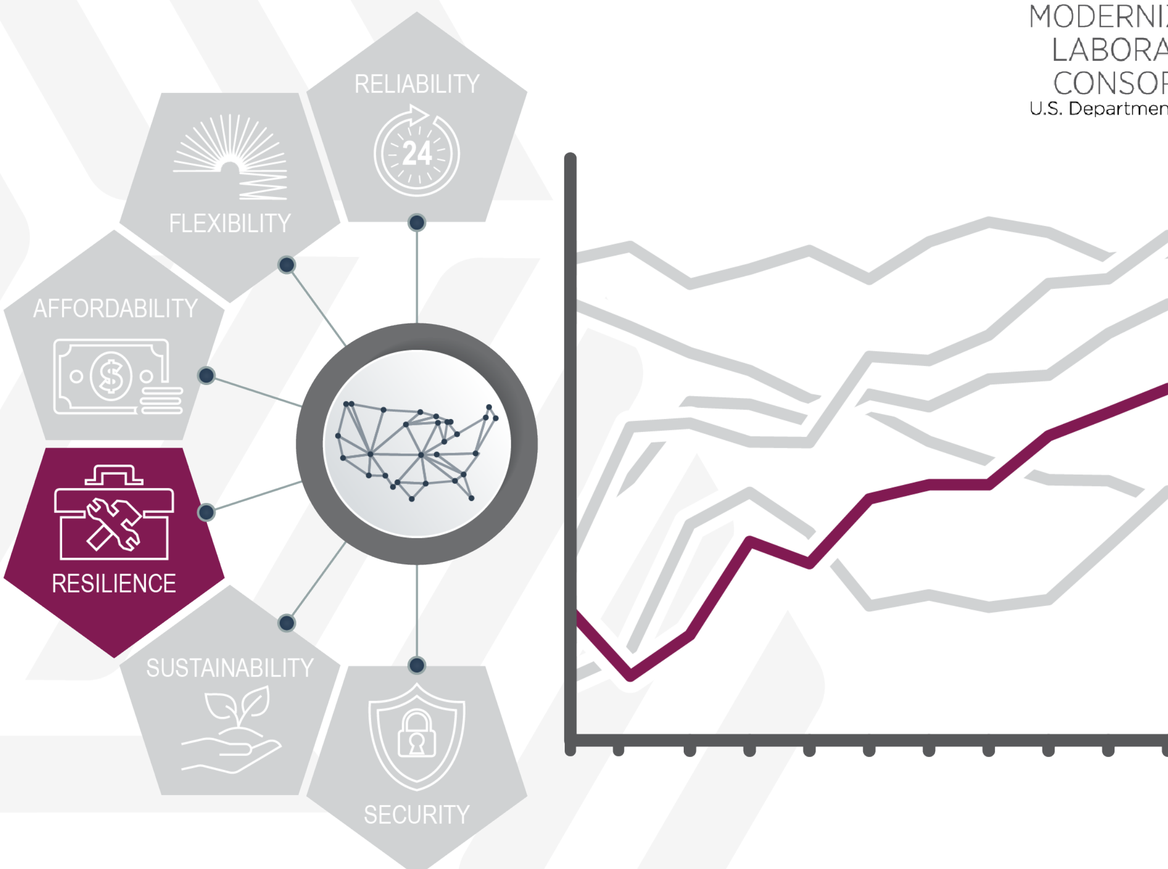

Grid Modernization: Metrics Analysis (GMLC1.1) – Resilience

Reference Document
Volume 3

April 2020

Grid Modernization Laboratory Consortium

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Grid Modernization: Metrics Analysis (GMLC1.1) – Resilience

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Summary

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Resilience

The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions, including the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents

The Grid Modernization Laboratory Consortium (GMLC) Metric Team: 1) Contributed to the definition and application of resilience concepts to the electricity sector; and 2) Developed two analysis approaches that each embody aspects of these concepts (including supporting resilience metrics) and can be used independently or in conjunction with one another to measure and assess the resilience of electric power systems.

S.1. Motivation

Historically, US government policy toward critical infrastructure security has focused on physical protection. However, after the terrorist attacks of September 11, 2001, the devastation from Hurricane Katrina in 2005, and a series of other disasters in the early 2000s, the infrastructure security community in the US and around the world recognized that it was simply not possible to prevent all threats to all assets at all times. Consequently, assuring critical infrastructure resilience emerged in the US and across the globe as a complementary goal to prevention-focused activities. Whereas critical infrastructure security policies historically emphasized prevention of terrorism, accidents, and other disruptions, critical infrastructure resilience activities emphasize the infrastructure's ability to continue providing goods and services even in the event of disruptions. Together, critical infrastructure security and resilience strategies provide a more comprehensive set of activities for ensuring that critical infrastructure systems are prepared to operate in an uncertain, multi-hazard environment.

Today, resilience is at the forefront of several efforts by local, state, and federal governments and agencies. However, no consensus exists at present about how to define or quantify resilience. This issue was highlighted in the National Academy of Sciences' report on disaster resilience: "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" (NRC 2012). To date, resilience metrics development is a very active area of research.

S.2. Outcomes/Impact

The Grid Metrics team pursued two main categories of metrics that can be used independently or in conjunction with one another to quantify the resilience of grid infrastructures.

The first category is called multi-criteria decision analysis (MCDA). MCDA-based metrics generally try to answer the question: "what is the current state of resilience of the electric system, and what are the options to enhance its resilience over time?" MCDA metrics provide a baseline understanding of the system's current resilience and facilitate consideration of resilience enhancement options. Thus, they typically include categories of system properties that are generally accepted as being beneficial to resilience. Examples of these categories might include elements of robustness, resourcefulness, adaptiveness, or recoverability. 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 weighting values that represent the relative importance of the survey responses, and performing a series of calculations that result in numerical scores for the resilience attributes. The baseline can then be used to conduct "what if" analysis to understand the impacts of targeted investments or actions to improve the resilience posture of one or more of the attributes. Figure S.1 illustrates the major category groupings that are used to develop a resilience index using MCDA.

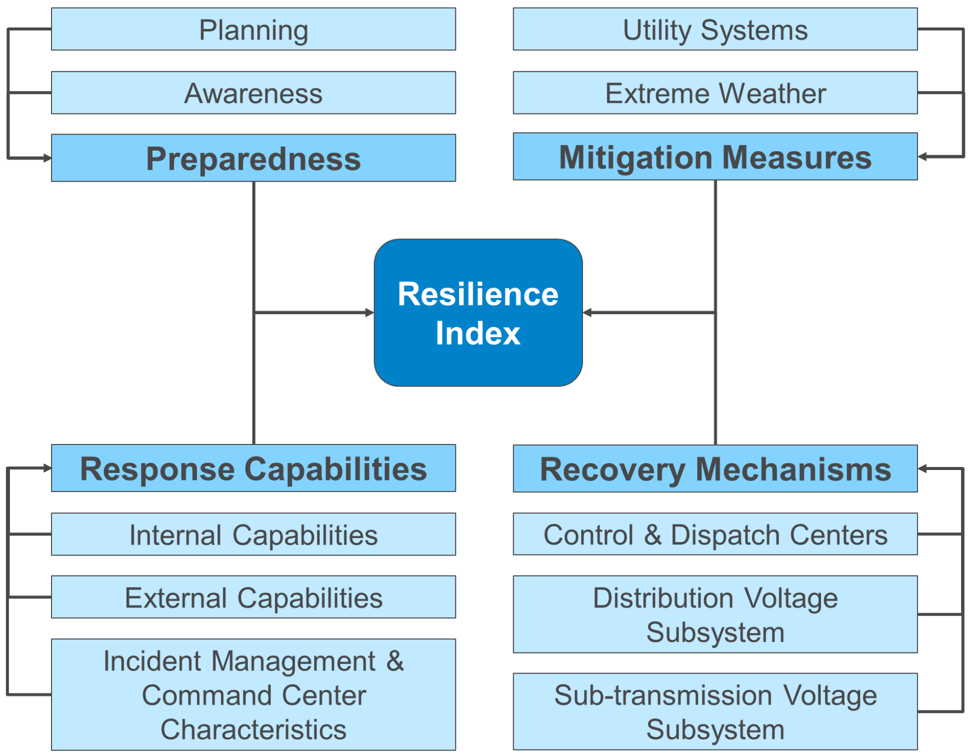

Figure S.1. Major Level 1 (Bold Font) and Level 2 Category Groupings Constituting the Resilience Index

The second category is called performance-based. Performance-based metrics generally try to answer the question: "how would an investment impact the resilience of my system?" They are used to quantitatively describe how the grid has been impacted or compromised in the event of a specified disruption (such as a natural disaster). 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. Table S.1 provides examples of resilience consequence categories and metrics that might be developed using the performance-based approach.

Table S.1. 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 an 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 backup fuel requirement)
Monetary	Loss of assets and perishables
	Business interruption costs
	Impact on Gross Municipal Product or Gross Regional Product
Other Critical Assets	Key production facilities without power
	Key military facilities without power

Combining these two approaches allows for a more comprehensive analysis of grid resilience and the potential consequences resulting from disruptions of electricity supply, thereby representing both electric grid and community resilience benefits. The MCDA approach can be used first to provide a high-level characterization of a grid's resilience and allows comparing different resilience enhancement options. The performance-based approach can then be used second by incorporating the outputs of the MCDA approach to deepen the resilience assessment of a grid by integrating economic and regional considerations. See Figure S.2.

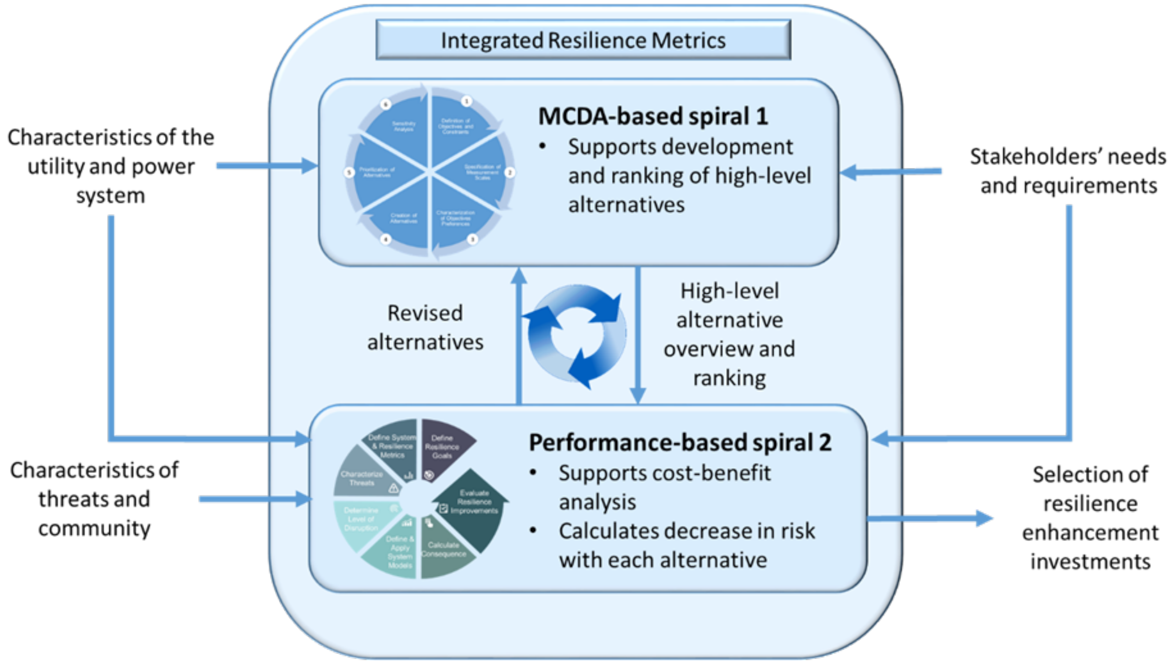

Figure S.2. Integration of Resilience Metric Approaches

At the time this report was prepared (winter 2019), the team is in discussions with a variety of stakeholders to conduct an integrated demonstration of the two complementary approaches.

Acknowledgments

The development of metrics to assess the resilience of the electric grid must specifically answer stakeholders' needs and requirements. The work conducted would not have been possible without the support of governmental and industry partners. The methodology presented in this report builds upon previous work funded by the U.S Department of Homeland Security (DHS) and the U.S. Department of Energy (DOE) Office of Electricity. Over the course of the project, several partners have been involved in the project. Their feedbacks and comments have been paramount to ensure the success of the development of these new metrics. The authors are particularly thankful to Electric Power Research Institute (EPRI), DHS, the City of New Orleans, Entergy, Pennsylvania-New Jersey-Maryland Interconnection (PJM), the Institute of Electrical and Electronics Engineers, the DOE/Office of Energy Policy and Systems Analysis, and North American Electric Reliability Corporation (NERC) Critical Infrastructure Protection Committee. Finally, the authors would also like to recognize the contribution of two of their colleagues, Julia Phillips and Robert Jeffers, who initiated this work.

Acronyms and Abbreviations

CHP	combined heat and power
CVaR	Conditional Value at Risk
DOE	U.S. Department of Energy
EEI	Edison Electric Institute
EPRI	Electric Power Research Institute
GMLC	Grid Modernization Laboratory Consortium
GMLC1.1	Grid Modernization Laboratory Consortium Project Metrics Analysis
MCDA	Multi-criteria decision analysis
MMI	Mitigation Measures Index
NARUC	National Association of Regulatory Utility Commissioners
NERC	North American Electric Reliability Corporation
OE	(DOE) Office of Electricity Delivery and Energy Reliability
PI	Preparedness Index
PPD	Presidential Policy Directive
PV	Photovoltaic
RAP	Resilience Analysis Process
RI	Resilience Index
RCI	Response Capabilities Index
ReMI	Recovery Mechanisms Index
Tesla	Tesla Electric
VaR	Value at Risk

Contents

Figures

Tables

1.0 Introduction

1.1 Project Background and Motivation

The U.S. Department of Energy's (DOE's) 2015 Grid Modernization Initiative Multi-Year Program Plan states that as the US electric grid transitions to a modernized electric infrastructure, policy makers, regulators, grid planners, and operators must seek balance among six overarching attributes (DOE 2015a): (1) reliability, (2) resilience, (3) flexibility, (4) sustainability, (5) affordability, and (6) security. Some attributes have matured and are already clearly defined with a set of metrics (e.g., reliability), while others are emerging and less sharply defined (e.g., resilience). To provide more clarity to the definition and use of the attributes, the DOE is funding an effort that will evaluate the current set of metrics, develop new metrics where appropriate, or enhance existing metrics to provide a richer set of descriptors of how the US electric infrastructure evolves over time.

The DOE engaged nine National Laboratories to develop and test a set of enhanced and new metrics and associated methodologies through the Grid Modernization Laboratory Consortium's (GMLC's) Metrics Analysis project, generally referred to as GMLC1.1.

The project supports the mission of three DOE Offices—Office of Electricity Delivery and Energy Reliability (OE), Office of Energy Efficiency and Renewable Energy, and Office of Energy Policy and Systems Analysis—by revealing and quantifying the current state of the nation's electric infrastructure and its evolution over time.

This project started in April 2016 and ended in March.

1.2 Metric Category Definitions

The Multi-Year Program Plan uses the term "attribute" to describe the characteristics of the power grid. In this report, we use the term "metric areas" or "metric categories." Metrics are physical or economic considerations that can be measured or counted. Several metrics can be grouped into a metric category.

The six metric categories explored in this project are described in Table 1.1. The purpose of this table is to list commonly-used definitions and indicate which aspects of the large breadth within a metric category this project addresses.

Table 1.1. Metrics Descriptions and Focus Areas

Metric Categories	Definitions	Focus Areas Under GMLC 1.1
Reliability	Maintain the delivery of electric services to customers in the face of routine uncertainty in operating conditions. For utility <u>distribution systems</u>, measuring reliability focuses on interruption of the delivery of electricity in sufficient quantities and of sufficient quality to meet electricity users' needs for (or applications of) electricity. For the <u>bulk power system</u>, measuring reliability focuses separately on both the operational (current or near-term conditions) and planning (longer-term) time horizons.	We are developing new metrics of distribution reliability, which account for the economic cost of power interruptions to customers, with the American Public Power Association. We are developing new metrics of bulk power system reliability for use in the North American Electronic Reliability Corporation's Annual State of Reliability Report. We are demonstrating the use of probabilistic transmission planning

Metric Categories	Definitions	Focus Areas Under GMLC 1.1
		metrics with the Electric Reliability Council of Texas, Inc. and Idaho Power.
Resiliency	Can prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions, including the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents (Obama 2013).	We developed a hybrid approach combining the multi-criteria decision analysis and performance-based techniques. This approach provides the information needed to characterize the resilience of the electric grid distribution system and to prioritize investments for resilience improvements.
Flexibility	Respond to future uncertainties that may stress the system in the short term and require the system to adapt over the long term: Short-term flexibility to address operational and economic uncertainties that are likely to stress the system or affect costs. Long-term flexibility to adapt to economic variabilities and technological uncertainties that may alter the system.	We focus on flexibility of the bulk power system needed to accommodate the variability of net load, which is the load minus variable generation including high penetrations of variable resource renewables.
Sustainability	Provide electric services to customers minimizing negative impacts on humans and the natural environment.	We focus on environmental sustainability specifically in Year, 1 assessing metrics for greenhouse gas emissions from electricity generation. In Years 2 and 3, we also explore water metrics.
Affordability	Provide electric services at a cost that does not exceed customers' willingness and ability to pay for those services (Taft and Becker-Dippman 2014).	We document established investment cost-effectiveness metrics and focus our research on emerging customer cost-burden metrics.
Security	Prevent external threats and malicious attacks from occurring and affecting system operation. Maintain and operate the system with limited reliance on supplies (primarily raw materials) from potentially unstable or hostile countries. Reduce the risk to critical infrastructure by physical means or defense cyber measures to intrusions, attacks, or the effects of natural or manmade disasters (Obama 2013).	We develop metrics to help utilities evaluate their physical security posture and inform decision-making and investment.

The aforementioned metrics provide valuable information to stakeholders for enhancing their decision-making processes with respect to modernization of the electric grid. The categories of metrics (i.e., reliability, affordability, resilience, sustainability, flexibility, and security) are the means to measure progress toward modernization. The decision space in which stakeholders must operate is highly complex, requiring consideration of multiple, sometimes conflicting, objectives. Understanding trade-offs between these objectives is a critical component toward implementation of the developed metrics and ensuring they are useful, usable, and used. Considering trade-offs between multiple objectives in the face of uncertainty is extraordinarily difficult and compounded by uncertainty associated with the decision problem. The synthesis of the different metrics is beyond the scope of the GMLC 1.1 Metrics project and has been addressed in the GMLC 1.2.4 Valuation project. However, for developing the resilience metrics, it remains important to differentiate between the different metric categories to avoid overlaps. The next section specifically discusses the main differences between reliability and resilience that could be mistaken for each other.

1.3 Resilience and Reliability

Reliability metrics are defined in the context of outages and disruption under routine or design operating conditions and typically are calculated as aggregated totals over all events—large and small—occurring over the course of a year. Reliability metrics rely on aggregations of historical records (or projected future impacts) to calculate reliability of a system over a period of time, such as a year. Resilience metrics focus on individual events. These events, moreover, are generally low-probability events; thus, historic data may not exist or may be sparse and insufficient to fully characterize resilience.

Resilience metrics are more useful for capturing the impacts of singular, infrequent large-scale events like hurricanes, earthquakes, and terrorist attacks. The difference in disruption magnitudes leads to a difference in temporal durations. Most reliability events are shorter in duration, but resilience focuses on individual events that could last days to weeks. Resilience metrics are often forward-looking and derived from extensive simulations performing what-if analyses. They also can include secondary impacts to systems when power is lost, such as economic impacts, impacts to critical infrastructure, and effects on local and regional communities. Reliability metrics generally do not include secondary impacts.

Grid resilience metrics should quantify the consequences that occur from strain on or disruption of the power grid. These consequences can be closely related to grid operations and power delivery (e.g., megawatt-hours of power not delivered because of a storm, utility revenue lost, cost of recovery to the utility, etc.) and hence have some similarities to existing reliability metrics. They can also be measured in terms of greater community impacts, such as populations without power (e.g., measured in people-hours), business interruption costs resulting from the power outage, impacts on critical infrastructure functionality, loss of Gross Regional Product, etc. Traditional reliability metrics do not distinguish among the types of customers impacted and aggregate information on the actual duration of interruptions. Currently, an hour of power loss to a hospital is equally weighted as an hour of power loss to an empty shed.

As illustrated by the definitions of resilience and reliability in the *Quadrennial Energy Review* and in the *Framework for Establishing Critical Infrastructure Resilience Goals*, there is a time-variant relationship between reliability and resilience:

- **Reliability** refers to the ability of the system or its components to withstand instability, uncontrolled events, cascading failures, or unanticipated loss of system components (DOE 2017)
- **Resilience** refers to the ability of a system or its components to adapt to changing conditions and to withstand and rapidly recover from disruptions (DOE 2017). Said another way, resilience characterizes the ability to anticipate, absorb, adapt to, and/or rapidly recover from a disruptive event (NIAC 2010).

Recognized in the *Framework for Establishing Critical Infrastructure Resilience Goals* (NIAC 2010) and in the North American Electric Reliability Corporation (NERC) Reliability Issues Steering Committee (NERC 2018), resilience adds a time-based component for further consideration. More specifically, resilience represents the time-based aspects of reliability in electric grid operations. The range from preparedness to recovery offers many opportunities spread across time to enhance resilience through the application of various organizational processes, plans, drills and various types of equipment and automation that can directly benefit and enhance the electric network. The concept that "resilience is a time-based component of reliability" is widely accepted in the electric industry and was promoted by NERC to the Federal Energy Regulatory Commission in their response to Docket No AD18-7-000 (Grid Resilience in Regional Transmission Organizations and Independent System Operators 2018). NERC emphasizes the point that their definition of "adequate level of reliability or 'ALR' [includes] resilience as a time-based component of reliability" (Grid Resilience in Regional Transmission Organizations and Independent System Operators 2018).

Their argument is further supported by recognition that comprehensive, adequate-level reliability objectives intentionally address all four aspects of resilience (Grid Resilience in Regional Transmission Organizations and Independent System Operators 2018; NERC 2018).

- **Steady State** – the period before a disturbance and after restoration has achieved normal operating conditions
- **Transient** – the transitional period after a disturbance and during high-speed automatic actions in response
- **Operations Response** – the period after the disturbance where some automatic actions occur and operators act to respond
- **Recovery and System Restoration** – the period after a widespread outage through initial restoration to a sustainable operating state and recovery to a new steady state.

Therefore, enhancing resilience or reliability encompass similar elements to maintain the electric grid's operations at an acceptable level of performance. However, they differ slightly by the characteristic and timeframe of the disturbing events.

1.4 Approach

A key challenge in reporting grid-related metrics is that DOE is neither responsible for providing primary supporting data nor "owns" much of the data from which grid metrics are expected to be derived. An ideal outcome is for the organizations that bear this responsibility to adopt metric methodologies developed, successfully tested, and accepted by a broad range of electric system stakeholders via GMLC 1.1.

The original approach for the GMLC 1.1 Metrics project consisted of developing, testing, and applying the six metric categories. Year 1 defined the characteristics of the different metrics and develop them. Years 2 and 3 focused on validating metric methodologies by applying them to real-world situations with electric sector partners and establishing partnerships with key data providers, including federal and state agencies and regional entities that could potentially help institutionalize the final products and results of GMLC 1.1. This approach is described in Figure 1.1.

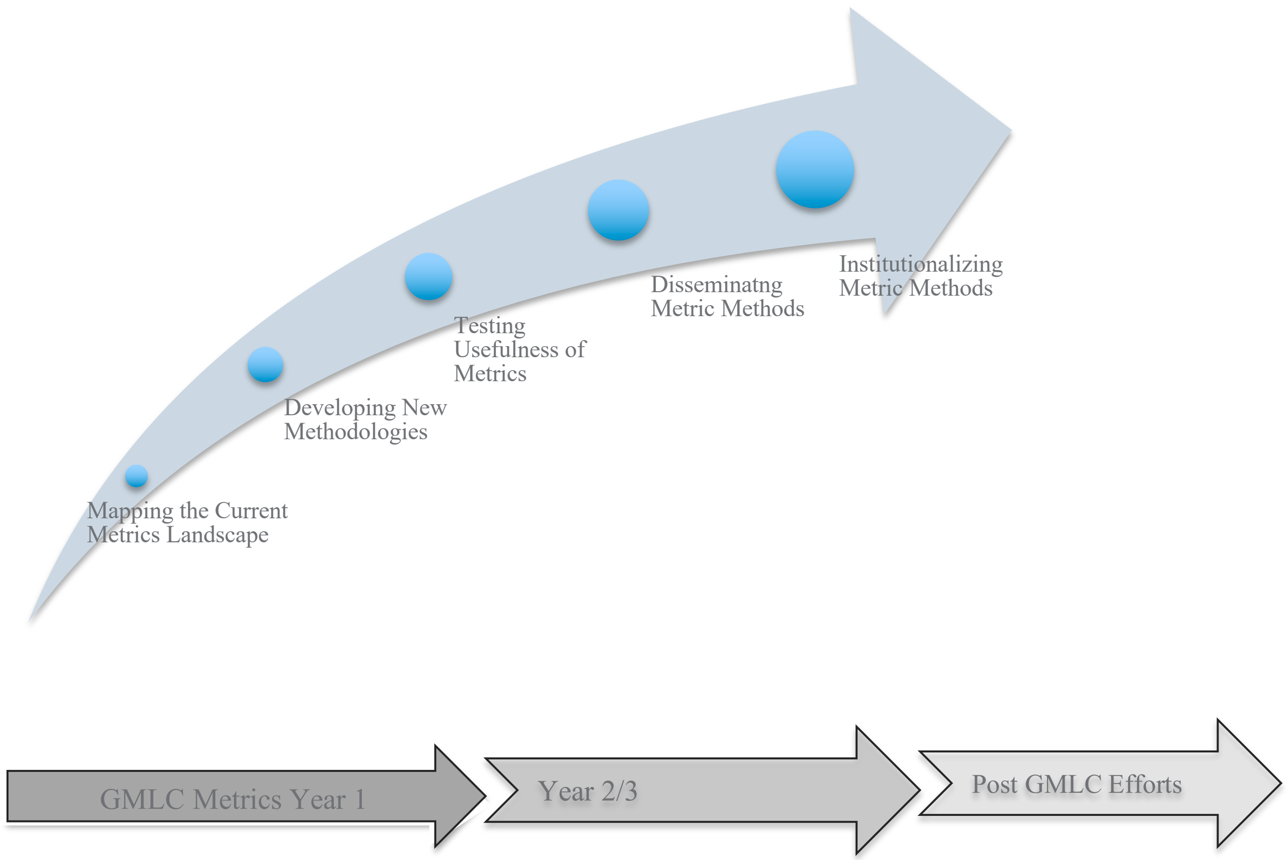

Figure 1.1. Time Line for GMLC1.1 Activities

Specific approaches to formalizing metrics varied across the six metrics category teams, depending on the maturity of metrics development and use in the area, the existence of publicly collected and disseminated sets of supporting data, and the presence of other organizations working in the space. The specific approaches included:

- Mapping the current metrics landscape to identify stakeholder's needs and requirements, and define the focus of GMLC Metrics work
- Developing new methodologies by collaborating with industry partners and leveraging related efforts of established national data providers or industry associations to explore and develop with them new ways of looking at their data
- Testing the usefulness of these metrics with industry partners to ensure the methodologies are adapted for specific stakeholder's needs
- Disseminating metrics methods and testing broader-scale adoption
- Institutionalizing metric methods by working with selected system operators and utilities to carefully identify the existing measurement landscape and to support a longer-term research program to develop methodologies that could be effectively applied across jurisdictions.

Metrics are categorized by their ability to characterize the electricity system's properties historically (*lagging* metrics) or the system's ability to respond to challenges in the future (*leading* metrics). Lagging metrics are backward-looking, or retrospective, where the impact of a collection of activities on a specific system can be assessed after their actual implementation. As such, they can be helpful aggregate indicators of progress being made in grid modernization. Leading metrics are forward-looking or prospective, where the future impact of an activity can be estimated prior to its actual completion or implementation on a system. As such, they can be used to inform decisions on infrastructure investments or policy interventions.

1.5 Stakeholder Engagement for GMLC 1.1

A critical aspect of this project is to ensure the metrics being developed directly benefit the electricity sector. Throughout the process of developing and testing the metrics from this project, input and feedback are sought out from stakeholders. Key national organizations in the electric industry were identified as Working Partners at the inception of the project and engaged to provide both strategic and technical input to the project as a whole. Three types of organizations were also identified for each of the six individual metric areas: (1) primary metric users, (2) subject matter experts, and (3) data or survey organizations. These stakeholders were engaged at various stages of the project, especially at but not limited to the beginning and scoping stages of the effort and for a more formal review of the different metrics over the course of their development and application.

2.0 Objective

Historically, US government policy toward critical infrastructure security has focused on physical protection. However, after the terrorist attacks of September 11, 2001, the devastation from Hurricane Katrina in 2005, and a series of other disasters in the early 2000s, the infrastructure security community in the US and around the world recognized it was simply not possible to prevent all threats to all assets at all times. Consequently, assuring critical infrastructure resilience emerged in the US and across the globe as a complementary goal to prevention-focused activities. Whereas critical infrastructure security policies historically emphasized prevention of terrorism, accidents, and other disruptions, critical infrastructure resilience activities emphasize the infrastructure's ability to continue providing goods and services in the event of disruptions. Together, critical infrastructure security and resilience strategies provide a more comprehensive set of activities for ensuring critical infrastructure systems are prepared to operate in an uncertain, multi-hazard environment.

Today, resilience is at the forefront of several efforts by local, state, and federal governments and agencies. However, no consensus exists at present on how to define or quantify resilience. This issue was highlighted in the National Academy of Sciences' report on disaster resilience: "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" (NRC 2012). To date, resilience definition and metric development are very active areas of research.

In the context of the GMLC 1.1 project, the main objective in terms of resilience is to develop a metric to not only promote the resilience of the electric grid, but also of the communities served by the grid. To achieve this objective, two specific goals have been defined:

1. Define the concept of resilience applied to the electric grid and its relationship to other metrics, such as reliability. Defining what constitutes the resilience of the grid is essential to guide the development of an effective resilience metric.
2. Develop a hybrid approach combining multi-criteria decision analysis (MCDA) and performance-based techniques to propose a comprehensive resilience metrics capability that integrates both the technical characteristics of the grid and its operating environment.

3.0 Approach

3.1 Methodology

The approach used for developing the resilience metric is directly aligned with the general GMLC 1.1 activities supporting the development of the five other metrics. The strategy to develop the resilience metric promotes a collaborative approach to ensure the stakeholders' participation throughout the project. However, the development of the resilience metric also presents some specificities due to the choice to combine decision analysis and performance-based techniques. This approach is described in Figure 3.1.

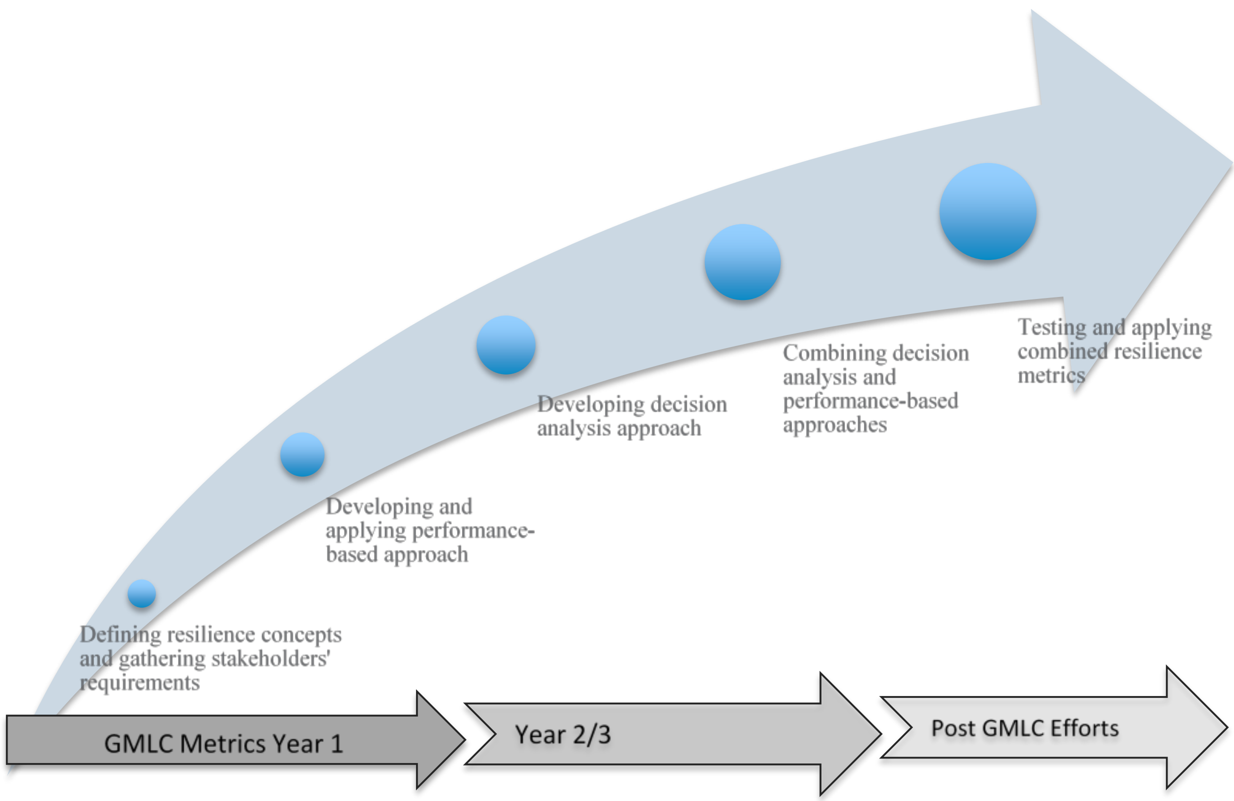

Figure 3.1. Time Line for Resilience Metrics Activities

Year 1 was specifically dedicated to (i) gathering stakeholders' requirements for guiding the development of the resilience metrics, (ii) defining the components of the resilience metrics and the difference between the resilience metrics and other metrics, and (iii) starting the development and application of the performance-based approach. The development of the MCDA approach was not launched until Year 2. Due to this time constraint, the MCDA approach focused on the electric grid distribution system to limit scope, while still providing an opportunity for the meaningful demonstration of the MCDA capability. Defining the elements needed to combine the two resilience metric approaches (i.e., performance-based and MCDA-based) started in the second part of Year 2. Year 3 allowed the refinement of the concepts supporting the combined resilience metrics and the opportunity to contact grid owners and operators for potential application of the hybrid methodology developed. Despite positive feedback from an electric utility, the utility could not commit to fully engage with the development team to wholly adopt testing and apply the combined methodologies to a real case study. Such application should be conducted in ongoing work after this GMLC 1.1 project. This would allow the project to (i) refine the combination of performance-based and MCDA-based approaches, and (ii) expand the MCDA-based approach to include all dimensions of the electric grid from generation through distribution.

3.2 Stakeholder Engagement for Resilience Metrics

For the resilience metrics, stakeholder engagement was slightly different from other metric categories. Even though stakeholders were highly involved from the beginning and scoping stages of the effort through the definition and development of the resilience metrics, the hybrid methodology combining performance-based and MCDA-based approaches have not been formally tested and applied to a real case study. Stakeholder engagement leading up to that point evolved over the course of the project.

3.2.1 Stakeholder Engagement During Year 1

During Year 1, a briefing was conducted with domain experts to review the work on the definition of resilience and the application of the performance-based approach in New Orleans. The reviewers represented the Electric Power Research Institute (EPRI), the Department of Homeland Security, the City of New Orleans, Louisiana, and PJM.

3.2.2 Stakeholder Engagement During Year 2

During Year 2, several discussions and meetings occurred with the City of New Orleans, New Orleans Sewage and Water Board, and Entergy to present the hybrid resilience metrics approach and the possibility of applying this new methodology in New Orleans. Entergy and the City of New Orleans were very interested in the hybrid resilience metrics. However, due to the lack of time and internal staffing, they were not able to provide specific feedback on the development of the MCDA-based approach and the overall benefits of the combined approaches.

3.2.3 Stakeholder Engagement During Year 3

During Year 3, additional contacts with the industry have been made to socialize the characteristics of each resilience methodology, to articulate the concepts supporting their coordination in an integrated approach, and to find potential partners interested in applying the resilience metrics to case studies. Individuals contacted represented the Institute of Electrical and Electronics Engineers, DOE/Office of Energy Policy and Systems Analysis, and NERC Critical Infrastructure Protection Committee. Although various levels of interest were expressed by these stakeholders, it did not result in tangible collaborations or applications and validation of the resilience metrics. The concepts and question set constituting the foundation of the multi-attribute approach have also been communicated, and feedback overall is very positive on the MCDA-based approach and its combination with the performance-based approach.

The hybrid resilience metrics were also presented in several peer review conferences, such as the Society for Risk Analysis (SRA) annual conference and resilience week. During the SRA annual conference, the symposium T4-A specifically addressed the challenge to develop resilience metrics. This symposium provided a unique opportunity for researchers from the US and Europe to exchange concerns about the challenges of developing methodologies and metrics to address infrastructure and community resilience. During this symposium, the combination of the MCDA and performance-based approaches was specifically discussed among the panel (i.e., Sandia National Laboratory, Argonne National Laboratory, the National Institute of Standards and Technology, and a representative from the European

SmartResilience Project) and governmental agencies and academia in the audience. Presentations and discussions during these conferences provided adjustments to the approach to better integrate stakeholder concerns.

3.3 Users of This Research

The primary users of the resilience metrics outcomes are the owners and operators of the electric grid. The research conducted allows users to differentiate between reliability and resilience and to propose a scientifically sound hybrid methodology combining MCDA and performance-based approaches to operationalize resilience concepts. This information will help the industry define options to enhance the resilience of their systems.

Results of this research are also useful for regional decision makers who can use the resilience metrics to better understand the functioning of the electric grid and its effect on economic sectors served by the grid, and to prioritize resilience enhancement investments.

4.0 Outcomes

Although still at an early stage, the work conducted for developing the resilience metrics is a first attempt to combine two approaches (MCDA and performance-based) to assess both the resilience of the electric system and the community it serves. Besides the comparison between resilience and reliability, the core of this research specifically focused on the development of MCDA and performance-based approaches specific to the electricity distribution system and the development of concepts to combine them in a hybrid and iterative resilience metrics.

4.1 Definition of Resilience

Although resilience has been defined and studied in several fields (e.g., ecology, social science, economy, and computing) since the seventies, no resilience definitions have been universally accepted by the grid community.

Still, a rich discussion and body of research on this topic is currently ongoing. When considering infrastructure systems, there is considerable variation in the definition of resilience depending on the level of analysis (i.e., asset, facility, system, or system of systems). The main difference between existing definitions resides in consideration of activities taking place before or after a disruption. Most definitions characterize resilience as the capability of an infrastructure to bounce back after a disruption and therefore as its ability to restore and recover its operations. Elements taken prior to the disruption are not always considered. Traditionally, an infrastructure system's capacity to resist, anticipate, or prepare for an adverse event relate to vulnerability assessment. However, these two concepts of resilience and vulnerability are strongly related; both connect to the state of the infrastructure and have a direct influence on the level of consequences.

Even so, vulnerability and resilience assessments have different implications. Vulnerability is about the potential of a critical infrastructure to be impacted by a given hazard and addresses the potential degradation of the infrastructure's operating state. Resilience is more about the change of the infrastructure system's state and integrating the system's capability to adapt and transform its operations to deal with stresses, all while maintaining an acceptable operational level. Assessing resilience requires consideration of the evolution of the state of the infrastructure system over time and determination of both the amount by which the activity/well-being declines and the time required to return to the pre-event level of operations or to a new level of equilibrium. Therefore, elements characterizing the capabilities of the infrastructure systems both before (i.e., anticipation, resistance, and absorption) and after (i.e., response, adaptation, and recovery) adverse events are important to consider in resilience definition and strategies.

Since 2013, the Presidential Policy Directive 21 (PPD-21) (Obama 2013) asserts the following definition of resilience:

> The term 'resilience' means the ability to prepare for and adapt to changing conditions while also withstanding and recovering rapidly from disruptions, including deliberate attacks, accidents, or naturally occurring threats or incidents.

PPD-21 establishes a national policy on critical infrastructure resilience; additionally, PPD-21's resilience definition is consistent with most other proposed definitions (Carlson et al. 2012; Biringer et al. 2013).

However, even if the concept of resilience is defined in national policies, discussions are still ongoing about the resilience components and metrics. One of the main concerns is the absence of industry or government initiative to develop a consensus on or to implement standardized assessment approaches (DOE 2017). Consequently, the GMLC1.1 project leverages the PPD-21 definition of resilience for establishing grid resilience metrics.

4.2 Existing Metrics and Their Maturity

Resilient system metrics are useful to understand the resiliency of an infrastructure, region, or community to specific threats or vulnerabilities. Proposed resilience metrics should be quantitative and operationally available to decision makers who will be tasked with allocating resources and prioritizing disaster response. Qualitative assessments are not ideal because they often rely on individual stakeholder input. Although the stakeholder input is valuable, it is often internally focused. There may not be an incentive to increase the resilience of an entire system. One of the fundamental difficulties of resilience for infrastructure systems is the public/private nature of infrastructure. The electric power grid is the perfect example of this public/private conundrum.

Even though universally accepted, grid resilience metrics do not currently exist. A number of leading organizations within the community have asserted needs and requirements for resilience metrics and analysis methodologies. For example, the National Association of Regulatory Utility Commissioners (NARUC) has asserted current reliability metrics are not sufficient for informing analyses on investments for large-scale disruptions (such as hurricanes, earthquakes, etc.), and resilience metrics need to be designed to meet that gap (NARUC 2016). The EPRI is researching the development of risk-based metrics, methods for quantifying resilience, and methods for selecting among various options for reducing the risk of damage to the bulk power and distribution systems during severe events (EPRI 2015a). The Edison Electric Institute (EEI) notes 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" (EEI 2014). PJM is actively developing tools to analyze the resilience of the grid to cascading failures. DOE has also explored energy resilience analysis frameworks in the Quadrennial Energy Review and Quadrennial Technical Review (Watson et al. 2015; DOE 2015b, c).

GMLC1.1 identified two main categories of metrics that can be combined for quantifying resilience in the grid and other infrastructure:

- MCDA-based: MCDA-based metrics generally try to answer the question "what makes my system more or 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 generally accepted as being beneficial to resilience. Examples of these categories might include elements of robustness, resourcefulness, adaptivity, or recoverability. 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 weighting values that represent the relative importance of the survey responses, and performing a series of calculations that result in numerical scores for the resilience attributes.

- Performance-based: 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 to 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.

Combining these two approaches allows for a more comprehensive analysis of the resilience of the grid and the potential consequences resulting from the disruption of electricity supply, thereby representing both electric grid and community resilience benefits. The MCDA approach provides high-level characterization of the grid resilience and allows comparing different resilience enhancement options. The performance-based approach uses the outputs of the MCDA approach to deepen the resilience assessment of the grid by integrating economic and regional considerations.

4.3 Combining MCDA and Performance-Based Approaches

4.3.1 Requirements

To establish a set of needs and requirements for grid resilience metrics, GMLC1.1 engaged with stakeholders from the grid community and reviewed the current literature on this topic. The project identified the following as commonly asked resilience questions:

- How do I measure the resilience of my system?
- If a disruptive event is imminent (i.e., will occur within hours to days), what can I do to mitigate the consequences of such an event and increase the resilience of my system?
- How should I plan and invest to make my system more resilient across the spectrum of uncertain future events?

Stakeholders further noted the following considerations for resilience metrics:

- Context. Grid resilience metrics should be specified in the context of low-probability, high-consequence potential disruptions. This context will help distinguish them from reliability metrics.
- Performance-based and MCDA metrics. Grid resilience metrics should be based on the performance of power systems. MCDA metrics can provide a baseline understanding of the system in its current state. The combined use of performance-based and MCDA metrics will maximize the utility of grid resilience metrics for baseline assessments, response and recovery activities, and planning and investment efforts.
- Consequences. Grid resilience metrics should quantify the consequences that occur because of strain on or disruption of the power grid. These consequences can be closely related to grid operations and power delivery (e.g., megawatt-hours of power not delivered because of a storm, utility revenue lost, cost of recovery to the utility, etc.), and hence have some similarities to existing reliability metrics. They can also be measured in terms of greater community impacts, such as populations without power (e.g., measured in people-hours), business interruption costs resulting from the power outage, impacts on critical infrastructure functionality, loss of Gross Regional Product, etc.
- Prioritization. Resilience metrics should be useful for prioritizing which hazards should be planned for and which investments and response actions should be taken to improve resilience to these hazards. This ability would not only help grid operators decide which actions are beneficial, but it could also prove useful for supporting rate-cases and grant applications.
- Forward-looking. Much of the current focus on resilience analyses involves planning for the future, with less emphasis being placed on benchmarking. Hence, resilience metrics should be forward-looking and characterize the power system's ability to cope with hazards that could potentially happen in the future.

- Modeling and simulation. Given that many resilience analyses focus on low frequency events such as geomagnetic disturbances or electromagnetic pulses, sufficient historical data may not be available to characterize grid resilience for all hazards of interest. Hence, grid resilience metrics should have sufficient flexibility to use data from modeling and simulation activities that explore postulated hazards and scenarios, if needed. Though the current state of modeling and simulation tools may be limited or of research grade for certain hazards, grid resilience metrics need to be designed with enough flexibility to include data for these tools when they are ready.
- Consistency. A current challenge for resilience analyses is the lack of standard grid resilience metrics and analysis methods. Stakeholders have identified a need for standardized consistent metrics that can enable hazard prioritization, mitigation, investment comparisons, etc.
- Uncertainty. 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.
- Emerging and future metrics.

The following sections present an overview of the MCDA and performance-based approaches, and the concepts supporting their integration to meet the identified requirements.

4.3.2 MCDA Approach

The MCDA approach is intended to serve as a screening step to refine and customize options for grid resilience enhancement and provide alternatives that will be analyzed with the performance-based approach. The main objectives of this approach are to:

1. Consider resilience attributes that are qualified and important but difficult to directly monetize;
2. Promote a voluntary approach and consider all hazards; and
3. Develop a resilience metric pertinent to the private sector that will serve as input to the resilience performance-based approach.

To achieve these three objectives, the first phase of the GMLC resilience metrics project proposes to use decision analysis techniques to characterize components contributing to resilience in accordance with traditional emergency and risk-management phases (i.e., preparedness, mitigation, response, and recovery). Table 4.1 illustrates how resilience relates to the four emergency management phases.

Table 4.1. Relation Between Emergency Management Phases and Resilience Components (Carlson et al. 2012)

Preparedness	**Mitigation**	**Response**	**Recovery**
Anticipate	Resist, Absorb	Respond, Adapt	Recover
Define the hazard environment	Prior to an event, plan how to reduce the severity or consequences of a hazard	Manage the adverse effects of an event	Return conditions to an acceptable level of operations

The definition of the different phases of emergency management and their relation to resilience components constitute the frame of the resilience index (RI) developed using MCDA techniques.

Decision analysis is a systematic and logical set of procedures for analyzing complex, multi-criteria decision problems. It utilizes a "divide and conquer" philosophy in which hard-to-define, high-level objectives are successively divided into lower-level objectives that are more easily understood, defined, and evaluated. Decision analysis develops meaningful and useful measurement scales for objectives, examines trade-offs among conflicting objectives, and incorporates uncertainty and risk attitudes as appropriate. For characterizing the resilience of the electric power grid, Argonne National Laboratory used the concepts of MCDA (Keeney and Raiffa 1976) and the value-focused technique (Keeney 1992) to construct an index to inform decisions. The decision analytic approach, used for developing the system RI, consists of six iterative phases, which are described in more detail in the following subsections (Figure 4.1).

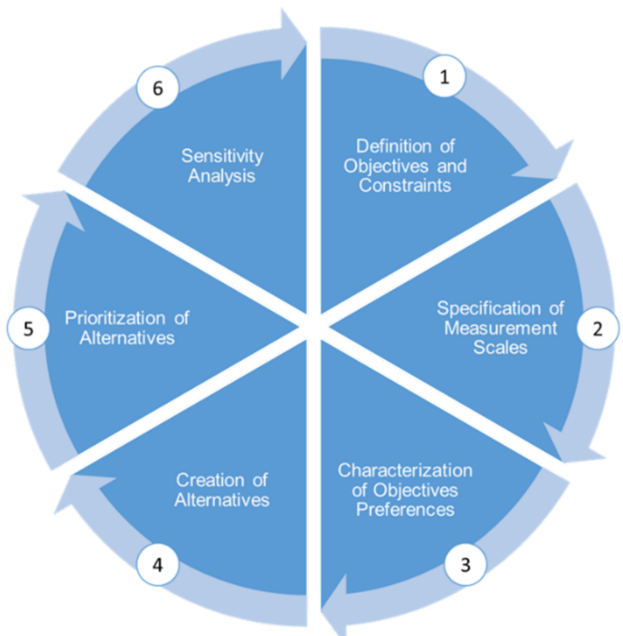

Figure 4.1. MCDA Approach

4.3.2.1 Definition of Objectives and Constraints

The development of a good RI requires an established and agreed-upon set of objectives or goals. The main objective is to enhance the resilience of the electric grid.

Based on the definition of resilience, the main objective of enhancing resilience can be subdivided into four sub-objectives:

- Enhance preparedness to capture the capability of the electric grid to anticipate disruptive events;
- Enhance mitigation measures to capture the capability of the electric grid to resist and absorb the effects of disruptive events;
- Enhance response capabilities to capture the capability of the electric grid to respond and adapt to the effects of disruptive events; and

- Decrease the time required to recover from disruptive events.

4.3.2.2 Specification of Measurement Scales

After the objectives have been identified, the next step is to develop measures that identify the degree to which each objective can be achieved. A good measure not only spans the plausible range of performance by potential alternatives, but also is operational (i.e., discriminates among alternatives) and understandable. For developing the value hierarchies (i.e., identifying the resilience attributes and defining the overall structure of the index), Argonne used a combined standard approach (Parnell et al. 2013). The approach consisted of reviewing approved documents (i.e., resilience and business continuity standards, energy policy and regulations) and conducting facilitated discussions with subject matter experts representing critical infrastructure owners and operators, the DOE, standards authorities, and professional associations. It also leveraged the work conducted to develop the Resilience Measurement Index, which characterizes the resilience of critical infrastructure assets (Petit et al. 2013).

The electric power grid is constituted of four general stages that naturally partition the MCDA approach (Figure 4.2).

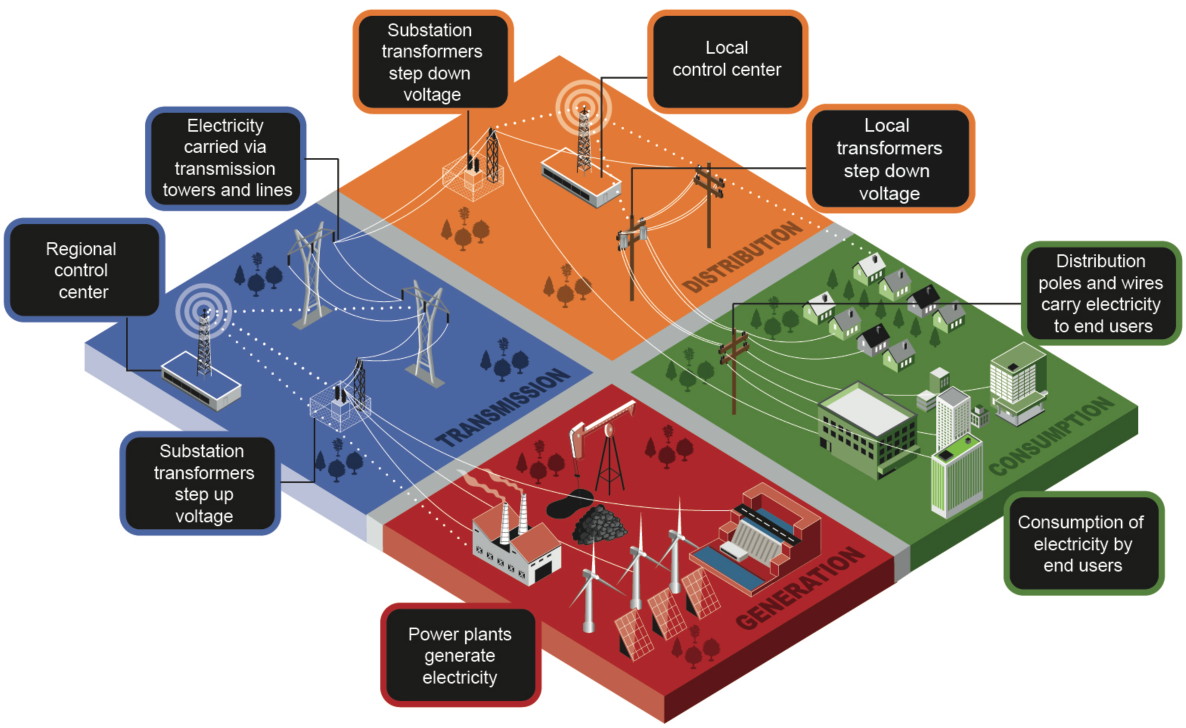

Figure 4.2. Stages of Electric Power Supply, Delivery, and Consumption (Finster et al. 2016)

For developing an index characterizing the resilience of the entire grid, the management and operation of the assets constituting the generation, transmission, and distribution stages, and the way they influence preparedness, mitigation, response, and recovery capabilities, must be considered. However, due to time constraints in this project, development was focused primarily on distribution assets, which constitute the interface between the electric power grid and consumers (Figure 4.3).

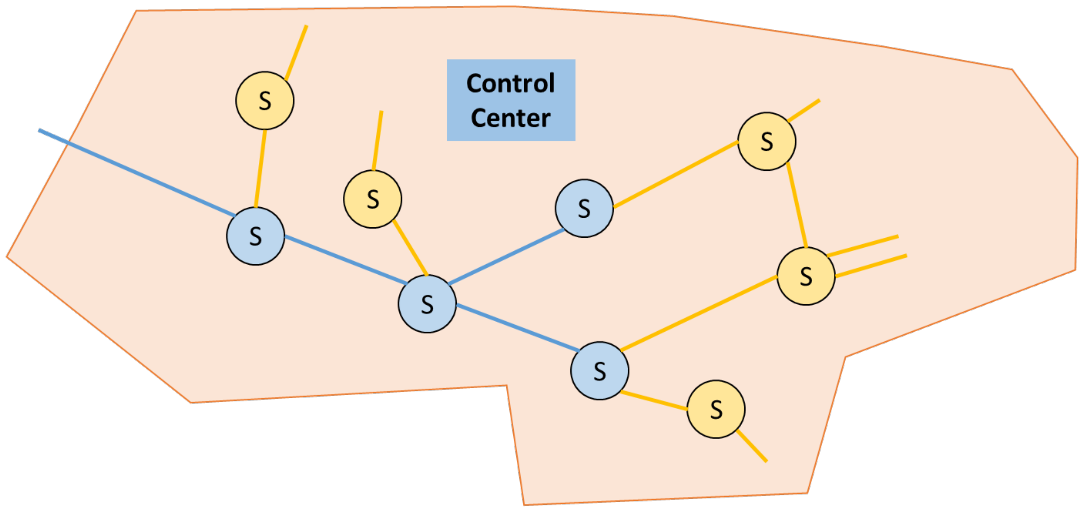

Figure 4.3. Overview of Assets Constituting the Distribution Stage

The distribution stage comprises subtransmission voltage systems (in blue in Figure 4.3) and distribution voltage systems (in yellow in Figure 4.3). Three types of assets constitute the subtransmission and distribution voltage systems: substations (noted as "S" in Figure 4.3), the lines connecting the substations, and the control center(s) for monitoring and operating electric power distribution. The elements contributing to the achievement of the four resilience objectives are captured by using data collection questions covering the different attribute categories while defining their potential values and associated measures. The survey combines attributes characterizing the resilience of the whole utility and of the specificities of the subtransmission and distribution voltage assets. To avoid the characterization of each asset in a utility's system, the question set differentiates between "less than typical," "typical," and "more than typical" assets. These buckets represent the general sense of resilience for these assets in both subtransmission and distribution voltage systems. For example, when considering equipment like reclosers, a less than typical substation may not have reclosers, but a more than typical substation may include them. Similarly, the presence and absence of other important types of equipment further differentiate the subtransmission and distribution substations assigned to these three discriminators.

In addition to the resilience and business continuity standards, several other sources have been used to define the 1,200 attributes that contribute to the RI:

- NERC;
- Federal Energy Regulatory Commission;
- DOE-OE;
- Quadrennial Energy Review;
- National Association of State Energy Officials;
- NARUC;
- EPRI; and
- EEI.

The question set also includes electric utility industry inputs gathered through facilitated discussions. The question set is organized in six main sections:

- General Utility Information;

- First Preventers/Responders;
- Extreme Weather Events;
- Information Sharing;
- Resilience Management Profile; and
- Utility Characteristics.

The current version of the question set has been developed by leveraging elements from the Resilience Measurement Index, developed for the Department of Homeland Security Office of Infrastructure Protection, and the Energy Resilience Assessment Program-Distribution (ERAP-D), developed for the DOE-OE. Specific to electric power distribution systems, the question set captures the following: utility characteristics, potential consequences, electric distribution specific mitigation measures, existing agreements and information sharing processes, resilience planning, response capabilities, and dependencies supporting the system.

4.3.2.3 Characterization of Objective Preferences

After the objectives and associated scales have been agreed upon, it is necessary to determine the relative importance of each objective to the decision maker via an elicitation. Relative importance can be assessed by having decision makers “swing-weight” each objective. Swing-weighting asks decision makers to attribute an importance weight to each objective based on the importance of moving from that objective’s worst performance to its best. These weights can be then entered into a utility function to help determine a “best-fit” alternative.

The utility function defines a calculated index that varies from 0 to 100 and represents a relative value of the grid’s resilience. Interpretation and implication of the index are important for decision makers to understand. A low overall value does not mean every type of hazard will lead to an immediate system shutdown. A high overall value does not mean a specific event will have minimal consequences. Simply stated, the index allows comparison of different levels of resilience. The scaling of the index is such that improvement from 20 to 40 is equivalent to improvement from 60 to 80. Determining the system RI and how different options affect this index is useful for establishing the most effective ways to improve a system’s overall resilience.

The RI is used to assess and prioritize potential grid modernization alternatives. Each desired characteristic is represented by an objective that should be achieved to the greatest feasible extent, subject to factors such as time and cost, among others. The performance of each system with respect to each of the objectives must be determined (i.e., characterized). Once this is accomplished, different combinations of specific resilience measures define a possible alternative. Given the preferences within and across the objectives, it is possible to create alternatives that will integrate stakeholders’ objectives and requirements. The prioritization processes may appear to yield a final recommendation; often these recommendations differ. Thus, they should be used only as information to aid decision makers. As always, a review should be conducted to ensure each recommendation makes sense and no factors are missing from the analysis. Finally, sensitivity analysis is conducted, which enables analysts to assess the importance of uncertainties in the criteria value judgments and scale measures.

The MCDA techniques allowed the development of an RI that organized around 1,200 attributes in 350 category groupings to characterize the resilience of the electric grid distribution system. Figure 4.4 illustrates the two first levels of category groupings constituting the RI.

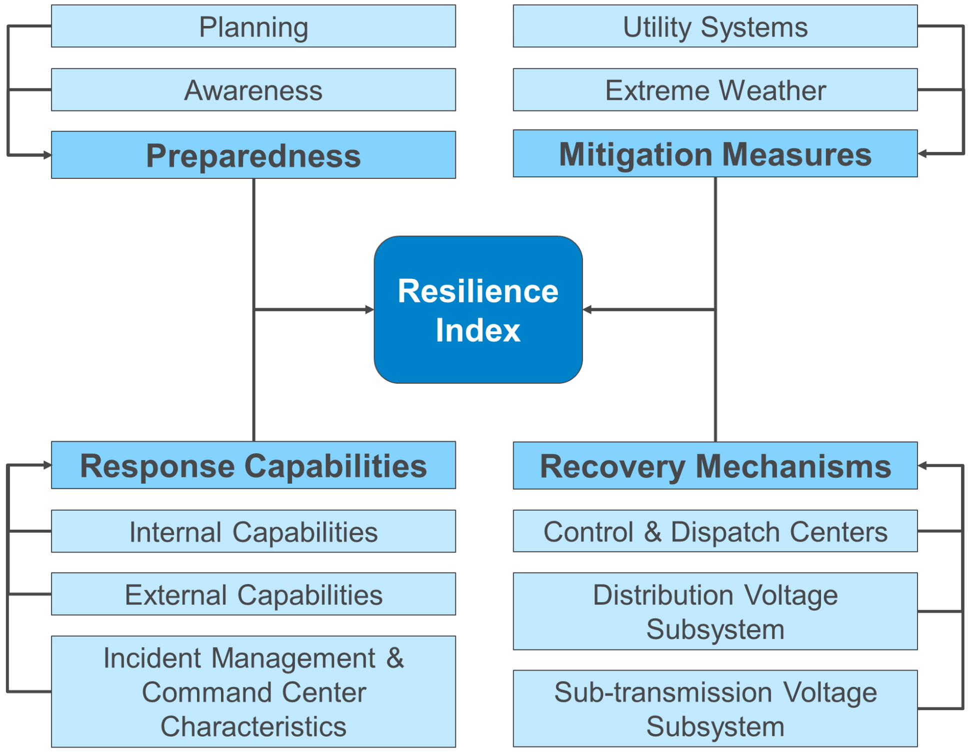

Figure 4.4. Major Level 1 and Level 2 Category Groupings Constituting the Resilience Index

Preparedness characterizes procedures and actions undertaken at the enterprise level to enhance awareness to potential natural and manmade hazards (e.g., information sharing, hazard assessments, and training and exercises) and management plans (e.g., emergency action, business continuity, supply management, and preventive maintenance). Preparedness comprises around 300 components organized into 70 grouping categories. Figure 4.5 shows high-level groupings under preparedness.

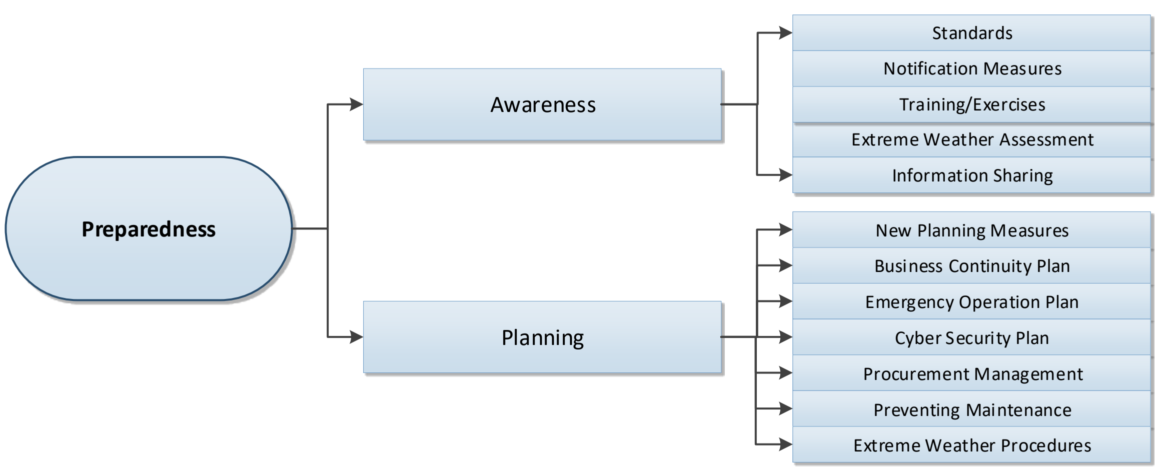

Figure 4.5. Resilience Components Contributing to Preparedness

Components contributing to preparedness are aggregated using Equation 1 into a single value that varies from 0 to 100.

$$PI = \sum_{i=1}^{2} a_i * Z_i \qquad \text{Equation 1}$$

where:

PI = Preparedness Index (ranging from 0 to 100);

a_i = scaling constant (weight; a number between 0 and 1) indicating the relative importance of possibility $i(i = 1, 2)$ of preparedness; and

Z_i = index value of component i of preparedness (i.e., awareness and planning).

Mitigation measures characterize the distribution grid capabilities at both enterprise and asset (e.g., substations, and control centers) levels to resist a hazard or to absorb its consequences. Mitigation measures is the largest grouping of the RI and considers elements of redundancy, mitigating equipment, and interdependencies that affect grid operations. Mitigation measures group around 550 components organized into 190 grouping categories. Figure 4.6 shows high-level groupings under mitigation measures.

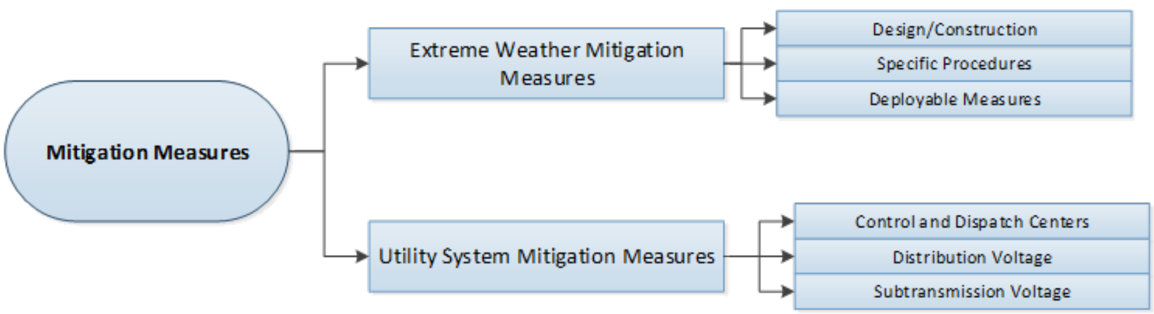

Figure 4.6. Resilience Components Contributing to Mitigation

Components contributing to mitigation measures are aggregated using Equation 2 into a single value that varies from 0 to 100.

$$MMI = \sum_{i=1}^{2} b_i * Y_i \qquad \text{Equation 2}$$

where:

MMI = Mitigation Measures Index (ranging from 0 to 100);

b_i = scaling constant (weight; a number between 0 and 1) indicating the relative importance of possibility $i(i = 1, 2)$ of mitigation measures; and

Y_i = index value of mitigation measures component i (i.e., extreme weather mitigation measures and utility system mitigation measures).

Response capabilities characterize activities, tasks, programs, and systems undertaken at both enterprise and asset levels to respond to an accident with and without the support of the emergency services sector, and to coordinate business continuity and response management. Response capabilities comprise around 320 components organized into 50 grouping categories. Figure 4.7 shows high-level groupings under response capabilities.

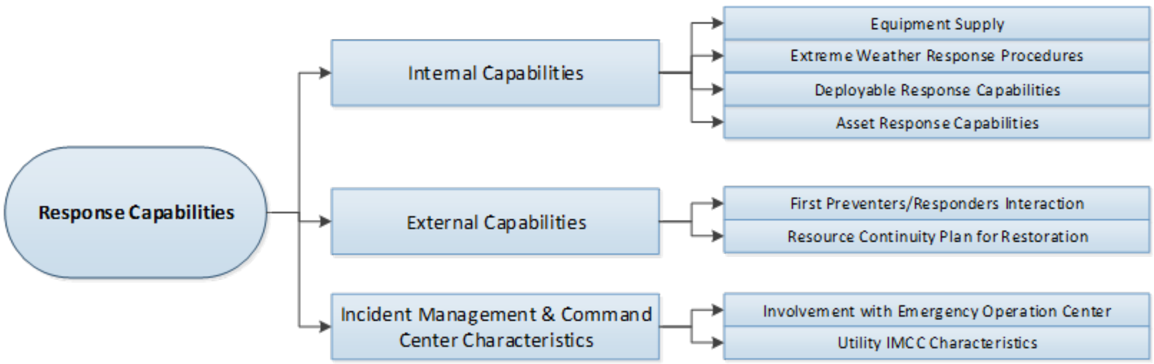

Figure 4.7. Resilience Components Contributing to Response Capabilities

Components contributing to response capabilities are aggregated using Equation 3 into a single value that varies from 0 to 100.

$$RCI = \sum_{i=1}^{3} c_i * X_i \qquad \text{Equation 3}$$

where:

RCI = Response Capabilities Index (ranging from 0 to 100);

c_i = scaling constant (weight; a number between 0 and 1) indicating the relative importance of possibility *i* (*i* = 1, 2) of response capabilities; and

X_i = index value of response capabilities component i (i.e., internal capabilities, external capabilities, and incident management and command center characteristics).

Recovery mechanisms characterize activities and programs undertaken at the asset level to efficiently and quickly restore the grid distribution system. Recovery mechanisms comprise around 50 components organized into 40 grouping categories. Figure 4.8 shows high-level groupings under recovery mechanisms.

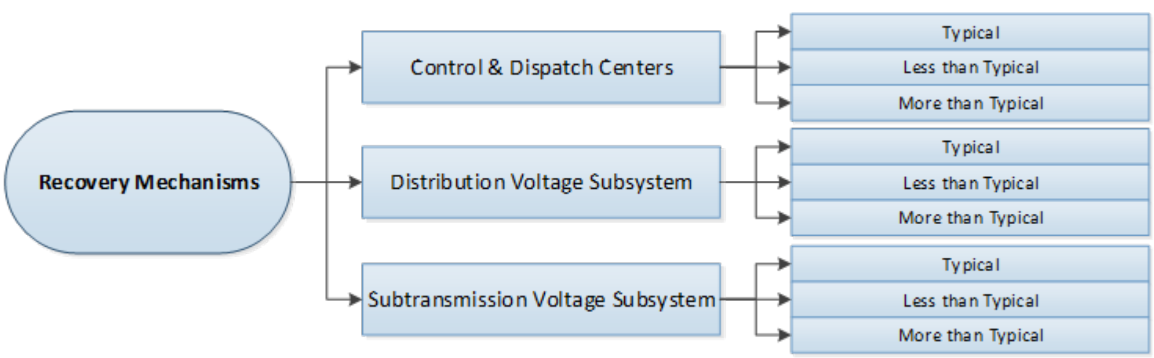

Figure 4.8. Resilience Components Contributing to Recovery Mechanisms

Components contributing to response capabilities are aggregated using Equation 4 into a single value that varies from 0 to 100.

$$ReMI = \sum_{i=1}^{3} d_i * W_i \qquad \text{Equation 4}$$

where:

ReMI = Recovery Mechanisms Index (ranging from 0 to 100);

d_i = scaling constant (weight; a number between 0 and 1) indicating the relative importance of possibility *i* (*i* = 1, 2) of response capabilities; and

W_i = index value of recovery mechanisms component *i* (i.e., control and dispatch centers, distribution voltage system, and subtransmission voltage system).

The four Level 1 indices (i.e., PI, MMI, RCI, and ReMI) are aggregated to calculate the RI. The overall aggregation formula is presented in Equation 5.

$$RI = \sum_{i=1}^{4} e_i * V_i \qquad \text{Equation 5}$$

where:

RI = Resilience Index (ranging from 0 to 100);

e_i = scaling constant (weight; a number between 0 and 1) indicating the relative importance of possibility *i* (*i* = 1, 2, 3, 4) of resilience; and

V_i = index value of resilience component *i* (i.e., PI, MMI, RCI, and ReMI).

After completion of the MCDA utility function, use cases should be conducted to perform the last three steps of the decision analytics approach to validate and refine the resilience metrics. These three last steps help to refine the data collection process to ensure the uniformity and reproducibility of the data collected by developing explanations, training, and quality assurance review. Visualization capabilities can be developed to perform sensitivity analyses on potential grid modernization options. An interactive dashboard can also be used to compare existing characteristics of the grid and future developments to determine if grid resilience has improved. The dashboard allows the user to see—in real time—the impacts of component modifications on the overall index value as well as on the specifically selected and modified components.

4.3.2.4 Creation of Alternatives

The next step consists of identifying or constructing alternatives. Each desired characteristic is represented by an objective that should be achieved to the greatest feasible extent, subject to factors such as time and cost, among others. The performance of each distribution system, and its assets, with respect to each of the objectives must be determined (i.e., characterized). Once this is accomplished, different combinations of specific resilience measures define a possible alternative. Given the preferences within and across the objectives characterized during the first step of the MCDA approach, it is possible to create alternatives that will integrate stakeholders' objectives and requirements.

4.3.2.5 Prioritization of Alternatives

After alternatives are characterized, the MCDA utility function can be used to prioritize alternatives that would enhance the resilience of the electric grid distribution system. Although prioritization processes may appear to yield a final recommendation, they should only be used as information to aid decision makers. As always, a review should be conducted to ensure each recommendation makes sense and no factors are missing from the analysis.

4.3.2.6 Sensitivity Analysis

The last step is the sensitivity analysis, which enables analysts to assess the importance of uncertainties in the criteria value judgments and scale measures.

Using decision analytics aids in analyzing existing measures at the asset and corporate levels and identifying ways to improve resilience. The indicators allow for comparison of like assets (e.g., substations or urban electricity distribution systems) by providing managers a report on both the strengths and weaknesses of their resilience posture. The ultimate objective is to provide insightful information to help decision makers make better-informed management decisions.

This project focused primarily on the three first steps of the decision analytics approach: defining the objectives and constraints and specifying the attributes and scales of the future electricity distribution system RI. This first phase contributed to the development of (i) a question set that allows one to gather all information and elements that characterize the resilience of the electricity distribution system and (ii) utility functions to calculate five indices (i.e., PI, MMI, RCI, ReMI, and ultimately the RI). The questions, MCDA structure, and resulting RI utility function are currently integrated in an excel spreadsheet. This tool will ultimately allow the gathering of the information needed for both the RI and to automatically calculate the five indices. To complete the operability of this tool, an elicitation is needed to gather the stakeholders' trade-offs and define the relative importance of each attribute included in the utility function. The last three steps of the MCDA approach, and the elicitation process, can be completed during the pilot testing and when applied to a case study.

The decision analytic approach allows decision makers to consider different objectives that contribute to the resilience of the grid and to assess the level of achievement of these objectives. This approach can be used as a screening tool to compare potential resilience enhancement alternatives and identify the ones that would constitute interesting options. A unique RI value and specific combinations of corporate and asset-level attributes will characterize each alternative. The MCDA approach provides the following results that can serve as inputs for the performance-based approach:

- 1,200 attributes characterizing both the electric power distribution system at both corporate and asset levels;
- Five indices characterizing the preparedness, mitigation, response, recovery, and overall resilience capabilities of the electric power distribution system. These indices allow comparison between different alternatives to enhance the resilience of the utility system;
- Possible options, which may represent a wide spectrum of cost alternatives, to enhance the resilience of the electric grid.

4.3.3 Performance-Based Approach

With the above documented requirements, the project has developed a set of grid resilience metrics and a process for calculating them. The metrics and process have been developed to accomplish the following:

- 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;
- Provide an effective, precise, and consistent means for utilities and the communities they serve to communicate about resilience issues;
- Leverage the attribute-based metrics to inform and catalogue the baseline resilience for the system being examined. The attribute-based metrics assist in targeting long-term resilience investments.

GMLC1.1 recommends grid resilience metrics be performance-based and, to the extent possible, 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, so consequence estimates may take the form of probability distributions.

Table 4.2**Error! Reference source not found.** includes a list of example consequence categories that could serve as the basis for resilience metrics. All consequence categories are measured for the defined system specifications and therefore may be measured across spatial (geographical) and temporal (duration) dimensions.

Table 4.2. 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 an outage during a specified 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 backup fuel required).
Monetary	Loss of assets and perishables. Business interruption costs. Impact on Gross Municipal Product or Gross Regional Product.
Other critical assets	Key production facilities without power. Key military facilities without power.

To include uncertainties, resilience metrics need to include a measure of consequences and the relevant statistical property from the probability distribution of those consequences. Table 4.3 lists examples of relevant statistical properties, and these properties should be combined with consequence categories to define resilience metrics. For example, mean time to recovery and probability that utility revenue losses will exceed $100 M are two examples of how consequence (time to recovery and utility revenue losses) and statistical properties (mean value and probability of exceedance) can be combined.

Table 4.3. Examples of Statistical Properties that Can Represent 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	A measure of the risk for a chosen probability. For example, a 5% Value at Risk of 1,000 means there is a 5% probability the distribution exceeds 1,000 units. 5% is a commonly selected probability for Value at Risk.
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; that is, CVaR considers a distribution's tail shape. For example, a 5% CVaR of 5,000 means the expected value of the largest *5*% of the distribution is 5,000.
Maximum/Minimum (Worst Case)	The largest/smallest predicted value; depending on the metric, it 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 CVaR accounts for a risk-averse approach that also takes into account average outcomes.

Though the goal is to identify metrics for quantifying grid resilience, it is just as important to describe the process for calculating those metrics. We recommend an extension of the Resilience Analysis Process (RAP), originally developed by Watson et al. (2015) for the 2015 Quadrennial Energy Review, be used to develop and apply grid resilience metrics. The RAP **Error! Reference source not found.**is a seven-step process that can be used to help specify resilience objectives for utilities, select the appropriate metrics that are reflective of those objectives, gather the necessary data to populate the metrics, and ultimately decide on the best path forward for making resilience-based decisions. The seven steps are as follows:

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, the specific goal could be to assess the resilience of a power system to a previous historical event. Alternatively, the goal could be to evaluate possible system improvements. In some instances, multiple goals may exist, such as assessing a historical event and evaluating options if the system was deemed not to be sufficiently resilient to the historical event. 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.

2. **Define consequence categories and resilience metrics.** In the context of a specified hazard, the RAP measures the resilience of a power system by quantifying the consequences of the hazard to the power system and other infrastructures and communities that depend upon the power system. The second step in the RAP is to select the appropriate consequence categories, which should reflect 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 other 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, healthcare, 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.). This**Error! Reference source not found.** includes a list of example consequence categories that could serve as the basis for resilience metrics. Data availability may also affect selection of consequence categories. Resilience analyses are not restricted to a single consequence category when developing metrics. Rather, the use of multiple consequence categories can be beneficial for representing various stakeholder perspectives.

3. **Characterize 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 prioritized, limited number of hazards or list of concerns. 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 affected by 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.

4. **Determine the level of disruption.** The fourth step is determining the level of disruption. This step specifies the level of damage or what stress 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 something like "substation X is nonfunctional due to being submerged by sea water, lines Y and Z are blown down due to winds," etc. Damage specification should not only indicate which assets are nonfunctional or degraded, but how severely the asset is impaired and what recovery steps are needed to repair overall system functionality.

5. **Collect consequence data via system model or other means.** When assessing the resilience of a power system in response to an actual, historical event, data collection can be typically performed by gathering system or community data that describe the magnitude and duration of the disruption to power delivery. Utilities maintain outage management systems, which are often a rich source of data for resilience analyses; however, these systems often lack details, such as the actual locations of the causes of the individual outages and information about system design and condition, for the largest events. 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 projects how the damage results in the load not being served. Multiple system models may be required to capture all 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 the systems models used how to assess the systems perform during the restoration period.

6. **Calculate consequences and resilience metrics.** When evaluating resilience, direct impacts on system output because of damage are only part of the story. Most energy systems provide energy for some larger social purpose (e.g., transportation, healthcare, manufacturing, economic gain). During this step, outputs from system models are converted to the resilience metrics that were defined during Step 2. When uncertainty is included in this process, probability distributions will characterize the resilience metric values.

7. **Evaluate resilience improvements.** Unless this process is being undertaken purely for assessment purposes, it is likely decisions must be made about how to modify operational decisions or plan

investments to improve resilience. After developing a baseline for resilience quantification by completing the preceding steps, it is possible and desirable to populate the metrics for a system configuration that is in some way different from the baseline to determine which configuration would provide better resilience. This could be a physical change (e.g., adding a redundant power line); a policy change (e.g., allowing the use of stored gas reserves during a disruption); or a procedural change (e.g., turning on or off equipment in advance of a storm).

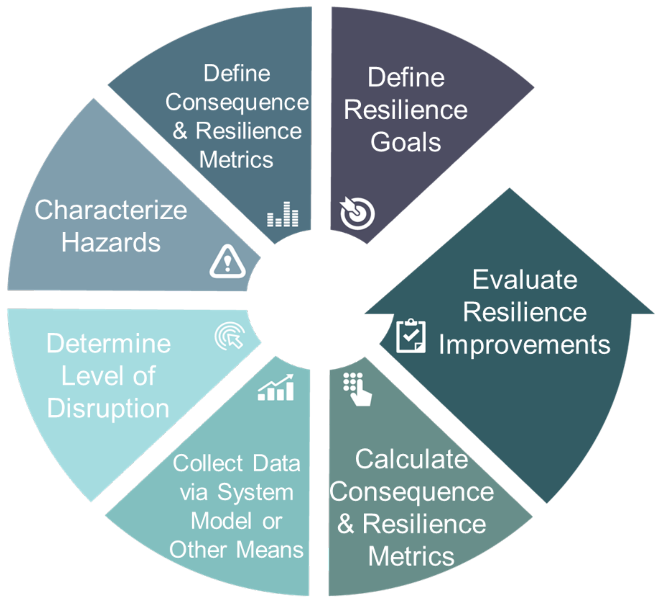

Figure 4.9. The Resilience Analysis Process (Watson et al. 2015)

Consider Superstorm Sandy and the impact it had on power delivery when it made landfall on the evening of October 29, 2012. The day after the storm hit, 8.7 million customers experienced power outages; 90 percent of those customers were in Long Island and over 1 million of Con Edison's 3.3 million customers were affected. In some areas, the impacts lasted for months. The following hypothetical application is presented to demonstrate how the RAP can be used in practice.

Consider that a hypothetical utility, Tesla Electric (Tesla), had its operations severely compromised by Superstorm Sandy. Tesla has identified two possible options for enhancing its resilience to future storms. Option A focuses on hardening 20 substations damaged by the storm and whose injury resulted in 80% of the lost load. Option B focuses on installing advanced metering infrastructure upgrades that would facilitate a more rapid restoration but not prevent any actual damage. Both options would also include installation of combined heat and power (CHP) in critical infrastructure assets, enabling photovoltaic (PV) systems to operate in islanded mode.

Table 4.4. Resilience Enhancement Options

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

Tesla chooses to evaluate the options by assessing how each would lessen potential consequences that could occur in the event of future storms. They are interested in consequences to their customers, the community they serve, and themselves. Specifically, Tesla selects three consequence categories: magnitude of power outages that could occur in the event of a future storm; estimated costs to Tesla for repairing the storm damage and recovering; and the number emergency service assets (e.g., hospitals and police stations) expected to be without power for more than 48 hours. These consequences establish the resilience metrics that Tesla will use to evaluate the two investment options.

Table 4.5. 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 borne 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* denote the number of hospitals, police stations, and fire stations, respectively, in Tesla's service region that lost power for more than 48 hours.

Given that no one can predict with complete certainty the precise characteristics of future storms, Tesla selects two storm scenarios for their analysis. The first scenario is a Superstorm Sandy-like event that is a Category 1 hurricane with Sandy-level flood ranges. The second scenario is a more severe storm, a Category 2 hurricane with more extreme flooding. Based on projections from the research literature, Tesla estimates the probabilities that Category 1 and Category 2 storm scenarios occur before 2100 are 33% and 17%, respectively.

For the two hurricane scenarios, the utility then projects the resulting level of damage on each component in the power system, leveraging their outage management system to characterize the damage inflicted by historical events like Sandy for different storm categories. For each critical utility component, the utility can assign a probability, conditional upon each of the two hazard scenarios and the options implemented, that the component will be damaged.

The utility then exercises their power flow model in a Monte Carlo simulation. In each realization, the following parameters are determined stochastically:

1. Category (1 or 2) of the storm: The individual probabilities 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 on critical assets. They use these data to calculate the expected values for each of the resilience metrics.

Simulation results describing Tesla Electric's results for each option are shown in Table 4.6**Error! Reference source not found.**. Mean consequences are reported. The 10th and 90th percentiles of the distributions are also included to illustrate the variability of the estimates.

Table 4.6. Simulation Results for Multiple Scenarios Describing Damage Uncertainty

Option	Disruption	Cumulative Customer-Day Outages (Millions)	Critical Facilities Outages	Cost of Recovery (M$)
	Mean	1.1	1	319
A	*10th %ile*	0.5	0	189
	90th %ile	1.35	8	330
	Mean	1.3	1	450
B	*10th %ile*	1.05	0	300
	90th %ile	1.46	8	500

The results in Table 4.6**Error! Reference source not found.** confirm that Option A, even with its higher investment costs, would likely provide greater 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.

The above example is a simplified version of how the RAP and grid resilience metrics could be applied to inform a set of resilience-related decisions. See Vugrin et al. (2017) for a more detailed discussion of the RAP and recommended grid resilience metrics.

4.3.4 Synergy of Combining Both Approaches to Meet Stakeholder Needs

A common roadblock to resilience projects has been convincing the owners of infrastructure to assume additional risk. Any investment on their part is a risk because the future payoff is unknown. The MCDA and performance-based approaches to forming resilience metrics have complementary uses within many decision-making processes. For example, the integrated resource planning process used by many electric utilities to suggest and evaluate alternative system investments can be augmented to include resilience goals by using both approaches. As shown in Figure 4.10, the MCDA approach is used as a screening process that supports development and ranking of high-level alternatives.

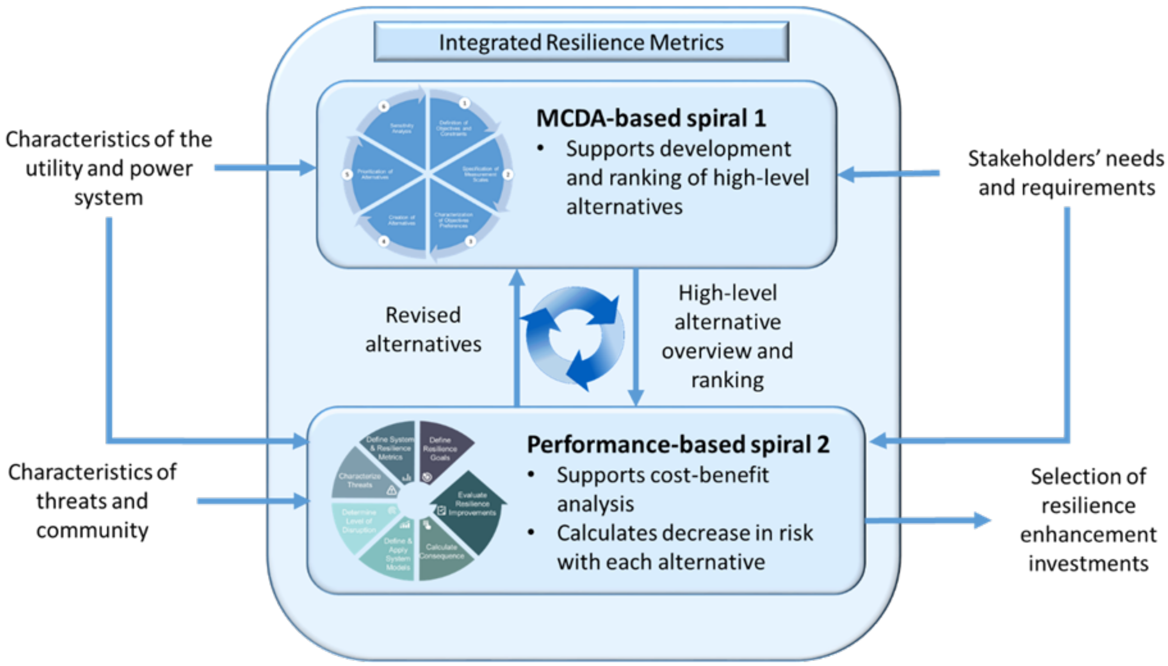

Figure 4.10. Integration of Resilience Metric Approaches

The two approaches lend themselves to multiple iterations within a single planning process; outputs from one approach becoming the inputs of the other approach. Table 4.7 illustrates the inputs and outputs of the two assessment spirals that define the transitions between the two analytic approaches.

Table 4.7. Inputs and Outputs for the Two Analytic Spirals

Inputs	Approach	Outputs
• Enterprise overall planning and management processes. • Characteristics of electricity distribution assets. • Electric distribution system alternatives. • Performance-based resilience enhancement options.	MCDA	• Characterization of the system-level distribution of preparedness, mitigation, response, and recovery capabilities. • Resilience index value of the distribution system, ranging between 0 and 100. • Ranking of electric distribution system enhancement alternatives.
• Characteristics of threats and community. • Consequence categories. • MCDA Alternatives and their RI values.	Performance-based	• Outage impact. • Recovery costs. • Community impact. • Resilience enhancement options.

As illustrated in Table 4.7, the MCDA approach centers on the resilience of the grid itself to characterize the resilience of the community served by the grid, while the performance-based approach also factors in other socioeconomic considerations. As a result, the combined approach facilitates a highly comprehensive analysis characterizing both the electric grid and community resilience benefits.

Consider the application of the combined approach in the context of electric utility planning. Utility planners can use the MCDA approach to understand where their system could benefit most from resilience investment—whether through better preparedness, mitigation, response, or recovery procedures. Resilience is a cumulative effect of many individual decisions by many unique actors within a system. To understand the outcome of decisions by stakeholders, there must be a mechanism for comparison. This is especially important when achieving system-level resilience requires coordination among numerous private and public entities. Because this phase also lends itself to comparison across utilities, planners can gain insight into the relative importance of additional resilience instead of investments in other system goals, such as sustainability or efficiency. This high-level gap analysis feeds into the performance-based approach, which can calculate a baseline risk and suggest several refined alternatives for improving the attributes identified as gaps in the first phase. The planner may benefit from an additional iteration that again uses the MCDA approach to rank and filter new design alternatives based on the planner's unique insight and results from the first use of the performance-based approach. The new alternatives and their ranking defined by the MCDA will again feed the performance-based approach to evaluate the subset of alternatives that have been identified as most promising by the attribute-based approach.

4.3.5 Additional Considerations

In addition to intrinsic characteristics of the MCDA and performance-based approach, other considerations guide the development of resilience metrics and analysis.

First, the MCDA approach provides an index value based on the aggregation of attributes characterizing the electric grid distribution system. Each of these attributes has been weighted by subject matter experts to indicate its relative importance to the electric grid distribution system's resilience. The value of the index ranges between 0 (low resilience) and 100 (high resilience). A high index value does not mean that a specific event will not affect the grid distribution system or have severe consequences. Conversely, a low index value does not mean that a disruptive event will automatically lead to a failure of the grid and to serious consequences. The RI value, instead, is used to compare the level of resilience of different alternatives and to inform the performance-based approach.

Second, the availability of computer modeling and simulation tools that can be used to inform grid resilience analysis and planning is relatively limited. PJM and Sandia National Laboratories are currently piloting computer modeling tools for a limited number of hazards. However, additional research and development is needed to expand the hazards that can be analyzed using similar computer modeling capabilities. In addition to the research and development of these tools, demonstration applications are needed on actual power systems to validate the tools and provide stakeholders with sufficient confidence in the results.

Third, the use of probabilistic measures for grid analysis may represent a culture shift for some grid stakeholders. Effectively communicating risk and probabilities is a common challenge, so it should be noted that the use of probabilistic grid resilience metrics may face similar challenges.

Fourth, grid resilience decisions are (almost) never made without consideration of more traditional grid measures, such as reliability. When evaluating grid resilience enhancement options, grid stakeholders simultaneously consider the potential effects the options could have on reliability, sustainability, and other measures. In some instances, changes can be beneficial to grid resilience and other measures; in others, a change can benefit resilience but have a negative impact on other measures. Ultimately, grid operators and stakeholders evaluate the potential trade-offs before taking actions. Decision-making should therefore consider all GMLC1.1 metrics to enhance the performance of the electric grid.

4.4 Scope of Applicability

4.4.1 Asset, Distribution, and Bulk Power Level

The metrics are reasonably well suited for distribution and bulk power systems. They are generally not applicable to individual assets such as an individual transformer or individual line. However, attributes characterizing general subtransmission and distribution voltage lines are considered in the MCDA approach.

4.4.2 Utility Level

The metrics have been specifically designed for use at the utility level. Pilot studies of the performance-based approach have been conducted at this scale in the City of New Orleans. This project specifically assesses the possibility of implementing microgrids to enhance the city's resilience.

4.4.3 State Level

The metrics have not been designed for use at the state level.

4.4.4 Regional Level

The metrics are potentially useful at a community or regional scale; exact geographic distribution, though dependent upon the power system, is determined by the extent of the power distribution system, the communities, and the infrastructure systems that are included within the study.

4.4.5 National Level

The metrics have not been designed for use at the national level. Like State level application, this would require additional system modeling capabilities to assess the functioning of the grid and its interdependencies with other critical infrastructure systems.

4.5 Value of Resilience Metrics

As noted by NARUC, there is a need for grid metrics that can be used to measure and plan for low-probability, high-consequence disruptions to the grid. Reliability metrics were not designed for these situations, so there is a recognized gap. Resilience metrics are intended to address that gap.

The hybrid resilience metrics method, combining MCDA techniques and the RAP, is specifically designed to help utilities plan for and respond to these kinds of events. The methodology is well-tailored to identify enhancement alternatives and prioritize planning and investment decisions. It also provides a uniform, repeatable process for conducting resilience analyses. Its rigor, transparency, and repeatability can help remove some of the ambiguity around resilience and facilitate precise, detailed conversations between utilities and grid stakeholders. Finally, the inclusion of uncertainties with resilience metrics helps provide a more comprehensive understanding of how the grid will perform in the event of a hazard and how much potential mitigations will truly benefit the utilities and dependent communities.

4.6 Feedback from Stakeholders

- This section summarizes the feedback the research team received from domain experts regarding the resilience metrics definitions, the relevance to the community's needs, the overall value of monitoring progress as the grid evolves, and the development of the hybrid resilience metrics. Reliability and resilience are closely related. The impact metrics of failed reliability and/or failed resilience are outages measured by their extent (i.e., number of customers or load affected) and by their duration. The difference between reliability and resilience is that, for resilience, those threats or operational hazards that are considered are more severe than those for reliability and include off-design conditions, such as exposure to hurricanes and flooding.
- It is not clear whether any measure performed to increase resilience will also improve reliability. What was observed in the aftermath of Hurricane Sandy was that improved resilience increased the flexibility of the grid such that circuits could be sectionalized and switched.
- Collaboration with industry: As part of a GMLC regional partnership project with New Orleans, the local utility company (i.e., Entergy) is collaborating with DOE laboratories to work on resilience analyses using the laboratories' approach.
- Value to the community: It is very important from a recovery assistance perspective to have transparent and repeatable methodologies developed that prioritize investment options for improving the resilience of any infrastructure. The approach developed here for the electric grid will hopefully be employed across all sectors, so we understand better how risk affects the resilience of our communities.
- Implementation of resilience metrics and analysis processes: 1) regulators could require reporting of resilience assessments, and 2) recovery funding from federal sources could require some prior resilience assessment as part of the request for recovery funding.
- The methodology described in this document is not yet standardized in a tool that is available either as an open source product or through commercial vendors. Individual components, such as power flow models, exist, but many other analytics are employed to perform a full risk-based hazard/threat assessment and perform modeling to estimate the improved system behavior and operational survivability of grid assets relative to a given threat.
- Regarding retrospective versus prospective views of resilience, several of the participants noted the importance of forward-looking metrics because their organizations tend to pose forward-looking analysis questions, such as how to prioritize investments to achieve improved resilience.
- The ability to represent uncertainties in metrics is needed, but it is expected to be a challenge. Representing uncertainties provides a more realistic picture of confidence in consequence estimates; however, probabilistic metrics may represent a culture shift and take some getting used to.
- The spatial scope of the analysis may dictate the complexity of the resilience assessment. For instance, assessment of cities or metro areas with highly integrated infrastructure systems may require analysis of failed(?) interactions. However, resilience analyses for a regional transmission organization area may focus on the electric grid because the interactions with other infrastructures are weak or loosely coupled.
- Several stakeholders (i.e., City of New Orleans, Entergy, NERC) showed interest in the methodology. However, due to the range of other projects and priorities requiring their attention, they were not able to apply the methodology to real case studies. They provided general feedback on the MCDA survey and the importance of considering both asset-level and system-level attributes. They also emphasized the need to differentiate between substation assets and control

centers in terms of resilience while reducing the burden of data collection by avoiding characterizing a utility's individual substations.

- The organization of the MCDA RI in terms of preparedness, mitigation, response, and recovery was also well received by utilities and the NERC Critical Infrastructure Protection Committee. Stakeholders are familiar with these traditional phases of emergency management and understand that using this terminology to develop the MCDA utility function simplifies the interpretation of the index value.
- The combination of MCDA and performance-based approaches received positive feedback when presented in scientific conferences. Audiences reemphasized the importance of combining socioeconomic and technical elements that characterize the resilience of not only the electric grid but also of the communities served by the grid.

The stakeholder feedbacks gathered during the project directly guided the development and refinement of the resilience metrics.

5.0 Next Steps

The MCDA approach still needs to be finalized. After the completion of the utility function for characterizing the resilience of the electric grid distribution system, additional work should be conducted to develop similar approaches for the two other main components of the electric grid (i.e., transmission and generations subsystems).

The two approaches, MCDA-based and performance-based, have been developed independently. Use cases will be conducted to combine and validate the two approaches. This will allow for testing of not only how the hybrid methodology would be applied to address stakeholder concerns and requirements but also to conduct a sensitivity analysis to refine the resilience metrics.

The modernization of the grid does not encompass only resilience enhancement. Several other metrics (i.e., reliability, sustainability, flexibility, affordability, and security) are currently being developed by the GMLC to address several characteristics that will constitute the future of the grid. An approach to synthesizing all these metrics and providing an overview of potential enhancement options for the grid is yet to be developed.

Finally, the grid does not operate in isolation. There are several operational interdependencies with other critical infrastructure sectors and public/private owners of infrastructure. It is important to include the modernization of the grid in a more comprehensive risk and resilience management program, including the different elements characterizing a region or a jurisdiction.

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Appendix A

Metrics Inventory

Appendix A

Metrics Inventory

A.1 Resilience

A.1.1 Data

	Categorization			Summary											Historical Supporting Data - Lagging Metrics				
Metric #	Sector	Category *(from list)*	Electric System Infrastructure Component *(from list)*	Metrics Name	Description	Motivation	Units	Metric Type *(from List)*	Metric Classification *(from List)*	Metric Use *(from List)*	Primary User *(from List)*	Secondary User *(from List - if applicable)*	Metrics Tense *(Lagging/ Leading)*	Applicable to Valuation Project *(Yes/No)*	Data Available? (Yes/No)	Geospatial Resolution *(from list)*	Temporal Frequency of Data Reporting *(from list)*	Citation/Data Source Reference #	Potential Issues/ Comments
1	Electricity	Resilience	Transmission system, Distribution system	Electrical service, measured with one or more of the following units: Cumulative customer-hours of outages; Cumulative customer energy demand not served; Average number (or percentage) of customers that experience an outage during a specified time period				Quantitative, Numerical	Outcome	Decision-Making, Learning	Utility, System Operators	Communities, federal/state/local agency/regulator	Leading (primarily), but also lagging; depends on particular analysis and usage	Yes	Yes, in some cases (e.g., OMS have much outage data)	Interconnection, RTO, state, utility service area, distribution system footprint, customer footprint	TBD: triggers for calculations could be change in hazard conditions, new investment planning initiative; perhaps an annual review		Note: for leading metric analyses, consequence data may include uncertainty, i.e., be characterized as a probability distribution, histogram, mean and standard deviation, etc. In addition to selecting the consequence categories, it is important to select the appropriate statistical property (e.g., mean, value at risk, maximum, minimum, etc.) that best fits the analysis and risk tolerance of the interested parties.
2	Electricity	Resilience	Transmission system, Distribution system	Critical Electrical Service, measured with one or more of the following units: Cumulative critical customer-hours of outages; Critical customer energy demand not served; Average number (or percentage) of critical loads that experience an outage				Quantitative, Numerical	Outcome	Decision-Making, Learning	Utility, System Operators	Communities, federal/state/local agency/regulator	Leading (primarily), but also lagging; depends on particular analysis and usage	Yes	Yes, in some cases (e.g., OMS have much outage data)	Interconnection, RTO, state, utility service area, distribution system footprint, customer footprint	TBD: triggers for calculations could be change in hazard conditions, new investment planning initiative; perhaps an annual review		
		Resilience	Transmission system, Distribution system	Restoration, measured with one or more of the following units: time to recovery, cost of recovery				Quantitative, Numerical	Outcome	Decision-Making, Learning	Utility, System Operators	Communities, federal/state/local agency/regulator	Leading (primarily), but also lagging; depends on particular analysis and usage	Yes	Yes, in some cases	Interconnection, RTO, state, utility service area, distribution system footprint, customer footprint	TBD: triggers for calculations could be change in hazard conditions, new investment planning initiative; perhaps an annual review		
		Resilience	Transmission system, Distribution system	Monetary, measured with one or more of the following units: Loss of utility revenue; Cost of grid damages; Cost of recovery; Avoided outage cost				Quantitative, Numerical	Outcome	Decision-Making, Learning	Utility, System Operators	Communities, federal/state/local agency/regulator	Leading (primarily), but also lagging; depends on particular analysis and usage	Yes	Yes, in some cases	Interconnection, RTO, state, utility service area, distribution system footprint, customer footprint	TBD: triggers for calculations could be change in hazard conditions, new investment planning initiative; perhaps an annual review		

	Categorization			Summary											Historical Supporting Data - Lagging Metrics				
Metric #	**Sector**	**Category *(from list)***	**Electric System Infrastructure Component *(from list)***	**Metrics Name**	**Description**	**Motivation**	**Units**	**Metric Type *(from List)***	**Metric Classification *(from List)***	**Metric Use *(from List)***	**Primary User *(from List)***	**Secondary User *(from List - if applicable)***	**Metrics Tense *(Lagging/ Leading)***	**Applicable to Valuation Project *(Yes/No)***	**Data Available? (Yes/No)**	**Geospatial Resolution *(from list)***	**Temporal Frequency of Data Reporting *(from list)***	**Citation/Data Source Reference #**	**Potential Issues/ Comments**
		Resilience	Transmission system, Distribution system	Community function, measured with one or more of the following units: 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); Key production facilities without power Key military facilities without power ;				Quantitative, Numerical	Outcome	Decision-Making, Learning	Utility, System Operators	Communities, federal/state/local agency/regulator	Leading (primarily), but also lagging; depends on particular analysis and usage	Yes	Yes, in some cases	Interconnection, RTO, state, utility service area, distribution system footprint, customer footprint	TBD: triggers for calculations could be change in hazard conditions, new investment planning initiative; perhaps an annual review		
		Resilience	Transmission system, Distribution system	Monetary measurements for the community, measured with one or more of the following units: Loss of assets and perishables; Business interruption costs; Impact on Gross Municipal Product (GMP) or Gross Regional Product (GRP);				Quantitative, Numerical	Outcome	Decision-Making, Learning	Utility, System Operators	Communities, federal/state/local agency/regulator	Leading (primarily), but also lagging; depends on particular analysis and usage	Yes	Yes, in some cases	Interconnection, RTO, state, utility service area, distribution system footprint, customer footprint	TBD: triggers for calculations could be change in hazard conditions, new investment planning initiative; perhaps an annual review		

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