/nri/expected-annual-loss

[20] Zuzak, C., E. Goodenough, C. Stanton, M. Mowrer, A.Sheehan, B. Roberts, P. McGuire, and J. Rozelle. 2023. National Risk Index Technical Documentation. [NRI Shapefile Census Tracts Data] Federal Emergency Management Agency, Washington, DC. Retrieved 9 June 2023 from https://hazards.fema.gov/nri/data-resources#shpDownload

B.2 EAL Calculation by Census Tracts:

Census tracts are small, relatively permanent subdivisions of counties or other similar entities. They are designed to be relatively homogenous with respect to population characteristics, economic status, and living conditions.[21] Accordingly, each consequence type should be relatively uniform across a census tract. Thus, it is reasonable to assume that EAL is distributed uniformly across a census tract for ease of calculation.

The calculation of EAL total for a specific hazard type for utilities is described in two steps below:

- For each census tract, the census tract EAL total is calculated. Census tract EAL total is the sum of EAL total for each threat included in the hazard type.
- For each utility, the EAL total is the sum of a proportion of the hazard type EAL total for each census tract intersection with the utility's service territory. The proportion is a spatial proportion calculated by

$$Service\ Territory\ EAL = \sum_{\substack{\forall\ hazard\ (h),\\ \forall\ census\ tract(ct)}} \left(\frac{area_{st} \cap area_{ct}}{area_{ct}}\right) \times EAL_{ct,h} \qquad \text{[Equation 1]}$$

where *st* denotes a utility's service territory.

[21] U.S. Census Bureau. (1994, November). Geographic Areas Reference Manual, Chapter 10: Census tracts and block numbering areas. Retrieved 11 July 2023 from https://www2.census.gov/geo/pdfs/reference/GARM/Ch10GARM.pdf

Appendix C. Distribution Resilience Framework Components

Utility investments and investment prioritization for several use cases (wildfires, winter storms, and non-winter storms and hurricanes) are evaluated according to common components found in resilience frameworks. Here we define the different components of the framework that will be applied to each hazard case.

C.1 Preliminary Hazard Characterization

Preliminary hazard characterization is a process used by utilities to determine the relative risk of different hazards and to determine where to focus resilience investments. Because there are many hazards, this preliminary hazard characterization tends to be qualitative and based on engineering judgement more than detailed analysis. It is a hypothesis-driven scoping exercise and is designed to inform utilities where more detailed analysis is needed, which is ideally performed with the *Threat Risk Analysis* defined in C.3 Threat Risk Analysis. For some utilities the preliminary hazard characterization is directly related to threat risk analysis and there may not be a clear distinction between these processes. A typical outcome of a preliminary hazard characterization is a categorical label for the risk level associated with different hazards. For example, a utility might perform a climate change risk assessment and determine that rising temperatures carry a "low risk" and increased flooding carries a "high risk." This assessment may lead to a detailed *Threat Risk Analysis* and *Investment Prioritization* to determine cost-effective options for managing flooding.

C.2 Metric Stack

Attribute Metrics

Attribute metrics help characterize systems and describe the ability of utilities to anticipate, absorb, withstand and recover from hazards. Attribute metrics can provide utilities with options to improve their performance metrics. Examples of attribute metrics:

- Percent undergrounded lines
- Right-of-way width (vegetation)
- Asset failure probability

Attribute metrics can be categorized by system's ability to anticipate, withstand, absorb, and/or recover from hazards. These resilience capabilities are further defined as follows:

- **Anticipation** describes the likelihood or nature of an impact due to a hazard. Anticipation metrics can be used to identify improvements in all resilience phases, including the ability to withstand, absorb and recovery more effectively. An example of this is asset ignition probability. They are sometimes referred to as "driver metrics".
- **Withstand** describes a system's ability to avoid impact from a hazard altogether. An example is the percentage of undergrounded lines, which can describe the ability of the lines to withstand strong winds.

- **Absorb** describes the strategic acceptance of hazard impacts. Resilience hubs are one example of an investment that help utilities absorb threats. Resilience hubs may not support normal system operations during a hazard, but they reduce the consequence of the damage incurred by those impacted.
- **Recover** is defined by the phase immediately following a disruptive event. Investments to improve the rate of recovery can be described by attribute metrics such as crew repair time.

The impact of investments to do each of these things is shown in Figure 1. It should be noted that some investments may fall into multiple categories.

Performance Metrics

Performance metrics track a utility's progress towards improvements in its core objectives (e.g., affordability, safety, reliability, resilience, equity). Examples of performance metrics:

- Restoration time
- Crew repair time
- Total number of customers de-energized

Comparing Attribute and Performance Metrics

Some metrics can be described as both attribute and performance metrics. For example, restoration time could be used by regulators to track utility performance during major storms, but it could also be used to describe the system a utility has in place to restore power. If the restoration time is subdivided into different restoration phases (e.g., determining outage locations, travel time, repairs), then utilities would have further actionable information about where to investment and how to reduce overall restoration time.

Performance metrics are more widely used than attribute metrics because they can help utilities and regulators understand if they are meeting their core objectives. However, a shortcoming of performance metrics is that they do not necessarily tell utilities *how* to make improvements. Because attribute metrics characterize systems, they are typically more helpful at determining a set of options for improving performance. Historical and forward-looking threat risk analysis can be used to draw inferences between improvements in attribute metrics through investments and improvements in performance metrics.

C.3 Threat Risk Analysis

Threat risk analysis is the processes that utilities use to identify exposure to threats, including whether their entire territory is exposed to a threat or if there are specific areas that can see a greater impact. There are two categories of analysis, historical analysis and simulations. Historical data can be inputs to simulations.

Examples of historical analysis

- During Superstorm Sandy, which specific substations were impacted, what was the water level, and what was the extent of the damage due to salt water?

Examples of simulation

- Floods: if flooding occurs due to inland precipitation, a simulation can identify which areas will be flooded and what the water level would be.

Historical and forward-looking simulations have different strengths. Historical analysis is based on historical data and impacts, so it offers compelling evidence for making investments. Forward-looking simulations are more speculative, but they provide a broader risk assessment and can account for changing conditions (e.g., climate change) that may not be captured with historical data.

A threat risk analysis examines the components of the risk equation, defined in Equation 2. A threat risk analysis identifies major threat factors and the likelihood of their impact for a particular hazard. A threat risk analysis can characterize the current state of the grid or identify how a component of the risk equation can be manipulated to minimize the risk with potential investments.

$$Risk = Probability\ x\ Vulnerability\ x\ Consequence \quad \text{[Equation 2]}$$

The components of the risk equation and examples of how a threat risk analysis might be applied to each are as follows:

- **Probability** is the likelihood of the occurrence of a hazard.
  - An example of an investment to mitigate risk through reducing probability is reducing recloser shots or using PSPS to minimize the probability of ignition.
- A **vulnerability** in a system has a high likelihood of failure in the event of a hazard.
  - An example of an investment to mitigate risk through reducing vulnerability is undergrounding lines so they cannot be damaged by wind.
- **Consequence** is the impact resulting from a hazard and can include physical impacts such as damage to assets or outages, economic impacts from loss of service or restoration costs, or social impacts from outages or system damages. Social impacts can be validated and informed though community engagement.
  - An example of an investment to mitigate risk through reducing consequence is the use of distribution automation to reroute power to customers during outages on other distribution network assets.

Threat risk models can make use of the performance metrics identified in section 3.2, which can quantify the outputs of the threat risk analyses, and therefore the impact of possible resilience investments. Threat risk analyses take into account the change in risk due to an investment in order to aid in prioritization.

C.4 Investments

These are the specific actions and infrastructure the utility can take to improve system resilience. Depending on the hazard, this could target various levels of utility infrastructure and community support.

Table 8. Utility investment categories and examples of investments that fall into each category.

Category	Examples
Vegetation	Targeted vegetation management Widening right-of-way for lines
Overhead Hardening	Pole materials (e.g. steel poles) Fire wrapping poles
Undergrounding	Targeted undergrounding
Network Redundancy	Split network Adding primary feeder loops within and between networks Ties between exposed substations Ties between exposed distribution networks Additional distribution substations
Non-Electric Grid Physical Infrastructure	Floodwalls at substations Debris booms near fire damaged area More frequent equipment maintenance to mitigate increased equipment wear
Grid Modernization	DER and NWA AMI for targeted load shedding Microgrid formation Automated switching operations Energy storage, on-site generation Resilience hubs
Forward Looking Analysis	Stochastic event analysis Hazard modeling and analysis Debris flow exposure projections Coastal storm exposure projections
Advanced Resource Planning	Mutual Aid Assistance Resilient supply chains
Operations	Training and threat response Emergency drills

C.5 Investment Prioritization

This includes any process to examine the impact of an investment and possibly its cost. Investments can be prioritized by cost, risk reduction, other benefits, or some combination of these investment impacts. Prioritization can be done with the sole objective of hardening a system against a specific threat or can be a part of a multi-objective framework. An investment that supports multiple objectives might support both resilience and other system objectives, such as clean energy or grid equity. In all cases, investment decisions can be informed through stakeholder engagement such as community outreach to evaluate the potential impact of such investments on community well-being.

Appendix D. Distribution Utility Resilience Frameworks

In this section, we review existing resilience frameworks that can be applied to distribution utility resilience planning. These resilience frameworks are ISO 31000,[22] the bowtie method,[23] California's Risk Assessment and Mitigation Phase (RAMP)[24] Avista's "Wildfire Resilience Framework,"[25] Sandia's "Conceptual Framework for Developing Resilience Metrics,"[26] the Western Coalition's "West-Wide Wildfire Risk Assessment" framework,[27] FEMA's "Local Mitigation Planning Handbook[28] and PNNL's "Integrated Resilience Distribution Planning" report.[29] Although not described as a framework, we also include EPRI's "Distribution Grid Resiliency" reports[30] and LBNL's utility case studies on economic impacts from damage to infrastructure during extreme events[31]. Several of these resilience frameworks are shown in Figure 4–Figure 8. This section is not intended as a critique of these frameworks or to inform the development of a new framework. Rather, these frameworks were reviewed to identify similarities and to identify resilience planning components that enable comparisons among utilities. In contrast to the resilience frameworks in Figure 4–Figure 8, we do not focus on workflow, which can provide utilities with valuable insight, such as the iterative nature of resilience planning. We next review the selected resilience components.

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[22] https://onlinelibrary.wiley.com/doi/10.1111/j.1539-6924.2010.01442.x

[23] For the history of this method, see - https://en.wikipedia.org/wiki/Bow-tie_diagram

[24] https://www.cpuc.ca.gov/about-cpuc/divisions/safety-policy-division/risk-assessment-and-safety-analytics/risk-assessment-mitigation-phase/sce-ramp/sce-2022-ramp

[25] https://www.myavista.com/-/media/myavista/content-documents/safety/2023-wildfire-resiliency-report_011923_final.pdf

[26] https://www.energy.gov/oe/articles/conceptual-framework-developing-resilience-metrics-electricity-oil-and-gas-sectors

[27] https://www.thewflc.org/sites/default/files/WWA_FinalReport_3-6-2016-1.pdf

[28] https://www.fema.gov/sites/default/files/2020-06/fema-local-mitigation-planning-handbook_03-2013.pdf

[29] https://gridarchitecture.pnnl.gov/media/advanced/Integrated_Resilient_Distibution_Planning.pdf

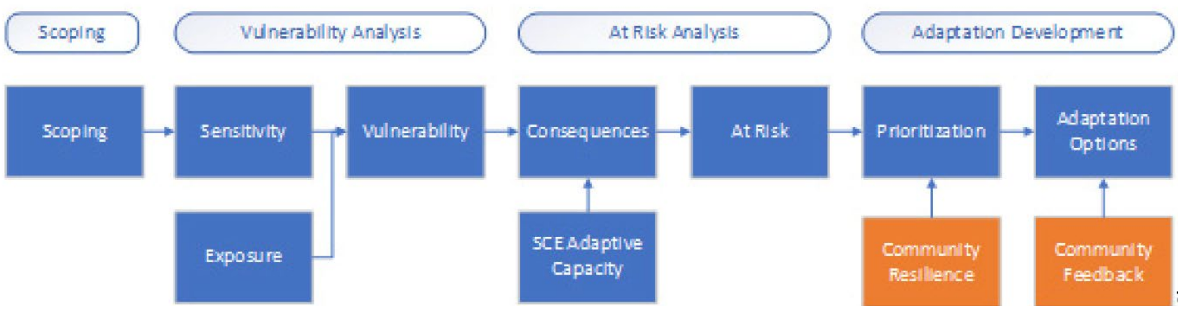
[30] https://eprijournal.com/making-distribution-grids-stronger-more-resilient/

[31] https://emp.lbl.gov/publications/case-studies-economic-impacts-power

D.1 Preliminary Hazard Characterization

The first comparison component is preliminary hazard characterization. This component is useful for utilities that do not yet know which hazards have the greatest risk in their service territory. For example, utilities trying to understand the risks of climate change often perform a preliminary hazard characterization to assess heat waves, precipitation, extreme weather and other climate change risks. This component may also be useful for utilities that may have a sense of which hazards have a high probability of occurrence in their territory, but do not know which of their assets are vulnerable to these hazards. For example, a utility may face an increased risk of flooding, but may need to identify which of their assets are subject to corrosion from salt water. Two utility examples of preliminary hazard characterization are provided by the SCE's Climate Adaptation Vulnerability Assessment (CAVA) reports[32] (Figure 4) and Duke Energy's 2022 interim report on "Climate Risk and Resilience." Duke determines asset vulnerability from exposure to hazards, sensitivity of assets to that exposure, impact from events, and consequences associated with those impacts. This vulnerability then informs resilience planning.

Figure 4. SCE Climate Adaptation Vulnerability Assessment (CAVA), a preliminary Hazard Characterization Framework.



Southern California Edison Company (SCE). 2022. *Climate Change Vulnerability Assessment Pursuant to Decision 20-08-046*. Rosemead, CA: SCE. https://edisonintl.sharepoint.com/:b:/t/Public/TM2/EY7Wy9MCrcVGl7XKg_tczQoBM0k8RKtJhwvWlf6qxlJvbg?e=ptXS0i

We observe preliminary hazard characterization in several of the resilience frameworks. In ISO 31000:2009 (Figure 5), it is described as "Establishing the context" and "Risk Identification." In SCE's bowtie implementation, it is described as "Exposure." Sandia (Figure 6) has phases for "Defining Resilience Goals" and "Characterizing Threats". Task 5 of FEMA's Local Mitigation Planning Handbook is to perform a risk assessment, which includes the hazard identification worksheet.

[32] https://www.sce.com/about-us/environment/climate-adaptation

Figure 5. Adapted from ISO 31000:2009 Risk Management Framework.

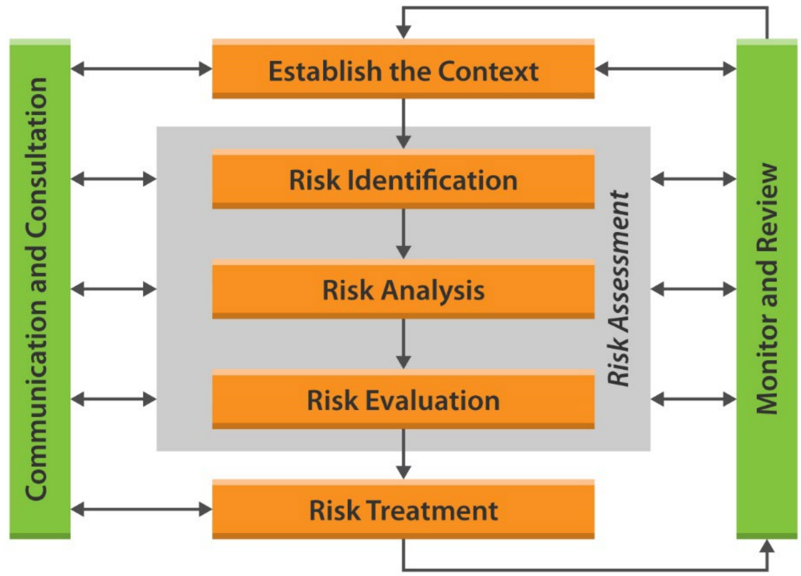
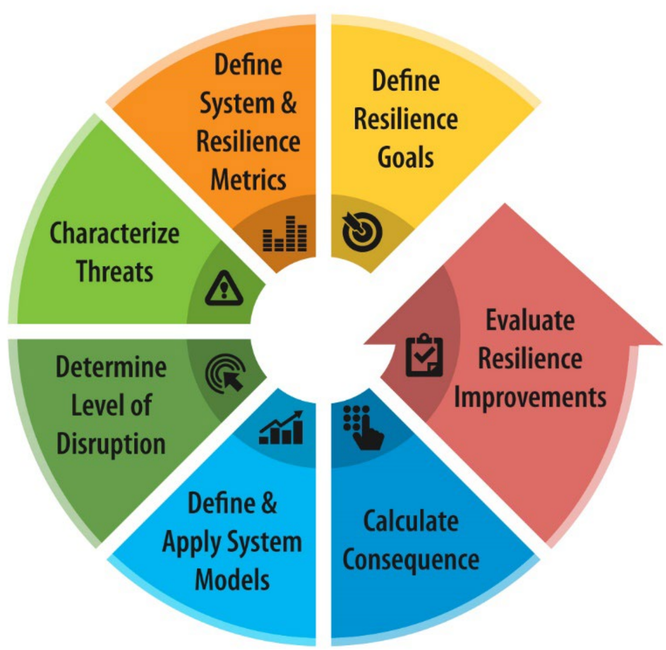


Figure 6. Adapted from Sandia's Resilience Framework.

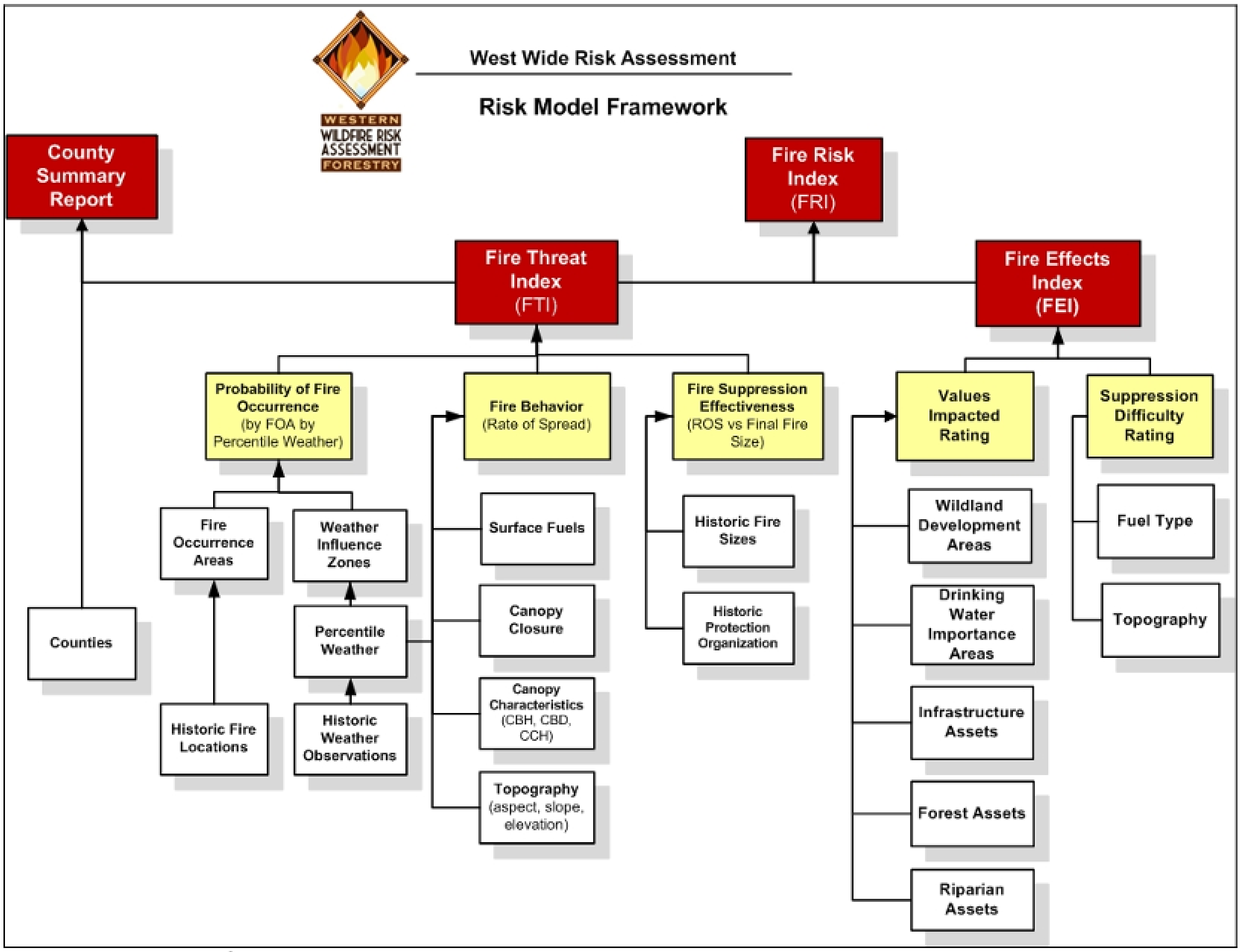


D.2 Attribute and Performance Metrics

The second comparison component is the use of *attribute and performance metrics*. *Attribute metrics* help characterize systems and to describe the ability of utilities to anticipate, absorb, withstand, and recover from hazards. Attribute metrics can provide utilities with options to improve their performance metrics. *Performance metrics* track a utility's progress towards improvements in its core objectives (e.g., affordability, safety, reliability, resilience, equity).

Attribute and performance metrics are less common in the resilience frameworks that we reviewed. Metrics are not mentioned in ISO 31000:2009. While utilities must collect environmental data (e.g., surface fuels) for the "West Wide Wildfire Risk Assessment" resilience framework (Figure 7), power system attribute metrics and performance are not part of the framework. In their "Local Planning Mitigation Handbook", FEMA writes the "planning team may develop a list of metrics to evaluate progress toward goals on an annual basis" but does not elaborate on suitable metrics. In contrast, both attribute metrics and performance metrics are fundamental components of the SCE RAMP. SCE releases a yearly set of performance metrics and the driver metrics shown in Figure 8 that are analogous to "anticipation metrics." Avista describes metrics as important for "understanding the risk" of hazards but appears to focus on performance metrics. Metric development is a fundamental component of the Sandia risk framework. Guidelines for performance metrics are provided, but attribute metrics are not mentioned. Without attribute metrics describing a system's ability to anticipate, withstand, and recover, engineers will have less insight into potential actions to improve performance metrics.

Figure 7. Western Coalition's "West-Wide Wildfire Risk Assessment" framework. Image from the Oregon Department of Forestry.



Oregon Department of Forestry. 2013. *West Wide Wildfire Risk Assessment: Final Report*. State of Oregon, Department of Forestry, https://www.thewflc.org/sites/default/files/WWA_FinalReport_3-6-2016-1.pdf

Figure 8. Bowtie method used in SCE's RAMP report.

Southern California Edison Company (SCE). 2022. *Application of Southern California Edison Company (U 338-E) Regarding 2022 Risk Assessment Mitigation Phase (RAMP)*. Rosemead, CA: SCE, https://docs.cpuc.ca.gov/PublishedDocs/Efile/G000/M476/K640/476640383.PDF

D.3 Threat Risk Analysis

The third component is *Threat Risk Analysis*. Threat Risk Analysis can be performed with historical data and simulations. This is analogous to the "Risk Analysis" and the application of "System Models" described by ISO 31000:2009 and Sandia, respectively. Although threat risk analysis is not mentioned explicitly in the bow-tie method, the SCE RAMP uses simulations extensively to predict wildfire risk. The Avista framework mentions "planning for the probability of events," which could include historical and simulated analysis.

Few of the frameworks we reviewed make a clear distinction between historical and simulated analysis. We make this distinction because each approach has strengths. Historical analysis is grounded in utility experience, which can carry more weight during decision making processes. In contrast, simulations enable forward-looking analysis, which is becoming more important as local weather and climate patterns change. One exception is FEMA. After making suggestions to "Describe Hazards" and "Identify Community Assets, FEMA recommends analyzing the risk of different hazards with historical analysis and using forward-looking scenario analysis where data does not exist, such as for low frequency, high consequence events.

In order to perform a threat risk analysis, a clear definition of risk is needed. We define this as the product of probability, vulnerability and consequence [Equation 1]. ISO 31000:2009 defines risk as "the effect of uncertainty on objectives". This definition is appropriate for an industry agnostic standard but may be too abstract for utility engineers. SCE, Avista, and FEMA consider all elements of risk but use different terminology. Probability and vulnerability are included in the "driver metrics", while "financial", "reliability", and "safety" *consequences* are considered. Avista defines risk as the product of probability and financial impacts; it also makes distinction between "inherent" and "managed" risk, which is analogous to "vulnerability" in our risk definition. The "West-Wide Wildfire Risk Assessment" includes probability in their "Fire threat Index", while vulnerability and consequence are captured by the "Fire Effect Index". FEMA uses "extent" to describe the magnitude of a hazard, "previous occurrences" to estimates probability, "identification of community assets" (i.e., people, economy, built environment, natural environment) to estimate consequence, and "exposure" to describe vulnerability.

D.4 Investment Considerations

The fourth component is the consideration of variety of resilience investments. This component is not mentioned by the ISO 31000:2009, Avista, and bowtie resilience frameworks, but it is often included in resilience reports. The FEMA Local Mitigation Planning Handbook discusses mitigation options but specific investments are not suggested and the handbook's scope is not specifically targeted for electric utilities. In their distribution grid resilience reports, EPRI covers different investment options extensively. These resilience investment options include overhead structures, vegetation management, undergrounding, modern grid technology and storm response practices. We adopt some of several of these categories in Table 8.

D.5 Investment Prioritization

The fifth component is investment prioritization that 1) identifies cost-effective investments for minimizing risk, or applies cost-benefit analysis 2) is integrated into existing planning processes, and 3) considers multiple utility objectives. Investment prioritization is not mentioned by ISO 31000:2009, Avista, bowtie, Sandia, the “West-Wide Wildfire Risk” frameworks. However, it is a fundamental component of the EPRI Distribution Grid Resilience report, the PNNL “Integrated Resilience Distribution Planning” report, SCE’s RAMP, FEMA’s Local Mitigation Planning Handbook and LBNL’s case studies. The integration of resilience planning processes into existing planning processes and consideration of multiple objectives within a “cost effectiveness” framework is also integral to the PNNL “Integrated Resilience Distribution Planning” report.

Although CBAs are an effective way to investment prioritization, they can be challenging to implement. LBNL examined the ability of seven utilities (Florida Power & Light, Con Ed, AEP Texas, CenterPoint Energy, SDG&E, Unitil Energy Systems, Inc. of New Hampshire, and BGE of Maryland) to prioritize resilience investments using cost benefit analysis. While most utilities are able to collect costs associated with extreme events, few estimate the economic and societal benefits of avoided outages. LBNL found that CBAs were only performed in New York, Texas and Maryland, but the benefits were based on short duration outages and did not include long duration outage costs. LBNL writes “The case studies indicate a clear need to develop new estimates of avoided economic impacts of power interruptions on residential, commercial, and industrial customers as well as the broader economy.” CBAs can be challenging to conduct due to the lack of avoided cost estimates for long duration outages and the difficulty of valuing some utility objectives (e.g., equity). In their Integrated Distribution Planning Framework, PNNL recommends a cost-effectiveness analysis that is based on stakeholder input to prioritize investments based on “value-spend” efficiency scores. All FEMA grants require FEMA-approved CBA and provide a CBA toolkit. FEMA also recognizes that communities “face challenges with demonstrating cost-effectiveness of their projects”[33] and offers a variety of alternative CBA methods and “streamlined” methods for predefined investments.

[33] https://www.fema.gov/sites/default/files/documents/fema_alternative-cost-effectiveness-methodology-for-FY2022-BRIC-and-FMA.pdf

Background on GDO

The U.S. Department of Energy's Grid Deployment Office (GDO) works to provide electricity to everyone, everywhere by maintaining and investing in critical generation facilities to ensure resource adequacy and improving and expanding transmission and distribution systems. Working in strong partnership with energy sector stakeholders on a variety of grid initiatives, GDO supports the resilience of our Nation's electric system and deployment of transmission and distribution infrastructure. GDO's priority is to develop and deploy innovative grid modernization solutions to achieve the Administration's clean energy goals and mitigate climate change impacts while ensuring the availability of clean, firm generation capacity, like hydropower and nuclear energy.

GDO's works to make sure all communities have access to reliable, affordable electricity by leveraging unique authorities to:

- Improve resource adequacy by maintaining and investing in critical generation facilities
- Support the development of nationally significant transmission lines
- Drive transmission investment

Background on National Renewable Energy Laboratory

The National Renewable Energy Laboratory (NREL) is the U.S. Department of Energy's primary national laboratory for renewable energy and energy efficiency research. From scientific discovery to accelerating market adoption, NREL deploys its deep technical expertise and unmatched breadth of capabilities to drive the transformation of our nation's energy resources and systems. NREL's innovations span the spectrum of clean energy, renewable electricity, and energy efficiency. The laboratory is home to three national research centers—for solar, wind, and bioenergy—and several programs that advance cutting-edge research in areas such as strategic energy analysis and energy systems integration. At NREL, we are transforming energy.

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Current Practices in Distribution Utility Resilience Planning for Hurricanes and Non-Winter Storms

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