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PNNL-28776

Framework for Quantitative Evaluation of Resilience Solutions: An Approach to Determine the Value of Resilience for a Particular Site

March 2022

Mark R Weimar

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

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Summary

A monetary value of resilience for electricity and water, which varies between sites, can help provide the financial justification for resilience investment decisions. The approach in this paper provides a best practices approach to calculating whether solution alternatives provide a cost beneficial investment in reducing a site's risk. A probabilistic approach has been developed that goes beyond the reliability calculation to provide a resilience value to high-impact, low frequency events associated with changing weather patterns, other natural hazards, and human threats. The approach requires the ability to collect site specific data on hazards, vulnerabilities (in terms of resistance and damage), and the losses associated with asset restoration for energy and water efficiency measures. The simplified equation calculates the probability of the hazard multiplied by the probability of the resistance multiplied by the probability of damage multiplied by the probability of loss values to determine the value of asset damage, repair costs and restoration time. Restoration time provides the estimate of lost load and is the basis for calculating the value of lost load for the baseline. The baseline resilience value is compared with the resilience value associated with each of the resilience solution alternatives. A life cycle cost analysis provides the discounted net present value of the costs of investment, the resilience improvements including any additional benefits and costs and compares them to the baseline in terms of reduced losses (costs) and increased benefits. A decision portfolio is developed to quantify the decision maker's financial criteria for solution alternatives along with any non-monetary benefits and costs to help the decision maker determine which alternative best meets the goals for their site.

Acronyms and Abbreviations

CGE	Computable General Equilibrium
DCE	Discrete Choice Experiments
DoD	U.S. Department of Defense
FEMP	Federal Energy Management Program
ICE	Interruption Cost Estimate
LCC	Life Cycle Cost
IO	Input-Output
LBNL	Lawrence Berkeley National Laboratory
MMMI	Maximum Modified Mercalli Intensity
NOAA	National Oceanic Atmospheric Administration Center
NPV	Net Present Value
SME	Subject Matter Expert
TRN	Technical Resilience Navigator
USGS	U.S. Geological Survey
VOLL	Value of Lost Load

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1.0 Introduction

Due to the increase in extreme events, approaches to estimating the costs and returns of providing greater resilience of water and energy infrastructure have become increasingly important. Hurricanes, 100-year floods, and higher storm surge with the resulting damage occur more frequently than in the past. These types of extreme events are known as high impact, low-frequency events. This report provides an approach to valuing resilience to provide justification for hardening water and energy infrastructure that can be used by expert users/economists in undertaking investment-grade valuations to validate the appropriateness of funding for resilience mitigation projects.

These investment-grade valuations are often a key step in federal project procurement processes. Today, many federal agencies are unable to include resilience benefits in these processes, thus potentially undervaluing the benefits to the facility, site, or agency from a proposed scope of work. The procedures described in this report go into more detail than resilience planning processes described in many tools. For example, the Federal Energy Management Program's (FEMP's) Technical Resilience Navigator (TRN) uses a risk screening approach within its risk assessment that provides unweighted outputs in annual outage hours and weighted outputs that are unitless that reflect relative importance; however, management and leadership investment decisions often require evaluation in terms of dollars.

The approach described in this report provides a methodology for getting towards a dollar figure for decision making within institutional processes. Building on the resilience valuation methodology in Weimar et al (2018)[1] in evaluating mitigation solutions for energy and water projects, the quantitative approach described in this paper enables a benefit/cost analysis of different resilience solutions, compares them with the baseline, and presents the results of the analysis to the decision maker. In cases where the mission value is so high that failure to mitigate the risk is unacceptable, cost effectiveness analysis or the least cost solutions can be used instead of benefit/cost analysis.

1.1 Resilience

Resilience in this paper follows the same definition as found in the TRN: "the ability to anticipate, prepare for, and adapt to changing conditions and to withstand, respond to, and recover rapidly from disruptions through adaptable and holistic planning and technical solutions. Highly resilient systems prevent disruption or reduce the magnitude or duration of disruptive events caused by hazards. The resilience of a system can be characterized in terms of resourcefulness, redundancy, robustness and recovery.

- Resourcefulness is the ability to skillfully prepare for, respond to, and manage a crisis or disruption as it unfolds.
- Redundancy is the availability of backup resources to support the primary source in case of failure.
- Robustness is the ability to maintain critical operations and functions in the face of crisis.
- Recovery is the ability to return to and/or reconstitute normal operations as quickly and efficiently as possible after a disruption."

Because of this broad definition of resilience, the quantitative methodology is purposefully expansive to cover a wide variety of costs and benefits that could impact any of the above factors.

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[1] Weimar MR, DM Anderson, B Kravitz, RT Dahowski, SA Brown, JM Niemeyer, A Somani, and KS Judd. 2018. *Methodology for Valuing Resilience to Severe Events for the Department of Energy Sites.* PNNL-27257, Pacific Northwest National Laboratory, Richland WA. Available at https://www.osti.gov/biblio/1602427

1.2 Resilience Valuation within the Resilience Planning Process

The valuation methodology and terminology described in this report, and the foundational 2018 paper, complement the processes described within the TRN.

- **The approach uses data from a wide variety of stakeholders across a site**. Quantitative analysis may require additional team members with specialties in hazard analysis and forecasting, vulnerability analysis, and cost estimation. In addition, the decision maker with authority to obtain the data required to undertake the quantitative analysis may need to be identified as the data collection process can cross lines of authority.
- **Baseline data is collected.** The approach requires the development of a system's baseline operational status for energy and water systems with which to compare resilience solutions. This methodology describes additional information that must be collected on the systems above and beyond the data collection described within the TRN, including the monetary value of components by system, operations and maintenance costs, more detailed maintenance and age of assets, and information on repair costs that are needed for valuation. The term "assets" will be used to discuss valuation as the asset failure leads to the lost load. The restoration time for the affected assets will determine the amount of lost load.
- **Baseline data provides insight into expectations of how the site will be resilient to realized hazards or threats.**[2] The baseline is used to evaluate the resilience of the site's energy and water systems to hazards through the probability of the hazard(s), the likelihood of damage from that the hazard through a vulnerability analysis, and the consequence(s) in dollars to calculate a cost of the damage.
  - Quantitative analysis requires a more thorough analysis of the risk probabilities, including the probabilities by magnitude or severity of the hazard or threat. In addition, the vulnerability of systems increases as the category or magnitude increases above the systems' threshold to resist damage. This methodology looks at secondary factors above and beyond the value of redundant systems to critical functions at a site, such as restoration costs and, for commercial entities, lost revenue, which need to be included.
  - The value at risk is calculated over the time frame of the assets involved or longer if an upward trend in hazard occurrence is expected. The paper reviews alternative approaches to calculating the value of lost load so that sites can determine the value of resilience based on their site's needs. The results are discounted back to the present at the appropriate discount rate. The methodology then evaluates proposed mitigation solutions that would improve the resilience of the system.
- **Develop resilience solutions.** This methodology assumes that users have a short list of potential resilience solutions or alternatives that may have undergone some prioritization effort in the past but have stopped short of a full quantitative evaluation and prioritization process. Development of mitigation solutions within this methodology does not significantly differ from the processes described within the TRN, thus it is not described in detail within this report.
  - Resilience solutions address resilience gaps identified in baseline analysis and risk assessment. Solutions may reduce the hazard, vulnerability, or consequence. Sometimes the solutions may mitigate or solve vulnerabilities to more than one hazard. Subject matter experts (SMEs) and stakeholders should be queried for potential resilience solutions.

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[2] The term *hazards* usually refers to natural or operational hazards, while *threats* refer to human-caused events. Throughout this report, the term hazards will be used to cover both hazards and threats.

- **After solutions are developed, they are prioritized against each other for decision making.** Within the TRN, solutions are prioritized by factors such as risk reduction potential, general cost estimates, and how well they meet self-identified criteria (e.g., how well solutions meet sustainability goals). This methodology evaluates each resilience solution against alternative proposals compared to a quantitative baseline to determine which solution should move forward; this is conducted according to the detailed requirements for investment-grade decision making. Requirements differ by agency. Agencies such as the Air Force provide guidance on benefit cost analysis in what is now called Economic Analysis.[3]
  - In quantitative analysis, the costs of implementing solutions require detailed estimates. Additionally, mission value is an explicit consideration along with other items such as the reduced costs in restoration time and any other costs/benefits associated with implementing the solution (monetary and non-monetary benefits). Non-quantifiable benefits are evaluated based on the relative importance of each criterion in meeting the site's goals and objectives and how each solution's benefits compare relative with the other solutions' benefits for each criterion. The methodology allows for additional economic criteria and weights to meet the decision-makers' funding and appropriation requirements. These economic criteria and weights may be the same – or different – from resilience priorities used to develop the initial short-list of solutions depending on the site and decision-maker.
- **Review prioritized solutions for decision making.** This methodology allows for a life cycle cost analysis to be conducted for the baseline and alternatives, resulting in overall project cost estimates with resilience benefits explicitly included and a benefit/cost analysis to be undertaken.[4]

  This methodology allows for the results of the life cycle cost analysis to be presented in a decision matrix with cost, NPV, NPV/Investment cost ratios, and any non-monetary criteria ranked to show how well the alternatives met the criteria, weighted with the decision maker's weights. This is a crucial step in the project procurement process.

This report focuses on energy and water critical infrastructure, for which data can be obtained to undertake a quantitative valuation of the probabilities of hazards and vulnerabilities, as well as the value of assets and mission value to estimate the value of resilience of the baseline and alternative solutions. For energy and water, three components likely will be estimated: 1) the cost of restoring the system back to operation, 2) the value of lost operations due to the outage, and 3) any lost revenue associated with the outage. For most evaluations, the hardest task is developing the data required to estimate the probabilities of hazards and vulnerabilities, as well as the value of the assets and the resultant damages such as mission value. Some sites have extremely well-defined data, while others may require combing reports to determine probabilities and damages from hazard realization on the specific assets.

The remainder of the report is organized as follows. The report starts with a more detailed discussion of the quantitative resilience valuation process with a detailed methodology discussion of the three components of the baseline evaluation: hazard probabilities, vulnerability probabilities, and consequence estimation, including a description of economic best practices in determining the value of resilience. The baseline is completed with a discussion of the life cycle cost and NPV analysis for the baseline resilience value. The process continues with the resilience solutions being evaluated for their reductions in overall risk and cost. Lastly, the results are organized into a decision matrix.

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[3] US Air Force. 2011. "Air Force Manual 65-506: Economic Analysis." Available at https://www.acq.osd.mil/dpap/ccap/cc/jcchb/Files/FormsPubsRegs/Pubs/AFMAN65-506.pdf and

[4] Benefit/cost analysis is an analysis of costs and benefits using life cycle cost analysis where the costs and benefits are associated with specific years within the timeframe of analysis. NPV and Benefit Cost Ratios (BCR) are metrics used in benefit/cost analysis.

2.0 Determine If a Benefit/Cost Analysis Is Feasible

The quantitative approach assumes that the site has several resilience solutions currently available (potentially developed and qualitatively or semi-quantitatively prioritized using other processes) and now is considering more robust evaluation of the solutions to use within a formal project development process. To determine if the quantitative analysis is feasible, the decision maker needs to be identified along with their risk preferences and whether the data required can be obtained.

Identify the site decision maker[5] who will make the formal decision to proceed with a benefit/cost analysis. Two points are important:

- What are the risk preferences of the decision maker and what level of risk does the site face?
- Does the data exist to undertake the assessment?

The first component determines what type of analysis should be undertaken (cost effectiveness, benefit/cost analysis, or none) and the second determines whether there is adequate data to undertake the appropriate analysis.

2.1 Ensure Access to Data

The decision maker will assure access to the more detailed data required for quantitative evaluation, including:

- Site-specific criteria to undertake choosing between alternatives, including financial criteria.
- Criteria weights used to evaluate the relative financial value of the alternatives toward meeting the decision maker's financial goals and objectives. The weights reflect the importance of each criterion to meeting the stated resilience goals and financial criteria.[6]
- The data required to understand the resistance (age, maintenance, characteristics such as materials, structural design, codes, etc.,) and fragility of the electrical and water structures and the value of the losses (salary structures; cost basis of affected components, government cost estimates of repairs, maintenance, O&M, etc.) associated with the baseline risks identified in the TRN screening process.

Specific data needs and their associated use in calculations are discussed in Section 3.

2.2 Authorize Personnel and Resources

The decision maker provides access and cooperation of personnel and resources required to obtain the data and information to undertake a resilience valuation. While personnel may have been previously identified to assist with the resilience planning process, given the increased level of effort required by quantitative evaluation, the decision maker is needed to formally task the appropriate personnel to undertake the work required.

The decision maker's authority can be delegated, but they must have the authority to commit the resources required to obtain the data. The importance of finding the decision maker with the required

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[5] This report uses "site" as the unit of analysis, but quantitative evaluation can be conducted at a more granular level, such as facility. This report uses "site" as a shorthand going forward.

[6] Weighting in quantitative evaluation may be the same as developed within more qualitative processes, such as the Solution Prioritization module within the TRN, but given the increased granularity of data and increased precision in benefits, this methodology recommends re-verifying any existing resilience weighting previously developed.

authority cannot be emphasized enough. Without the authority to obtain the data required to undertake a quantitative evaluation, the quality of the resulting analyses diminishes and a much wider variance in the results becomes apparent. For a fully quantitative evaluation, economists, hazard specialists, and experts in vulnerability assessment are required as well as the individuals who worked on any previous resilience assessment.

2.3 Express Risk Preferences Driving Quantitative Analysis

The risk preferences of the decision maker drive the direction of the quantitative evaluation. Risk preferences are individual in nature; what is intolerable to one decision maker may not be intolerable to another. Thus, the decision maker's preferences on what levels of risk they are willing to accept, can manage if reduced, or find intolerable will set the risk acceptance thresholds used within quantitative evaluation. shows the risk breakpoints divided into three parts:

- At the top of the inverted triangle in Figure 1 are risks that are intolerable and must be mitigated because the consequence of a hazard/vulnerability occurring is unacceptable to the decision maker. Solutions that maximize cost-effectiveness are appropriate.
- At the middle of the inverted triangle are risks that can only be accepted if they are mitigated. Thus, mitigation solutions can be evaluated for solutions where the NPV is greater than 0 to make the risk as low as reasonably possible (ALARP).
- At the bottom of the inverted triangle are risks that can be accepted because the risk is *de minimus* or tolerable. These tolerable risks may have already been filtered out in previous qualitative or semi-quantitative risk analyses.

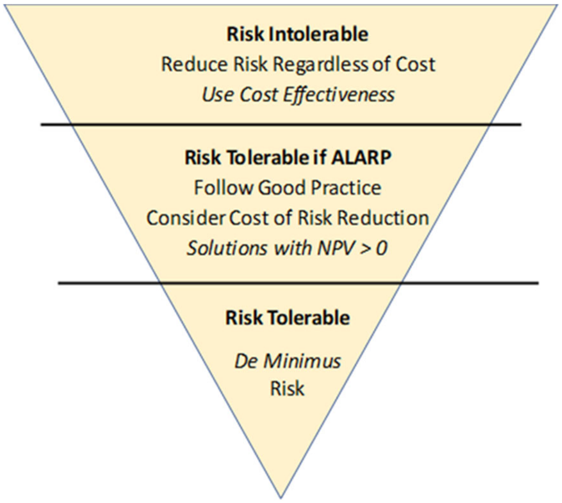

Figure 1. Risk Acceptance and Tolerance

Benefit/cost analysis is performed for baselines and alternatives only for those risks in the middle section of the graphic in and where adequate data can be obtained to undertake the analysis, while cost-effectiveness analysis is performed for intolerable risks. If the risk is *de minimus*, no further action need be taken.

3.0 Develop Baseline Resilience Value

The quantitative, investment-grade, approach to valuing resilience requires a more detailed and granular analysis of the risk being evaluated than is used in screening methods, such as the methods employed in the TRN, which focuses on risk assessment in terms of outage hours. To arrive at that monetary valuation, the quantitative approach analyzes not only the outage time, but damage done to assets and costs to restore electricity and water and any other benefits/costs identified.

The value of resilience in this framework is defined as the value at risk given the probability of a hazard, vulnerability, and consequence over time, where consequence is considered the monetary and non-monetary costs associated with a realized hazard. The quantitative approach divides vulnerability into two aspects: resistance (the capacity to resist impact from the realization of a hazard or threat) and damage (probability of damage given the realization of exceeding the resistance value and hazard or threat). In addition, it evaluates the consequence as a probability of the dollar value of loss given that consequences are not known without error. The baseline resilience value is compared with the value of resilience solutions to understand the monetary improvement to the risk stance at a site.

3.1 Framework Calculations

Eq. (1) provides a mathematical representation of the value at risk while Figure 2 depicts the approach to calculating the baseline resilience value or the value at risk for the hazard/threat/vulnerability/assets combinations that will be evaluated. The equation and figure introduce resistance and damage, which when combined are the vulnerability of the system/functions/loads. The approach provides a method to evaluate severe hazards, but the method is applicable to operational hazards as well. For example, lack of maintenance would decrease the mean time to failure for machinery. The characteristics, maintenance level, and climate zone are a part of the value for the resistance for each type of asset, and the probability of the failure would be the damage. The loss is the value of the damage including the value of lost load (VOLL) that occurs. Eq. (1) provides the mathematical definition of the value at risk. Note in the equation, the hazard is conditioned upon the site; the resistance is conditioned on the hazard; the damage conditioned on the resistance of the assets in question; and the loss is conditioned on the damage to the assets.

$$V = Prob(H|S) * Prob(R|H) * Prob(D|R) * Prob(L|D) \tag{1}$$

where:
V = value at risk
Prob = probability
H = hazard
S = site
R = resistance to indicated hazard
D = damage that occurs to the asset
L = dollar value of the loss that occurs due to damage

Eq. (1) and Figure 2 simplify the value at risk as one hazard may have many items that are damaged. For example, hurricanes may damage the assets of an entire site. Additionally, hazards may come in combinations. Earthquakes near coastlines may induce tsunamis. Hurricanes are often associated with flooding, either from storm surges or high rainfall quantities. Thus, the hurricane damages are not just the loss of electric poles due to high wind but may also include damage to substations and the conductors as a combination of wind, flooding, and storm surge. In addition, each probability of different intensities for each hazard will have a different impact on the damage and loss probabilities. Thus, the value at risk is the sum of the different hazards and hazard intensities, resistance, damage, and loss probabilities. Furthermore, note that this is a simplified version of the value at risk equation and each term includes a quantification of its associated probability as well as the associated outcome. For example, the loss term (L) includes both the probability of a loss at a given level and the dollar amount of that loss.

The damage function provides the probability of loss to each of the asset types as a combination of the resistance and hazard intensity probabilities. The value at risk must be further calculated by determining the cost of restoring the electricity and/or water to accommodate the load. In addition, the forecast duration of the lost load (outage duration) must be determined in order to value the kilowatt-hours (kWh) lost or the value of water forgone as a result of the hazard and vulnerability. The duration may be calculated by determining the amount of time to restore each component of load.

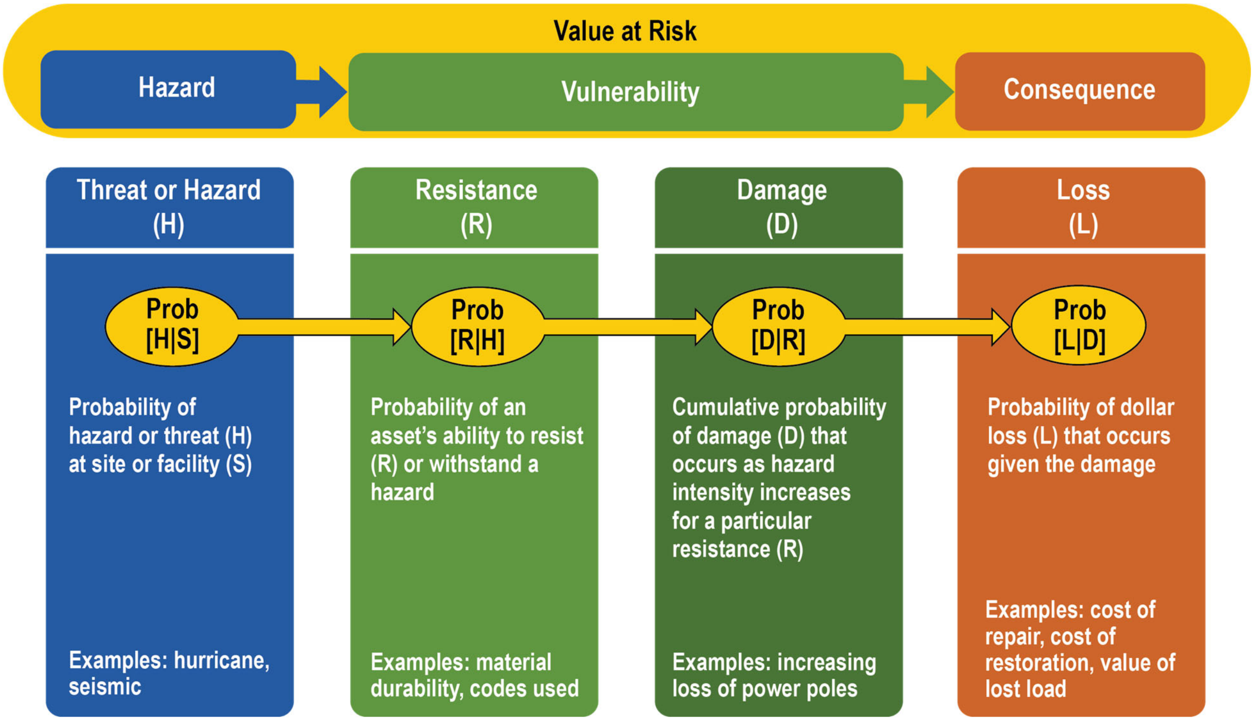

Figure 2. Quantitative Approach to Vulnerability and Risk Assessment and Benefit/Cost Analysis[7]

3.2 Key Considerations for the Framework

To calculate the baseline resilience value, several key considerations are required to quantify the probabilities correctly:

- The hazard probability is the forecast probability of the hazard by category and location.
- Vulnerability is a combination of the resistance (refers to the structural response of the asset) and damage as a result of a hazard based on asset's resistance.
  - Each asset's resistance is based on its structural composition and condition and will have its own response or resistance function.

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[7] Based on Porter K. July 2018. *A Beginner's Guide to Fragility, Vulnerability and Risk*. University of Colorado and SPA Risk LLC, Boulder and Denver, CO. 112 pp., http://spot.colorado.edu/~porterka/Porter-beginners-guide.pdf.

  - Damage reflects the probabilities of the hazard category and the asset’s resistance exceedance.
- Consequences will have unknowns in terms of the exact value of the replacement, repair, and restoration time value and even the value of lost load.

The resulting outage time due to the failure of the asset leads to the damage to production/mission and impact on human health. The probability associated with the damage can be represented as a cumulative damage function called a fragility curve, as shown in Figure 3. The figure indicates the percentage of wooden electric poles lost as the wind speed increases. A few select resources that provide additional context for characterizing hazards and vulnerabilities can be found in Appendix A.

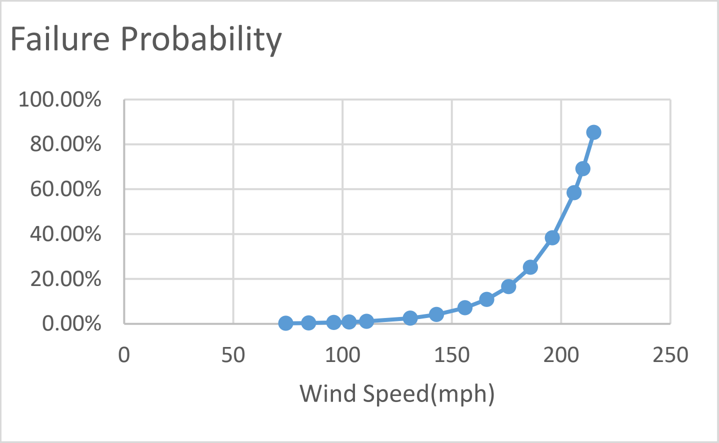

Figure 3. Cumulative Damage Function for Wooden Electric Poles

3.3 Assess Hazard Probabilities

The quantitative analysis requires a deep dive into the hazards of importance to a site in order to quantify more clearly the probability of the hazards at the site and the resistance and damage associated with the different hazard intensities. The quantitative analysis uses the baseline and resilience solutions and specifically identifies the hazard intensities present expected to impact the site and their associated probabilities (see Table 1).

Sites may have a shortlist of key hazards from previous assessments (such as the TRN); if not, this list and each hazard’s expected intensities must be identified first. Note that only hazard intensities high enough to impact the site need to be evaluated. Quantitative analysis requires an understanding of both the probability of a hazard occurring and the probability of the hazard of a specific intensity occurring. Quantification of hazard, resistance, and damage probabilities requires experts to understand and interpret the output of the models used to develop the probabilities by intensity.

Only a few common hazards are included in Table 1, which separates hazards into three categories: natural, operational, and human threats. Natural hazards include weather-related items and items that are natural but aren’t weather related such as earthquakes and geomagnetic pulses. Threats are adversarial in nature, such as intentional damage caused by individuals.

Table 1. Hazard Examples

Natural Hazards			Operational	Threats/Human
Hurricanes	Blizzards	Earthquake	Operational	Terrorism
High winds	Lightning	Tsunami	Accidents	Intentional
Flooding	Ice storms	Landslides	Deferred maintenance	Cyber
Storm surge	High temperatures	Geomagnetic pulses		Electromagnetic pulses
Drought	Severe cold	Desertification		
Wildfire	Heat waves	Invasive species		

The quantitative analysis will evaluate all the damage that the solutions mitigate, including damage to the electricity and water assets involved. The quantitative analysis looks at a minimum timeframe of the asset life associated with solutions; thus, a longer-term profile for the hazard may need to be developed. That analysis would then be compared to the analysis that may have been completed only looking at near-term solutions. For example, an annual threat of 1 percent would only have a 26 percent chance of being realized in 30 years. Thus, a longer time frame may be necessary to find the value required to pay for a solution.

3.3.1 Hazard Intensity

Quantitative analysis requires an understanding of the hazard intensity. The subsections below provide a brief overview of three hazards that commonly have intensity considerations that must be understood before conducting analysis. Note that this overview is not exhaustive and that sites should consider hazards relevant to their circumstances.

3.3.1.1 Hurricanes and Storm Surge

Hurricanes are divided into categories 0-5 using the Saffir-Simpson scale.[8] The scale separates the categories based on the sustained wind speeds measured in the hurricane. Category 0 represents tropical storms with wind speeds of less than 74 mph (39-73 mph). Category 1 ranges from 74 to 95 mph. A Category 5 hurricane has wind speeds greater than 156 mph. Major hurricanes are Category 3 and above. Each site will have probabilities of occurrence for each category. Those categories are combined with the resistance and damage associated with the assets involved. The damage rises with each category in terms of outage time and asset losses. In addition, hurricanes can also generate a multi-hazard events with floods and storm surges occurring. Thus, probabilities of storm surges and floods need to be analyzed at the same time as the hurricane.

The probabilities of storm surge and floods and their intensity may differ from the probabilities by category of hurricane, so care must be taken to get appropriate probabilities by intensity for these associated hazards. Below are resources where hazard data can be obtained. The probabilities may still need to be calculated, but the raw data is available. The probability of hurricane-related storm surge and flooding intensity can vary based on the storm's intensity, size, and motion, barometric pressure, and the depth of waters near the shoreline.[9] In one example provided, during Hurricane Ike (2008, Category 2 at landfall), the storm surge reached 15 to 20 feet while Hurricane Charley (2004, Category 4 at landfall) produced a 6- to 7-foot storm surge. Thus, the National Hurricane Center decoupled the storm surge from the wind speed category.

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[8] National Hurricane Center. ca 2020. "Saffir-Simpson Hurricane Wind Scale." Available at https://www.nhc.noaa.gov/aboutsshws.php.

[9] The Maritime Executive. March 2020. "NOAA's New Hurricane Wind Scale." Available at https://www.maritime-executive.com/article/noaas-new-hurricane-wind-scale.

Hurricane data for the United States can be found at the National Oceanic Atmospheric Administration Center (NOAA).[10] The data goes back to 1851, so there is enough information to determine long-term hazard probabilities and whether there is a change in frequency and intensity over time. On the website, a location is chosen, and filters are applied to determine the probability of each category. The categories run from extratropical to Category 5. Using the filter, the categories can be separated to determine probabilities by intensity.

The National Hurricane Center has a separate unit that provides the National Storm Surge Hazard Maps for the risk of storm surge by location and hurricane category. Using the hurricane probability by location and the storm surge risk by category, the probability of the storm surge intensity can be predicted.[11]

3.3.1.2 Flooding

Flood frequency data can be obtained from the U.S. Geological Survey (USGS).[12] State-by-state equations have been developed to provide exceedance probabilities to estimate ungauged streams from those with flow calculations.

The National Centers for Environmental Information compiles data on exceptional storms, e.g., storms that cause damage and may take human life.[13] The database contains data from January 1950 through present and indicates whether the storm happened in a county, zone, or marine location. The database also indicates the number of injuries, deaths, property damage, and crop damage. The database includes data on 48 storm types.

3.3.1.3 Seismic Events

Predictions of seismic events including their magnitude, location, and timing cannot be made due to the inherent complexity of earthquakes. However, earthquake occurrence can be characterized by probabilities. The USGS develops probabilities of earthquakes of certain magnitudes based on the average rate of historical events. They assume the annual rate is constant and provide probabilities in terms of the range of the number years between occurrences such as 1-in-30 years to 1-in-300 years based historical data. For some faults where historical occurrences aren't available, USGS uses the rate of slip along the fault to calculate a probability from 1-in-300 years to 1-in-3000 years. USGS also provides a non-interactive map of the frequency of damaging earthquake shaking in the 50 states and Puerto Rico.[14] The USGS website provides many tools for evaluating the probabilities of damaging earthquakes at a site. USGS tools can also be used to evaluate landslide, tsunamis, and volcanic hazards. The intensity of earthquakes is measured on two different scales: Moment Magnitude scale and Modified Mercalli Intensity (MMI). The Moment Magnitude scale, M_w, is defined to be comparable to the commonly discussed Richter scale, but is preferred by the seismic hazard community due to inherent technical limitations of the Richter scale. The M_w scale represents a 10-fold increase in the amplitude of seismic waves and a 32-fold increase in the amount of energy released for each whole number increase in the

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[10] NOAA – National Oceanic and Atmospheric Administration. 2020. "NOAA Historical Hurricane Tracks." Available at https://oceanservice.noaa.gov/news/historical-hurricanes/

[11] NOAA – National Oceanic and Atmospheric Administration. 2020. "National Storm Surge Hazard Maps." Available at https://www.nhc.noaa.gov/nationalsurge/

[12] USGS – US Geological Survey. "National Streamflow Statistics Program." Available at https://water.usgs.gov/osw/programs/nss/pubs.html

[13] NCEI – National Centers for Environmental Information. "Storm Events Database." Available at https://www.ncdc.noaa.gov/stormevents/ftp.jsp

[14] USGS – US Geological Survey. "Frequency of Damaging Earthquake Shaking Around the U.S.". Accessed April 14, 2020 at https://www.usgs.gov/media/images/frequency-damaging-earthquake-shaking-around-us

scale. The MMI runs from I to XII and indicates the level of shaking.[15] Damage is slight for Intensity VI and rises to total damage at Intensity XII; thus, the MMI provides a scale of the amount of damage created based on ground shaking intensity.

3.4 Assess Resistance and Damage to Determine the Vulnerability

Resistance and damage are integrally tied. The resistance of an asset is its characteristics with respect to what happens to the asset when it faces a specific hazard intensity. The resistance of overhead electricity lines is dependent on the types of poles, towers, transformers, and substations. Age, material, and maintenance levels are specific characteristics that will determine an asset's resistance to a specific hazard. Combined with the fragility curve, which determines the probability of damage, the amount of electricity outage time can be imputed to determine the length of time to restore the electricity system and provide electricity again. Similar approaches can be used on water assets to determine the amount of damage and restoration time and therefore the quantity of lost gallons of water.

The probability of exceeding a certain damage state based on the asset's component and hazard intensity defines the fragility curve. Some fragility curves exist, but they may have been developed for specific purposes. Thus, care needs to be used to determine when the literature is providing a fragility curve that measures the actual damage expected at a specific site/facility. Four general approaches have been suggested to develop appropriate fragility curves to determine the damage:

1. Empirical: Uses data to determine the fragility curves based on data or controlled experiments.

2. Analytical: Characterizes the limits of the specific asset type by using structural models. The characteristics include the material properties, temperature, and humidity. For example, wood electric poles in the tropics tend to sustain damage more heavily at earlier ages than in more dry climates.

3. Hybrid: Combines the empirical and analytical approaches or combines with the judgmental approach to provide the fragility curve.

4. Judgmental: Approach of last resort due to potential bias of the expert developing the fragility curve.[16]

3.5 Assess Monetary Losses

Asset losses are calculated based on the probabilities of hazard intensity, probabilities of structure type resistance[17], and probabilities of damage given the fragility curves by asset type and characteristics as well as the probability of the value of the loss. Once the damage to the asset is calculated, the probability of the value of the asset's losses can be calculated. Additionally, once the physical damage is understood,

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[15] USGS – US Geological Survey. "Earthquake Magnitude, Energy Release, and Shaking Intensity." Available at https://www.usgs.gov/natural-hazards/earthquake-hazards/science/earthquake-magnitude-energy-release-and-shaking-intensity?qt-science_center_objects=0#qt-science_center_objects

[16] Dunn S, S Wilkinson, D Alderson, H Fowler. 2018. "Fragility Curves for Assessing the Resilience of Electricity Networks Constructed from an Extensive Fault Database." In *Natural Hazards Review* 19:1.

[17] Every structure type has a probability of associated with its resistance measurement. Most of the time, the standard deviation is too small to include in analysis, but it is worth noting that resistance values are based on empirical data. They may be described as a point estimate, but in reality, there is a probability associated with their exceedance values. The resistance measure could also have a frequency component if more than one asset type is being evaluated.

the cost of restoration and time to restoration can be determined. The cost of restoration will include cleanup, repair and replacement costs. The value to customers of undelivered electricity and water is called the value of lost load (VOLL). The value of undelivered electricity has been studied at length while water has not. Based on just a few cases, the value of the lost load is often more valuable than the cost of restoration. If the entity being analyzed is a commercial venture like a utility, the value of lost revenue can also be included in the analysis. This lost revenue is not accounted for in the value of the lost load. The value of the lost load reflects the productivity losses of the customers, not the utility, and is therefore a relevant metric for federal sites considering a resilience valuation.

There are several cost-estimation approaches to determine the value of damage. Utilities usually have databases of costs for transmission and distribution systems and as such may have information relevant to sites and buildings. There are more than 20 construction cost databases that can easily be found using an internet web search.

3.5.1 Assets Under Consideration for the Analysis

The site or facility should consider the inventory of assets at a site/facility associated with the specific resilience solutions to be evaluated. Only the assets that are affected by the aggregate of the risk-reducing resilience solutions need to be considered. The inventory includes the structural composition of assets, their age, and their condition based on the level of continued maintenance. Assets may be evaluated by class if the analysis is being done for a site. For example, buildings of similar age, construction, and maintenance can be combined for analysis.

Human assets are also a part of the site/facility assets. Damage to human assets includes lost work time, injury, and death.

3.5.2 Direct or Indirect Impacts

The hazard, resistance, and damage may also have direct and indirect impacts on other less critical assets/loads that may not have been included in the initial resilience analysis. Direct impacts are losses to productivity due to the loss of electricity and water. In addition, there may be injuries and loss of human life due to the hazard. Indirect impacts include the loss of medical services that may impact human life due to loss of refrigeration of medical supplies, and inoperable medical facilities if appropriate backup power was not provided or failed to operate. Besides lost electricity, there may be other equipment that is lost as a result of a realized hazard. Potential solutions will drive whether both direct and indirect impacts need to be examined. As an example, if flooding impacts a switchyard at a site, a solution may not only protect the switchyard, but also protects other buildings from flooding and damage. Types of direct and indirect items that may be identified by systems engineering or discussions with site personnel are listed below:

- Value of interrupted mission
- Value of lost work time
- Equipment damage, costs of repair, replacement, and cost of restoration
- Human injuries and deaths
- Food spoilage
- Any commercial losses associated with site/facility damages
- Value of fuel used in backup generators

Organizations also need to consider the monetary impacts as a result of lost load, such as reduced cash outflows when personnel or hourly workers are not working. Additionally, there may be fuel and other raw materials that are not used, as well as the value of any scrap material. The following three subsections on hazard, resistance, damage and loss probabilities go into the greater detail that may be required to complete a monetary valuation of site/facility resilience.

3.6 Value of Lost Load or Customer Damage Functions

For electricity, VOLL is a primary indicator of economic losses associated with outages and is usually measured by $/kWh. VOLL is also known as the customer interruption cost or the customer damage function. The value of lost water has not been studied as extensively as the value of lost electricity and thus there are not surveys that value a gallon of lost water. The same approaches that are used for electricity could be used to value the lost water as well.

Given that the value of electricity and water differs by customer type, the VOLL may need to be developed for industrial, commercial, residential, and government customers. There are several approaches to calculating the VOLL, which are discussed in this section because the analyst will need to pick an appropriate approach for determining the VOLL. These include the following:

- Government loss – suspended operations value
- Macroeconomic modeling
    - Input-output modeling
    - Computable general equilibrium
- General equilibrium modeling
- Revealed preferences
- Stated preferences
    - Willingness to pay
    - Willingness to accept
    - Discrete choice experiments
- Blackout studies
- Insurance

The approaches are compared briefly in Table 2 and more completely thereafter in Section 3.6.1.

Table 2. Value of Lost Load Approaches, Pros, Cons and Method

Method	Approach	Pros	Cons	Method
Government loss	Mission value calculated as the loss to the nation/state/local government from the lack of service	Needed for government procurement justification	Hard to calculate when there is no clear value to loss of electricity or water other than lost cost of labor	May use GDP impact due loss of government output
Macroeconomic: input/output modeling	Approach to calculating inputs to and output	Easily calculated with appropriate software	Doesn't show value of residential load but can be adapted	Aggregated economic data

Method	Approach	Pros	Cons	Method
	from each sector affected in the economy		to provide the information	
Computable general equilibrium (CGE) modeling	General equilibrium model of economy to show impacts of shocks to the economy	Provides time path to impact results	Data requirements greater than input/output approach	Aggregated economic data
General equilibrium modeling	Subset of the CGE model that evaluates impacts by sector	Granularity at the level required to complete the analysis	Potential of a lack of data to drive model	Aggregated economic data
Revealed preferences	Market-based estimates of losses	Provides data on actual losses	Current approaches don't measure long-duration lost load	Obtained through surveys
Stated preferences: willingness to pay	Ask individuals what they are willing to pay to keep a service operating	Most commonly used approach and widely accepted	Not theoretically correct and may not be appropriate for long-duration lost load	Obtained through surveys
Stated preferences: Willingness to accept	Measures what an entity is willing to accept in remuneration to give up load	Alternative approach to willingness to pay	Not theoretically correct and may not be appropriate for long duration lost load	Obtained through surveys
Stated preferences: Discrete choice experiments	Evaluates the equivalent variation (loss of welfare) of lost load to customer	Most theoretically correct method of calculating lost load	May suffer from entities not providing accurate answers due to not having experienced long-duration lost loads	Obtained through surveys
Blackout studies	Actual data from blackouts to calculate value of lost load	Accurate cost of specific blackout	Significant cost of the analysis	Data collected based on analysis of the event
Insurance	Data collected and evaluated based on actuarial analysis	Can be more accurate because it is actual data	Suffers from self-selection bias and difficulty to obtain from insurance companies	Loss data collected by insurance companies

Due to some of the features and uses of electricity, the longer the duration of the loss, the higher the cost of the lost load. For example, freezers can keep foods frozen for a period, after which thawing will occur, and after more time, spoilage if the food is not used. Thus, the VOLL tries to capture the consequence of the loss over time. In addition, the time of day may impact the VOLL because work loss may be more consequential during work hours for the government, commercial, and industrial customers, while the evening, night, and morning hours may be more consequential to residential consumers.

The most widely used values for short duration electricity outages for residential, commercial, and industrial customers is the Lawrence Berkeley National Laboratory (LBNL) Interruption Cost Estimate (ICE) Calculator (https://icecalculator.com/home). This tool can calculate reliability and uses SAIDI (System Average Interruption Duration Index) and SAIFI (System Average Interruption Frequency Index). The ICE calculator, however, has a few drawbacks. First, reliability is only a component of resilience not all of it. In addition, SAIDI and SAIFI are system averages and that assumes that every entity faces the same outage time which is clearly not true for a specific building or site. In addition, the current version does not calculate VOLL past 16 hours. Severe hazards, such as earthquakes or hurricanes, can cause outages that last for days. The calculator also does not provide a value for government lost load.

In addition, the "willingness to pay" methodology has received criticism for not being economically correct[18] because the cost of the lost electricity does not have to equal the value that the residential customer is willing to pay to avoid the lost load. However, willingness to pay is an accepted approach. LBNL and Nexant have published a guide for utilities on how to calculate the VOLL to the customers.[19] Revealed preferences and stated preference approaches are usually determined through surveys. Survey methods establish the scope of what is being estimated and, using statistically designed surveys, obtain the VOLL by customer type, time of day, and time of year. Surveys require approximately $0.75–$1 million to undertake. Drawbacks include the cost and time to develop the survey and obtain results.

3.6.1 Discussion of VOLL Methods

Government mission value. Mission value may be difficult to calculate since there is no market to price the government services performed. The losses can be calculated as the direct loss to the government for lost assets, the cost to restore those assets, and the cost required to complete the agency's mission. The VOLL for a government agency can often be listed as the unproductive time paid while electrical service is unavailable; this may include any overtime paid if the original schedule is to be restored. Sometimes the mission value can be calculated as the loss to the nation/state/local population from the lack of service, e.g., value the service at the budgetary cost per hour of lost time. Other times the consequence is much larger, in that it is human loss due to illness, injury, and/or death, as well as the assets that the mission was serving. For example, if the Centers for Disease Control loses water or power, the lack of vaccine development could cause more people to become infected with an illness than would have been if the power or water hadn't failed. The amount of time associated with the setback in vaccine development could then be multiplied by the death rates/day, loss of productivity associated with added illness and any additional hospitalization costs. The added time lost to re-open the economy could additionally be a hit to gross domestic product.

Macroeconomics approaches. Macroeconomic approaches use data from aggregated economic sector information to calculate the impact of hazards on the economy of the affected region. They may be the most appropriate value for long duration lost load, for government facilities. Three approaches are described: the input-output (IO) model, the CGE model, and the general equilibrium model.[20] Macroeconomic models can also be used to evaluate policy issues associated with resilience. However, macroeconomic models generally lack the ability to quantify non-market values, such as death, injury and residential consumer losses.

IO models specify the requirements of each sector and the outputs of each sector on what can be as small as county data to as large as national data. The IO model can be used to evaluate both policy questions

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[18] Roark J. 2019. "Evaluating Methods of Estimating the Cost of Long-Duration Power Outages." In Frontiers in the Economics of Widespread, Long-Duration Power Interruptions. Eds. PH Larsen, AH Sanstad, KH LaCommare, JH Eto. Lawrence Berkeley National Laboratory, Berkeley, CA.

[19] Sullivan, M., M.T. Collins, J. Schellenberg, and P.H. Larsen. 2018. Estimating Power System Interruption Costs: A Guidebook for Electric Utilities. Berkeley, CA: Lawrence Berkeley National Laboratory. LBNL-2001164.

[20] Wing, I.A., and A. Rose. 2019. "Topic 3: "Economic Consequence Analysis of Electric Power Infrastructure Disruptions: An Analytical General Equilibrium Approach." In Frontiers in the Economics of Widespread, Long-Duration Power Interruptions. Eds. P.H. Larsen, A.H. Sanstad, K.H. LaCommare, and J.H. Eto. Berkeley, CA: Lawrence Berkeley National Laboratory.

and benefit/cost problems. Although not as granular as the survey-based data, macroeconomic models can show the regional cost of long-duration lost load to a large government presence and the regional population or a utility and their commercial and industrial customers. IO data does not reflect the value of residential customer lost load, but from a utility's perspective, it can be used to justify projects from a benefit/cost approach. The IO model is limited because of the fixed coefficients, the non-substitutability of inputs, and the fixed price nature of the IO model.[21]

CGE models are much more complex dynamic models that use the data from the IO model to generate time paths for adjustments in the economy based on shocks to the economy, where a hazard is an external shock rather than a policy shock. Only if the analyst follows the shock through time will they provide an immediate impact of a shock as well as the outcome after the shock. If the analyst only looks at the impact after adjustment, most CGEs will show little change. The main drawback to the CGE model is that the data requirements are greater for the CGE data than the IO model. The CGE model also lacks the granularity of the survey methods and insurance data.[22] . Whether CGE is used or not may depend on the site. Some sites (e.g. large-scale federal installations) may have a disproportionate impact on the local community, thus the CGE might be the best solution to determine the regional economic value of an impact at that site.

The general equilibrium model, a subset of the CGE model, provides a model of the economy as a whole and may become as granular as necessary to analyze the probabilities, vulnerabilities, and consequences of a problem. The model breaks down impacts in the commercial, industrial, and residential losses. The main shortcoming is the lack of accurate data to drive inputs to the model. The advantage is that it is less time consuming to build than the CGE model.[23]

Revealed preferences. Market-based estimates are a form of revealed preferences where actual data collected reveals the preferences using actual costs for lost load and any associated benefits. For example, the U.S. Department of Defense (DoD) provided an estimated cost to DoD of a lost day of electricity placing the value at between $179 million to $225 million for FY 2013 through 2015.[24] The data being collected are as follows:

- The value of lost production.
- Other related costs that are directly associated with the loss of electricity. The costs include items such as overtime to make up lost production, damage to equipment and a reduced feedstock used.
- Any benefits that might arise from loss of electricity. The benefits include items such as wages saved if employees are only paid for time worked rather than if they are salaried.

Revealed preferences can also reflect the costs incurred to avoid a short-term loss of electricity. The strength of this approach is that it is based on actual observed behavior. The drawbacks include lack of data availability and lack of observed variability in the observations.

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[21] Weimar, M.R., D.M. Anderson, B. Kravitz, R.T. Dahowski, S.A. Brown, J.M. Niemeyer, A. Somani, and K.S. Judd. 2018. Methodology for Valuing Resilience to Severe Events for the Department of Energy Sites. Richland, WA: Pacific Northwest National Laboratory. PNNL-27257. https://epe.pnnl.gov/pdfs/Benefit_Cost_Analysis_Puerto_Rico_HUD_final.pdf.

[22] Roark J. 2019. op. cit.

[23] Wing, I.A., and A. Rose. 2019. op. cit.

[24] DoD–U.S. Department of Defense. 2016. Annual Energy Management Report Fiscal Year 2015. Washington, D.C. Accessed April 20, 2020 at https://www.acq.osd.mil/eie/Downloads/IE/FY%202015%20AEMR.pdf. The DoD suggested using the values stated in the FY 2015 report but didn't provide any methodology about how the data were collected or what they represented. As such, they are hard to use since the installations from which they were gathered may differ in size and the importance of the facilities to critical missions.

Stated preferences. Stated preferences include willingness to pay, willingness to accept, and discrete choice experiments. These approaches ask hypotheticals of what a consumer is willing to avoid, willing to accept, or which option the consumer would choose between to avoid lost power.

The willingness to pay or contingent valuation approach is probably the most commonly used approach but suffers from a lack of coherent economic theory as well as a hypothetical bias because the respondent may either undervalue or overvalue the lost electricity. The method may also be biased by the questions asked if they influence the results of the survey. Willingness to pay appears to be the most common approach to valuing residential custom lost load. The willingness to pay approach may not be able to value long-term lost load because of lack of experience by the consumer with long-term lost load.

Willingness to accept is an alternative approach to willingness to pay. The willingness to accept approach asks individuals what the minimum is they are willing to accept in order give up their electricity for different time periods. In the federal context, willingness to accept could be determined by asking an agency administration how much cost associated with an outage they would accept to be willing to experience the outage. Willingness to accept and willingness to pay are supposed to provide the same answer. The literature indicates that willingness to pay almost always indicates a lower VOLL than willingness to accept. In addition, the National Bureau of Economic Research evaluated how closely they matched, they found little correlation between the two measures. The analyst may want to use willingness to pay if they are interested in using more conservative values.[25]

Discrete choice experiments (DCEs), according to the literature, are the most theoretically correct stated preference approach. The DCE sets up a survey based on economic theory (using random-utility theory), that provides an equivalent variation approach to characterizing the attributes of lost load and the cost that consumers associate with it. DCE may be better able to calculate a value to long duration lost load than willingness to pay because the DCE approach determines the value by attribute of the outage. One problem with the discrete choice experiment is the ability of the survey recipient to understand the scenarios being evaluated. Evaluation of DCE indicated that small changes in experiment design can provide different results.

Blackout studies. Blackout studies use actual data from blackouts to calculate the actual value of the lost load. They are expensive to undertake, and they represent a small portion of outages.[26] However, they represent the more likely long-term outage associated with resilience solutions.

Insurance approaches. Insurance approaches use data collected and analyzed through actuarial analysis to determine the probabilities of hazard vulnerabilities and consequences. The data collected can be more accurate than all of the other approaches, but the actual insurance data (if obtainable) can be limited by the bias of who purchases insurance and who does not.[27] Approaches are required to expand the data to the population experiencing the outage. Limitations include the ability to obtain the data from insurance companies and the cost of obtaining the data by using the same actuarial approach. In addition, people who obtain insurance may be the people who cannot afford the consequences of the realized hazard and may be self-selecting in the insurance company’s portfolio.

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[25] Chapman, J, M Dean, P Ortoleva, E Snowberg, C Camerer. Oct 2017. *Willingness to Pay and Willingness to Accept are Probably Less Correlated than You Think*. National Bureau of Economic Research Working Paper Series No. 23954. Accessed April 23, 2020 at https://www.nber.org/papers/w23954.pdf

[26] Sullivan, M., M.T. Collins, J. Schellenberg, and P.H. Larsen. 2018. op. cit.

[27] Per the U.S. Government Accountability Office, the federal government prefers to self-insure and is also an insurer of last resort when market failures occur. As such, there is little easily available data on the cost of self-insurance to the federal government.

3.7 Develop Monetary Value of Baseline

Once quantitative values have been developed for the forecast annualized probabilities of the hazard over time, the resistance and the damage to associated assets, the probable monetary value of those damages to the baseline needs to be calculated.

For electricity, these costs include the cost to restore the system to its prior condition, including repairs to the electrical system. A lightning strike, for example, could cause damage to building assets' systems as well as the work being conducted utilizing those assets. Hurricanes could damage electric distribution systems. Values for all the interdependent systems need to be developed. This includes the VOLL and the cost of running backup electricity, if any, to compensate for the lack of grid electricity. For systems with backup generation, the only cost may be the cost of maintaining and running backup generation systems. The impacts to other energy and water systems would be similarly calculated where the cost and duration of restoring the system is calculated, the value of the impact of lost energy or water is determined, and all downstream and interdependent impacts are included.

Resilience valuation is a forward-looking problem; thus, the value of the baseline is the cost due to probabilities of hazards or threats, resistance damage and value of those losses over a specific time horizon and evaluated on an NPV basis using the appropriate discount rate for a federal facility. The appropriate discount rate is dependent on the type of capital investment being contemplated to improve the resilience of the system. The FEMP real discount rate of 3% is appropriate for all federal capital projects that relate to energy conservation (e.g., energy efficiency), renewable energy projects, and water conservation projects for federal facilities. Office of Management and Budget (OMB) Circular A-94 rates of return apply to all other federal capital projects. OMB discount rates for 2018 are listed in Table 3. The rates are updated annually and can be found in NISTIR 85-3273-XX, where XX was 33 for 2018.[28]

Table 3. Real Discount Rates for Non-energy Capital Projects

Maturity	3-year	5-year	7-year	10-year	20-year	30-year
Rate	-0.8%	-0.6%	-0.3%	-0.1%	0.2%	0.6%

The time horizon over which the project should be evaluated depends on three factors. The longest-lived asset may be the primary factor for determining the time period. In other cases, the severe hazard analysis may provide a different timeframe, perhaps 50–100 years.[29] A third timeframe may also present itself, which may be a project timeline, such as a mission timeline, as determined by the decision maker. The economic lives of most energy conservation projects can be found in an agency's guidance document (e.g., a DoD guidance document).[30]

To determine the life cycle costs and NPV of the baseline (and it can be used to calculate the life cycle costs and NPV of each solution), use Eq. (2):

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[28] Lavappa, PD and JD Kneifel. 2018. *Energy Price Indices and Discount Factors for Life-Cycle Costs Analysis - 2018*. Annual Supplement to NIST Handbook 135. NISTIR 85-3273-33, National Institute of Standards and Technology, U.S. Department of Commerce, Washington, D.C.

[29] For severe hazards for example, a hazard with a 1% annual probability, this would translate to a 26% chance of occurring during a 30-year timeframe typical of projects developed through contracts such as an energy savings performance contract. Thus, potentially not showing an actual savings if in a guaranteed savings type contract.

[30] Office of the Assistant Secretary for Defense. 2017. *FY 2019/FY 2020 Energy Resilience and Conservation Investment Program and Plans for the Remainder the Future Years Defense Program Guidance*. Washington, D.C.

$$NPV = \sum_{0}^{n} {(-V_{ij} + I_{kj} + B_{lj})}\Big/{(1+d)^{j}} \qquad (2)$$

where:

NPV = net present value of the life cycle costs
V = the status quo value at risk based on the value at risk of equation 1 above for each year associated with the baseline
I = any investment cost required, most likely to be included for proposed resilience solutions.
B = any current benefits based on the value at risk of equation 1 above for each year associated with the baseline
d = the discount rate or weighted average cost of capital
i = the i*th* value at risk
k = the k*th* investment cost
l = the l*th* benefit
j = the j*th* year of the project between 0 and n
n = project length in years

Thus, the value of the baseline is the sum of the values at risk over time. This may be accomplished with *Monte Carlo* models or some other model that simulates the probabilities of the four components over time. Benefit values and investment costs are more likely to occur with solutions than with the baseline. The values for each year are discounted to time zero and the sum becomes the life-cycle cost of the baseline. The LCC value here will be compared with the values for each of the solutions discussed in the next section to see if there are improvements.

4.0 Value Resilience Solutions

This methodology relies on two key steps: 1) evaluate resilience solutions based on the new estimated probabilities for the hazard, resistance, damage and/or loss; and 2) monetize the impact. In Sections 4, 5, and 6, a consistent set of three resilience solutions for a distribution system that reduce the VOLL in the case of a hurricane are provided to demonstrate how these steps apply to different examples:

1. Solution 1: implement a more efficient HVAC system.
2. Solution 2: include a microgrid.
3. Solution 3: install a site battery.

4.1 Evaluate Resilience Solutions to Determine Resilience

Depending on the approach for reducing damage to the mission, the appropriate portion of the "value at risk" equation needs to be evaluated. If the site is moved, new probabilities for the hazard will need to be forecast. If the vulnerability is adjusted, new resistance values and damage functions will need to be identified and implications for all affected assets will need to be examined. All the solutions provide a reduced consequence.

SMEs and facility/site stakeholders should be consulted to understand the damage reduction that might be expected for each alternative studied. In addition, fragility and damage functions can be found in the literature. For example, replacing wooden poles with steel monopoles or reinforced concrete poles requires new fragility functions that show the reduced damage to the poles due to the same wind intensities. Lastly, if assets are replaced, the value of the new asset must be estimated.

4.2 Value Each Resilience Solution

Adjusting the appropriate hazard, resistance, damage, and/or loss probabilities will enable the analyst to see the value at risk of the resilience solutions. The approach for valuing the baseline is repeated for each solution determining costs and time period (time zero, interval for major repair, annual costs). Thus, the costs of each alternative need to be developed. The installed costs for the investment should be determined and placed at the beginning of the investment period. Any annual or periodic operations and/or maintenance costs need to be included. Some resilience measures may provide operations and maintenance savings. Care must be taken to assure that the savings are real. For example, military installations must maintain backup generation units for each identified critical system, and those costs must still be accounted for even though the costs of those backup units may be substantially reduced in years where a 14-day run is not required.

5.0 Complete a Benefit/Cost Analysis and Obtain the NPV

Benefit/cost analysis provides the basis for investments intended to reduce risk to a level that is as low as reasonably possible (ALARP). The benefit/cost analysis can also be used to evaluate alternative investments based on expectations of future conditions. Two documents from two institutes can provide guidance for principles and standards in conducting benefit/cost analysis: *Community Resilience Economic Decision Guide For Buildings and Infrastructure Systems*, from National Institute of Standards and Technology[31], and *Toward Principles and Standards in the use of Benefit Cost Analysis*, from the University of Washington.[32]

5.1 Compare Valuation of Action to Inaction

The next step in the analysis is to compare the value of the alternatives to the baseline. For resilience valuation one of the major benefits is the reduction in the value-at-risk that is achieved through implementing a resilience solution. Because of this, the benefit/cost analysis for resilience valuation can be summarized using the Net Present Value (NPV). To calculate NPV of resilience for an investment, the LCC should be calculated for the baseline (as in Section 4) and each resilience solution. The difference between the life cycle costs by period for the baseline and each solution is taken. The differences for each period are summed. The NPV is calculated for the stream of values for each solution alternative based on the cost/benefit analysis.

Table 4 provides the change in value from the baseline. As such, the table provides the improvements in resilience value for each alternative. Only the differences are shown for the alternatives. Resilience Solution 1 is infeasible, Solutions 2 and 3 are positive, and Solution 3 provides additional resilience for a little more investment. The values in the cells are the expected values from the life cycle cost analysis summed across all the components for each year of the analysis.

There are uncertainties associated with the analysis that need to be accounted for in the benefit/cost analysis. Those uncertainties can include the probabilities associated with the improvements in vulnerabilities and/or the investment costs required to implement the alternative. It is important to identify the uncertainties in the analysis and provide quantification if possible. An uncertainty analysis should be used to provide ranges for results based on data or expert judgment; it is important to clarify how wide the uncertainty in the analysis is.

Results can additionally be provided as a ratio of the NPV to the investment, or the NPV/investment ratio, where the investment includes only the initial investment. This ratio highlights the investment costs associated with each resilience solution and can help to frame the comparison of solutions in the context of available funding.

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[31] Gilbert, SW DT Butry, Jennifer F. Helgeson, RE Chapman. 2015. *Community Resilience Economic Decision Guide For Buildings and Infrastructure Systems*. NIST Special Publication 1197, National Institute of Standards and Technology, Washington, D.C.. http://dx.doi.org/10.6028/NIST.SP.1197

[32] Zerbe Jr, RO, TB Davis, N Garland, T Scott. 2010. *Toward Principles and Standards in the use of Benefit Cost Analysis*. Benefit-Cost Analysis Center, Evans School of Public Affairs, University of Washington.

Table 4. Net Present Value Calculations as a Change from the Baseline for Each Alternative ($)

	Year =>	0	1	2	3	4	. . .	49	50
More efficient HVAC System	NPV total	Investment							
Electricity restoration			1,500	1,500	1,500	1,500	. . .	1,500	1,500
Electricity VOLL			7,500	7,500	7,500	7,500	. . .	7,500	7,500
Water restoration			500	500	500	500	. . .	500	500
Water value			300	300	300	300	. . .	300	300
Communications			3,000	3,000	3,000	3,000	. . .	3,000	3,000
Computer systems			9,000	9,000	9,000	9,000	. . .	9,000	9,000
NPV	(426,302)	(1,000,000)	21,800	21,800	21,800	21,800	. . .	21,800	21,800
Install Microgrid									
Electricity restoration			5,550	5,550	5,550	5,550	. . .	5,550	5,550
Electricity VOLL			27,750	27,750	27,750	27,750	. . .	27,750	27,750
Water restoration			1,850	1,850	1,850	1,850	. . .	1,850	1,850
Water value			1,110	1,110	1,110	1,110	. . .	1,110	1,110
Communications			11,100	11,100	11,100	11,100	. . .	11,100	11,100
Computer systems			33,300	33,300	33,300	33,300	. . .	33,300	33,300
NPV	558,605	(1,500,000)	80,660	80,660	80,660	80,660	. . .	80,660	80,660
Install Site Battery									
Electricity restoration			6,495	6,495	6,495	6,495	. . .	6,495	6,495
Electricity VOLL			32,475	32,475	32,475	32,475	. . .	32,475	32,475
Water restoration			2,165	2,165	2,165	2,165	. . .	2,165	2,165
Water value			1,299	1,299	1,299	1,299	. . .	1,299	1,299
Communications			12,990	12,990	12,990	12,990	. . .	12,990	12,990
Computer systems			38,970	38,970	38,970	38,970	. . .	38,970	38,970
NPV	707,510	(1,700,000)	94,394	94,394	94,394	94,394	. . .	94,394	94,394

Parentheses indicate cost higher than baseline.
Year 0 represents the initial investment

5.2 Establish Non-monetary Benefits and Costs

Certain benefits and costs are hard to value monetarily. Non-monetary benefits may be either quantifiable or non-quantifiable.

- Quantifiable non-monetary benefits and costs include issues like injuries, deaths, increased or decreased productivity, reduced deterioration rates for electronic equipment, and reduction in environmental damage.
- Non-quantifiable benefits include issues like improvements to morale, improved safety and societal benefits such as protecting cultural and historical assets, aesthetics, and improved relations with the larger community.
  - These non-monetary benefits may include resilience goals such as reductions in risk, reduction in time required to implement projects, ease of implementation, alignment with existing project and/or site priorities, satisfaction of organizational policies, alignment with sustainability standards, alignment with energy and/or water efficiency standards, alignment with environmental management standards, reductions in kilowatt-hours lost, improved power quality, and reduced light flicker.
  - The non-monetary benefits may include previous resilience prioritization criteria or goals, as well as newly determined issues more closely aligned to financial decision making once the preliminary quantification has been completed.

Economists often try to put a value on many of these non-monetary benefits and costs through the same process that can be used for valuing lost load through several approaches described below. However, that may require a significant amount of additional study. Thus, many times quantifiable non-monetary benefits are added by a physical number, while non-quantifiable values use a relative value, such as negative, none, low, medium, or high. Non-monetary benefits important to the site may have previously been established and can be obtained from the SMEs working on the resilience projects. Discussing the likely impacts of the alternatives can usually elucidate what monetary and non-monetary benefits are likely to occur.

Injury and death rates can be reduced directly through the resilience of water, electricity, and energy systems. Ensuring that buildings and distribution systems are maintained to code can reduce direct deaths and injuries due to natural hazards. Providing adequate water and fuel storage along with backup power can reduce downstream injuries and deaths by providing clean potable water, improved use of medical devices, and refrigeration for medicine.

Deaths are an easy numerical example even though the U.S. Environmental Protection Agency provides a value for human life of $7.4 million (2006$).[33] Some sites may prefer not to attach a monetary value to a human life and can evaluate the impact of solutions simply on the number of deaths prevented. For the baseline, an estimated or forecast level of deaths may be required. The hope is that each resilience alternative would reduce the number of deaths (i.e., a benefit for each alternative would be fewer deaths).

Productivity can be increased or decreased depending on the state of water and electricity systems. Poor power quality can deteriorate equipment, making workers less productive while machines are replaced. Alternatively, providing computer power backup can reduce the impacts of poor power quality and maintain equipment. Productivity may be hard to quantify as workers may still be on the job, but the output differential may be hard to directly measure.

Safety may be improved by the implementation of some resilience alternatives but may reduce morale. Improved upkeep of water and energy systems may require added training and safety features to operate and maintain automated systems to keep workers safe during the maintenance procedures. The additional protocols may be annoying and lower morale among maintenance workers. Morale is an item that may be hard to quantify, while safety could be estimated as the reduction injury number

Aesthetics is a non-quantifiable example for relative values. A berm placed to reduce inundation may reduce the visual appeal of an otherwise perfect coastal view, which would yield a negative rating. The berm also could reduce environmental damage to lowlands while protecting the water and energy systems. On the other hand, providing undergrounding of distribution lines with flood-proof access vaults would improve the visual appeal of the site but perhaps could increase environmental damage. Thus, there can be tradeoffs between non-monetary benefits.

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[33] EPA – Environmental Protection Agency. “Mortality Risk Valuation.” Last updated on February 18, 2018. Accessed April 28, 2020 at https://www.epa.gov/environmental-economics/mortality-risk-valuation#whatisvsl.

6.0 Create a Decision Matrix to Compare Valuation Outputs

With resilience alternatives, there may be multiple financial criteria and site objectives that need to be met. In addition, the alternatives may provide differences in how many types of assets are impacted by the proposed alternatives and clear choices may not be obvious using only NPV as the sole determinant.[34] In those cases, decision-making under risk and uncertainty requires tools to help the decision maker understand how the baseline and alternatives measure up to the site's goals and objectives.

The decision matrix provides a tool by which the analyst can help the decision maker evaluate the economic results associated with the resilience alternatives evaluated using this methodology. This tool is recommended because it gathers together relevant information for NPV, costs, NPV/investment (ratios, and non-monetary costs and benefits and places them in a format that allows for direct comparisons – and allows for valuation criteria and weights developed from the decision maker to assess how each alternative compares. Decision criteria and weights in the context of our example could include both monetary and non-monetary values and weighting:

- NPV savings; weighting = 30%
- NPV/Initial Investment Cost; weighting = 15%
- Average megawatt-hours savings; weighting = 25%
- Reduced deaths; weighting = 30%

The following approach assumes that the benefit/cost approach is required to facilitate the choice among alternatives that otherwise would not provide a clear decision between the approaches. In the federal context, agencies will have specific documentation when benefit/cost approaches are required. The process of obtaining data and understanding site/building assets may change how the decision maker views the original criteria and weights to meet the goals and objectives.

6.1 Apply Economic Decision Criteria

Once the decision criteria and weights have been determined, the results can be summarized in a decision matrix. Table 5 provides an example for a distribution system that is facing a hurricane hazard. The green highlighted cells indicate the best alternative for each category.

Solution 1 (implement a more efficient HVAC system) is infeasible, as the NPV and NPV/Investment ratio are negative. Because of potentially competing objectives, the highest NPV may not be the best. In some cases, budget constraints may make the best solution less desirable because of the total budgeted outlays required. Additionally, obtaining upfront capital for construction expenditures may be limited. In this case, Solution 2 has a lower upfront capital cost based on the information in Table 3. Thus, lower-cost options with larger returns per unit of cost may be better. In some cases, because operations and maintenance budgets may be constrained, options that provide for upfront capital may be more useful for resilience because they may need less annual upkeep.

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[34] The highest NPV provides the best financial metric if the alternatives are mutually exclusive and only financial metrics are being used to make a decision.

Table 5. Example Decision Matrix

Alternative	NPV ($000)	NPV/ Investment Ratio	Average kWh Savings	Reduced Deaths	Wgt'd by Criteria
More efficient HVAC System	-426	-0.426	2,000	200	
Install Microgrid	558	0.372	5,000	1,000	
Install Site Battery	708	0.416	4,000	100	
Weights	30%	15%	25%	30%	
More efficient HVAC System	-0.602	-1.023	0.400	0.200	-0.174
Install Microgrid	0.788	0.893	1.000	1.000	0.920
Install Site Battery	1.000	1.000	0.800	0.100	0.680

In Table 5, the example from Table 4 shows that Solution 3 (install a site battery) provides the best NPV. In an unlimited capital view, the battery provides the best NPV. However, the battery is more costly than the microgrid (Solution 3). Additionally, the microgrid provides a better alternative based on kilowatt-hours and lives saved.

The goldenrod area at the bottom of Table 5 applies one multi-criteria decision-making approach to normalizing the values so a decision can be made. The green highlighted cells indicate the best items given the criteria and best solution overall. The tan cells provide the weights. The normalization approach divides each value by the best value in the column for criteria where larger is better. To complete the analysis, the values for each alternative are weighted by criteria weights and summed. In this case, Alternative 2 is shown as the best alternative given the decision maker's weights.

Table 5 does not show any cost only metrics; for costs-only criteria where lower cost is better, the lowest value is divided by the other values in the column. For non-quantifiable criteria, a grading system with a set of subjective levels such as very high, high, medium, low and very low could be added. A numbering system could be associated from one to five with the best value as a five and the lowest value as a one. The non-quantifiable criteria could then be included in the weighting. The decision maker may decide to exclude them from the decision matrix and just note them a pros and cons to the decision.

6.2 Provide Decision Matrix

The last step in the process is to provide the decision maker with the results of the analysis through a presentation that provides the basis for the decision matrix and the implications of the decision criteria outcome. The basis includes the assumptions that underlie the analysis. The assumptions include the discount rates, the fragility functions that provided the damage associated with the vulnerabilities, the approach to determining the amount of lost load in the baseline, and the reductions with each of the resilience solution alternatives. The supporting analysis provides the basis for the decision matrix and may include an analysis of assumptions that determine the degree to which the best estimates can vary and still provide a similar outcome.

7.0 Conclusions

A methodology has been developed to provide a monetary value of resilience for electricity and water. The approach provides a best practices approach to undertaking the benefit/cost analysis of the life cycle costs. The probabilistic approach goes beyond reliability to provide a resilience value to high-impact, low probability events associated with changing weather patterns, other natural hazards, and human threats. The approach requires the ability to collect data on hazards, vulnerabilities (in terms of resistance and damage), and the losses associated with asset damage and restoration time to calculate the baseline resilience value. The same approach is used to calculate resilience values for energy and water resilience solution alternatives. The simplified equation calculates the probability of the hazard multiplied by the probability of the resistance multiplied by the probability of damage multiplied by the probability of loss values for costs of asset damage, repairs and restoration time to calculate the amount of lost load and its value for the baseline for direct and indirect impacts. The baseline life cycle cost values are compared with life cycle cost values calculated for solution alternatives. The difference between the baseline and each resilience solution for each year is used in a life cycle cost analysis. A net present value analysis of the difference in life cycle costs is undertaken to complete the benefit cost analysis by evaluating the discounted NPV of the costs of investment against the improvements to the baseline in terms of reduced losses and any other increased monetary benefits that may accrue to a solution. A decision portfolio is developed to quantify the decision maker's financial criteria for solution alternatives along with non-monetary benefits and costs to help the decision maker determine which alternative best meets their goals.

8.0 Bibliography

Baik S, S Sirinterlikci, JW Park, A Davis, M Granger, Morgan. 2019. “Estimating Residential Customers’ Costs of Large, Long-Duration Blackouts.” In *Frontiers in the Economics of Widespread, Long-Duration Power Interruptions.* Eds. PH Larsen, AH Sanstad, KH LaCommare, JH Eto. Lawrence Berkeley National Laboratory, Berkeley, CA.

Coles GA, SD Unwin, GM Holter, RB Bass, and JE Dagle. 2011. “Defining resilience within a risk-informed assessment framework.” *Int. J. Risk Assessment and Management* 15(2/3):171-185.

DOE–U.S. Department of Energy. 2017. *Valuation of Energy Security for the United States*. Washington DC. Available at https://www.energy.gov/sites/prod/files/2017/01/f34/Valuation%20of%20Energy%20Security%20for%20the%20United%20States%20%28Full%20Report%29_1.pdf.

Ebrahimi R, A Babaee, and M Hoseynpoor. 2011. “Customer Outage Costs on a Distribution Feeder.” *Australian Journal of Basic and Applied Sciences* 5(7):588-595.

Eyer J and A Rose. 2019. “Mitigation and Resilience Trade-offs in Electricity Outages.” In *Frontiers in the Economics of Widespread, Long-Duration Power Interruptions.* Eds. PH Larsen, AH Sanstad, KH LaCommare, JH Eto. Lawrence Berkeley National Laboratory, Berkeley, CA.

FEMA–Federal Emergency Management Administration. 2018. *Threat and Hazard Identification and Risk Assessment (THIRA) and Stakeholder Preparedness Review (SPR Guide*). Available at https://www.fema.gov/media-library-data/20130726-1524-20490-7825/fema452_step3.pdf.

FEMA–Federal Emergency Management Administration. *Module 4-5: What are the Strengths and Weaknesses of the Community Vulnerability Assessment Tool: New Hanover County, North Carolina Model*. Available at https://training.fema.gov/hiedu/docs/hazrm/fema%20module%204-5.doc.

FEMA–Federal Emergency Management Administration. *Step 3: Vulnerability Assessment*. Available at https://www.fema.gov/media-library-data/20130726-1524-20490-7825/fema452_step3.pdf.

International Organization for Standardization. 2018. *ISO 31000-Risk Management*. Available at https://www.iso.org/iso-31000-risk-management.html.

Martin DM and M Mazzotta. 2018. “Non-monetary valuation using Multi-Criteria Decision Analysis: Sensitivity of additive aggregation methods to scaling and compensation assumption.” *Ecosystem Services* 29:13-22.

Pantelli M, C Pickering, S Wilkinson, R Dawson, and P Macarella. 2017. “Power System Resilience to Extreme Weather: Fragility Modeling, Probabilistic Impact Assessment and Adaptation Measures.” *IEEE Transaction on Power Systems* 32(5):3747-3757.

Porter K. 2018. *A Beginner’s Guide to Fragility, Vulnerability, and Risk*. University of Colorado Boulder. p. 112. http://spot.colorado.edu/~porterka/Porter-beginners-guide.pdf.

Preston BL, SN Backhaus, M Ewers, JA Phillips, CA Silva-Monroy, AF Tarditi, J Looney, and TJ King Jr. 2016. *Resilience of the U.S. Electricity System: A Multi-Hazard Perspective*. U.S. Department of Energy, Washington, D.C. Available at http://www.osti.gov/scitech/.

Proag S-K and V Proag. 2014. "The Cost Benefit Analysis of Providing Resilience." In *Procedia Economics and Finance.* 18(2014):361–368. 4th International Conference on Building Resilience, Salford Quays, UK.

Salman AM and L Yue. 2018. "A Probabilistic Framework for Multi-hazard Risk Mitigation for Electric Power Transmission Systems Subjected to Seismic and Hurricane Hazards." In *Structure and Infrastructure Engineering.* DOI: 10.1080/15732479.2018.1459741.

Schellenberg J, M Collins, M Sullivan, S Hees, and S Bieler. 2019. "Data Landscape: Challenges and Opportunities." In *Frontiers in the Economics of Widespread, Long-Duration Power Interruptions.* Eds. PH Larsen, AH Sanstad, KH LaCommare, JH Eto. Lawrence Berkeley National Laboratory, Berkeley, CA.

Shawhan D. 2019. "Using Stated Preferences to Estimate the Value of Avoiding Power Outages: A Commentary with Input from Six Continents." In *Frontiers in the Economics of Widespread, Long-Duration Power Interruptions.* Eds. PH Larsen, AH Sanstad, KH LaCommare, JH Eto. Lawrence Berkeley National Laboratory, Berkeley, CA.

Sullivan M, MT Collins, J Schellenberg, PH Larsen. 2018. *Estimating Power System Interruption Costs: A Guidebook for Electric Utilities*. LBNL-2001164, Lawrence Berkeley National Laboratory, Berkeley, CA.

Sullivan MJ, J Schellenberg, and M Blundell. 2015. *Updated Value of Service Reliability Estimates for Electric Utility Customers in the United States*. LBNL-6941E, Lawrence Berkeley National Laboratory, Berkeley, CA.

Weimar MR, DM Anderson, B Kravitz, RT Dahowski, SA Brown, JM Niemeyer, A Somani, and KS Judd. 2018. *Methodology for Valuing Resilience to Severe Events for the Department of Energy Sites*. PNNL-27257, Pacific Northwest National Laboratory. Richland, WA.

Wing S and IT Allison. 2019. "Economic Consequence Analysis of Electric Power Infrastructure Disruptions: An Analytical General Equilibrium Approach." In *Frontiers in the Economics of Widespread, Long-Duration Power Interruptions.* Eds. PH Larsen, AH Sanstad, KH LaCommare, JH Eto. Lawrence Berkeley National Laboratory, Berkeley, CA.

Appendix A – Assorted Resources

Data and Models to Support Estimation

Literature searches may be required to find the relevant information for determining the information required to calculate the impact of a hazard on relevant assets. For example, the U.S. Geological Survey (USGS) provides good information on the probabilities of earthquake hazards by region. Earthquake fragility curves are developed by the National Institute of Standards and Technology through the National Earthquake Hazards Reduction Program. In addition, there are many programs that provide fragility curves based on location. However, the associated fragility curves for specific assets types may need to be evaluated through the literature for some hazards. Appendix A of Weimar et al. 2018[1] provides additional information about developing cost baselines. In addition, the probabilities of natural hazards need to be forecast over time. Appendix B of the same document provides further information on establishing probabilities of a natural hazard. Below are some other resources and caveats. Seismic tools appear to be the most abundant, followed by hurricane tools. The following is a list of the potential tools.

Risk assessment resources:

- The HAZUS model provides damage estimates for hurricanes, floods, earthquakes, and tsunamis. Information on the model is located at https://www.fema.gov/summary-databases-hazus-multi-hazard. HAZUS contains data on “essential facilities, high potential loss facilities, selected transportation and lifeline systems, agriculture, vehicles, and demographics.” HAZUS uses a judgment approach to calculating fragility curves.
- The Facility Energy Decision System (FEDS) model can be used to evaluate heating, cooling, ventilation, lighting, motors, plug load, building shell, hot water systems, central plants, and thermal loop impacts based on the probabilities on future heat waves. More information and the tool can be obtained at https://www.pnnl.gov/FEDS/.
- The USGS provides specific data on seismic hazards and tools: USGS Seismic Hazard Maps and Site-Specific Data at https://earthquake.usgs.gov/hazards/hazmaps/.
- The National Oceanic and Atmospheric Administration National Hurricane Center provides information on hazard probabilities by category at https://www.nhc.noaa.gov/climo/.
- Coastal flood probabilities may be evaluated using tools developed by Climate Central at http://sealevel.climatecentral.org/maps. The Federal Emergency Management Administration provides flood probabilities at https://hazards-fema.maps.arcgis.com/apps/webappviewer/index.html?id=8b0adb51996444d4879338b5529aa9cd.

Important factors to consider when analyzing hazard and damage data:

- Difficulties may be encountered finding adequate damage functions and tools to quantify the probability of damage for specific types of assets. The approach is to look for damage functions specific to the assets that is being evaluated.
  - For example, there are fragility functions that specifically indicate what the damage was to specific types of electricity poles (wood, concrete, steel) based on wind speeds. Care needs to be taken, however, as undergrounding electric conductors in areas prone to flooding have

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[1] Weimar MR, DM Anderson, B Kravitz, RT Dahowski, SA Brown, JM Niemeyer, A Somani, and KS Judd. 2018. *Methodology for Valuing Resilience to Severe Events for the Department of Energy Sites.* PNNL-27257, Pacific Northwest National Laboratory, Richland WA. Available at https://epe.pnnl.gov/pdfs/Benefit_Cost_Analysis_Puerto_Rico_HUD_final.pdf.

  significantly less resilience than underground conductors in non-flood areas. The costs may also increase to accommodate water-tight vaults. In addition, undergrounding wires can be more expensive to repair and take longer to restore when a failure occurs.

- Damage functions often look at assets only, but there are potential damages to other dependent and interdependent systems.
  - All damage functions should be included, including all potential systems damaged from the hazard. For example, the downstream effects may include damage from lost communications, computer systems, and all the costs associated with their downtime. Lost electricity could include food spoilage from the lack of refrigeration.

When directly related data does not exist, a substitute or proxy may be found that approximates for it. An example could be that the resilience value of alternatives may rely on information associated with responses from other sites with similar conditions.

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