Resilience Metrics for the Electric Power System: A Performance-Based Approach

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Abstract

Grid resilience is a concept related to a power system's ability to continue operating and delivering power even in the event that low probability, high-consequence disruptions such as hurricanes, earthquakes, and cyber-attacks occur. Grid resilience objectives focus on managing and, ideally, minimizing potential consequences that occur as a result of these disruptions. Currently, no formal grid resilience definitions, metrics, or analysis methods have been universally accepted. This document describes an effort to develop and describe grid resilience metrics and analysis methods. The metrics and methods described herein extend upon the Resilience Analysis Process (RAP) developed by Watson et al. for the 2015 Quadrennial Energy Review. The extension allows for both outputs from system models and for historical data to serve as the basis for creating grid resilience metrics and informing grid resilience planning and response decision-making. This document describes the grid resilience metrics and analysis methods. Demonstration of the metrics and methods is shown through a set of illustrative use cases.

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1. INTRODUCTION

Presidential Policy Directive 21 (PPD-21) designates the energy sector as a uniquely critical infrastructure "due to the enabling functions [it] provide[s] across all critical infrastructure sectors" [1]. Energy infrastructure, especially the electrical power grid, enables basic, societal functions that are taken for granted as long as power is being delivered. From communications to transportation to banking and finance, almost every aspect of modern life relies upon the electrical power grid.

A continuous, uninterrupted supply of power provides many benefits to the country. However, when the electrical power system is disrupted, impacts can be realized almost immediately. The lights go out, traffic gets disrupted, hospitals have to suspend nonessential procedures, and businesses may not be able to operate. In fact, weather-related power outages cause $25 to $70 billion of economic losses annually in the United States [2]. In short, the United States relies upon electrical power, and interruptions to its continued supply causes significant, immediate problems.

Electric power utilities have long been leaders in the critical infrastructure community for contingency planning. Utilities are required at a minimum to demonstrate N-1 contingency planning such that they are able to serve peak demands during a sudden outage of any, single crucial elements, among other specified multiple contingencies [3]. Reliability metrics such as SAIDI, SAIFI, CAIDI, CAIFI,[1] and others have been widely accepted as a means for measuring reliability and for demonstrating that grid operators are sufficiently prepared for disruptions and have appropriately responded to and managed power outages that occur under relatively normal conditions.[2]

The power grid continues to evolve as the demands of society grow and change. At the same time, power grid operators are faced with a changing hazard landscape. Grid operations are increasing in complexity due to changing power demand, increased reliance on renewable sources, and increasing introduction of smart technologies. The frequency of natural disasters is on the rise [4], and climate change has the potential to effect negatively the power grid in many different ways [5]. Malicious, intentional attacks on the grid's physical assets (such as the 2014 sniper attack on PG&E's Metcalf Transmission Substation [6]) and cyber assets (such as malwares BlackEnergy and HAVEX) pose additional threats to the smooth, continued operation of the power grid.

Because of the changing hazard landscape, the critical infrastructure and power grid communities have recognized that reliability metrics are not sufficient by themselves to effectively plan for many of the emerging hazards [7]. Reliability metrics measure grid operations during expected outages that could occur under relatively normal conditions. However, reliability metrics typically do not include outage information when low-probability, high-consequence events such as storms, earthquakes, and cyber-attacks occur. As the hazard

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[1] System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), Customer Average Interruption Duration Index (CAIDI), Customer Average Interruption Frequency Index (CAIFI).
[2] NARUC [7] uses the term "blue sky days" to describe relatively normal conditions.

landscape continues to change, historical data used for reliability calculations may not be suitable for characterizing future potential outages because emerging threats can differ significantly from historical precedents.

Resilience is a concept that has recently emerged as a strategic objective within the critical infrastructure community. PPD-21 defines resilience as follows:

> "*The term 'resilience' means the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents.*" [1]

Whereas infrastructure security activities are generally focused on preventing a disruptive event from ever occurring[3], infrastructure resilience objectives are generally focused on ensuring that the infrastructure can continue to provide goods and services to the communities that rely upon them, regardless of the occurrence of disruptive events. It may not be possible to continue operating at nominal or pre-disruption levels, but operating at even reduced levels can reduce the impact of the disruptive events on the communities.

Though resilience as a formal concept is new to many in the critical infrastructure community, the goal of continuous power delivery is not a new idea to the power grid community; reliability itself is a related concept. However, reliability and resilience analyses are clearly distinct. For example,

- Grid reliability analyses are generally focused on grid operations for relatively normal conditions and in the context of limited number of expected disruption events (e.g., N-1, N-1-1). Grid resilience analyses are generally focused on grid operations and planning for the context of low-probability, high-consequence disruptive events. Disruptive events included in grid resilience analyses tend to be focused on events such as hurricanes, earthquakes, and other events that can result in extensive damage to the grid, that affect a large geographic region, and have other large scale consequences to the power grid and surrounding community. Outages from these types of events are excluded in reliability analyses. Reliability analyses do not capture the additional costs and/or resources that may come with efforts to avoid outages (e.g., the cost of purchasing additional power).

This distinction has prompted many in the power grid community to discuss and investigate the potential of operationalizing resilience.

Still, many challenges exist before standardized resilience metrics and analysis methods are broadly accepted and adopted by the power grid community. Though much research into grid resilience has occurred over the past decade and is currently ongoing, NARUC notes that resilience definitions are currently too imprecise "to be used as a regulatory term of art" [7]. The National Research Council further asserts that "without some numerical basis for assessing resilience, it would be impossible to monitor changes or show that community resilience has improved. At present, no consistent basis for such measurement exists" [8].

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[3] This perspective on security comes from PPD-21 and reflects perspectives from a variety of different infrastructure systems. The authors recognize that it may not entirely reflect definitions of grid security such as those put forth by NERC.

To address that gap, the U.S. Department of Energy, through the Grid Modernization Laboratory Consortium [9], is funding the Metrics Analysis for Grid Modernization project. The objective of this project is to define, develop, and validate a set of metrics that can be used to measure progress towards grid modernization. Six different categories of metrics have been selected: reliability, flexibility, sustainability, affordability, security, and resilience. This document has been developed to describe preliminary efforts to construct resilience metrics and methods for calculating these metrics. The remainder of this document is structured as follows:

- Section 2 provides a brief discussion of grid resilience metrics. Current and recent activities by power-related organizations are mentioned. Needs and tradeoffs for developing grid resilience metrics are also discussed.
- Section 3 describes a proposed set of resilience metrics and methodology for calculating those metrics. The section also describes the set of decisions that these metrics can inform.
- Section 4 provides a set of illustrative use cases that demonstrate how the proposed metrics can be used to support grid resilience-related decisions.
- Section 5 concludes the paper and contains a summary and discussion on requirements and challenges for application of the proposed metrics.

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2. CURRENT STATE OF GRID RESILIENCE METRICS
2.1 Previous Efforts

Though the concept of resilience in complex systems has existed for decades [10], resilience is relatively new to the infrastructure security community. The U.S. Department of Homeland Security's (DHS) Critical Infrastructure Task Force was one of the first organizations to push for increased resilience. The task force recommended that DHS elevate critical infrastructure resilience to a top level strategic objective and recommended that resilience be viewed not as a replacement for infrastructure protection but as an "integrating objective designed to foster systems level investment strategies" [11]. This recommendation spurred the development of resilience initiatives at the federal and local government levels (e.g., see [1], [12], [13], etc.) The private sector has also taken notice and actively contributed not only to the discussion on resilience (e.g., see [14]) but also started to take action to make infrastructure more resilient (e.g., see [15]- [17]).

Similarly, resilience has also started to receive greater attention within the power grid community over the past decade. Formal definitions, metrics, and methods for analyzing and operationalizing grid resilience are currently being discussed and are under development. At present, no grid resilience definitions, metrics, or methods have received universal recognition and acceptance.[4] However, a number of power grid-focused organizations have been leading the discussion and maturation of grid resilience concepts. For example, the National Association of Regulatory Utility Commissioners (NARUC) has written papers describing resilience in the context of the power grid, differences between resilience and reliability, recommendations for extending reliability metrics to create resilience metrics, and other resilience-related topics [7], [18]. One of NARUC's key findings is that current reliability metrics are not sufficient for informing analyses on investments for large-scale disruptions. The Electrical Power Research Institute (EPRI) has a number of efforts focused on grid resilience. These efforts include identifying innovative uses of existing and new technologies to improve resilience of distribution systems; resilience analyses for specific hazards, such as weather, geomagnetic disturbances, etc.; the development of risk-based metrics and methods to quantify resilience of distribution systems; among several other topics. The Edison Electric Institute (EEI) has compiled a listing of recent studies, programs, and policies related to grid hardening and resilience for distribution systems and large storms [19]. The institute notes that no single solution exists to make all systems more resilient; rather, "utilities and their regulators must look at the full menu of options and decide the most cost-effective measures to strengthening the grid" [19]. The Partnership for Energy Sector Climate Resilience is a joint effort between the U.S. DOE and seventeen U.S. utilities that are collaborating to improve resilience of the power grid to climate change and associated extreme weather events [20]. The U.S. DOE has also explored energy resilience analysis frameworks in the Quadrennial Energy Review and Quadrennial Technical Review ([21]-[23]). Those frameworks will be described in further detail in the following sections.

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[4] The Federal Energy Regulatory Commission's *Common Metrics Report: Performance Metrics for Regional Transmission Organizations, Independent System Operators, and Individual Utilities for the 2010-2014 Reporting Period* is 74 pages and does not contain a single mention of the term "resilience."

2.2 Metric Types and Tradeoffs

Much of the discussion included in current grid resilience efforts focuses on 1) the ability to evaluate proposed grid resilience enhancing options and investments; and 2) the development of formal methods and metrics to facilitate option analyses and communications between stakeholders. These issues are not unique to the electrical grid, and resilience metric research that has been ongoing for the past decade can inform grid-focused efforts.

Selection of appropriate metrics for resilience activities typically requires having to balance a set of trade-offs (Table 1). The ideal resilience metrics would be simple to calculate; enable retrospective and forward-looking analyses; be highly informative; and be highly consistent. In reality, the analyst has to prioritize the trade-offs and consider analysis objectives and the resources available.

Table 1. Metric Trade-Offs

Simpler vs. More Complex	
The simplest metrics require less data that are easy to obtain, and the process for integrating the data into metrics is fairly straightforward (e.g., simple arithmetic).	More complex metrics may require larger amounts of data that may be challenging to obtain. The process for integrating the data may require technical expertise, such as numerical modeling.
Retrospective vs. Forward-Looking	
Retrospective metrics typically measure the resilience of the system to previous events. They may be used to determine if previous performance was (un)satisfactory.	Forward-looking metrics typically measure the resilience of the system to future or hypothesized disruptions. These metrics are commonly used to inform planning and investment activities.
Targeted vs. Broadly Informative	
Targeted resilience metrics may provide limited information on a single, or limited number of topics (e.g., single threat).	Broadly informative metrics may be able to provide information that is useful across a variety of analysis topics (e.g., investment, planning, operational response).
Less Consistent vs. More Consistent	
Repeated application of resilience metrics with little consistency can be a challenge. If the metric results tend to change from analyst-to-analyst or do not enable comparative analysis, stakeholders may lose confidence in the metrics.	Consistent metrics enable reproducibility and comparison. Consistency builds confidence and leads to widespread usage of the metrics.

Resilience metrics come in many different forms, but they can generally be grouped into one of two categories: attribute-based and performance-based metrics. Attribute-based metrics generally try to answer the question "What makes my system more/less resilient?" and can be used to provide a baseline understanding of the system's current resilience, relative to other systems. Thus, they typically include categories of system properties that are generally accepted as being beneficial to resilience. Examples of these categories might include robustness, resourcefulness,

adaptivity, recoverability, etc. Application of these metrics typically requires that analysts follow a process to review their system and determine the degree to which the properties are present within the system. These determinations are usually made by collecting survey responses, developing a set of subjective weighting values that represent the relative importance of the survey responses, and performing a series of calculations that results in numerical scores for the resilience attributes. The Supply Chain Resilience Assessment and Management (SCRAM™) tool [24] and Argonne National Laboratory's Resilience Measurement Index [25] are two examples of attribute-based metrics.

Performance-based metrics are generally quantitative approaches for answering the question "How resilient is my system?" These methods are used to interpret quantitative data that describe infrastructure outputs in the event of specified disruptions and formulate metrics of infrastructure resilience. The required data can be gathered from historical events, subject matter estimates, or computational infrastructure models. Because the metrics can often be used to measure the potential benefits and costs associated with proposed resilience enhancements and investments, performance-based methods are often ideal for cost-benefit and planning analyses. Vugrin et al. [26], the Multidisciplinary Center for Earthquake Engineering Research [27] and Rose [28] have developed examples of performance-based methods.

Depending on the specific approaches, both attribute- and performance-based metrics can be retrospective or forward-looking. The primary difference between the two categories of metrics is generally their level of complexity and consistency. Attribute-based metrics tend to be relatively simple in terms of the mathematics required for calculations. The data requirements can vary, but the data required is typically easier to gather than the data for performance-based metrics. This simplicity is often made possible by greater inclusion of qualitative or semi-quantitative expert judgment that can affect the consistency of these methods. A limitation of attribute-based metrics is that they do not provide any estimation or confidence in how well the system will operate in the event of a disruption or the effectiveness of potential resilience enhancements and investments. Hence, attribute-based metrics may not be as informative as performance-based metrics for grid resilience planning and investment activities.

Performance-based resilience metrics can be rather complex and have significant data requirements. They often include computer models of grid operations, disruption, and recovery, and significant resources may be required for initial development of such models. However, these models can be highly informative. Not only can they be used to assess the resilience of power systems to previous events, but they can also be used to simulate how the power system could be affected to a variety of potential, future events and to assess the efficacy of proposed mitigations. Additionally, these methods tend to rely less on subjective or qualitative evaluations, thus enhancing the metrics' consistency. Consequently, performance-based metrics are getting increasing attention for use in resilience planning, investment, and cost-benefit activities. For a more extensive review of metrics that have been proposed for measuring resilience in the power grid, energy infrastructure, and other infrastructure systems, see Chapters 8-10 in Biringer et al. [29] and Willis and Loa [30].

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3. A PROPOSED APPROACH FOR CREATING GRID RESILIENCE METRICS

One goal of the Metrics Analysis for Grid Modernization project is to develop grid resilience metrics and methodologies that:
- Help utilities better plan for and respond to low-probability, high-consequence disruptive events that are not currently addressed in reliability metrics and analyses;
- Provide an effective, precise, and consistent means for utilities and regulators to communicate about resilience issues; and
- Provide an effective, precise, and consistent means for utilities and the communities that they serve to communicate about resilience issues.

Specifically, this project aims to develop metrics to inform the following kinds of analyses:
- Baseline resilience assessments that quantify the current state of resilience for a power system;
- Emergency response and recovery activities that address near-term (hours to days), imminent hazards; and
- Planning and investment efforts (and their associated trade-off analyses) that seek to improve resilience to future hazards over a longer-term horizon (months to years).

As part of the 2015 Quadrennial Energy Review, Watson et al. [21] describe the Resilience Analysis Process (RAP), a conceptual framework for developing metrics and analyses for the power grid and other energy sectors. Watson et al. recommend that grid resilience metrics should meet the following criteria:
- Grid resilience metrics should be specified in the context of low-probability, high-consequence potential disruptions. This context will distinguish them from reliability metrics.
- Grid resilience metrics should be based on the performance of power systems, as opposed to relying on attributes of power systems. Use of performance-based metrics will maximize the utility of grid resilience metrics for baseline assessments, response and recovery activities, and planning and investment efforts.
- Grid resilience metrics should quantify the consequences that occur as a result of strain on or disruption to the power grid. These consequences can be closely related to grid operations and power delivery (e.g., MWh of power not delivered as a result of the storm, utility revenue lost, cost of recovery to the utility, etc.), or they can be measured in terms of greater, community impacts such as population without power (e.g., measured in people-hours), number of emergency service assets without power for more than a 24 hours, business interruption costs resulting from the power outage, etc.
- To the extent possible, grid resilience metrics should be reflective of the inherent uncertainties that drive response and planning activities. These uncertainties include disruption conditions (e.g., frequency of events, track of the hurricane, wind speeds), damage to the grid, demand from affected population, time required for response, and other factors.

Watson et al.'s guidance is consistent with many of the current grid resilience discussions. The focus on low-probability, high-consequence events addresses the gap that NARUC observed are present in reliability metrics. Consequence-based metrics that include the inherent uncertainties of these kinds of events are consistent with the risk-based metrics that EPRI is researching. The

use of disruption consequences and the ability to select from a variety of different consequence categories helps address the EEI's recognition that utilities need flexible capabilities to explore the space of cost-effective options.

Watson et al. developed the RAP for analyzing resilience of energy infrastructure systems (Figure 1) [21]. The RAP uses risk-based metrics, i.e., they include threat, vulnerability, and consequence factors, for quantifying the resilience of these systems (Table 2). In the context of the metric trade-offs in Table 1, the metrics that Watson et al. propose are:

- Relatively complex: Watson et al.'s metrics are probabilistic and rely on stochastic models of grid operations that can be relatively time- and data-intensive.
- Forward-looking: Watson et al. use the metrics to project consequences for potential future hazards.
- Broadly informative: the benefit of Watson et al.'s relatively complex formulation is that the resulting metrics can provide information for operational response, long-term planning, investment, and other topics. It is also scalable across varying geographic sizes and systems.
- More consistent: Watson et al.'s reliance on computational models increase the consistency of the metrics and limits (but not eliminates) subjective elements that can cause potential inconsistencies.

Table 2. Characterizing Reliability and Resilience under Watson et al.'s Resilience Analysis Process

	Reliability	Resilience
Events Considered	High Probability, Low Consequence Hazards	Low Probability, High Consequence Hazards
Risk-based?	No	Yes
Binary or continuous?	Operationally, the system is reliable or not [0 1]. Confidence is unspecified	Resilience is considered a continuum, confidence is specified
Measurement focus	Focus is on the measuring impact to the system	Focus is on measuring impact to humans

Given the consistency of the RAP with much of the current discussion on grid resilience, we propose an extension of Watson et al.'s approach to measure the resilience of power systems.[5] For a specified power system, we recommend that the resilience of that power system to a specified hazard (or sets of hazards) should be measured in terms of the consequences that will result if and when the hazard(s) occur. The consequence categories selected should be reflective of specific analysis questions being addressed by the resilience metrics and the relevant utility, community, regulatory body, and other stakeholder organizations involved with the analysis decision. To the extent possible, estimation of the consequences should include relevant uncertainties and be represented in a statistical format. The specific statistical nature of the

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[5] Whereas Watson et al. considered all energy infrastructure and only used numerical modeling to provide quantitative estimates of infrastructure performance, this paper focuses solely on the electrical grid and considers historical data and subject matter expert estimates, in addition to numerical modeling, for grid performance estimates.

metric (e.g., expected consequence, maximum consequence, probability the consequence exceeds some acceptable level, etc.) and units of the metric (e.g., MWh, time, money, etc.) reported should be reflective of the risk perspectives of the organizations involved.

The following details are how we propose to extend the RAP:

- Whereas Watson et al. relied exclusively on computation models to generate the effects of hazards upon overall grid operations, we propose that other sources can be used to quantify grid impacts. Historical data, expert elicitation, and other data sources can be considered under the RAP. As with all data sources, the quality of the data sources and the appropriateness of the data for a specific analysis need to be evaluated.
- Watson et al. focused on forward –looking analyses, and we extend to include the RAP to be able to conduct retrospective analyses, too. Retrospective analyses are one reason to include the use of historical data.
- Whereas Watson et al. required resilience metrics to be probabilistic, we relax this requirement to include deterministic analyses. We agree with Watson et al. that whenever possible, it is preferable to include sources of uncertainty and characterize the impact of those sources on the uncertainty in consequence and resilience estimates. However, in many instances, it may not be possible to suitable quantify the uncertainties or it may be time and resource prohibitive to do so. In these instances, benefits can still be derived by undertaking a deterministic approach.

The RAP and its extension provide flexibility and opportunity to customize metrics for a specific analysis. The primary challenges come from 1) selecting the appropriate consequence categories and 2) estimating the consequences. To assist in the approach, we provide a general, high level process for performing a grid resilience analysis. We also provide an illustration of how to actually calculate resilience metrics for a grid resilience analysis.
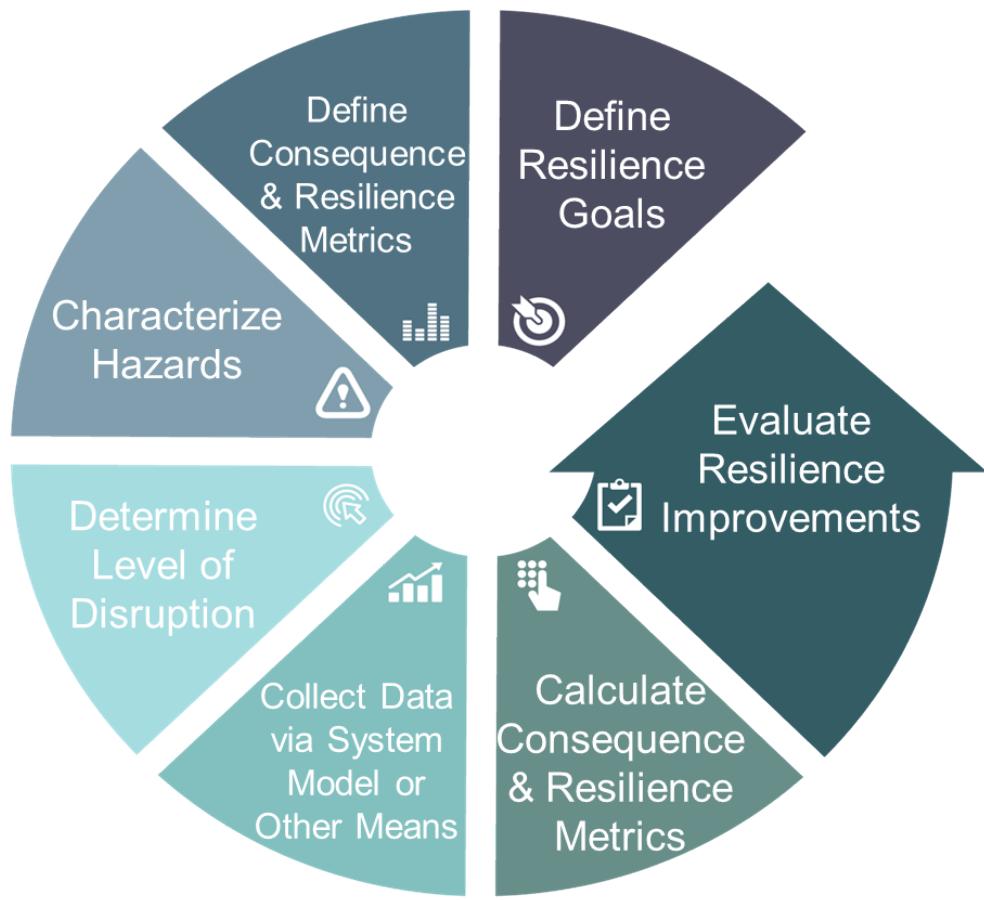
Figure 1. The Resilience Analysis Process.

3.1 Define Resilience Goals

The first step in the process is specifying the resilience goals of the analysis. The goals lay the foundation for all following steps. For example, discussion during this phase should determine whether assessing resilience of a power system to a previous historical event is the goal or if the focus is on evaluating possible system improvements. If evaluating improvements is within the scope of the analysis, a decision should be made about the kinds of changes to be considered and the types of questions the analysis should address. System specification (e.g., geographic boundaries, physical and operational components, relevant time periods, etc.) is also required. Additionally, in this stage key stakeholders and any possible conflicting goals should be identified.

Some examples of high-level goal language appropriate at this step of the process are:
- Improving a regional electric grid's resilience to natural disasters
- Evaluating a utility's allocation capital investment and maintenance budget options for improving resilience
- Ensuring availability of power to medical or transportation systems during disasters

3.2 Define Consequence Categories and Resilience Metrics

Definition of the consequence categories that serve as the basis for resilience metrics is the second step in the process. The consequence categories should be reflective of the resilience goals. In some instances, the consequence estimates and resilience metrics may focus on the impacts directly realized by the utility, such as power not delivered, loss of revenue, cost of recovery, etc. However, in some instances, direct impacts are only part of the resilience assessment. Energy systems provide energy not just for the sake of generating or distributing it, but for some larger community benefit (e.g., transportation, health care, manufacturing, economic gain). Resilience analyses that aim to include a broader community perspective may convert power disruption estimates into community consequence estimates (e.g., number of emergency service assets affected, business interruption costs, impact on gross regional product, etc.). Table 2 includes a list of example consequence categories that could serve as the basis for resilience metrics. All the consequence categories are measured for the defined system specifications and therefore may be measured across spatial (geographical) and temporal (duration) dimensions. Data availability may also affect selection of consequence categories. Resilience analyses are not restricted to a single consequence category to develop metrics. Rather, the use of multiple consequence categories can be beneficial for representing various stakeholder perspectives.

Table 2. Examples of Consequence Categories for Consideration in Grid Resilience Metric Development

Consequence Category	Resilience Metric
Direct	
Electrical Service	Cumulative customer-hours of outages Cumulative customer energy demand not served Average number (or percentage) of customers experiencing outage during a specified time period
Critical Electrical Service	Cumulative critical customer-hours of outages Critical customer energy demand not served Average number (or percentage) of critical loads that experience an outage
Restoration	Time to recovery Cost of recovery
Monetary	Loss of utility revenue Cost of grid damages (e.g. repair or replace lines, transformers) Cost of recovery Avoided outage cost
Indirect	
Community Function	Critical services without power (e.g., hospitals, fire stations, police stations) Critical services without power for more than N hours (e.g., $N >$ hours of back up fuel requirement)

Monetary	Loss of assets and perishables
	Business interruption costs
	Impact on Gross Municipal Product (GMP) or Gross Regional Product (GRP)
Other critical assets	Key production facilities without power
	Key military facilities without power

3.3 Characterize Hazards

The third step in the process is characterization of hazards. Hazard characterization involves the specification of hazards of concern (e.g., hurricane, cyber-attack, etc.) Any number of hazards can be specified, but typically, stakeholders will have a limited number of hazards or a prioritized list of concerns. Determining which hazards are in and out of scope for the analysis is typically affected by 1) the likelihood the hazard will be realized; 2) the likelihood that severe consequences will be realized; 3) strategic priorities; and 4) resources available for performing the analysis.

This step also can also involve the formulation of hazard scenarios when considering uncertainty. Development of hazard scenarios includes detailing the specific hazard conditions. For example, if a hurricane is the specified hazard, the hazard scenario could specify the expected hurricane trajectory, wind speeds, regions with storm surge and flooding, landfall location, duration of the event, and other conditions needed to sufficiently characterize the hazard and its potential impact on the power system. Hazard characterization is typically the first step in which sources of uncertainty are included.

3.4 Determine Level of Disruption

The fourth step is determining the level of disruption. This step specifies the level of damage or stress that grid assets are anticipated to suffer under the specified hazard scenarios. For example, anticipated physical damage (or a range of damage outcomes when incorporating uncertainty) to electric grid assets from a hurricane hazard might include: substation X is nonfunctional due to being submerged by sea water, lines Y and Z are blown down due to winds, etc. Damage specification could not only indicate which assets are nonfunctional or degraded, but it could also specify how severe the asset is impaired and what recovery steps are needed to repair overall system functionality.

3.5 Collect Data via System Model or Other Means

The fifth step in the process is collecting consequence data via system models or other means. When performing a resilience assessment for a power system to an actual, historical event, data collection can be typically performed by gathering system or community data that describes the magnitude and duration of the disruption to power delivery. Utilities maintain Outage Management Systems (OMS), and these systems are often a rich source of data for resilience analyses. When conducting forward-looking analyses, system-level computer models can provide the necessary power disruption estimates. These models use the damage estimates from the previous RAP step as inputs to project how delivery of power will be disrupted. For example, anticipated physical damage (or a range of damage outcomes when incorporating uncertainty) to an electric grid from an earthquake can be used as input to a system model that ties those outages due to damage to load not served within the system over time. Multiple system models may be

required to capture all of the relevant aspects of the complete system. Furthermore, dependencies may exist between models. For example, a repair and cost model may be used to determine a repair schedule for components of an infrastructure. The schedule determined by these models may inform systems models to assess how the systems perform during the restoration period.

3.6 Calculate Consequences and Resilience Metrics

The sixth step of the RAP process is calculating consequence estimates and resilience metrics. In their most basic form, resilience metrics may simply be the consequence values. In some instances, it may be preferable to combine the consequences into a single value. For example, if the consequence categories are specified to be the utilities cost of recovery and lost revenue, the utility may choose to sum these two consequence categories into a single cost metric, such as total monetary losses.

When uncertainty is included in the analyses, system models are used to obtain multiple realizations of the consequences based on hazard scenarios developed in step 3. This collection of consequence realizations provides probabilistic information about consequences which then enables risk assessment of the threats. Because of the probabilistic nature of this information, a specific consequence statistic (e.g., mean) can be selected in the second step and then used to describe the resilience metric using a single value.

When including uncertainty in consequence estimates and resilience metrics, it is also necessary to specify the statistical format of the metric. That is, will the analysis use the mean consequence estimate, the maximum/minimum consequence estimate, the probability that consequences exceed a tolerance threshold, etc. The specific statistic selected should be reflective of the stakeholders' risk perspectives. In Table 3 we list statistical properties that can characterize the consequence categories.

Table 3. Examples of Statistical Properties that can define the uncertainty

Statistical Property	Description
Expected value (mean)	The probability weighted average
Quantiles (Confidence Intervals)	Quantiles divide the range of a probability distribution into contiguous intervals with equal probabilities, and the confidence interval is the specified probability that any predicted value lies within a given quantile.
Value at Risk (VaR)	A measure of the risk for a chosen probability. For example, a 5% VaR of 1,000 means that there is a 5% probability that the distribution exceeds 1,000 units. 5% is a commonly selected probability for VaR.
Conditional Value at Risk (CVaR)	Another measure of risk. Assuming a loss occurs (conditional) it estimates the expected value for the worst X percentage of cases. This is, CVaR takes into account the shape of the tail of a distribution. For example, a 5% CVaR of 5,000 means that the expected value of the

	largest *5%* of the distribution is 5,000.
Maximum/Minimum (Worst-case)	The largest/smallest predicted value, and depending on the metric, defines one of these extremes as the worst-case.
Other	In some cases, functions that combine several statistical properties are employed. For instance, a linear combination of the mean and the conditional value at risk accounts for a risk averse approach that also takes into account average outcomes.

3.7 Evaluate Resilience Improvements

Completion of the first six steps can provide a baseline assessment of the resilience of a power system. Most grid resilience analyses include some aspect of determining how to modify operations or plan investments to improve resilience, and so the seventh step of the RAP focuses on assessing the potential benefits and costs of proposed resilience enhancing options.

After completing a baseline assessment through the preceding steps, the seventh step can be performed by repeating the previous steps but for a system configuration that that reflects a set of postulated changes or investments that are intended to improve the resilience of the power system. The postulated changes could include

- a physical change (e.g., adding a redundant power line);
- a policy change (e.g., increased reliance on renewable power sources); or
- a procedural change (e.g., islanding to limit cascading blackouts).

After repeating the consequence estimation and calculation of resilience metrics for the new system configuration, the resilience metrics can be used to determine how much of a benefit the postulated improvement would provide. Analysts can then compare these benefits with the associated costs to determine which options are preferable or, ideally, optimal.

Figure 2(a) illustrates steps 5 and 6 in the grid resilience analysis process for a historical analysis. The key steps in the process are identifying data sets that describe the impact of the hazard scenario on the power systems ability to generate and deliver power. A reduction in that ability (represented as "ΔPower Delivered" in Figure 2) can have consequences on the utility and or the surrounding community (represented by "Consequences of ΔPower Delivered"), and data describing these consequences ultimately populate the resilience metrics. Power outages can have different consequences depending on where and when they occur, so, if possible, data describing "ΔPower Delivered" ought to include the timing and location of the disruption.

Figure 2(b) illustrates the steps for a forward-looking resilience planning process. The fundamental difference in the planning process is that numerical, system models are used to generate numerical estimates of "ΔPower Delivered". Within these system models, the analysts need to parameterize the impact of the hazard scenario upon grid operations. This parameterization can include specification of damaged assets, level of asset functionality (e.g., is it completely nonfunctional, operating as usual, or somewhere in between), or duration of

compromised functionality. The system models use this information along with information describing the restoration process to estimate "ΔPower Delivered". Additional models may be used to estimate "Consequences of ΔPower Delivered") or these data may require consultation with other community stakeholders.

Figure 3 illustrates the process when we consider sources of uncertainty, as well as where the sources of uncertainty enter into the calculation. In these analyses, the input parameters are represented as probability distributions, and, thus, the outputs "ΔPower Delivered" and "Consequences of ΔPower Delivered" are also probability distributions. Because these quantities are estimated numerically, they are more practically represented as histograms or summarized by their statistical properties (e.g., mean, standard deviation, etc.)

Thus far, the discussion of the recommended grid resilience metrics and analysis has been mostly general. The next section demonstrates application of the metrics and analysis process in a more concrete manner through a series of use cases.

(a)

(b)
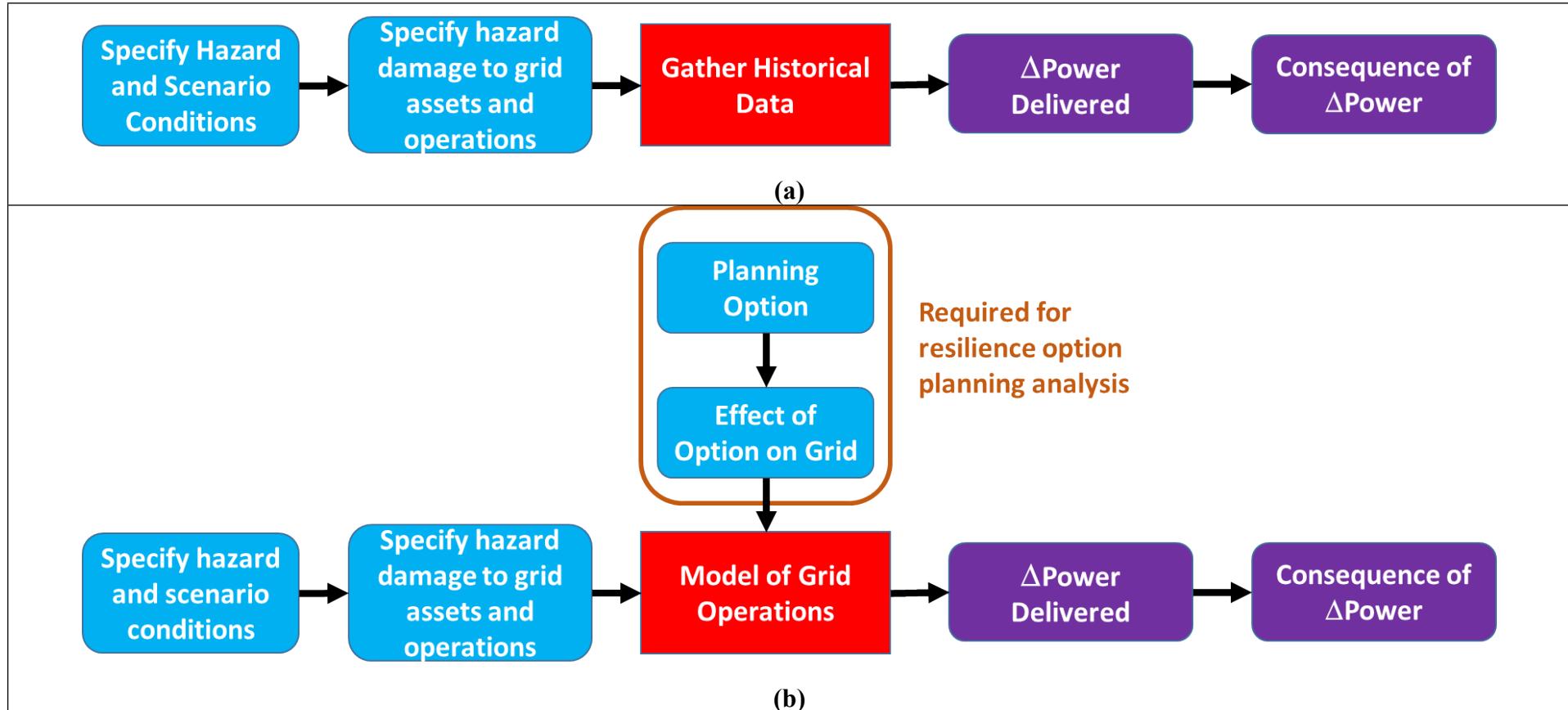
Figure 2. Calculation of Grid Resilience Metrics: for (a) historical assessment and (b) forward looking, planning analyses.
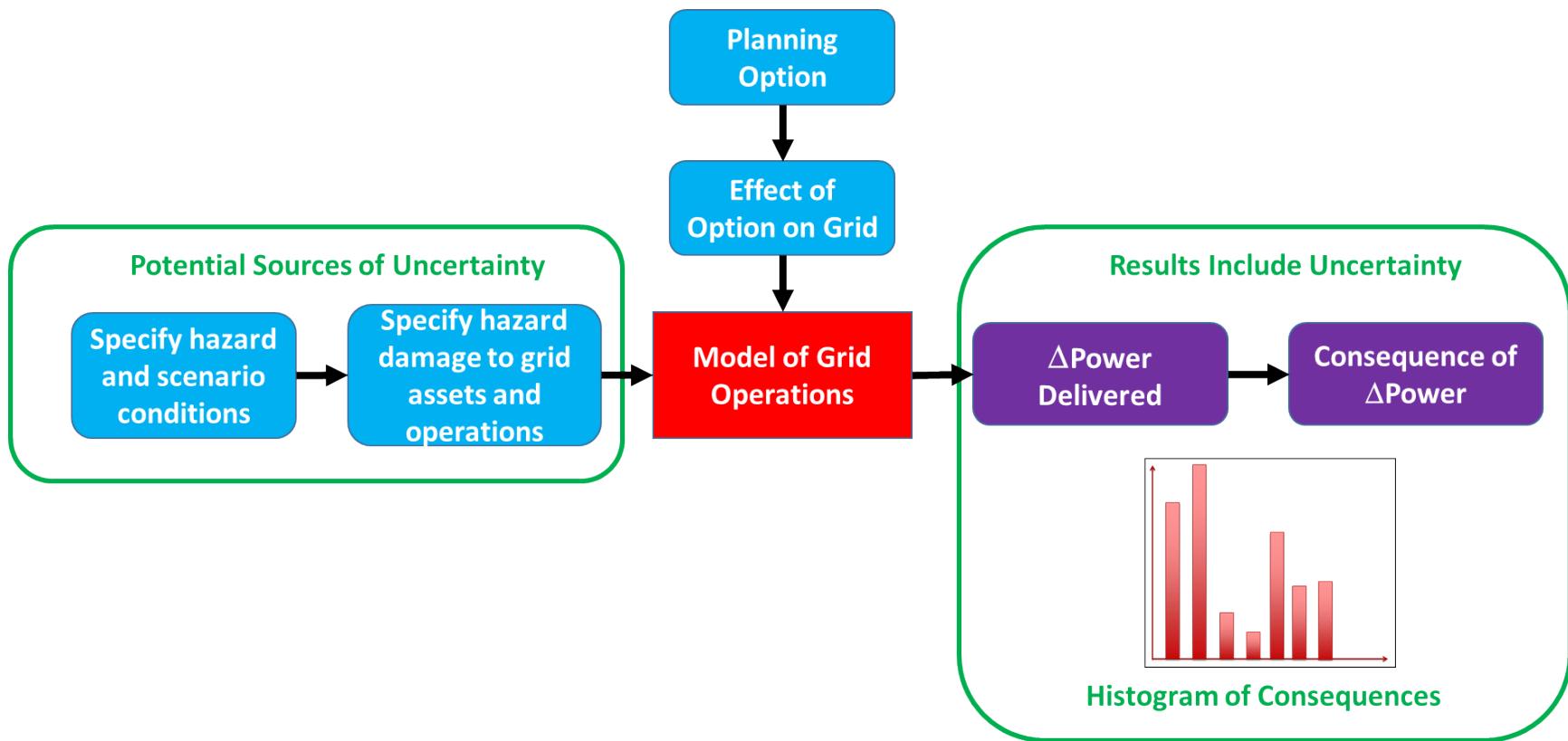
Figure 3. Calculation of Grid Resilience Metrics: inclusion of uncertainty.

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4. ILLUSTRATIVE CASE STUDY: SUPERSTORM SANDY

Superstorm Sandy had a devastating impact on the Northeastern United States when it made landfall near Atlantic City, New Jersey, on the evening of October 29, 2012. It impacted 21 states in total and was 1.8 million square miles in size at landfall [31]. The storm caused an estimated $65 billion in damages and 159 deaths, where 50 of those were attributed to power outages alone [32]. The day after the storm hit, 8.7 million customers experienced power outages [32], where 90% of those customers were in Long Island and over 1 million of Con Edison's 3.3 million customers were affected as well [33]. In some areas, the impacts lasted for months. In Rockaway, a peninsula of Long Island, New York, 10% of residents were still without power 5 months after Sandy [29]. Many who had power restored after Sandy lost power again in the nor'easter storm that followed 10 days after.

Superstorm Sandy is a canonical example of a large scale disruptive event that is not included in reliability analyses but is the focus of resilience planning activities. Hence, we use Superstorm Sandy and the effects that it had on the electrical power grid and communities to motivate a series of hypothetical use cases. These use cases include a hypothetical utility, Tesla Electric, and how its operations were disrupted by the storm. The use cases describe how Tesla Electric used the RAP to:

1) Conduct a baseline resilience assessment to compare how its performance during and after Superstorm Sandy compared against its resilience targets;
2) Evaluate which resilience investment options would better improve the resilience of the system if another storm similar to Superstorm Sandy happened in the future; and
3) Evaluate which resilience investment options would best improve the resilience of the system against a set of possible future storms. Because it is impossible to know what exactly might happen in the future, this evaluation would need to incorporate uncertainties about the storm specifics and impacts upon grid operations.

The first assessment is an example of a retrospective analysis that uses historical data; the second analysis is a forwarding looking analysis that uses systems models to project the potential benefits of investment options; and the third option demonstrates how to integrate sources of uncertainty within the systems model.

4.1 Baseline Assessment
Having experienced the destruction and impacts that Superstorm Sandy had upon its operations, the utility Tesla Electric decides to conduct a baseline resilience assessment for the storm by applying the RAP proposed in this paper. The utility does so by proceeding through the following steps:

1. Define Resilience Goals
2. Define Consequence Categories
3. Characterize Hazards
4. Determine Level of Disruption
5. Collect Data via System Model or Other Means
6. Calculate Consequences & Resilience Metrics
7. Evaluate or Propose Resilience Improvements

4.1.1 Define Resilience Goals

The first step in the RAP is to define the resilience goals that establish the scope of the assessment. To do so, the utility creates a team that includes management and staff from its relevant departments, including its reliability, planning, and operations departments. This team reviews how their operations were affected, what the utility's priorities are, and how the utility responded to the storm. In doing so, the team recognizes that utility seeks to understand

1) The extent and duration of power outages to critical and non-critical loads; and
2) The monetary cost of the storm that was borne by the utility as it recovered from the storm.

The team also recognized the important role that the utility has in enabling basic community functions, and that some of these functions were interrupted due to storm-caused power outages. Consequently, the team reaches out to community leaders to understand the city's needs and weaknesses, too. As a result of this outreach, the team further recognizes that emergency response assets for the community (hospitals, police stations, and fire stations) were significantly compromised due to outages. These assets typically have backup generation capacity for 48-72 hours, but because backup generation systems failed or outages exceeded 72 hours, a number of these critical assets were still affected.

After gathering this information, the team identified the following analysis objectives:

Assess the resilience of Tesla Electric to Superstorm Sandy by quantifying the storms effect on
1) *Power delivery to hospitals, police stations, and fire stations;*
2) *The extent and duration of power outages; and*
3) *The monetary cost of the storm borne by the utility as it recovered from the storm.*

For the purposes of this assessment, the utility restricts the analysis to:
1) *All of the utility's transmission and distribution assets in New York City that they own and/or operate. These assets include transmission and distribution lines, substations, poles, transformers, etc.*
2) *The time period spanning from Superstorm Sandy's landfall on October 29, 2012 to ten days later, November 7, 2012.[6]*

4.1.2 Define Consequence Categories and Resilience Metrics

Using the analysis objectives, the assessment team selects the consequence categories in Table 4 to be the resilience metrics.

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[6] A nor'easter subsequently impacted the utility starting on November 8, 2012. Given that the focus of this analyses is on Superstorm Sandy, the utility chose to restrict the analysis to dates where the utility was only affected by Superstorm Sandy.

Table 4. Consequence Categories for Resilience Analysis

Consequence	Resilience Metric	Units of Measurement	Calculation Process
Outage Magnitude	Cumulative daily power outages	Customer-days without power	$\sum_{t=1}^{10} x(t)$, where $x(t)$ is the number of customers without power on day t, and $t=1$ is the 1st day of the analysis (October 29, 2012), $t=2$ is the 2nd day, etc.
Recovery Costs	Repair and recovery costs bore by the utility	$ (dollars)	$\sum_{t=1}^{10} c_{labor}(t) + c_{materials}(t) + c_{parts}(t)$, where $c_{labor}(t)$ is the cost of labor spent on recovery activities on day t, $c_{materials}(t)$ is the cost of materials spent on day t, and $c_{parts}(t)$ is the cost of parts spent on day t
Community Impact	Emergency service assets without power for more than 48 hours	# of assets	$h + p + f$, where h, p, and f, denotes the number of hospitals, police stations, and fire stations, respectively, in Tesla's service region that lost power for more than 48 hours

The team also specifies the following resilience targets:
- 0 hospitals, police stations, and fire stations without power for more than 48 hours;
- No more than 1M customer-days without power. Given Tesla's 1.1M customers, this translate to a little less than 1 outage day per customer on average; and
- Recovery costs less than $100M;

If the system meets all of those criteria, the assessment will deem the utility to have an acceptable level of resilience for the storm.

It should be noted that since this analysis is relying upon historical data, the assessment team is treating all data as deterministic and is not including any sources of uncertainty, at this time.

4.1.3 Characterize Hazards
The utility characterizes Superstorm Sandy based on the impact that this hazard had on the overall system. The heaviest damage was due to record floods, where a storm surge of 12.65 feet caused flooding of 4-11 feet in lower Manhattan and a storm surge of 8.57 feet caused flooding of 2-9 feet in ten counties of New Jersey [2]. The highest recorded wind gust in New York was 90 mph at Islip and in New Jersey was also 90 mph at Tompkinsville 2N [34]. Figure 4 illustrates zones that were flooded as a result of Hurricane Sandy [35].

4.1.4 Determine Level of Disruption
The flooding caused the most damage to the power system due to many power plants, substations, underground cables, and other electrical infrastructure being clustered in or near coastal areas that resulted in long-term outages and damage due to floodwater [33,36]. As a

result, the flooding caused damage to many of Tesla Electric's infrastructure including most of their substations, and much of the infrastructure along the coastline where the Hudson River meets the Atlantic Ocean. Approximately 80% of the utility's non-critical loads that experienced power outages are serviced by 20 of the 50 substations damaged. Furthermore, the level of disruption experienced by Tesla Electricity is summarized in Table 5.
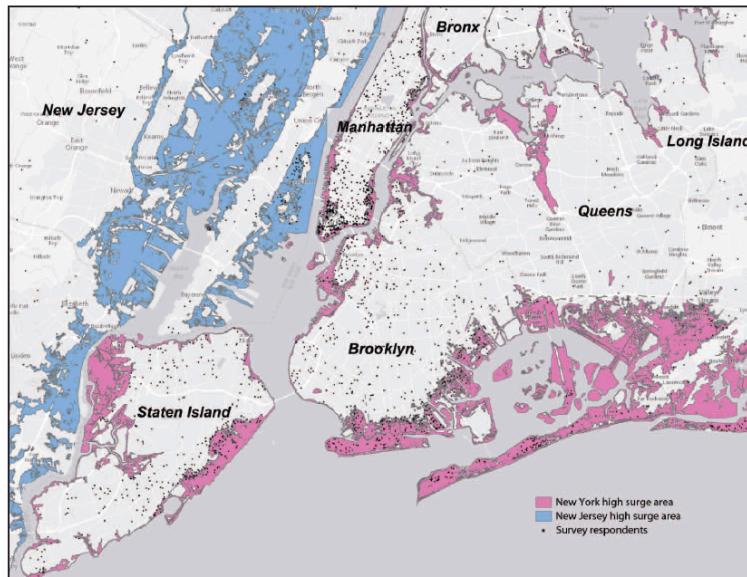
Figure 4. Hurricane Sandy inundation zones as of November 7, 2012

Table 5. Historical Consequence Data for Tesla Electricity

Infrastructure	Damage Count
Transmission Lines	150
Distribution Lock-outs	450
Substations	50
Distribution Poles	4,500
Transformers	2,500
Cross Arms	7,500
Miles of Wire	500

4.1.5 Collect Data via System Model or Other Means

Tesla Electric reviewed their OMS system for the analysis period, October 29, to November 7, 2012. At peak impact on October 29, over 90% of the utility's 1.1 million customers experienced power outages where 20% of these customers account for 60 locations of critical loads (including hospitals and first responders). Furthermore, 5 days after landfall 1% of critical loads were still without power. Figure 5 summarizes the number of customers without power for each day of the analysis. The assessment team also reviewed their accounting records to estimate the costs of recovery, provided in Table 6.

The team also contacted the city manager to determine how many critical assets were without power for more than 48 hours. Due to lack of electrification of filling stations, pipelines, oil

terminals, and storage tanks, first responders and other recovery officials were delayed by more than 48 hours in some instances. Furthermore, backup generators at three hospitals went unused or failed to generate enough electricity, resulting in hospital evacuations.
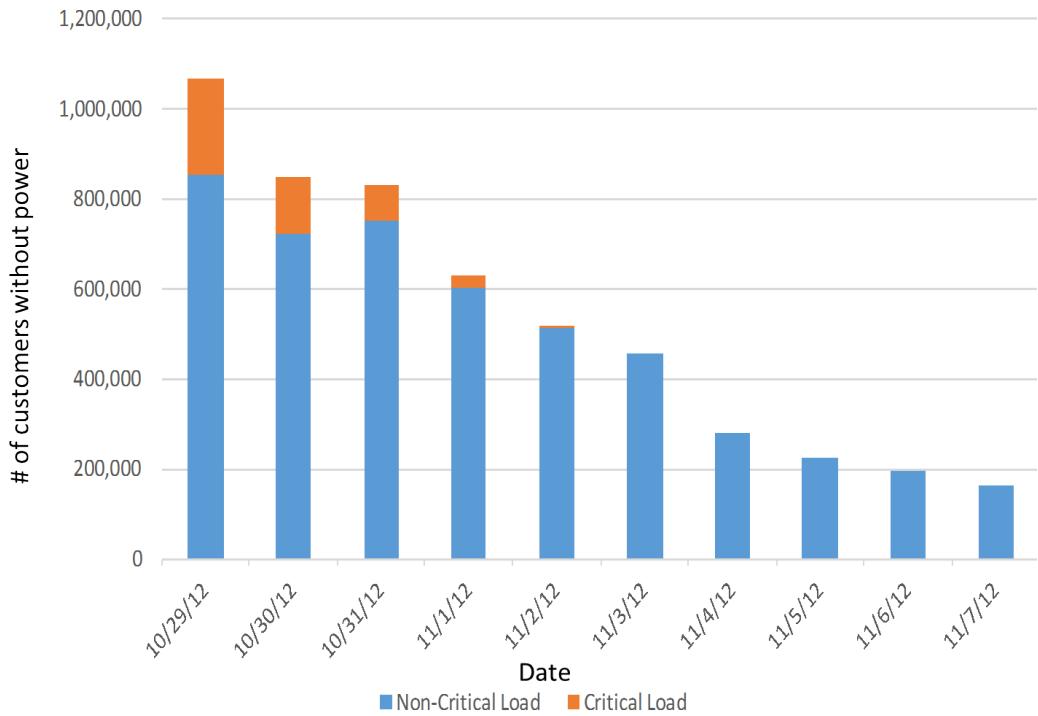
Figure 5. Daily Customer Outages, October 29 – November 7, 2012

Table 6. Recovery Costs

Cost Category	Amount
Labor	$200M
Materials	$300M
Replacement Parts	$500M

4.1.6 Calculate Consequences and Resilience Metrics

Figure 6 shows the cumulative outages in customer-days in the system for that time period. The value on Nov. 7 is around 5.22 million customer-days. Given that Tesla Electricity has 1.1 million customers, the average customer had experience around 4.75 days of outages due to the storm in the 10 days immediately following the event. For context, utilities generally use a one-day-in-ten-years (1-in-10) loss of load[7] as a goal for reliability purposes. Table 7 lists the resilience metrics for the analysis and compares them with the resilience targets.

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[7] There are a couple of interpretations of the 1-in-10 goal, one that assumes 1-in-10 loss of load events (LOLE), and another that assumes 1-in-10 loss of load hours (LOLH). A good discussion on the 1-in-10 reliability standard is found in [39].
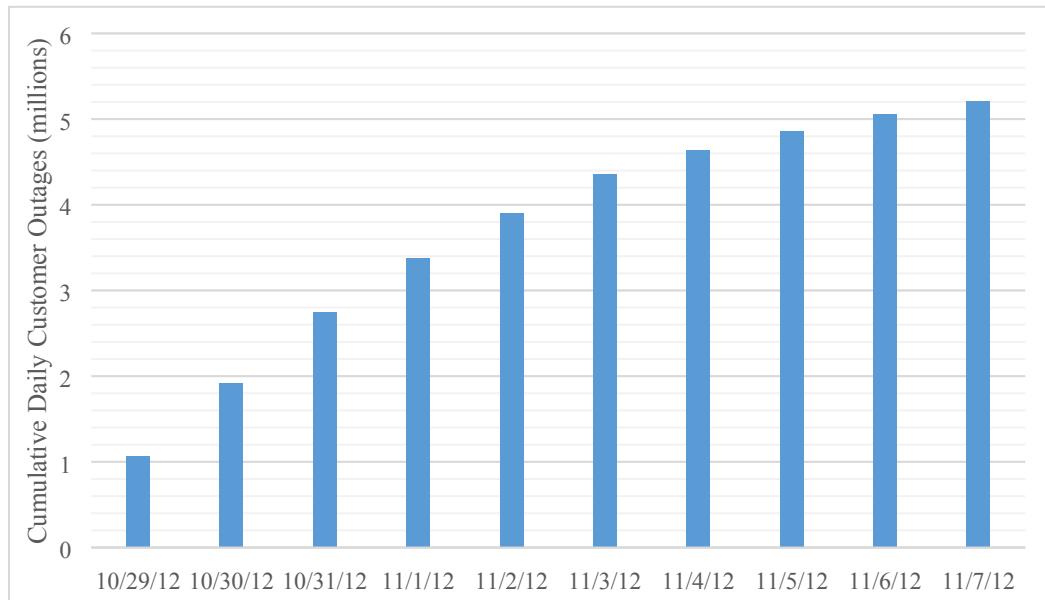
Figure 6. Cumulative customer-days of without power, by date

Table 7. Comparison of Resilience Metrics with Resilience Targets

| Category	Resilience Metrics	Target	Meets Target?
Outage Magnitude	5.2M customer-days	1M customer-days	No
Recovery Costs	$1,000M	$100M	No
Community Impact	60 assets	0	No

4.1.7 Evaluate/Propose Resilience Improvements

The assessment team reported to Tesla Electric's leadership that none of the resilience targets were met. Consequently, the utility asked the team to develop a list of potential options that could improve the resilience of their grid. The team put forth two sets of options (Table 8). Both options include installing combined heat and power (CHP) systems at the 60 hospital, police station, and fire stations that had extended power outages during Superstorm Sandy. They also both include modifying their tariff structure to enable PV system owners/operators to use their panels in islanded mode during emergency conditions. The primary difference in the options is that Option A includes hardening the 20 substations that accounted for 80% of the lost load during the hurricane Sandy power outages. This hardening would be achieved by elevating the substations to a) decrease the chance that flooding damages the substations as well as 2) decrease the damage to the substation if flooding still occurs. Instead of hardening substations, Option B includes the installation of advanced metering infrastructure (AMI) upgrades. Installation of the AMI upgrades would not prevent the occurrence of flooding, but it would enable remote detection and power restoration. In doing so, Option B could decrease the time required to restore and repair the grid. Option A is estimated to cost $350M, and Option B is estimated to cost $250M.

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Table 8. Resilience Enhancement Options[8]

Option A: $350M	Option B: $250M
• <u>Harden 20 substations that experienced 80% of loads with power outages</u> • Install combined heat and power (CHP) for uninterrupted heat and power in 60 critical community assets affected during the storm • Enable PV systems to operate in islanded mode	• <u>Install advanced metering infrastructure (AMI) upgrades to enable remote detection and power restoration</u> • Install combined heat and power (CHP) for uninterrupted heat and power in 60 critical community assets affected during the storm • Enable PV systems to operate in islanded mode

The two options show two approaches to increasing grid resilience. Option A emphasizes the "withstand" aspect of resilience, whereas Option B emphasizes the rapid "recovery" aspect of resilience. Without some additional analysis, it is not clear which option will better help the utility meet the resilience goals, so the assessment decides to conduct an additional forward-looking assessment to better characterize how each of these options would have affected their grid operations during Superstorm Sandy.

4.2 Option Assessment for Superstorm Sandy Measures

The assessment team works to extend the initial baseline assessment to include option analysis for the proposed resilience enhancement options, Options A and B. They continue to use the RAP, but because they already completed the baseline assessment, they do not need to repeat a number of the initial steps. Specifically, Steps 1 through 4 of the RAP are the same for the option assessment as they are for the baseline assessment. The primary difference in the analysis begins at Step 5, collecting the data for the analysis. Whereas the baseline assessment could use historical data that the utility had on hand or collected, the utility does not have data that corresponds to the effects of the storm if Options A or B had been implemented. Hence, they decide to use a computational model of their utility to project the effect that the options would have had if they were in place when Superstorm Sandy occurred.

4.2.1 Collect Data via System Model

Tesla Electric has a power flow model[9] that it uses for reliability and contingency planning. The model includes their assets (generators, lines, substations, loads, etc.) and operational information (e.g., capacities, connectivity, etc.). They perform a set of simulations that includes the following:
   • Modify the representation of the system in the model to include Option A changes;
   • Represent the effects of Superstorm Sandy on the system that includes Option A;
   • Simulation runs that span October 29 through November 7, 2016;

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[8] Though this use case is hypothetical, the resilience enhancement options included in the table are in line with actual hardening responses that utilities have taken after Superstorm Sandy [33,36-38].

[9] In this example, the utility uses a power flow model because it meets the particular needs of the analysis. However, any number of other model types could be used, as required by the analysis and the availability capabilities.

- Gather simulation data for projected customers without power, costs of recovery, and critical community assets that are expected to be without power for more than 48 hours.
- Repeat these simulations to include only Option B changes.

4.2.2 Calculate Consequences and Resilience Metrics

Figure 7 and Figure 8 show the simulation results for the daily and cumulative projected outages, respectively, for the baseline system, the system with Option A modifications, and the system with Option B modifications. Table 9 contains the resilience metrics for the baseline and option systems.
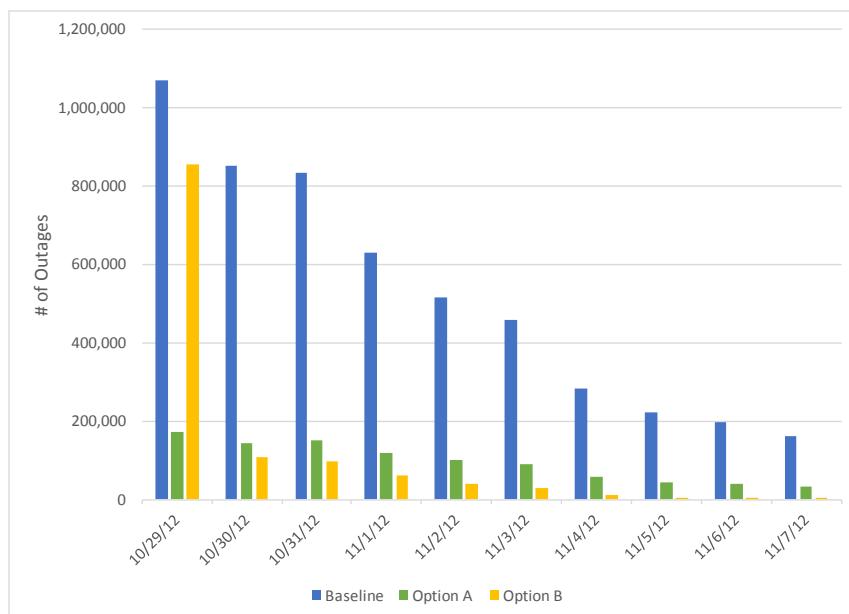

Figure 7. Power outages in Tesla Electricity of planning options A (green) and B (yellow) compared to baseline (blue)
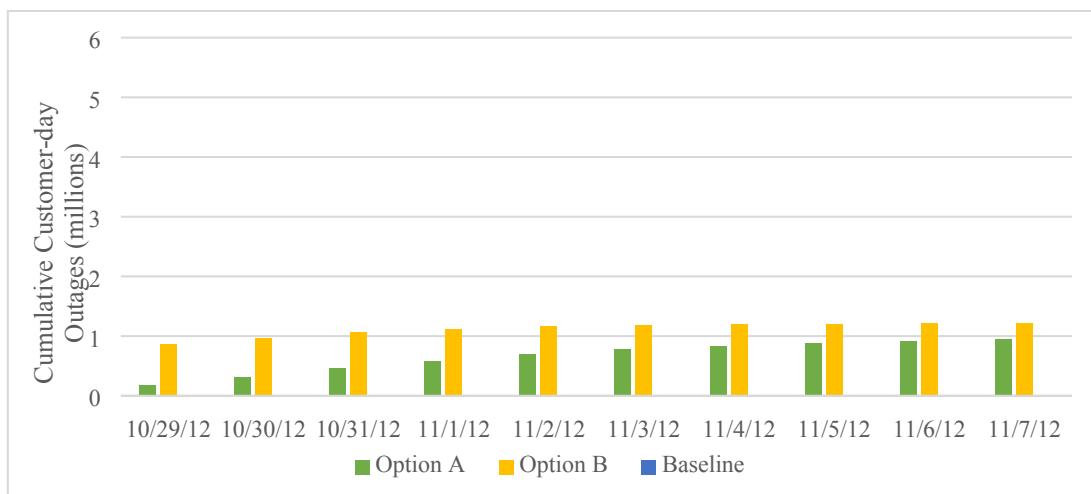

Figure 8. Cumulative Outages in Tesla Electric for baseline system (blue), and resilience enhancement options A (green), and B (yellow).

Due to the CHP installations at critical load sites, both options result in no critical load outages. The planning options do result in different power outage estimates. Estimates of daily customer outages, and cumulative customer outages are shown in Figure 7 and Figure 8, respectively, for the baseline, and options A and B. The quantity shown in Figure 8 for Nov. 7 is used as a resilience metric that measures the direct impact of the storm.

Table 9. Resilience Metrics for Options A and B

Category	Baseline	Option A	Option B	Target
Outage Magnitude (customer-days w/o power)	5.2M	0.95 M customer-days	1.2M	1M customer-days
Recovery Costs ($)	$1,000M	$250M	$450M	$100M
Community Impact (critical assets w/o power for 48+ hrs)	60	0	0	0

4.2.3 Evaluate Resilience Improvements

Overall, both options lead to significant improvements, as demonstrated by the resilience metrics in Table 9. In the event that Superstorm Sandy literally were to occur again, the CHP installations at the critical assets are expected to eliminate the number of critical assets without power for more than 48 hours. Option A, which includes hardening key substations, decreased the number of substations affected by flooding and subsequently decreased the severity and extent of power outages, an 80% reduction in power outages immediately following the storm. Additionally, since fewer substations were flooded, the restoration and recovery process occurred more rapidly and at a lower cost ($750M reduction), as compared with the baseline.

Option B, which installed AMI instead of hardening substations, also improved the expected performance of the system. Because AMI does not prevent damage, the number of power outages on the first day was comparable to baseline levels. Because AMI enables more rapid detection and restoration, option B actually caused a more rapid restoration of power. However, the cost of recovery under Option B was higher than it was for Option A ($450M vs. $250M) because more damage was sustained to the overall system.

The assessment team presented the results to the utility's leadership. Though Option A is estimated to cost $100M more than Option B, Option A meets the resilience targets for outages and has a lower estimated cost of recovery. Overall, Option A would have resulted in $400M in savings (i.e., $1,000M-$350M-$250M) while Option B would have resulted in $300M (i.e., $1,000M-$250M-$450M).

Although the utility leadership is confident that Option A would increase resilience of their

grid and community to another Superstorm Sandy, they are unsure whether Option A would provide similar benefits to other types of storm threats. Hence, leadership asks the assessment team to estimate potential benefits of Options A and B to a wider set of storms.

4.3 Option Assessment Including Uncertainty

The previous assessments included an actual hazard that occurred, so the utility conducted a deterministic assessment that numerically re-enacted Superstorm Sandy and its effects that were analyzed in the first assessment. However, utility leadership would like to know the effect of the resilience options against other potential future storms. Given the range of possible events that could happen in the future, the assessment team decides that it is important to include related uncertainties in order to more appropriately characterize the potential benefits of the options.

The assessment team uses the RAP again for this analysis. The first two steps (Define Resilience Goals and Define Consequence Categories) are the same as the previous analyses. However, because the assessment team is considering a broader set of storms, they must start at Step 3 (Characterize Hazards).

4.3.1 Characterize Hazards

Lopeman et al. estimate the probability that another category 1 hurricane will occur before 2100 with Sandy-level floods ranges between 2 and 65% [37]. The probability of a category 2 hurricane with increased flooding (Figure 9) is estimated to be half that amount.

For the purposes of the analysis, the assessment team sets the probability of a category 1 hurricane occurring to 33%, the median of Lopeman et al.'s estimate. They further assign the probability of a category 2 hurricane to be 17%, half of 33%. They determine that the probability of a category 3 or higher hurricane before 2100 to be sufficiently small that they do not include these storms in their analyses.
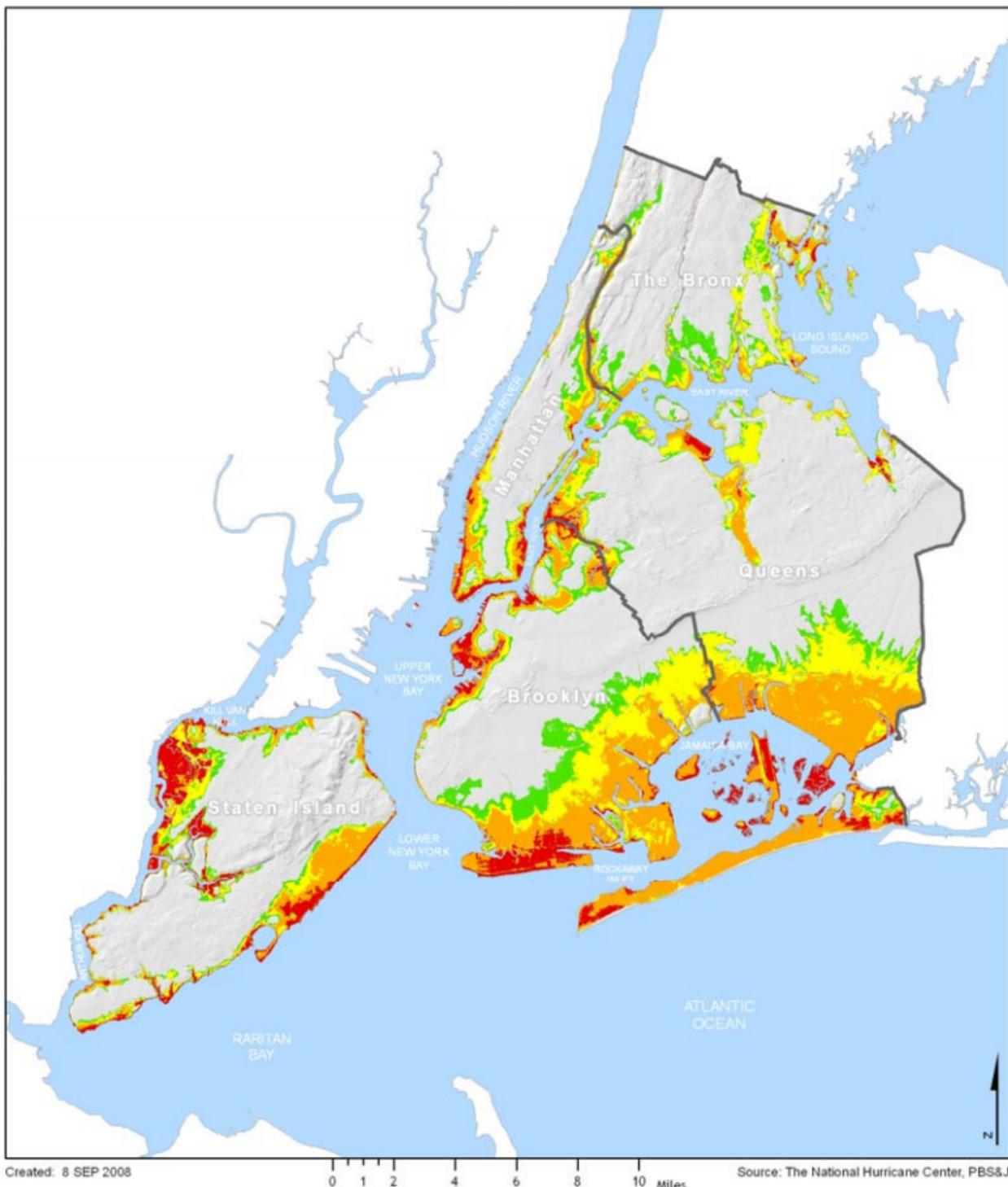
Figure 9. Areas at risk for future of category 1 and category 2 hurricanes

To characterize the hazard scenarios, the assessment team reviews published literature and consults with a research laboratory to understand the projected regions of flooding and damage to their system. Figure 9 shows the projected flooding areas predicted by the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) predictive model [39]. The assessment team considers the Category 1 and Category 2 predictions illustrated here.

4.3.2 Determine the Level of Disruption
For the two hurricane scenarios, the utility determines the resulting level of damage on each component in the power system. The utility leverages their OMS to characterize the damage inflicted by historical events similar to Sandy for different storm categories. For each critical utility component, the utility is able to assign a conditional probability that the component will be damaged, conditional upon each of the two hazard scenarios and the options that are implemented.

4.3.3 Collect Data via System Model or Other Means
The utility exercises their power flow model again for a Monte Carlo simulation. In each realization, the following parameters are determined stochastically:
1) Category (1 or 2) of the storm: the individual probabilities that a category 1 or category 2 storm will occur are 0.33 and 0.17, respectively. Because the utility wants to know the impact of the options if one of the storms happens in the future, they use the conditional hazard probability. That is, given that a storm will occur, there is a 0.66 probability the storm will be a category 1 hurricane and a 0.34 probability the hurricane is a category 2 hurricane.
2) Damage to a system component: component damage probabilities are conditional upon the hazard scenario and which option was installed.

For the Monte Carlo simulation, the utility performs 100 realizations for Option A and 100 realizations for Option B. The assessment team collects the simulation outputs for the projected outage estimates, costs of recovery, and impacts to critical assets. They use this data to calculate the expected values for each of the resilience metrics. Figure 10 contains an example histogram for projected power outage estimates for both Option A and Option B.
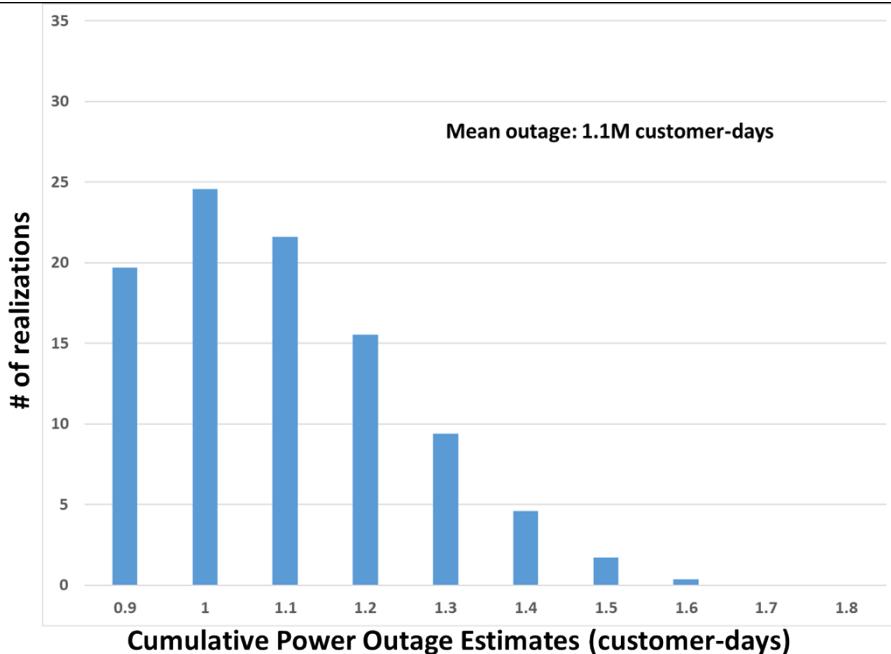
(a)
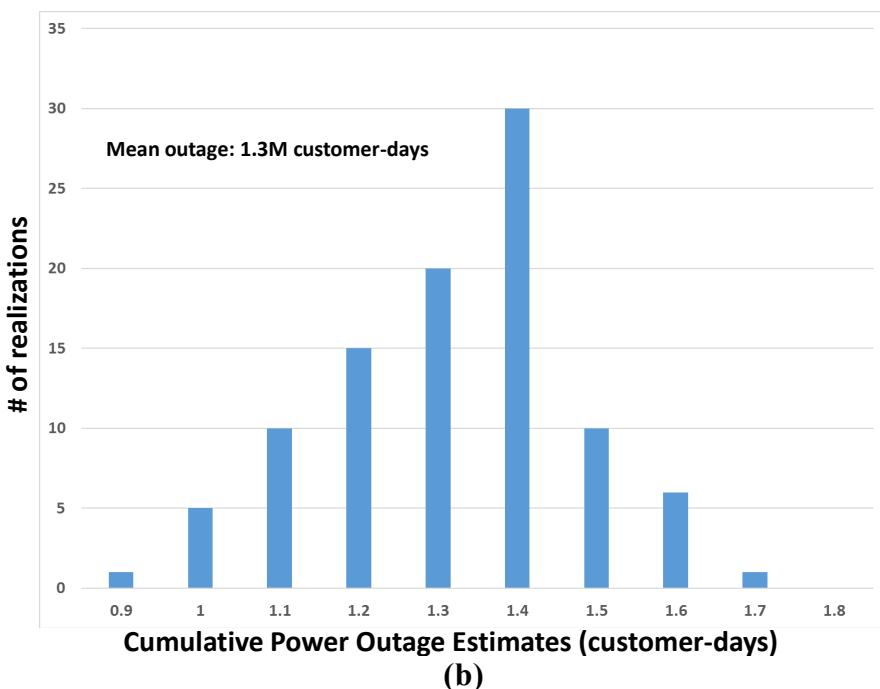
(b)

Figure 10. Histograms of Power Outage Estimates for Option A (a) and Option B (b)

4.3.4 Calculate Consequences and Resilience Metrics

Simulation results describing the results of Tesla Electricity for each option are shown in Table 10. Mean consequences are reported. Additionally, the 10th and 90th percentiles of the distributions are also included to illustrate the variability of the estimates.

Table 10. Simulation Results for Multiple Scenarios Describing Damage Uncertainty

Option	Disruption	Cumulative customer-day outages (millions)	Critical facilities outages	Cost of recovery (M$)
A	*Mean*	1.1	1	319
	10th %ile	0.5	0	189
	90th %ile	1.35	8	330
B	*Mean*	1.3	1	450
	10th %ile	1.05	0	300
	90th %ile	1.46	8	500

4.3.5 Evaluate Resilience Improvements

The results in Table 10 confirm that option A, even with its higher investment costs, would likely provide a higher benefit across all resilience metrics. On average, Option A would save $130M in recovery costs (i.e., $450M-$319M=$131M), helping make up for the larger upfront cost of Option A.

4.6 Additional Discussion

The previous use case descriptions were hypothetical and not intended to represent any specific utilities or utility decisions. The use cases were illustrative and included only to demonstrate the RAP, resilience metrics, and how they can be used to inform a variety of analyses and decisions.

The RAP provides much flexibility in the design of the analyses and use of modeling capabilities—the flexibility allows the utility to customize the analysis as their capabilities permit. The above use cases can be made more complex with the following additions:
1) Consider multiple threats: the above use cases focus on storms, but utilities could consider multiple hazard types, e.g., storms and cyber-attacks or other unrelated hazards.
2) Optimal investments: the above use cases compare postulated investment options. However, the use of optimization models could help determine the optimal investment for a specified investment level. For example, the assessment team in the previous use cases could have used optimization models to determine the optimal combination of substations to harden and installation of AMI that would maximize the resilience metrics. Or, the assessment team could develop a Pareto frontier that shows the tradeoffs between investment levels and resilience metrics (Figure 11).
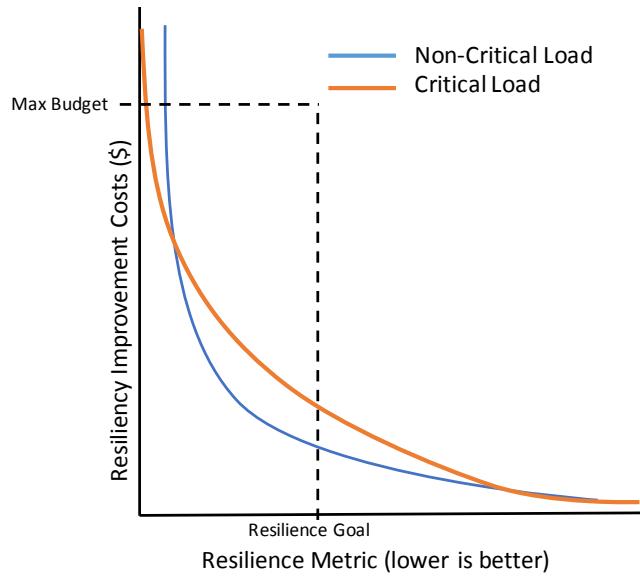
Figure 11. Pareto frontier for resiliency improvement costs versus power outages

Though the above use cases are hypothetical, the RAP has been operationalized and is currently being piloted. The U.S. Department of Energy, U.S. Department of Homeland Security, and Sandia National Laboratories is partnering with two power systems utilities to apply the RAP and inform the utilities' resilience planning activities. With American Electric Power (AEP), Sandia is applying the RAP and systems models to support analyses that are investigating AEP's resilience to storms and to security threats. With the Pennsylvania-Jersey-Maryland (PJM) interconnection, Sandia is applying the RAP and system models to conduct analyses about PJM's resilience to geomagnetic disturbances. Additionally, Sandia is applying the RAP to support a GMLC grid Resilience initiative in New Orleans, LA. The details of these analyses are proprietary, but they provide real, tangible examples of how the RAP is being put into practice and how utilities are able to use the RAP to inform their resilience planning activities.

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5. SUMMARY AND CONCLUSIONS

Grid resilience is a relatively new, emerging priority in the critical infrastructure and grid communities. EPRI, NARUC, EEI, and others are actively discussing and researching grid resilience, and grid resilience has been recognized as a concept that could meet some of the operational planning gaps for utilities that reliability metrics and analyses do not meet. Nevertheless, universally accepted definitions, metrics, and analysis methods do not exist yet for grid resilience.

Through the Grid Modernization Laboratory Consortium, the U.S. DOE is funding the Metrics Analysis for Grid Modernization project. The objective of this project is to define, develop, and validate a set of metrics that can be used to measure progress towards grid modernization. Six different categories of metrics have been selected: reliability, flexibility, sustainability, affordability, security, and resilience. This document describes preliminary efforts to develop resilience metrics and methods for calculating these metrics.

For a specified power system, we recommend that the resilience of that power system to a specified hazard (or sets of hazards) should be measured in terms of the consequences that will result if and when the hazard(s) occur. The consequence categories selected should be reflective of specific analysis questions being addressed by the resilience metrics and the relevant utility, community, regulatory body, and other stakeholder organizations involved with the analysis decision. To the extent possible, estimation of the consequences should include relevant uncertainties and be represented in a statistical format. The specific statistical nature of the metric (e.g., expected consequence, maximum consequence, probability the consequence exceeds some acceptable level, etc.) and units of the metric (e.g., MWh, time, money, etc.) reported should be reflective of the risk perspectives of the organizations involved. Furthermore, the RAP, first proposed by Watson et al., provides a consistent, logical process for performing resilience analyses and calculating resilience metrics.

It is recommended that numerical system models be used both to calculate the resilience metrics and to incorporate the effect of potential uncertainties. The development of appropriate system models is not a simple activity and is currently an active body of research (e.g., see [21]). Continued and expanded pilot efforts to develop and apply these models, such as those being performed with AEP and PJM, will benefit the ability to perform widespread grid resilience analyses.

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