Current Practices in Distribution Utility Resilience Planning for Wildfires

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Authors

Jeremy Keen, National Renewable Energy Laboratory (NREL)

Reiko Matsuda-Dunn, NREL

Gayathri Krishnamoorthy, NREL

Haley Clapper, NREL

Lila Perkins, NREL

Laura Leddy, NREL

Nick Grue, NREL

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List of Acronyms

AI	Artificial Intelligence
CAVA	Climate Adaptation and Vulnerability Assessment
CBA	Cost Benefit Analysis
CEMI	Customers Experiencing Multiple Interruptions
CPUC	California Public Utility Commission
DEI	Diversity, Equity, and Inclusion
EAL	Expected Annual Losses
FEMA	Federal Emergency Management Agency
GRC	General Rate Case
HECO	Hawaiian Electric Company
HFRA	High Fire Risk Area (used in California)
HFRZ	High Fire Risk Zone (used by PGE)
IEEE	Institute of Electrical and Electronics Engineers
IOU	Investor-Owned Utility
ISO	International Organization for Standardization
kV	Kilovolt
LiDAR	Light Detection and Ranging
MTCO2	Metric Tons of Carbon Dioxide
NESC	National Electrical Safety Code
NRI	National Risk Index
PG&E	Pacific Gas & Electric
PGE	Portland General Electric
PSPS	Public Safety Power Shutoff
RAMP	Risk Assessment and Mitigation Phase (used in California)
REFCL	Rapid Earth Fault Current Limiter
SCE	Southern California Edison
S-MAP	Safety Model Assessment Proceeding
SPD	California Safety Public Division
UAS	Unmanned Aerial System
USFS	United States Forest Service

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 identified in existing resilience frameworks. The focus of this report is on wildfires. Standalone reports focusing on *severe storms* (including hurricanes and non-winter storms) 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 in 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, 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 effects 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.

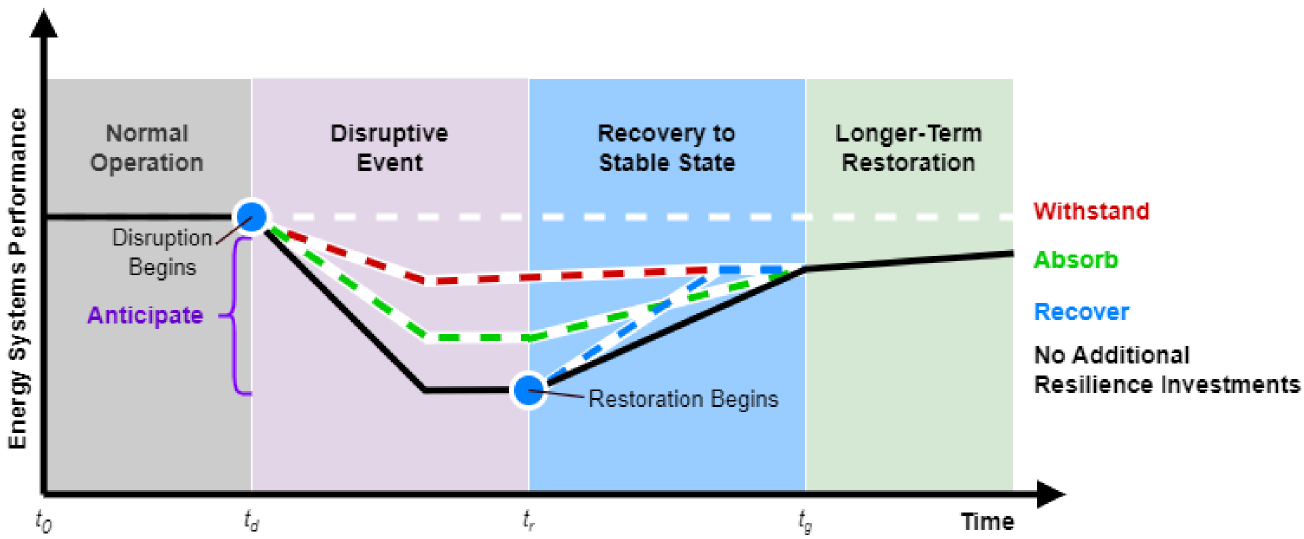

Figure 1. System resilience curves for the effects of investments to withstand, absorb, recover, or anticipate. Investments to withstand result in the system performance avoiding some impacts altogether, while not necessarily improving recovery rates. Investments to absorb the impact of an event will 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 Metrics* 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 type? 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?

Takeaways

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

- **Wildfire resilience plans are relatively advanced:** Wildfire resilience plans are advanced compared to utility resilience plans for other hazards. Several utilities are highlighted in this report that have resilience plans with many of the identified resilience components. We have not observed other hazards with the same degree of utility resilience planning. This might be a response to the role power system equipment can play as a source of ignition. The California Camp Fire of 2018, for instance, was attributed to ignition from a PG&E transmission line and is often cited in utility wildfire resilience reports.
- **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 severity 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.
- **There are opportunities to improve attribute metrics:** Utilities have many anticipation metrics incorporated into their wildfire resilience strategies, but fewer metrics that can characterize the system's ability to absorb, withstand and recover. Relatively few metrics were identified in the reviewed utility documents that capture the long-term consequence of smoke, environmental damage, and cascading hazards (e.g., mudslides) caused by

wildfires. PGE does use metrics related to social vulnerability and post-fire life safety impacts in its wildfire risk assessment process.[6]

- **There are opportunities to improve performance metrics:** Most performance metrics focus on the number of Public Safety Power Shutoff (PSPS) events, with an emphasis on utility-caused wildfires. A standardized set of performance metrics allowing comparison of utility performance (e.g., a wildfire SAIDI) does not yet exist. Utilities should consider tracking more metrics directly related to social impacts (e.g., homes lost) and that are agnostic to wildfire cause. For example, in its 2023 Wildfire Mitigation Plan, PGE added several social vulnerability variables related to poverty, vehicle access, and English as a second language.
- **Utilities are not following data collection standards:** Metric quality may be limited if data collection is not granular or consistent enough. SCE is the exception, as data reporting standards and publication of an ignition database are required by the CPUC.[7] IEEE 1782[8] is an example of a data collection standard that utilities could reference.
- **Utilities follow processes to systematically manage risk:** PGE is using ISO 31000[9], an industry-agnostic risk framework created with the input of hundreds of risk management experts. SCE is using S-MAP, which is required by the CPUC to understand how utilities are prioritizing and mitigating risk through investments. Utilities are also working with third parties to evaluate their system resilience plans and develop investment guidelines.
- **Many utility threat risk analyses are focused on preventing utility-caused wildfires:** This approach will increase resilience through improved anticipation but may lead to blind spots in a utility's ability to withstand, absorb, and recover from wildfires caused by other factors. Utilities may benefit from knowledge sharing of tools that are agnostic to wildfire cause, such as N-k wildfire continency analysis.
- **Tools exist to manage wildfire risk:** Simulations can help utilities improve data collection, define risk, and evaluate changes to risk due to changing conditions or investments. State-of-the-art tools use Monte Carlo simulations and machine learning. Some utilities have developed tools in-house, and others leverage the expertise of third-party vendors. While the development of these tools is important, they have not yet been assessed for accuracy.

[6] PGE cited the following documents as having helped inform its consequence modeling:

- California Council on Science and Technology, 2020, *The Costs of Wildfire in California: An Independent Review of Scientific and Technical Information*, Sacramento, CA.
- Wang, Daoping, Dabo Guan, Shupeng Zhu, Michael Mac Kinnon, Guannan Geng, Qiang Zhang, Heran Zheng et al., 2021, "Economic footprint of California wildfires in 2018." *Nature Sustainability* 4 (3): 252-260, https://doi.org/10.1038/s41893-020-00646-7.

[7] "Safety Performance Metrics Reports," accessed April 7, 2023, https://www.cpuc.ca.gov/about-cpuc/divisions/safety-policy-division/wildfire-and-safety-performance/safety-performance-metrics-reports.

[8] "IEEE Std 1782-2022 (Revision of IEEE Std 1782-2014) IEEE Guide for Collecting, Categorizing, and Utilizing Information Related to Electric Power Distribution Interruption Events," 2022.

[9] 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.

- **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.
- **There are opportunities to improve resilience investment prioritization:** In general, investment prioritization can be more integrated into utility planning processes and consider multiple objectives, such as equity, community impacts, and clean energy integration.

1.2 Utility Selection

Utilities were selected based on their wildfire risk profile, availability of published materials regarding utility wildfire 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 wildfire 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.

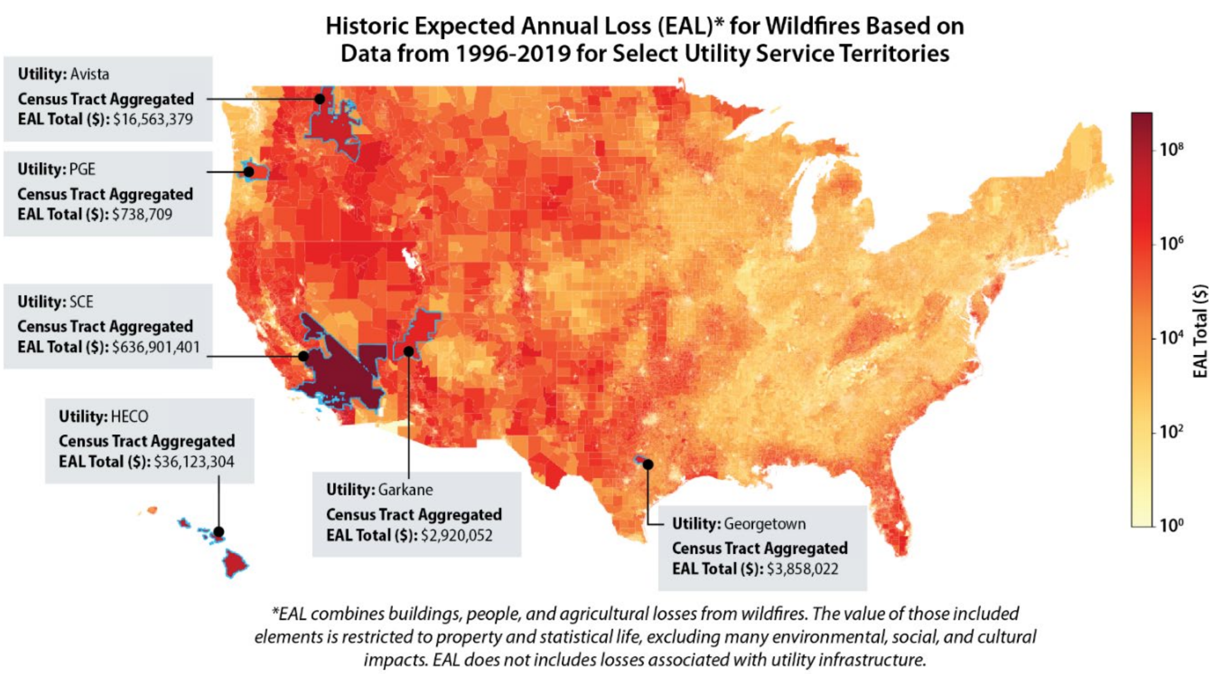

Figure 2. FEMA Expected Annual Loss (EAL) for the U.S.[10] EAL is a relative measure of risk that estimates the average economic loss in dollars resulting from natural hazards each year. The EAL quantifies economic losses from consequences of buildings, agriculture, and people. See Appendix B for more detail.

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

Context for wildfire 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 6 in Appendix A.

Table 2. Selected utilities, resilience report context, and reported spending. Information here is provided by the utility documents listed in Table 6 and FEMA's NRI.

Utility	Utility Hazards and Spending
Southern California Edison (SCE)	• SCE's Risk Assessment and Mitigation Phase (RAMP) report proposes an investment of $5.2 billion in wildfire mitigation for 2025-2028. • California IOUs such as SCE adhere to wildfire-specific standards put forth by the CPUC. Multiple wildfires in California have been attributed to power grid equipment, and SCE's territory encompasses counties with the highest wildfire risk index in the U.S. EAL for SCE's service territory is approximately $637 million.[11]
Portland General Electric (PGE)	PGE's wildfire mitigation investment costs are $15.1 - $27 million in capital expenses and $23.6 million in operation and maintenance for 2023. Forecasted capital investment costs are approximately $43-$49 million for 2024, $54-$74 million for 2025, and $59-$75 million for 2026. Forecasted operations and maintenance costs are approximately $45 million for 2024, $46 million for 2025, and $40 million for 2026.[12] • PGE serves counties in the 96.3 to 98.6 percentile of wildfire risk index. Portland and the surrounding areas are heavily vegetated with steep topography, making the service area prone to rapidly spreading fires. Wildfires are not new to Oregon, but they have increased in severity in recent years. EAL for the PGE's service territory is $739 thousand.[13]
Avista	• Avista's Wildfire Resiliency Plan highlights $269 million in capital expenses and $60 million in operating expenses from 2020-2029. Current figures from interviews with Avista project that spending for 2020-2029 will be closer to $410 million. • Avista, in eastern Washington and northern Idaho, has a lower wildfire risk (37^{th}-81^{st} percentiles) than many of the other utilities included in this report, but is anticipating increased likelihood of wildfires. During the firestorm of 2019, Avista's service territory experienced wildfires caused by line contact with vegetation. Avista is working with California utilities and monitoring wildfire mitigation efforts in California, but it is not implementing all of the same measures, such as PSPSs, at this time. EAL for Avista's service territory is $16.6 million.

[11] EALs are available at the county level. Utilities often serve a portion of a county.
[12] https://edocs.puc.state.or.us/efdocs/HAD/um2208had171425.pdf.
[13] In utility interviews and correspondence, PGE noted it does not view this EAL as accurate for its service territory.

Hawaiian Electric Company (HECO)	• HECO is currently seeking the approval of $190 million in resilience investments. This is not isolated to wildfire mitigation but includes all hazards examined in their application to the PUC. • In August 2023, the Lahaina Fire devastated communities in Maui County, leaving at least 99 people dead and an estimated $5.5 billion in damage, making it the deadliest wildfire in the U.S. in over a century.[14,15] The wildfire risk index of the Hawaiian Islands has a large range from relatively low in Kauai (74th percentile) to relatively high on the island of Hawaii (97.6). The frequency and severity of wildfires have increased in recent years. EAL for HECO's service territory is $36 million.
City of Georgetown Electric Utility	• Costs directly associated with electric utility wildfire mitigation are $25 thousand per year for tree trimming. Some of this may be managed by different organizations, including Parks and Recreation and Public Works. • The wildfire risk index of Williamson County is 94.2% and EAL is $3.9 million.
Garkane Energy Cooperative (GEC)	• Planned resilience spending was not provided in the wildfire protection plan reviewed. • The wildfire risk indices range from the 1.91 – 95.7 percentiles, and total EAL in Garkane is $2.9 million.

2 Preliminary Hazard Characterization

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

We identified preliminary hazard characterization in several of the reviewed utility reports. Both SCE and HECO have conducted this characterization as part of a climate adaptation effort. In contrast, Georgetown performed a preliminary hazard characterization prompted by recent federal disaster declarations in Williamson County. The *Preliminary Hazard Characterization* can then be used to focus the *Threat Risk Analysis* (Section 4) on hazards with the greatest risk. The reviewed documents did not point to any preliminary hazard characterization by PGE or Garkane, but PGE confirmed in utility interviews and correspondence that it has a long-established history of all-hazard monitoring, threat, and risk analysis. More information on PGE's process is included below.

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[14] "Maui County police find additional remains, raising Lahaina wildfire death toll to 99". *ABC News.* The Associated Press. Accessed October 21, 2023. https://abcnews.go.com/US/wireStory/maui-county-police-find-additional-remains-raising-lahaina-104187687

[15] National Centers for Environmental Information; National Oceanic and Atmospheric Administration (September 11, 2023). "U.S. Billion-Dollar Weather and Climate Disasters 1980-2023". United States Department of Commerce. https://www.ncei.noaa.gov/access/billions/events.pdf

Each utility's preliminary hazard characterization considered a variety of hazards. Examples of PGE hazard assessments have included (but are not limited to) wildfires, storms (both winter and non-winter), and cybersecurity attacks. SCE assessed five hazards on timeframes ranging from 2030-2070. These hazards were rising temperatures, sea level, precipitation, wildfires and cascading impacts. HECO focused on hurricanes, earthquakes, tsunamis, volcanos, wildfires, and physical and cyberattacks in their service territory. Georgetown's characterization included wildfires, dam failure, drought, erosion, extreme heat, flood, hail, high winds, infectious disease, lightning, severe thunderstorms, space weather, tornados, and winter weather.

All-hazards analysis is not a direct scope item for PGE's WMP and was thus not found in the plans we reviewed, but PGE representatives noted factors that inform utility hazard prioritization include (but are not limited to) regulatory response, societal and political concerns, and asset information.[16] SCE and Georgetown prioritize hazards by their associated risk, while HECO conducts hazard characterization through a stakeholder-driven decision-making process. HECO's Resilience Working group considers the probability of each hazard at different levels of "severity" (a term referring to both the consequence and vulnerability associated with the hazard). HECO's initial hazard identification is followed up with deeper analyses to determine consequence. SCE combines probability with vulnerability, after which they examine the consequence of a vulnerable asset's exposure. Georgetown's characterization process includes a public community survey to understand how hazards impact businesses and residents, accounting for consequence in characterizing the risk of each hazard. Hazards are prioritized through ranking by the preparedness committee.

3 Metrics

In this section, we summarize the attribute and performance metrics identified in these reports.

3.1 Attribute Metrics

HECO, PGE, SCE, and Avista use attribute metrics, as shown in Table 3. The anticipation metrics have the most representation and are used by SCE and PGE threat analyses to predict wildfire risk and inform PSPS events. Fewer withstand, absorb and recovery metrics are reported.

[16] PGE representative, personal communication, October 27, 2023.

Table 3. Attribute metrics identified in the utility reports. Metrics with an asterisk(*) are both performance and attribute metrics.

Utility	Attribute Metrics	Resilience Category
PGE	Asset age, location, condition	Anticipate
	Asset density by HFRZ	Anticipate
	Asset failure probability	Anticipate
	Asset ignition probability	Anticipate
	Fire probability estimate based on weather, vegetation	Anticipate
	Probability of exceeding manual control	Anticipate
	Ignition Potential Index (function of wind speed, fuel dryness, and heat per unit area)	Anticipate
	Extreme burn probability	Anticipate
	Real-time air quality monitoring and alarming for PGE employees[17]	Anticipate/Withstand
	USFS Wildfire Risk to Communities by HFRZ	Anticipate
	Wildfire Threat Index (product of Conditional Ignition Potential Index, Conditional Impact, and weighted Weather Type Probabilities)	Anticipate/Withstand
	Road condition vulnerability	Anticipate/Withstand
	Population at risk from PSPS Events*	Anticipate/Withstand
	Percent households 200% below federal poverty line by HFRZ	Anticipate/Withstand
	Household disability composition by HFRZ	Anticipate/Withstand
	Hispanic or Latino by HFRZ	Anticipate/Withstand
	Age 65+ by HFRZ	Anticipate/Withstand
	Housing/transportation vulnerability by HFRZ	Anticipate/Withstand
	Overall social vulnerability by HFRZ	Anticipate/Withstand
	Ecological and cultural vulnerability, critical habitats by HFRZ	Anticipate/Withstand
	Cultural/historical/protected areas by HFRZ	Anticipate/Withstand
	Wildland-urban interface by HFRZ	Anticipate/Withstand

[17] PGE also provides these air quality data for free through its weather network vendor (PGE representative, personal communication, October 27, 2023).

	Fire Response Time*	Withstand/Recover
	Fire station within 5 minutes by HFRZ	Withstand/Recover
	Access/egress road density by HFRZ	Anticipate/Withstand/Recover
	Outage history by HFRZ*	Anticipate/Withstand/Recover
	Fire Detection Probability*	Recover
SCE	T&D Wires Down Frequency	Anticipate
	Probability and consequence associated with all identified wildfire drivers	Anticipate
	Circuit miles of distribution infrared inspections	Anticipate
	Faults in HFRA – measure changes in rate of fault events which are precursor to both ignition and safety events*	Anticipate
	Wire Down Incidents in HFRA – measure changes in rate of wire down events*	Anticipate
	Number of 230 and 500 kV transformers that meet the IEEE seismic standard	Anticipate/Withstand
	Circuit miles of distribution conductor upgrade/replaced	Withstand
Avista	Number of pole fires[18]	Anticipate
	Annual distribution system risk tree inspection miles	Anticipate
	Distribution system vegetation remote sensing miles photographed	Anticipate
	Distribution system tree fall ins*	Anticipate
	Distribution system tree grow ins*	Anticipate
	Distribution pole fires*	Anticipate
	Fire mode ready reclosers installed	Anticipate/Withstand
	Fire Safe distribution reclosers installed	Anticipate/Withstand
	Substation fire safety mode breakers installed	Anticipate/Withstand
	Distribution grid hardening miles completed	Anticipate/Withstand
	Distribution system risk trees removed	Anticipate/Withstand
	Safe tree program tree removals	Anticipate/Withstand
	Fuel reduction grant and agreement acres	Anticipate/Withstand

[18] For example, see - https://www.myavista.com/connect/articles/2018/09/fire-on-the-pole#:~:text=What%20should%20you%20do%20if,the%20fire's%20ability%20to%20persist.

	Number of fires within 200 meters of Avista facilities	Recover
HECO	Relative humidity to determine wildfire potential	Anticipate
	Wind speed to determine wildfire potential	Anticipate
	Precipitation levels	Anticipate
	Drought conditions (data from the National Integrated Drought Information System)	Anticipate
	Ignition density (data from the Pacific Fire Exchange)	Anticipate
	Number and percentage of critical customers benefiting from circuit hardening	Anticipate/Withstand
	Type and condition of vegetation on perimeter of substations in potential wildfire areas	Anticipate/Withstand
	Proximity of residents	Anticipate/Absorb
	Significant voltage imbalances	Recover
	Accessibility for fire response	Recover
GEC	Not listed in publicly available documents.	n/a
City of Georgetown	Keetch Byram Drought Index (KBDI) which relates current and recent weather conditions to potential fire behavior	Anticipate

3.2 Performance Metrics

Table 4 shows the metrics that each utility is using to measure wildfire resilience performance. Of the utilities included in this report, only PGE and SCE calculate electric grid performance metrics for wildfires. California utilities release performance metrics reports yearly and implement suggestions from the California SPD evaluations.[19] HECO's report identifies tiers of customers that represents the stakeholders' views of the prioritization of customers with the greatest need to be returned to service quickly. The report notes that further refinement is needed to develop transparent and objective criteria for identifying critical customers, and based on interviews with utility representatives, HECO is in the process of implementing the use of these tiers in prioritizing resilience efforts.

All the reviewed utilities could improve their performance metrics by more fully integrating metrics agnostic to wildfire cause and that relate directly to societal consequences. PGE does consider societal consequences, especially through metrics related to burn probability and social vulnerability. Georgetown also tracks several non-electric grid performance metrics, such as homes lost, that are directly related to the societal consequences of wildfires. HECO

[19] "Safety Performance Metrics Reports," https://www.cpuc.ca.gov/about-cpuc/divisions/safety-policy-division/wildfire-and-safety-performance/safety-performance-metrics-reports

discusses the development of performance metrics that are agnostic to wildfire cause (e.g., long duration outage), but these are not currently adopted.

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

Utility	Performance Metrics
PGE	Fire Detection Probability*
	Fire Response Time*
	Population at risk from PSPS Events*
	Outage history by HFRZ*
	Carbon emissions from wildfires in metric tons of carbon dioxide MTCO2
	Aerosol impacts by land acres
SCE	Faults in High Fire Risk Areas (HFRA) – measure changes in rate of fault events which are precursor to both ignition and safety events*
	Wire Down Incidents in HFRA – measure changes in rate of wire down events*
	CPUC reportable ignitions in HFRA – measure changes in rate of ignitions between years
	Total number customers de-energized – measure the scale of impact of outages due to PSPS to customers
	Average duration of de-energization in PSPS – measure the magnitude of the effect
	% customers notified prior to a PSPS event – measure success rate of notification
Avista	Distribution system tree fall ins*
	Distribution system tree grow ins*
	Distribution pole fires*
	Overhead equipment failure
	Distribution system spark events
HECO	Outage duration categorized by short and long duration, and by customer criticality. Customer criticality refers to customers that are essential for or support national security, public safety and health, or power system restoration.
	Time to restoration for customers experiencing extended outages, by customer criticality
	SAIDI and SAIFI both performance benchmarks mandated by the Hawaii PUC
GEC	Not listed in publicly available documents.
City of Georgetown	Acreage burned
	Homes and structures lost
	Injuries and fatalities

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. Of the utilities reviewed in this document, only PGE, SCE, and GEC threat analyses are guided by resilience frameworks. PGE follows the ISO-31000 and ISO-55000 risk framework. SCE follows a risk informed planning framework created in California's S-MAP agreement. GEC follows the Western Coalition's "West-Wide Wildfire Risk Assessment" framework.[20] Each of these frameworks includes the probability, vulnerability, and consequence risk components that we define in Appendix C.3.

4.1 Historical Analysis

PGE, SCE, and GEC perform site-specific wildfire risk assessments based on terrain, surface fuels, and historical weather. PGE and SCE assessments also include asset-specific, ignition tracking data collection systems with real-time weather monitoring to estimate fire risk. IEEE 1782 was developed to guide utilities in the collection and categorization of information related to interruption events but was not referenced in these data collection systems. SCE has committed to making their data public in its Wildfire Safety Data Mart and Portal (WiSDM). Currently, GEC and Georgetown rely solely on historical weather and fire data to inform their wildfire risk analysis. Georgetown has a small service territory, so it does not identify site-specific variations in wildfire probability, but it does identify variations in wildfire vulnerability and consequence, especially along its wildland urban interface. Avista uses data from the U.S. Department of Agriculture along with wind direction and fuel type data to identify structures that could be impacted by a fire ignition at a given location (see Forward-Looking Analysis below).

4.2 Forward-Looking Analysis

There are many tools publicly available[21] to estimate wildfire risk if a utility has sufficient input data. PGE and SCE use Monte Carlo simulations and machine learning models, respectively, to estimate wildfire risk. These utilities enact Public Safety Power Shutoff (PSPS) events based on wildfire risk, which includes the probability, vulnerability, and consequence of an event. PGE and SCE also consider the risk of PSPS events separately. PGE uses a tool developed by 'Pyrologix'[22] to perform their risk modeling, and SCE uses a tool developed by 'Technosylva'[23] and SimTable[24]. An analytical gap of these tools is that they focus on utility-caused wildfire propensity (i.e., resilience anticipation) and less on withstanding or recovering from wildfires. HECO is starting an effort to develop wildfire risk models. GEC and Georgetown do not use simulations, which will limit their ability to understand how specific investments can reduce wildfire risk. The static score that Avista calculates as part of their historical analysis is used as an input into an algorithm that takes numerous dynamic factors to output an overall risk score

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

[21] Richard D. Stratton, "Guidance on Spatial Wildland Fire Analysis: Models, Tools, and Techniques" (Ft. Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 2006), https://doi.org/10.2737/RMRS-GTR-183.

[22] "Pyrologix," n.d., http://pyrologix.com.

[23] "Technosylva," n.d., https://technosylva.com/products/wildfire-analyst/.

[24] https://www.simtable.com

relative to their distribution system and communities. Environmental risk thresholds were identified based on historical large fire events and are used for dynamically activating protection settings on their system in a tool named the 'Fire Weather Dashboard.'

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 wildfire resilience investments cited by the utility wildfire resilience reports are listed in Table 5. 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. Advanced resource planning and network redundancy are absent from the documentation of all utilities reviewed.

We also observed that several utilities follow standard guidelines and specifications for their investments. SCE follows the IEEE 693 guide for seismic design of substations, HECO meets or exceeds National Electrical Safety Code (NESC) criteria for overhead infrastructure, and GEC follows standards set by the rural utility service.

Table 5. Resilience investments made, considered, or proposed by utilities reviewed and their corresponding investment categories.

Utility	Investment	Category
PGE	Remote automated weather stations	Grid modernization
	AI-enhanced ultra-high-definition cameras (Pano AI cameras)	Grid modernization
	Early fault detection pilot project to detect anomalies on feeders in real time	Grid modernization
	Remote sensing pilot project, used primarily for vegetation management program planning	Grid modernization
	Storm Predictive Tool to assess wildfire risk to PGE equipment, using weather data from across the PGE service territory (testing and validation phase)	Grid modernization
	5G PGE Energy Lab, focused on the development of innovative wildfire mitigation technologies	Grid modernization

	Portable battery pilot to offer no-cost battery devices to provide backup power to PSPS-impacted residential customers also enrolled in PGE's medical certificate program (proposed project)	Grid modernization
	Fire mesh	Overhead hardening
	Ductile iron poles	Overhead hardening
	Fiberglass crossarms	Overhead hardening
	Tree wire	Overhead hardening
	Copper replacement	Overhead hardening
	Reconductoring in areas where undergrounding is not feasible or cost-effective	Overhead hardening
	Fuse replacement with fire-safe fuses and/or ELF (non-expulsion) fuses to eliminate a potential ignition source	Operations
	Electronic/intelligent reclosers and switching devices to increase operational flexibility and minimize customer impacts through the application of wildfire operational settings	Operations
	Replace undersized conductors for operational flexibility	Operations
	Annual training for ignition prevention inspection crews	Operations
	Annual wildfire training	Operations
	Line maintenance	Operations
	Vegetation management and maintenance	Vegetation
	Conductor undergrounding	Undergrounding
	Undergrounding feeders and distribution lines	Undergrounding
Avista	Vegetation management	Vegetation
	Widen transmission right-of-way	Vegetation
	Steel poles	Overhead hardening
	Fire retardant transmission poles. (Current practice is to use fire retardant paint, future recommendation is to use Fire-Mesh wrap, which has a 20-year life expectancy.)	Overhead hardening
	Digital data collection: LiDAR data to automatically identify vegetation conflicts	Grid modernization and vegetation
	Add SCADA to substations	Grid modernization
	Fuel reduction partnerships with Fire Agencies to remove fuels near critical infrastructure	Operations

	Dry Land Operating Mode: During fire season, distribution lines do not automatically reclose	Operations
	Next Gen Dry Land: Deployment of more reclosers in elevated fire risk areas	Operations
	Fire-Weather Dashboard: consistent guidance regarding fire likelihood and consequence based on weather forecasts and fire threat conditions	Operations
	Additional reclosers in elevated fire risk areas	Operations
	Emergency training with fire crews	Operations
HECO	Hazard tree removal	Vegetation
	Vegetation management program (trimming, removing, and herbicide spraying of vegetation on prescribed cycles)	Vegetation
	Addressing conductor sag, tension, and clearance issues with overhead conductors (use of LiDAR to identify overhead issues, re-tensioning conductors, replacing cross-arms, changing horizontal conductor configurations)	Overhead hardening
	Preventive replacement of facilities (e.g., poles, structures, hardware, conductors, shield wires, guy wires)	Overhead hardening
	Targeted reconductoring with tree wire or spacer cable	Overhead hardening
	Applying fire-retardant paint or mesh to wood poles in potential wildfire areas	Overhead hardening
	Critical pole hardening, replacing wood poles with steel poles where cost-effective and in areas of potential extreme wind (to align with NESC extreme wind criteria)	Overhead hardening
	Pole and shield-wire replacements prioritized in wildfire risk zones	Overhead hardening
	Replacing copper conductors with aluminum in wildfire risk zones	Overhead hardening
	Replacing nonexempt equipment with Cal Fire approved equipment	Overhead hardening
	Critical customer circuit hardening	Overhead hardening
	Targeted lateral undergrounding in vulnerable areas	Undergrounding
	Distribution feeder ties	Network Redundancy
	Microgrids	Grid modernization

	Installing video cameras to improve fire response when there is an outage in a potential wildfire area and weather conditions are ripe for a potential wildfire	Grid modernization
	Installing weather stations in/near potential wildfire areas to monitor wind speed and relative humidity to monitor high-risk conditions	Grid modernization
	Pilot broken conductor detection on distribution and transmission.	Grid modernization
	Secondary line monitoring devices (outage notification, heat and smoke sensor features, and voltage imbalance monitoring capabilities)	Grid modernization
	Advanced predictive maintenance and AI technologies to detect distribution issues before failure	Grid modernization
	Resilience modeling including wildfire risk analysis	Forward looking analysis
	Upgrading distribution substation electromechanical relays to microprocessor-based relays.	Operations/Grid Modernization
	Creation of wildfire focused watch office.	Operations
	Protective relaying schemes to better detect high-impedance faults and downed conductors;	Operations
	Increasing the tripping speed of circuit breakers and reclosers in potential wildfire risk areas	Operations
	Consideration of sparkless fuses where cost-effective in place of reclosers/smart fuses	Operations
	Deploying fault current indicators for portions of 46 kV and 34.5 kV lines in potential wildfire areas	Operations
	Smart reclosers and smart fuses to minimize sparks caused by line contact	Operations
	Workforce: plan for additional crews and provide more training	Operations
	Preventive maintenance inspection program for distribution system and substations in wildfire areas (3 to 5-year inspection cycle that incorporates use of LiDAR and UAS technologies as appropriate)	Operations
	Test & Treat preventive maintenance inspection program to check condition of wood poles throughout distribution system	Operations
	Field visits and structural loading calculations for poles to determine which are eligible for upgrade based on resilience planning criteria	Operations

SCE	Hazard tree mitigation program	Vegetation
	Fire resistant poles	Overhead hardening
	Wildfire covered conductor program	Overhead hardening
	Targeted undergrounding	Undergrounding
	Distribution ground and aerial inspection	Grid modernization
	Early Fault Detection (EFD)	Grid modernization
	Weather stations	Grid modernization
	Transmission ground and aerial inspection	Grid modernization
	Remote-controlled automatic reclosers	Grid modernization
	Weather and fuel modeling	Forward looking analysis
	Rapid Earth Fault Current Limiter (REFCL)	Operations
City of Georgetown Electric Utility	Tree trimming program	Vegetation
GEC	Vegetation management	Vegetation
	Overhead conductor/equipment replacement, animal abatement, deteriorated pole replacement	Overhead hardening
	Situational awareness	Grid modernization
	Operational practices	Operations
	Enhanced inspections	Operations
	Procedures for de-energization, reclosing, and restoring power	Operations
	Public safety and notification	Operations

6 Investment Prioritization

The investments listed in Table 5 represent some of the possible investments a utility can make to improve wildfire resilience. How utilities select investments varies; considerations found in the reviewed documents include wildfire risk reduction, utility worker safety, cost, community input, and other multi-objective considerations.

HECO, PGE, and SCE use historical data and simulations to predict how investments will reduce wildfire risk. PGE, SCE, Avista, and the City of Georgetown investments are prioritized according to their spend efficiency, which measures risk reduction relative to investment cost. PGE and SCE engage communities and integrate DEI principles into their investment prioritization. One example of DEI is PGE's use of wildfire notification messages in multiple languages. GEC does not describe an *investment* prioritization process; however, it does provide a low/moderate/high risk designation for all of its T&D lines with mitigation strategies.

Ideally, resilience spend efficiency is not considered in isolation when making investment decisions. Resilience investments should be considered alongside other utility priorities and as part of an integrated planning process. The City of Georgetown, SCE, PGE and HECO's publications suggest a multi-objective philosophy. PGE's investment portfolio offers co-benefits in addition to wildfire mitigation value; for example, many of the PGE feeders with the highest Customers Experiencing Multiple Interruptions (CEMI) values are designated for hardening. PGE estimates the non-wildfire-related resilience benefits of its investments using traditional asset management expected risk and net risk benefit ratios. PGE also integrates resilience into standard planning processes by proactively performing asset replacement for resilience objectives in tandem with additional asset maintenance. Georgetown considers multiple hazards and how they may be addressed with common investments. HECO's resilience working group report suggested a "resilience composite index" be used to evaluate an investment's value.

The City of Georgetown's planning process is unique among those reviewed in that it aims for an inclusive process that distributes efforts across many city departments, not the electric utility alone. It should be noted that this is because the Georgetown Hazard Mitigation Plan is for the city as a whole and includes the municipal electric utility as a city department. Nevertheless, this context allows for agencies to share investment efforts.

7 Conclusion

This report analyzes the wildfire resilience of several utilities according to their metrics, threat risk analysis, investment considerations, and investment prioritization processes. Key takeaways are listed in Section 1.2. Overall, utility wildfire resilience plans are relatively advanced. This is reflected, in part, by their use of standardized processes to manage risk and relatively high annual spending. However, all utilities have opportunities to improve. Utility metrics largely focus on utility-caused wildfires; they focus less on the ability to absorb, withstand, and recover from non-utility caused wildfires. Finally, utilities have made advances in the use of investment prioritization, but further work is needed to consider multiple objectives in investment decisions and to integrate resilience planning into standard utility planning processes.

Appendix A. Utility Sources

Our literature reviews initially focused on one document per utility. We relied on utility interviews to provide additional context and available resources. Many utilities do not share all relevant information in public-facing documents.

Table 6. Selected utilities, sources, and resilience report context.

Utility	Source and Document Context
Southern California Edison (SCE)	• California IOUs published Risk Assessment and Mitigation Phase (RAMP) reports to the California Public Utility Commission (CPUC) as a first step in the submission of the 2023 General Rate Case (GRC). It is evaluated by the Safety Public Division (SPD) staff within the commission, and conforms to the S-MAP, a proceeding that defined the California IOU's resilience framework. • SCE representatives were interviewed and feedback was included. • SCE continues to advance its risk modeling capabilities and some of the information contained in its 2022 RAMP filing may be superseded by other regulatory filings as of the publication date of this report.
Portland General Electric (PGE)	• PGE's 2022 Wildfire Mitigation Plan was required by Oregon Administration Rule 860-300-0002(2) and received guidance and review from the Oregon Public Safety Commission. • Updated information from PGE's 2023 Wildfire Mitigation Plan was also integrated into this report. • Several interviews with PGE were conducted.
Avista	• Avista's Wildfire Resiliency Plan was motivated internally to mitigate "wildfire risk associated with the delivery of electricity." • Avista representatives were interviewed and feedback was included.
Hawaiian Electric Company (HECO)	• On June 30, 2022, HECO filed an application to the PUC of Hawaii, "For Approval to Commit Funds in Excess of $2,500,000 for Climate Adaptation Transmission and Distribution Resilience Program and to Recover Costs through the Exceptional Project Recovery Mechanism." Approval is pending and scope may change as a result of the Lahaina Fire and the $95.3 million U.S. Department of Energy Grid Resilience Utility and Industry Grant awarded to HECO. • HECO representatives were interviewed. Per HECO's recommendation, we incorporated additional information on metrics and investments from the HECO Wildfire Mitigation Plan which was made publicly available in November 2023. • Per HECO's recommendation, we also reviewed HECO's response to PUC-HECO-IR-11 in Dkt. No. 2022-0135 for additional information on metrics and investments.

City of Georgetown electric utility	• The City of Georgetown 2021 Hazard Mitigation Plan was written to assess a range of hazards in the face of recent disaster declarations in Texas. Wildfires are one of these hazards; the document cites a recent increase in wildfires and federal and state identification of wildfires as a source of concern. This plan does not limit its scope to the municipal electric utility but identifies investments and strategies that can be supported by the effort of multiple City organizations.
Garkane Energy Cooperative (GCE)	• Utah House Bill 66 requires utility and electric cooperatives to submit wildfire protection plans.

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.[25] The EAL data is from FEMA's National Risk Index (NRI) data resources.[26] 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 used 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.

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

[26] 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

- 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.

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.[27] 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:

1. 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.
2. 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

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

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

[27] 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 Appendix C.3. 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 a 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 invest 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.

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

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 A.1, 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 7. 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,[28] the bowtie method,[29] California's Risk Assessment and Mitigation Phase (RAMP)[30] Avista's "Wildfire Resilience Framework,"[31] Sandia's "Conceptual Framework for Developing Resilience Metrics,"[32] the Western Coalition's "West-Wide Wildfire Risk Assessment" framework,[33] FEMA's "Local Mitigation Planning Handbook[34] and PNNL's "Integrated Resilience Distribution Planning" report.[35] Although not described as a framework, we also include EPRI's "Distribution Grid Resiliency" reports[36] and LBNL's utility case studies on economic impacts from damage to infrastructure during extreme events[37]. Several of these resilience frameworks are shown in Figure 3–Figure 7. 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 3–Figure 7, 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.

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) reports38 (Figure 3) 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

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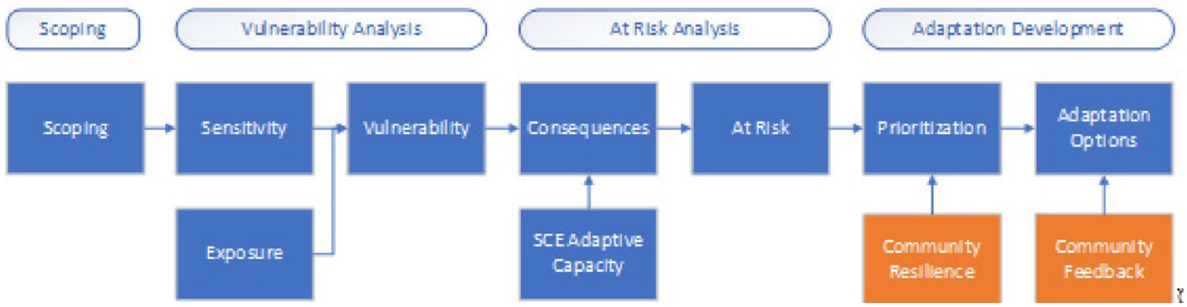
[28] https://onlinelibrary.wiley.com/doi/10.1111/j.1539-6924.2010.01442.x
[29] For the history of this method, see - https://en.wikipedia.org/wiki/Bow-tie_diagram
[30] https://www.cpuc.ca.gov/about-cpuc/divisions/safety-policy-division/risk-assessment-and-safety-analytics/risk-assessment-mitigation-phase/sce-ramp/sce-2022-ramp
[31] https://www.myavista.com/-/media/myavista/content-documents/safety/2023-wildfire-resiliency-report_011923_final.pdf
[32] https://www.energy.gov/oe/articles/conceptual-framework-developing-resilience-metrics-electricity-oil-and-gas-sectors
[33] https://www.thewflc.org/sites/default/files/WWA_FinalReport_3-6-2016-1.pdf
[34] https://www.fema.gov/sites/default/files/2020-06/fema-local-mitigation-planning-handbook_03-2013.pdf
[35] https://gridarchitecture.pnnl.gov/media/advanced/Integrated_Resilient_Distibution_Planning.pdf
[36] https://eprijournal.com/making-distribution-grids-stronger-more-resilient/
[37] https://emp.lbl.gov/publications/case-studies-economic-impacts-power
[38] https://www.sce.com/about-us/environment/climate-adaptation

events, and consequences associated with those impacts. This vulnerability then informs resilience planning.

Figure 3. 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 5) 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.

Figure 4. Adapted from ISO 31000:2009 Risk Management Framework

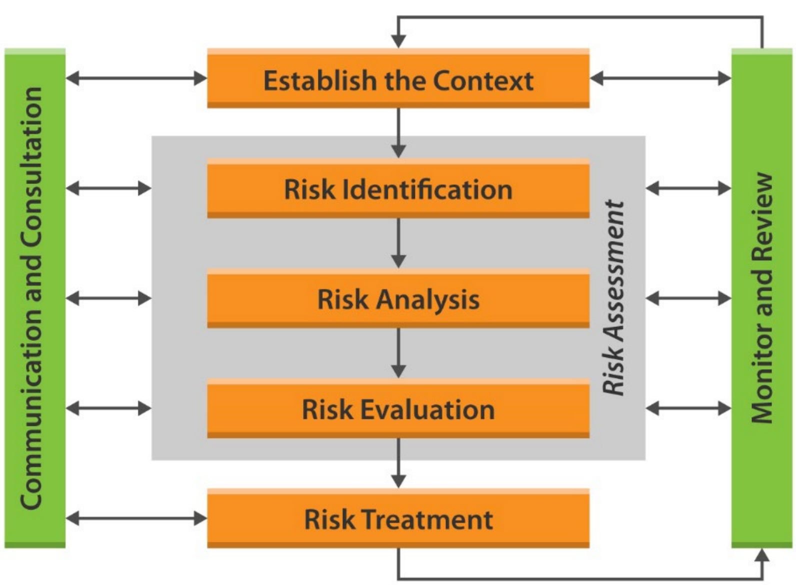


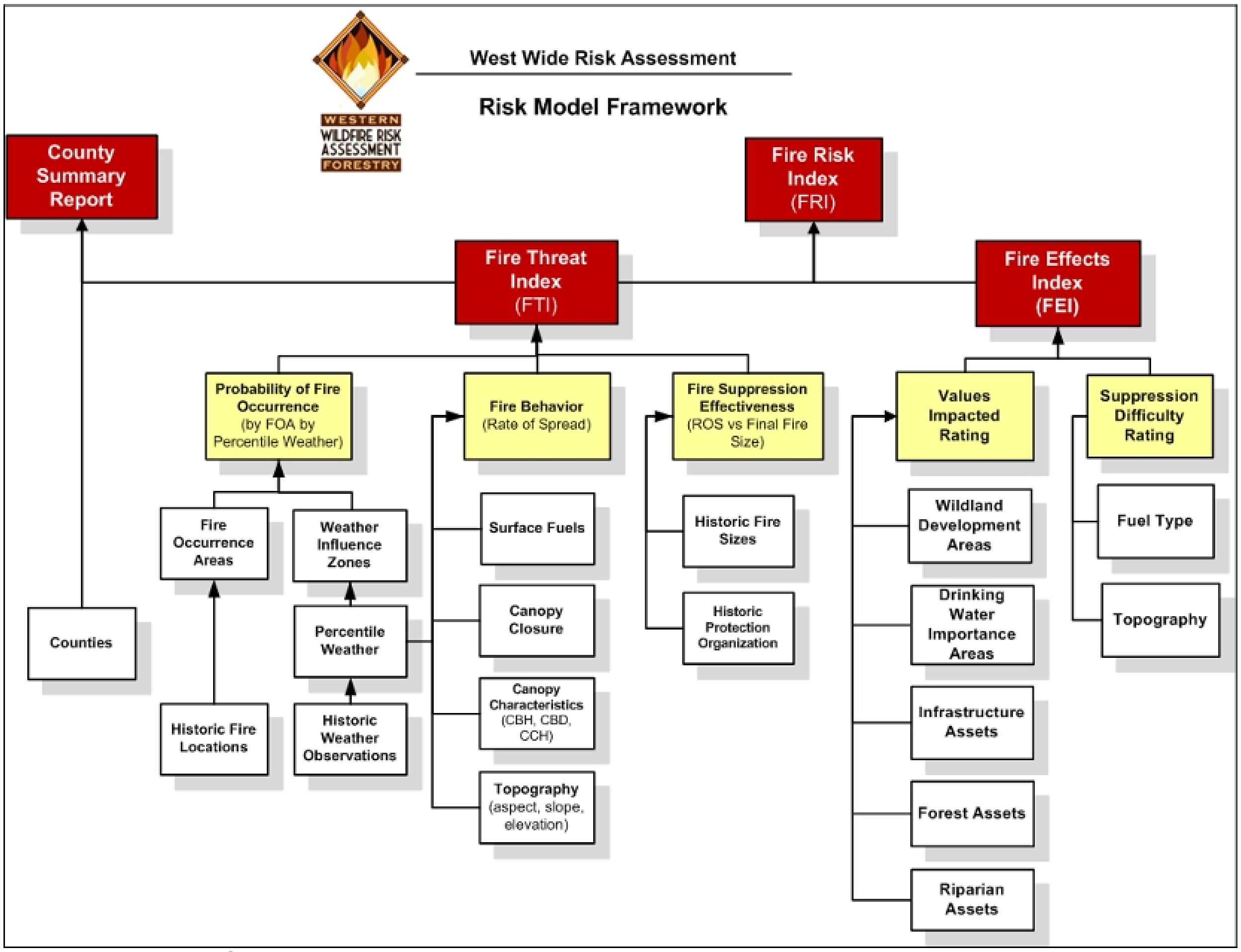
Figure 5. Adapted from Sandia's Resilience Framework.

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 6), 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 7 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 6. 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 7. 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 2]. 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 a 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 a 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 its 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 several of these categories in Table 7.

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”[39] and offers a variety of alternative CBA methods and “streamlined” methods for predefined investments.

[39] 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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GridDeploymentOffice@hq.doe.gov

www.energy.gov/gdo

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